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Nicole Zibrid, BSc

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Dedicated to my mother.

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List of abbreviations

ADP	Adenosindiphosphat
ATP	Adenosintriphosphat
AU	Astronomical Unit
CAM	Crassulacean acid metabolism
CCN	Cloud condensation nuclei
CIA	Cloud interstitial aerosols
CME	Coronal mass ejection
EM	Electromagnetic
HRD	Hertzsprung Russell diagram
IR	Infrared
L	Luminosity, sometimes L-type star → known from the context
LC	Light compensation
LS	Light saturation
M	Mass
NADP+	oxidized form of Nicotinamidadenindinukleotidphosphat
NADPH	Nicotinamidadenindinukleotidphosphat
PAR	Photosynthetic active radiation
PS	Photosystem
PS I	Photosystem I
PS II	Photosystem II
RS	Rayleigh Scattering
RTM	Radiation Transfer Model
SED	Spectral energy distribution
T_{eff}	Effective Temperature
TOA	Top of the atmosphere
UV	Ultraviolet
X-ray	X-radiation

1 Introduction

In the last decades the discoveries of extrasolar planets increased on the basis of recent and precise technologies.

The detection of larger planets like Jupiter-like planets and Super-Earths is much easier than to detect a planet that is Earth-like or smaller sized. But the origin from low mass planets is not more unlikely than the formation of planets with greater masses than Earth.

Since it is known that stars with smaller masses, like M-stars, are more common in the universe than high mass stars they became a target for the search for life-as-we-know-it. They are interesting on the basis of a few properties. The most important characteristic of M-stars is that they are long-lived. This gives living organisms the chance to originate and evolve. This means that they are great examples for potentially habitable worlds.

Negative properties are also present. They show a strong activity in their younger age and are therefore predicted to be harmful to life. It is possible that during the evolution of an atmosphere strong stellar winds and CMEs could prevent the evolution or destroy a nascent atmosphere. But there is no reason why, after destroying the first, a second atmosphere could not evolve, if there is still enough material for outgasing processes available.

It is also likely that an atmosphere of a planet that has evolved around another star has a completely different composition than the Earth has or even the planets in our solar system. This has to be taken into account because the molecules of an atmosphere have influences on the incoming radiation.

Another disadvantage of M-stars is their radiation. They have a limited flux and another energy distribution of the spectra due to their low mass. The maximum wavelength of the sun is located around 501 nm. In contrast the maximum wavelength of M-stars is approximately situated above 1000 nm, and therefore is positioned in the IR.

This is a disadvantage for plants. Plants, as we know them here on Earth, use the blue and red part of the spectrum to assimilate carbon hydrates and the essential oxygen. It is unknown if there is enough radiation in the red part of the spectra or if M-stars also emit a few, but not much, photons with higher energy levels to start photosynthesis.

That photosynthesis is possible on Earth with the known atmospheric composition and the present distance to the sun is committed. But also of prime importance is the question if plants are also able to produce oxygen during other planetary situations. A change of the atmospheric composition could lead to other absorption- and scattering-effects and shorter or longer distances to the host star could change the received radiation in a harmful way. The possibility of life-as-we-know it in the form of plants is therefore arguable but not excluded.

Therefore the aim of this master's thesis is to prove the possibility of using the radiation of M-stars and G-stars for photosynthesis of higher plants as we know them on Earth.

Different atmospheric compositions are chosen for the test planets and for calculating the changes of the radiation by passing through these different atmospheres. The model used for the thesis is based on the software Streamer. Streamer is a public domain code from J. R. Key and A.J. Schweiger (1998) [Ludwig et al., 2015]. It was modified by D. Neubauer in his thesis 'Modellierung des indirekten Strahlungseffekts des Hintergrundaerosols in Österreich' (2009) (see [Neubauer, 2009]). D. Neubauer expanded the code with a cloud model and a radiative convective model.

Because of this modifications it is possible to expand the configurations of the chosen setups to atmospheres with and without clouds.

First of all I will give an introduction about the stars which were selected as host stars for the planetary systems. The most important properties as well as the positive and negative properties for the evolution of planets and phototrophic organisms will be explained in more detail. This includes oxygenic and anoxygenic photosynthesis.

In chapter 3 I will present the most important characteristics of an atmosphere. The general structure, the cloud formation and the factors that have to be taken into account if radiation passes through an atmosphere will be explained primarily on the basis of the Earth's atmosphere, in accordance with the fact that this is the best investigated. Furthermore the atmospheres of the two test planets and Titan, which is the largest moon of Saturn and the only one with an atmosphere, will be presented. Also the influence of tidal locking on planets that are close to their host stars has to be explained.

Chapter 4 deals with photosynthesis. The fundamental information will be clarified to establish a general understanding for one of the most complicated biological processes that still is not fully understood yet.

Furthermore important effects and factors, like the Emerson effect and the limiting factors, will be defined because they show basic properties of the photosynthetic process that are also important for the interpretation of the generated results.

Different kinds of photosynthesis have also to be taken into account: oxygenic and anoxygenic photosynthesis as well as plants with different CO₂ fixation processes to adapt to arid areas.

In chapter 5 and 6 I will go into detail about the code and the setup for the models as well as the presentation of the computed results.

The last chapter will be concerned with the conclusion, the interpretation of the results and a discussion whether enough photons are emitted from the host star, if photosynthesis is possible and as active as on Earth and if it produces oxygen in the same amount as on Earth.

2 Host Star

2.1 Introduction

To investigate the possibility of photosynthesis a host star for the test planet has to be chosen.

In this case the decision has been made for two different spectral classes, each with a different distances of the planet in the system to the host star.

The first host star will be an M-type star where the test planet is situated inside a zone where water can be liquid (~ 273 K - ~ 373 K).

The second host star will be a G-type star where the test planet is not situated inside a zone where water can be liquid. The borders of the zone for the liquid water will be calculated and the planet will be located closer to the star and farther away from the star thus lying outside the zone.

The categorisation of stars by means of their spectra in a spectral class defines their properties and their evolution.

The spectra are classified in the following sequence:

O B A F G K M L T.

The order of letters has a historical background [Unsöld and Baschek, 2005]. First of all the sequence started with A but then it was discovered that the order is most of all based on the temperature [Weigert et al., 2009]. O and B stars are more bluish coloured, A, F and G-types are defined as yellow and G- and M-type stars are more red [Unsöld and Baschek, 2005]. The basis of the classification are the absorption lines in the spectra [Weigert et al., 2009]. Due to that a few letters were rejected and the order was changed to the nowadays known sequence. For a better differentiation another system has been added. 10 Subclasses (0 to 9) can be coupled on the spectral class [Weigert et al., 2009].

In Figure 2.1 the correlation between the surface temperature and therefore the spectral class (M coldest, O hottest) and the luminosity can be seen. This diagram was investigated by Ejnar Hertzsprung and Henry Norris Russel and is therefore called the Hertzsprung-Russell-diagram [van den Broek and Russo, 2014]. It has to be mentioned that these two scientists discovered this relationship independently [van den Broek and Russo, 2014].

Most of the stars are located in the so called ‘Main sequence’ [Unsöld and Baschek, 2005]. Here the stars are in thermodynamic equilibrium and hydrogen burning is the main energy source. The main difference of the spectral classes is, as mentioned before, the surface temperature [Weigert et al., 2009]. This is also indicated by the change in the colour from bluish-white to yellow and to red [Weigert et al., 2009]. At the left top of the diagram the stars are the most luminous ones [van den Broek and Russo, 2014]. They also have a higher surface temperature (T_{eff}) [van den Broek and Russo, 2014]. Following the main sequence down to the right lower end the surface temperature drops and the colour becomes reddish.

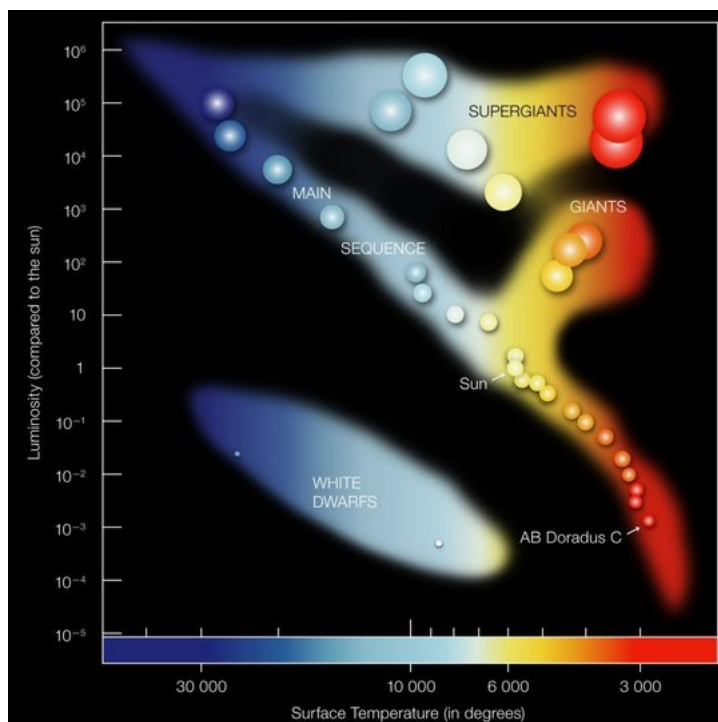


Figure 2.1: Hertzsprung-Russell-Diagram [Max Planck Society, 2003-2015]

For our purposes the G-type and M-type stars are the most important ones. They are situated in the right lower corner of the HRD. So they have lower surface temperatures and weaker luminosities. O and B stars can be excluded for the search for habitable planet because they are not long-lived enough. L and T stars were added later to the sequence (1999, 2002) to imply cooler stars like brown dwarfs [Weigert et al., 2009] and can also be excluded.

For the research I selected the G-type due to the fact that it is already known that is possible for plants to use the red and blue wavelength range of the visible spectrum for photosynthesis. The important question here is if it is also possible if the planet is not situated in a zone where water can be fluid. Affects the location of the planet the atmosphere in a way that the spectra of the star after passing through it not longer applicable for photosynthesis?

The second selected case will discuss the M category and their spectra. They are very different to comparison G-type stars. The characteristics will be discussed in the following chapters. Therefore the question if photosynthesis is possible with M-stars as host stars can not be answered in an intuitive way.

2.2 M-Star

2.2.1 Characteristics

M-type stars show a few characteristics that make them interesting for the search for extraterrestrial life-as-we-know-it. Otherwise some properties also speak against this possibility.

The major advantage is that there are a lot stars of this spectral class in the Universe. Even 75% of the stars belonging to the solar environment are members of the M class (see Figure 2.2) [Lissauer, 2007] and could be the central star of a planetary system [Engle and Guinan, 2012].

M-stars are located at the bottom of the main sequence (see figure 2.1) [Schreiber, 2006].

Main features (see [Schreiber, 2006]):

- T_{eff} : 2600 - 3800 K
- L : 0.003% - 3% $L_{\odot}$
- M : $\sim 30\%$ $M_{\odot}$
- Age: 100×10^9 yr

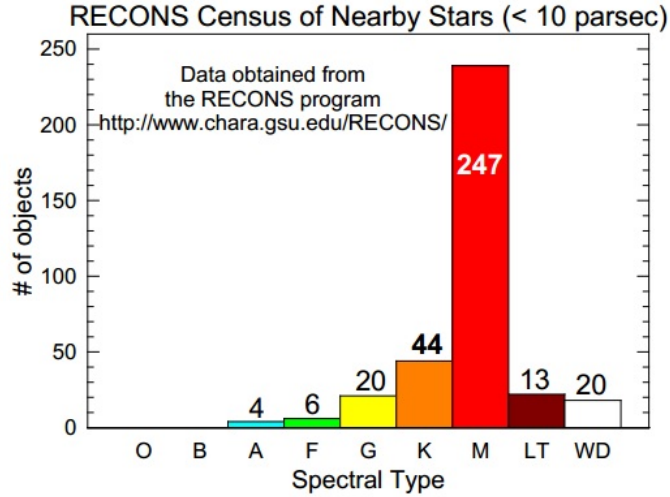


Figure 2.2: Number of known stars in the solar environment within 10 pc, M stars are by far the most common spectral class [Engle and Guinan, 2012]

To summarize the nature of this category of stars: They are a target for exoplanet search because they are very numerous [Scalo et al., 2007]. Due to the principle of planet formation it is also possible that the majority of planets is located around an M-star. Otherwise it is debatable if many planets form in a narrow zone very close to the host star [Schreiber, 2006] which is necessary because of habitability reasons.

Furthermore spectral classes often cover a wide range of masses. The mass range of M-stars is in between of 0.6 and 0.08 $M_{\odot}$ [Scalo et al., 2007], where the lower limit is the natural boundary to brown dwarfs (no energy production via nuclear reactions) [Heath et al., 1999]. Therefore they also cover a wide range of luminosities.

Table 2.1 shows different characteristics of stars of the M dwarf category compared to the Sun running from 0 to 9 (hottest to coldest) and luminosity class V (main sequence) [Tarter et al., 2007].

Spectral type	Temperature [K]	Mass [$M_{\odot}$]	Luminosity [% $L_{\odot}$]
Sun (G2V)	5800	1.00	100
M0 V	3900	0.50	6
M3 V	3600	0.29	3
M6 V	3000	0.10	0.5
M9 V	2400	0.08	0.02

Table 2.1: Characteristics of M Dwarfs, adapted from [Tarter et al., 2007]

Also the ratio of different wavelengths on the SED changes from a M0 to M9 star [Buccino et al., 2007].

M0: 1.9% of the flux lies in the visible range, 16% in the IR [Buccino et al., 2007]

M9: $1.4 \times 10^{-14}\%$ in the visible range, 0.13% in the IR [Buccino et al., 2007]

However, the brightest M-star, which is an M0 star, has a 10 times weaker luminosity than the Sun [Scalo et al., 2007]. This also leads to the long lifetimes of a few 100×10^9 years on the main sequence [Engle and Guinan, 2012].

The luminosities of about $0.0008 L_{\odot}$ to $0.06 L_{\odot}$ [Guinan and Engle, 2009] lead to a liquid water zone (LW zone) which is very close to the star. Due to that a planet situated in that zone will be tidally locked [Segura et al., 2010]. For more see paragraph 2.2.4.1.

The fact that a planet in the LW zone always shows the same side to the host star goes hand in hand with other properties of M-stars. On one side young M-stars are 10^9 years of their lifetime very active [Schreiber, 2006]. They emit energetic particle fluxes, UV-radiation, CMEs, X-rays and stellar winds [Khodachenko et al., 2007]. For further information see subchapter 2.2.3.

Another possible problem could be that red stars emit less radiation in the optical and blue part of the spectral energy distribution [Scalo et al., 2007] than the plants of the earth are familiar with. The maximum of the SED of M-stars is situated near the IR region [Weigert et al., 2009]. This is due to their low effective temperature [Segura et al., 2005]. The lack of PAR could be a problem for the photosynthetic activity of plants and thereby also for the O_2 production. In fact the spectra of M-stars are dominated by molecular absorption bands [Weigert et al., 2009], especially titanium oxide where the absorption bands are situated between 459 and 625 nm [Segura et al., 2005]. This

leads to missing radiation in a wavelength area between 400 and 720 nm, caused by this absorption bands [Schreiber, 2006].

On the other hand the fact that the planet is most likely rotationally bound could here be advantageous. Thus, one side is always illuminated and gets the maximum dose of radiation that the star irradiates [Schreiber, 2006].

2.2.2 Radiation

It is not easy to find a complete spectrum of a M-star [Segura et al., 2005]. The UV flux of M-stars is rarely existing and therefore it is not detectable, even with space telescopes [Segura et al., 2005]. The emitted UV flux is too low [Segura et al., 2005]. To receive a spectra that is covering the full wavelength range observations in the UV, IR and visible have to be synchronised [Segura et al., 2005]. For the M-star AD Leonis there is a time-averaged spectrum [Segura et al., 2005].

The spectrum is supposed to extend from ~ 300 nm to the IR wavelengths [Engle and Guinan, 2012].

The UV radiation that is emitted from non active M-star is marginal compared to the output of the sun [Heath et al., 1999]. The IR and visible spectrum shows molecular absorption bands [Tarter et al., 2007]. This is due to the low temperature of this spectral class [Tarter et al., 2007]. TiO and VO are the most prominent absorption bands in the optical range because they have a high opacity in this wavelength region [Tarter et al., 2007]. The IR part of the spectrum is influenced by steam and CO features [Tarter et al., 2007].

The variability of the dwarf stars ends by reaching the main sequence [Engle and Guinan, 2012]. Due to their slow nuclear fusion and therefore slow evolution the luminosity and effective temperature remains mostly constant for a certain mass [Engle and Guinan, 2012]. This supports the origin and evolution of life-as-we-know-it [Engle and Guinan, 2012].

PAR: The TiO_2 absorption bands mentioned before lead to a visible difference between the M-star SED and a black body energy distribution [Heath et al., 1999].

Heath et al.(1999) mentioned in his publication that there should be still enough PAR emitted for photosynthesis [Heath et al., 1999]. What has to be taken into account are the atmosphere, the contained clouds and the lower PAR due to the larger pathway through the atmosphere if the plants are not located in the substellar point [Heath et al., 1999].

Another disadvantage related to the tidal locking will be the constant radiation angle of the host star. Higher plants will stand in their own way so that the upper leaves offer shade to the lower leaves and shield them from the needed radiation [Heath et al., 1999].

Otherwise the tidal locking leads to permanent irradiation and thereby to more photon exposure and more received energy. Also the scattering of shorter wavelengths can lead to more energy that will be received from organisms.

If the SED of M-stars covers the needed wavelength range of chlorophyll for photosynthesis this is one of the main question of this treatise.

The maximum wavelengths of M-stars, calculated with the temperatures of table 2.1, between 2400 K and 3900 K are situated in the IR part of the spectrum. Therefore the (anoxygenic) IR photosynthesis should be taken into account. Bacteria use anoxygenic photosynthesis (exclusion: Cynobacteria), and probably the oxygenic photosynthesis has evolved from this kind of phototrophy [Madigan et al., 2012].

Chlorobium (green sulfur bacteria) particularly use light at wavelengths of about 840 nm [Heath et al., 1999].

Further IR photosynthetic bacteria are (see [Heath et al., 1999]):

Rhodospirillum rubrum and Rhodopseudomonas capsulata (purple non-sulphurate bacteria): 870 nm

Chromatium (purple non-sulphur): 890 nm and

Rhodopseudomonas viridis (form of bacteriochlorophyll b): 960 nm.

2.2.3 Stellar Activity

Young M-stars are very active [Segura et al., 2005]. Stellar winds, energetic particle fluxes and CME (coronal mass ejections) [Khodachenko et al., 2007] as well as flairs of emitted UV and X-rays [Segura et al., 2005] can harm possible life-as-we-know-it. These events could provide enough energy to erode the atmosphere of a planet [Grießmeier et al., 2009].

Flairs, stellar cosmic rays and CMEs are counted among chromospheric and coronal phenomena [Scalo et al., 2007].

The strength of such an event depends on the rotation rate and the convective interior which generates a magnetic field [Khodachenko et al., 2007].

If the convection zone gets deeper or the rotation rate increases the magnetic dynamo gets stronger [Khodachenko et al., 2007] and leads to more massive stellar flairs [Tofflemire et al., 2011]. Stars at the age of less than 0.5×10^9 years have a rotation period between 0.5 and 10 days [Engle and Guinan, 2012].

The convective zone of a star gets deeper and larger when the stellar mass is getting less [Khodachenko et al., 2007].

The interaction between the dipole structure of a magnetic field and the atmosphere of a star drives disturbances [Tofflemire et al., 2011]. The differential rotation and convection leads to a environment that is unstable [Tofflemire et al., 2011]. The field lines of the magnetic field are fixed at their basis but swell and lift up from the stellar surface [Tofflemire et al., 2011]. This configuration leads to higher luminosities and temperatures and accumulates huge amounts of energy [Tofflemire et al., 2011]. The collapse of this structure results in an output of energy [Tofflemire et al., 2011].

The magnetic field and the activity is also connected to the age [Scalo et al., 2007]. As mentioned

before, the strength of the stellar activity depends on the rotation rate [Tarter et al., 2007]. This leads to the assumption that the magnetic field is generated by a dynamo [Tarter et al., 2007], as in our Sun. The angular momentum is reduced by the release of stellar winds and via losing angular momentum with time. So the dynamo, which generates the magnetic field, gets weakened [Engle and Guinan, 2012]. Therefore the coronal events lose strength with growing stellar age [Engle and Guinan, 2012].

Figure 2.3: Age 0 describes the reaching of the main sequence. While F-stars undergo a transformation in luminosity rapidly G-stars show a constant luminosity for more than 10×10^9 yr. In contrast K- and M-stars show constant luminosities over a period that is longer than the calculated age of the universe.

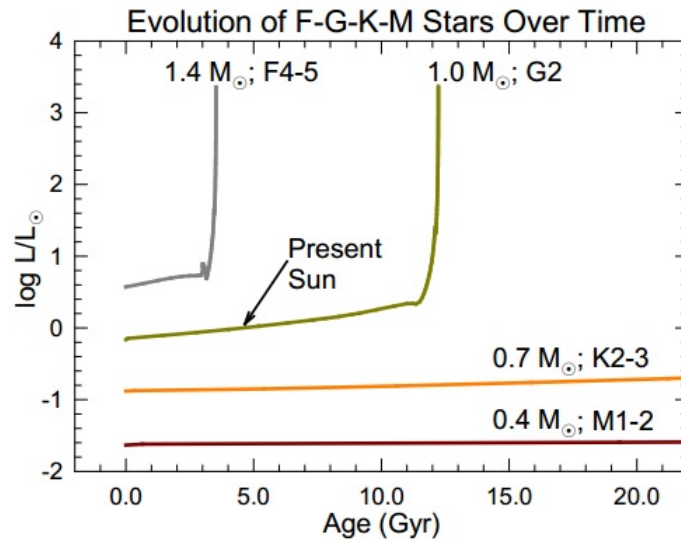


Figure 2.3: This figure shows the change of the Luminosity of 4 stars with different spectral classes over time [Engle and Guinan, 2012], excerpt from Figure 1

CME: Coronal mass ejections belong to the 'solar mass loss rate' because they are part of solar winds [Khodachenko et al., 2007] thereby they are plasma fluxes [Engle and Guinan, 2012].

Flares: The term 'Flare' describes an output of radiation in different wavelength regions like IR, visible, X-ray or UV [Heath et al., 1999]. These unexpected and unpredictable flares (energy release) boost the parts of the spectrum mentioned above [Scalo et al., 2007]. They are associated with a layer in energy accumulation in the chromosphere of the star and also in the corona and in between [France et al., 2013]. The length of a Flare refers to the available energy [Khodachenko et al., 2007]. These events can last from minutes to hours [Scalo et al., 2007].

The energy ranges from $\sim 10^{28}$ erg ('microflares') to $\sim 10^{34} - 10^{37}$ erg (most active stars, blue and UV) [Segura et al., 2005].

M-stars especially emit radiation in H α (IR region) and the UV radiation, which can be divided into

three classes [Heath et al., 1999]:

UV-A: 315 - 390 nm, least harmful part of the UV region

UV-B: 290 - 315 nm, injurious for life-as-we-know-it, potentially penetrating the atmosphere and reaching the surface in heavy amounts

UV-C: ≤ 290 nm, less gets through the atmosphere

Organisms could protect themselves from damaging radiation by evolutionary adaptation or escape gaps, caves or deeper water during this high energetic events [Heath et al., 1999].

The impact of Flairs and CMEs on the atmosphere (chemical composition, evolution, structure and climate) can not be specified [Tarter et al., 2007]. It is also not possible to predict the evolution of organisms that evolve on planets around M-stars [Segura et al., 2005].

2.2.4 Planets

This subchapter will list the most important Pro and Contra points for considering a terrestrial planet around an M-star as possibly habitable. Especially with an M-star as a radiation source for plants to carry on photosynthesis.

- Protoplanetary discs, where planet formation occurs, are not just common around G-type stars [Tarter et al., 2007]. They are also found around M-type stars [Tarter et al., 2007]. Therefore planet formation around M-stars is as possible as around G-type stars.
- Planets around M-dwarfs are generally exposed to the stellar activity mentioned in the subchapter above (chapter 2.2.3). Especially flairs send great amounts of damaging UV and X-ray radiation to the planets [Schreiber, 2006]. The most active time are the first $0.3 \times 10^9 - 1 \times 10^9$ years, until the star reaches the main sequence [Scalo et al., 2007]. This flairs could be 100 000 times stronger than the most powerful flair we know from our Sun [Schreiber, 2006]. One effect of the large amount of UV (particular XUV) radiation, that is harmful to life, is the possible erosion of the atmosphere that is formed by then [Engle and Guinan, 2012]. After reaching the main sequence the star is in a stable situation for about $10^{11} - 10^{13}$ yr [Scalo et al., 2007]. Since also the Earth's atmosphere is known to be a secondary atmosphere (see subchapter 3.2) it could also be possible that a new atmosphere will be formed by outgassing if there is enough molten material from the hot interior left which is outgassing volatile gases.
- The lack in PAR [Scalo et al., 2007] could probably lead to a collapse of the photosynthetic rate. Furthermore the lower luminosity results in a smaller stellar flux, which is just about 10% from present Earth [Schreiber, 2006]. This is potentially not enough to reach the light compensation point (see chapter 4.2.2). Especially these theories will be reviewed in this thesis.
- The tidal locking is on one hand a problem because it can lead to a breakdown of the atmosphere [Segura et al., 2010]. Indeed M. Joshi mentioned in his publications (see M. Joshi (2003) and Johsi et al. (1997)) that it is possible for an rotationally bound planet to keep an atmosphere (see subchapter 3.4). On the other hand this permanent irradiation can provide the photon flux that is needed for an effective photosynthesis.

An advantage of tidal locking is, that the planets should have a circular orbit [Tarter et al., 2007]. The negligible eccentricity of the orbit leads to the fact, that a planet, that is located in a zone where water can be liquid, is always located inside this zone. If there are no external perturbations the orbit will remain stable as circular orbit inside this zone.

2.2.4.1 Tidally Locked

If a planet forms close to its star or migrated too far inward it is possible that it gets tidally locked [Grießmeier et al., 2009].

A planet gets rotationally bound if a gravitational gradient arises through the rocky body [Khodachenko et al., 2007], if this body is located in a gravitational field that falls off with $\frac{1}{r^2}$, also inside a body with a certain dimension, it creates tides [Khodachenko et al., 2007].

This leads to different intensities of gravitational force on the facing and on the far-side of the planet. Because of that the rotation rate decreases until the rotation period is in an 1:1 resonance with the orbit period [Khodachenko et al., 2007]. Figure 2.4 shows the basic principle. One side of the planet always looks to the host star. The other side, also called far-side, is always averted.

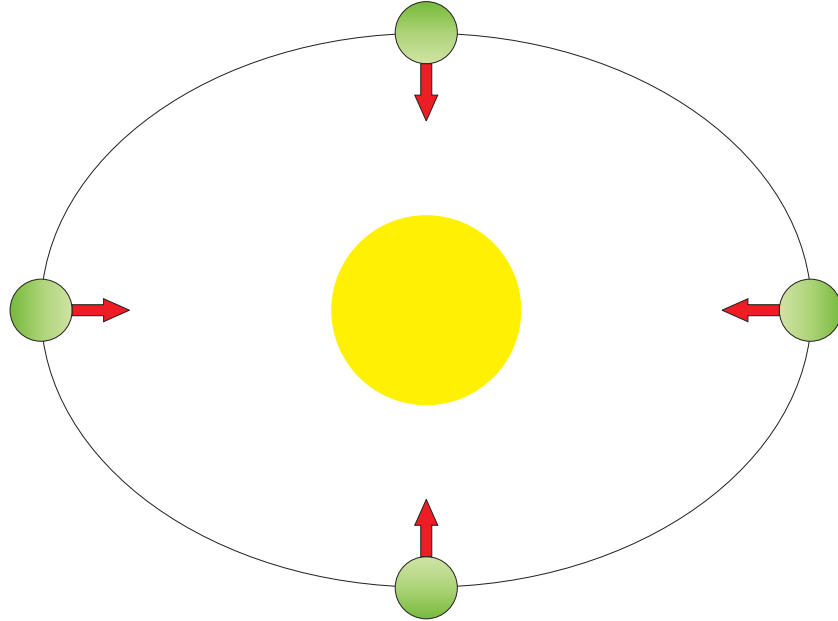


Figure 2.4: Basic principle of tidally locking, also called rotationally bound, Credit: own diagram

The time scale for getting in a resonance has a few influencing factors like the stellar mass and the composition of the terrestrial planet, but the most important one is the distance to the gravitational center [Khodachenko et al., 2007]. As mentioned before the gravitational force decreases with $\frac{1}{r^2}$, this leads to the fact that the nearer the planet is located the stronger the effect from the host star gets [Khodachenko et al., 2007].

If the distance from the planet to the star is equal or smaller than 0.2 AU the rotation can be assumed as bound [Segura et al., 2010]. However, it is also possible that a planet as close as 0.2 AU is not rotationally bound, but they are in 'resonance' [Tarter et al., 2007]. Mercury for example is in such a spin/orbit resonance [Tarter et al., 2007], just as Venus and Titan [Segura et al., 2005].

2.3 G-Star

2.3.1 Characteristics

This spectral class is the 3rd largest, right after K- and M-type stars [Vardavas and Taylor, 2007]. The maximum wavelength of the spectrum is shifted from the optical light to higher wavelengths [Weigert et al., 2009] toward the IR region of the SED (in contrast O, B, A and F stars) [Sol-Company, 2005-2013], only K and M stars are more luminous at higher wavelengths.

The spectrum is dominated by calcium lines that are more dominant than in the spectra of F-type stars [Max-Planck-Gesellschaft, 2003-2016]. Other indicators are lines of neutral metals [Max-Planck-Gesellschaft, 2003-2016]. The ionized lines get weaker [Weigert et al., 2009]. Dominant are magnesium, iron, sodium, titanium and calcium [Aller, 2014]. Another characteristic are the weak hydrogen absorption lines in the spectra of G-stars [Sol-Company, 2005-2013].

The intensity of the following prominent emission lines lessen with time [Vardavas and Taylor, 2007]:

$$\text{Ca II HK} \rightarrow 393.4 \text{ nm}$$

$$\text{Mg II} \rightarrow 280 \text{ nm}$$

$$\text{C IV} \rightarrow 155 \text{ nm}$$

$$\text{N V} \rightarrow 124 \text{ nm}$$

$$\text{Ly}\alpha \rightarrow 121.6 \text{ nm}$$

Furthermore, the cores of these low mass stars are more radiative and the outer layers are convective [Sol-Company, 2005-2013].

The mass- and temperature range of M0 to M9 stars are listed in table 2.2

Spectral-type	M/M _☉	T _{eff} [K]
G0	1.15	5980
G1	1.10	5900
G2	1.07	5800
G3	1.04	5710
G4	1.00	5690
G5	0.98	5620
G6	0.93	5570
G7	0.90	5500
G8	0.87	5450
G9	0.84	5370

Table 2.2: Parameter range for G-type stars [Vardavas and Taylor, 2007] excerpt of table 5.1, page 130

Figure 2.1 shows the position of G stars in the Hertzsprung-Russel diagram. Our sun is specially marked.

The sun is the most prominent example of a G-type star. More precisely it is characterised as a type G2V star [Tarter et al., 2007].

According to stellar theory, 3.8×10^9 years ago the sun was 25% to 30% less luminous than today [Gaidos, 1998]. During the pre main sequence phase the Lyman α flux was 10^4 times higher than today and the UV flux also exceeded the today's value [Vardavas and Taylor, 2007]. After reaching the main sequence the Sun has a calculated lifetime of about 10^9 years [Vardavas and Taylor, 2007]. Today the Sun is about 4.6×10^9 years old and irradiates the Earth with 1366 Wm^{-2} (solar constant, see chapter 3.2.4) on average at a distance of $1.496 \times 10^{11} \text{ m}$ ($= 1 \text{ AU}$) [Vardavas and Taylor, 2007].

As explained in chapter 2.2.3 on the basis of M-stars, G-type stars also show stellar activities. These activities are also e.g. solar flares and CMEs [Zell, 2015].

Flares: Flares, also called outbursts, are most prominent in $\text{H}\alpha$ combined with irradiation outbursts in the other wavelength ranges and the generation of energetic particles [Unsöld and Baschek, 2005]. This phenomenon originates from the same physical principles like solar flares of M-stars. The explosive events are linked to sunspots and the magnetic field of the star [Zell, 2015]. Younger stars show a more rapid rotation period and due to that dynamo activity this leads to stronger magnetic fields [Güdel, 2007].

The X-ray and UV fluxes drop with age [Güdel, 2007] because of decreasing rotation velocity and the drop of magnetic activity [Vardavas and Taylor, 2007].

Solar flares have a total energy of $\sim 10^{22} \text{ J} - 3 \times 10^{25} \text{ J}$ and usually appear in areas with a complex configuration of magnetic field lines [Unsöld and Baschek, 2005]. Micro flares have a diameter of about 1 arcsecond and last from seconds to hours [Unsöld and Baschek, 2005]. The emission in $\text{H}\alpha$ is the strongest indicator of a flare, but at least 10 min before an eruption takes place, FUV and soft X-ray emissions ($\gtrsim 10 \text{ eV}$) can be detected [Unsöld and Baschek, 2005].

Figure 2.5 shows an image from the Extreme ultraviolet Imager on the SOHO spacecraft taken on 04.11.2003 in the 19.5 nm emission line [ESA and NASA/SOHO, 2003].

They have only an impact on Earth when the flare is directed towards Earth, which means that the flare has to be ejected in exactly this direction [Zell, 2015].

CME: The solar atmosphere of a star is crossed by the magnetic field [Zell, 2015]. The finite solar atmosphere can abruptly eject large bubbles (a few 10^{12} kg) consisting of gas and magnetic fields and speed up to a few 10^6 km/h [Zell, 2015]. Often they are related to solar flares, but do not have to appear at the same time [Zell, 2015].

CMEs (plasma and magnetic field) can be ejected in any direction, and only if it is aligned via Earth it can be harmful [Zell, 2015].

Sunspots: The magnetic field of a star can come up to the surface [Güdel, 2007]. This leads to

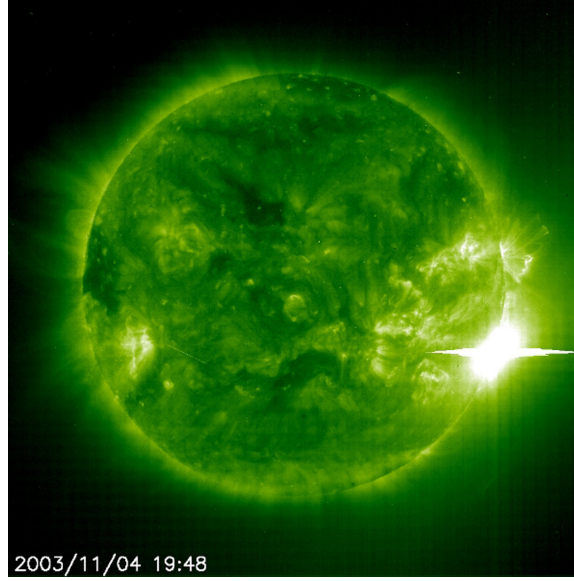


Figure 2.5: Image of a solar flare, released on 04.11.2003, Image taken from Extreme ultraviolet Imager at the SOHO spacecraft at the 19.5 nm emission line [ESA and NASA/SOHO, 2003]

disruptions in the emission of radiation at these certain areas [Vardavas and Taylor, 2007]. Sunspots are areas of reduced brightness, which means that the effective temperature of the star is lower in these regions [Unsöld and Baschek, 2005].

The spots appear in groups and the largest reduces the effective temperature of the sun from 5780 K to 3700 K, which is comparable to the effective temperature of a K-type star [Unsöld and Baschek, 2005]. In case of the sun the sunspot activity is subject to a 11-year-cycle [Hathaway, 2010]. The 11-year-cycle shows a minimum of about 10 sunspots and a maximum of about 100 sunspots [Vardavas and Taylor, 2007]. As researched in the master's thesis for our Sun by A. Lauterböck (see [Lauterböck, 1995]) and in the doctoral thesis of E. Svoboda (see [Svoboda, 2005]).

UV variation: Today's sun also shows changes in the UV flux. At wavelengths beyond 200 nm the alteration is about 10% [Vardavas and Taylor, 2007]. The Lyman α line shows a fluctuation of magnitude 2 [Vardavas and Taylor, 2007].

For planets the photochemistry generated by normal radiation and flairs has to be taken into account. In the mesosphere the solar $\text{Ly}\alpha$ radiation (Transition $1 \rightarrow 2$, 121.6 nm) plays an important role by affecting the oxygen molecules and water vapour [Vardavas and Taylor, 2007]. In the Thermosphere the $\text{Ly}\beta$ radiation (Transition $1 \rightarrow 3$, 102.6 nm) ionizes the oxygen and nitrogen [Vardavas and Taylor, 2007].

2.3.2 Planets

It is already known that planet formation around G-type stars is possible. The best example is our own planetary system.

G-stars are luminous enough to shift the zone where water can be liquid into a distance to the star that is large enough to prevent tidal locking. Furthermore, they show activity but it is a matter of common knowledge that the strong active period is not long enough to sterilize a planet and prevent the evolution of life-as-we-know-it.

The life time of G-stars is long enough for planetary evolution, the formation of an atmosphere and life-as-we-know-it as well as the evolution to higher plants.

3 Atmospheres

3.1 Introduction

The most habitable atmosphere for life-as-we-know-it and at the same time best explored atmosphere is our Earth's atmosphere. It protects us from high energetic radiation like the high energetic UV part of the spectral region and contains the essential oxygen.

The composition is well known. Our atmosphere consists of different gases which can be divided into three different groups, depending on their variability and amount [Klose, 2008b].

First of all the principal components like N_2 , O_2 and Ar and the second group (see subsection 3.3.1) is built up of permanent tracer gases [Klose, 2008b].

The third ones are variable tracer gases, and in this term variable means the changing in their special or in their temporary ratio [Klose, 2008b]. They are important for the energy balance of the Earth [Klose, 2008b].

Besides this, aerosols are also part of the variable components of the atmosphere [Bergmann and Schäfer, 2001]. Dust, pollen and also combustion processes are the main aerosol sources above world's landmass, but directly above the sea the dominating source are salt particles [Bergmann and Schäfer, 2001]. Furthermore, they also have an important influence on the formation of clouds.

However, it has to be taken into account that our atmosphere is very turbulent (horizontal and vertical processes) [Klose, 2008b]. Due to this fact the atmosphere can be supposed to have a constant composition up to an altitude of 100 km [Bergmann and Schäfer, 2001]. This can be one method to classify different layers in our atmosphere.

As already noted the principal particles are not the only components that can be found in the atmosphere. Moreover, the gas envelope of the Earth has also some other very important and interesting physical characteristics and properties.

The following chapters will give the reader an overview about the most important properties of the Earth's atmosphere. On the basis that the characteristics and compositions of extra solar planets atmospheres are unknown, these factors can be adapted from the Earth's atmosphere to the atmospheres of other celestial bodies.

The properties explained subsequently will be important for the scientific question this work deals with.

3.2 General Information

Not much is known about the exact formation of the Earth's atmosphere. Most assumptions start right after the planet formation ended and the Earth acquired its final mass.

The primordial atmosphere is not comparable to the atmosphere we know today [Ahrens, 2010] but it also has to be mentioned that the first atmosphere is not a remnant of the solar nebula that surrounded the Earth during its formation [Bergmann and Schäfer, 2001]. Earth's atmosphere is a so called 'secondary atmosphere', which means that it originated via gas emission [Hobbs, 2000].

The surface of the Earth was covered by molten material from the hot interior which was out-gassing volatile gases like hydrogen which formed the envelope or cooled and condensed to oceans and lakes [Ahrens, 2010]. This primordial atmosphere was very toxic to life-as-we-know-it today but thankfully the Earth further cooled, the crust and the atmosphere interacted with each other and raised a habitat for single celled microorganisms (needed no oxygen) [Saha, 2008].

For the evolution of more complex life the formation of oxygen was important. Certainly the splitting of water vapour in the primordial atmosphere by UV radiation only produced $\frac{1}{1000}$ of the O_2 content of the contemporary atmosphere [Bergmann and Schäfer, 2001].

Thus, the gas envelope was more or less toxic until the photosynthesis evolved in the sea and released the oxygen into the atmosphere [Saha, 2008] during the great oxygenic event. This permitted the development of plants and other multicellular life-forms and the stabilisation of the atmosphere to the present conditions [Ahrens, 2010].

One important factor for the formation and preservation of atmospheres is the **mass** of the planet. The gravitational force of a planet is important for the permanence of an atmosphere [James and Leon, 2015]. If the planet has not enough mass its gravity is too low to keep an atmosphere against the centrifugal force, this leads to an escape of the gaseous envelope [James and Leon, 2015]. The centrifugal force has a higher effect on lightweight elements (H and He) than on heavier ones, which leads to an atmosphere consisting of heavy elements for planets with slightly lower mass than the Earth [James and Leon, 2015]. A factor that also has to be taken into account is the proper motion of molecules and atoms [Klose, 2008b]. The proper motion depends on the thermal velocity (higher for lower molecule masses) and leads also to an escape of the lighter elements on the outer rim of the atmosphere [Klose, 2008b].

Properties of the Earth's atmosphere:

Usually the atmosphere will be considered as an ideal gas [Saha, 2008].

- **Pressure:** The pressure is defined as the force acting on an area.

The air pressure is defined as the weight of the air, which means the sum of all molecules in a vertical column, over a certain area [Ahrens, 2010]. The acting force is the gravitational force acting directly toward the ground level [Saha, 2008].

$$p(h) = \int_h^\infty \rho g \delta z \quad (1)$$

$p(h)$... pressure at height h

g ... gravitational acceleration

ρ ... mean density in an certain interval (Δz).

On the basis of the equation above it can be clearly seen, that the pressure on the surface is higher than on each other atmospheric level above the surface [Saha, 2008].

In the literature a lot of different unit systems can be found for the pressure, especially for the atmospheric pressure [Saha, 2008]:

$$1.013 \times 10^5 \text{ Pa} = 1013 \text{ mBar} = 1.013 \times 10^6 \text{ dynes/cm}^2 = 1 \text{ Atmosphere}$$

Variations in the atmospheric pressure can occur in time and space (horizontal and vertical) and obtain lower values at high altitudes and a maximum at the surface of the planet [Saha, 2008].

- **Temperature:** The temperature of the atmosphere can change along the surface, for example between the mainland and the sea, with time. Of particular importance is the variation with height [Saha, 2008].

Until a certain height level the temperature drop can be seen as linear until a minimal temperature is reached (the maximum height and temperature minimum can differ from region to region) [Roedel and Wagner, 1991, 1994, 2000, 2011].

In the mid-latitude regions the temperature drops approximately linear until a height of 10-13 km and the minimum temperature is reached at about -50 °C, in the tropics the h_{max} is located at about 18 km with -80 °C [Roedel and Wagner, 1991, 1994, 2000, 2011].

Following the temperature profile of the Earth's atmosphere does not show the same shape in all regions of the world and indicates also an increasing and decreasing temperature with height (see Figure 3.6, which leads to atmospheric layers with different temperatures [Ahrens, 2010], see Figure 3.6.

A more detailed explanation can be found in the chapter 'vertical structure'.

- **Density:** The equation of state indicates that the density depends on the temperature and the pressure of the atmosphere [Saha, 2008]. However, as already mentioned, the temperature and pressure show variations in time and space which lead also to an variation (in time and space) of the density [Saha, 2008].

The variation of space can occur in:

Horizontal direction: Leads to an movement of air masses across the surface, known as 'wind' [Ahrens, 2010]

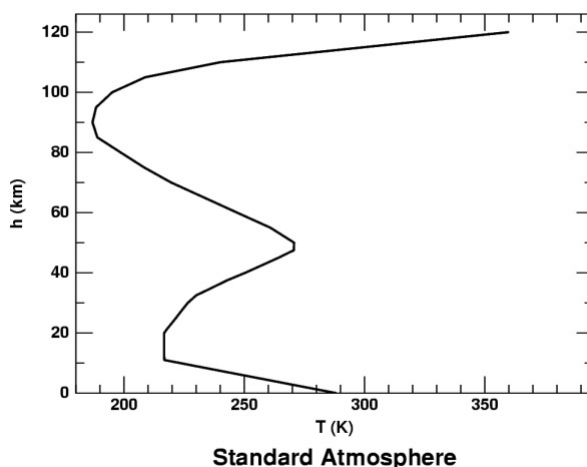


Figure 3.6: Temperature Profile of the Earth [Young, 2002, 2004-2007]

Vertical direction: The acting force in vertical direction is the gravitation. This potential leads to an separation of heavier elements (near surface) and lighter elements (more numerous in higher regions) and therefore to an fast decrease of density with height [Saha, 2008].

As side effect, the elements with lower masses have a higher thermal velocity, which causes a loss of atomic hydrogen from a height of 500 km (approximately the beginning of the Exosphere) [Klose, 2008b].

Furthermore, the atmosphere is not a changeless envelope around our planet. It moves, circulates and shows differences in large and small scales. This means that the general circulation is part of the properties of our atmosphere and also has to be explained.

Circulation of the atmosphere:

Most important for this treatise will be the understanding of the so called 'general circulation of the atmosphere'. Also called 'circulation of the atmosphere' or 'planetary circulation' [Blüthgen and Weischet, 1980]. This circulation describes the total moving mechanism of the atmosphere.

The reason why it is called 'general circulation' is due to the fact that it is not about individual small phenomena like storms in a single region, it is more across-the-board in a period of a month, season or year and it deals with the displacement of energy and mass in the atmosphere [Klose, 2008b].

This means that the circulation needs an energy source to produce the kinetic energy [Klose, 2008b] and this is the radiation produced by the nuclear fusion of the host star. What ultimately leads to this movement is the distribution of the incoming radiation on the different regions (degree of latitude, oceans, land mass) [Blüthgen and Weischet, 1980].

Considering the fact that the atmosphere can be seen as a closed system the movement has to be a circulation, which means it is a closed circular flow of air mass between regions with an energy

surplus and regions with energy deficit [Blüthgen and Weischet, 1980].

The problem of the description of the circulation of an atmosphere lies behind the interaction of every part of the variation in time and space in the fundamental movement and the specific circulation of a region and the fact that every segment has a consequence to the climate [Blüthgen and Weischet, 1980].

Figure 3.7 shows the three types of wind cells that are important for a global circulation of air mass (temperature and energy).

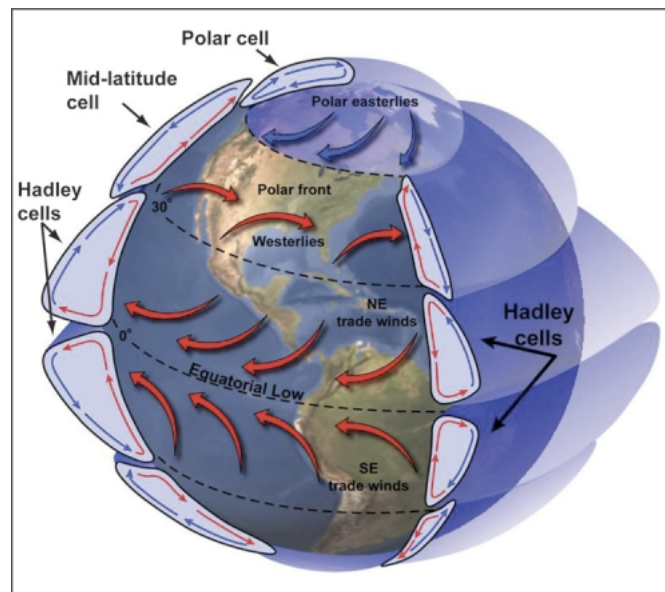


Figure 3.7: Atmospheric dynamic: Hadley Cells, Ferrel Cells (mid-latitude cells), and Polar Cells [Piana, 2010]

- **‘Hadley Cell’:** Looking at the radiation budget and the flattening of the spherical shape of the Earth the first thing to be noticed will be that the equatorial region gets more energy than the polar region [Klose, 2008b]. This temperature differences leads to the formation of the Hadley Cells which means that an energy transport is created, which only occurs in the lower layers of the atmosphere between 30° S and 30° N [Klose, 2008b]. The energy transport that takes place to prevent the thermal equilibrium by movement of the warm air in the direction of the poles, with an eastward drift due to the Coriolis force, and then the cold air from the poles to the equatorial region, with westward drift [Klose, 2008b]. Actually the Hadley Cells do not reach the poles, as mentioned before they end at about 30° latitude, and pass over to the ‘Farrell Cells’ [Piana, 2010]. This direct circulation is combined with the easterly winds and one can find the Hadley Cells on both sides of the equator [Klose, 2008b].
- **‘Farrell Cell’:** In the region between 30° and 60° the heat transport changes to an vertical circulation [Klose, 2008b]. When the Hadley Cells ends at about 30° [Piana, 2010], the indirect circulation of the Farrell Cells starts [Klose, 2008b].

W. Roedel explained that the Farrell Cells as such do not exist [Roedel and Wagner, 1991, 1994, 2000, 2011]. They are just individual processes summarized to this kind of Cell [Roedel and Wagner, 1991, 1994, 2000, 2011]. The above mentioned processes are high – and low pressure areas [Roedel and Wagner, 1991, 1994, 2000, 2011], see Figure 3.8. Low pressure areas are rather situated in the polar region and are characterised by the fact that the air rises [Roedel and Wagner, 1991, 1994, 2000, 2011]. High pressure areas are the direct opposite, and rather located in the subtropics [Roedel and Wagner, 1991, 1994, 2000, 2011]. To balance this effects, there have to be air flows and these flows can be summarized to the Farrell Cell, although this circulation is not steady [Roedel and Wagner, 1991, 1994, 2000, 2011].

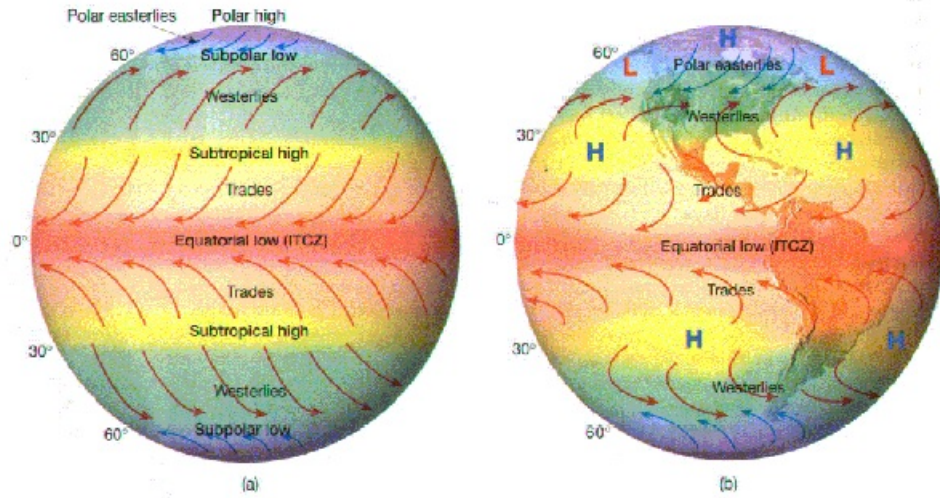


Figure 3.8: Pressure belts, Figure a: idealised, Figure b: actual [Schlanger, 2004]

- **'Polar Cell':** In the polar region one can find a separated thermal circulation [Klose, 2008b]. Here the cold air sinks at a latitude of about 90° and flows back in equatorial direction [Klose, 2008b].

The 3-Cell circulation Model of our Earth's atmosphere is just a simplified model, a idealized circulation. The 'not idealized' circulation is a lot more complicated but this simplified model fulfils our requirements.

3.2.1 Vertical Structure

The atmosphere can be divided into several layers, on the basis of different properties (see Figure 3.9).

The most popular one is the classification by the temperature:

1. **Troposphere:** lowest layer, between surface and 9 km to 16 km, $T_{min} \approx -55^\circ$ to -60° [Saha, 2008]
2. **Tropopause:** T_{min} of the Troposphere is reached [Saha, 2008]; first separation layer between two layers with different temperature gradient [Roedel and Wagner, 1991, 1994, 2000, 2011];

temperature can be stabilized by convection and heat transport (the surface absorbs the solar radiation and forces the heat exchange with the atmosphere [Saha, 2008])

3. **Stratosphere:** This layer is heated by radiation and reaches a T_{max} at about 50 km high $\rightarrow$ Stratopause, the high temperature comes from the absorption of the UV radiation by ozone [Houghton, 2002].

Due to the fact that the heat is produced by the UV this layer is also called ‘Ozonosphere’ [Saha, 2008]

$$T_{max} \approx 0\text{ }^{\circ}\text{C [Saha, 2008]}$$

Ozone: The formation occurs at a minimum height of 20 km where the radiation flux is high enough for photodissociation but the maximum of production takes place at 25 km [Klose, 2008b]. This means, that at this point the relation between the quantity of molecular oxygen and the UV radiation intensity reaches its optimum [Klose, 2008b]. Therefore, this layer is also called ‘Ozonosphere’ [Saha, 2008].

4. **Stratopause:** The boundary layer between the Stratosphere and the Mesosphere is reached when the temperature reaches its maximum [Houghton, 2002].
5. **Mesosphere:** The Mesosphere starts right after the Stratopause and ends when the temperature reaches its minimum at approximately -100 ° at 30 km height [Saha, 2008]. This means that in the Mesosphere the temperature is decreasing with increasing height due to very few radiation absorption [Houghton, 2002].
6. **Mesopause:** After this boundary layer the temperature rises again [Saha, 2008].
7. **Thermosphere:** In this layer the ionisation plays an important role [Saha, 2008]. The temperature is climbing up to more than 770 K [Ahrens, 2010], depending on the activity of the Sun [Saha, 2008]. The Thermosphere is very important for life on Earth because the oxygen and nitrogen inside the layer catch the high energetic radiation and get ionized [Saha, 2008]. This last level transits over into the ‘Exosphere’ and is also called ‘Ionosphere’ [Saha, 2008].

This classification is followed by the chemical classification:

Here one only differentiates between two layers the ‘Homosphere’ and ‘Heterosphere’ [Roedel and Wagner, 1991, 1994, 2000, 2011]. The layer between the surface and a height of 100 km is the Homosphere, in matters of the fact that here the contents of the layer are homogeneously mixed but above the 100 km limit a marked separation takes place [Roedel and Wagner, 1991, 1994, 2000, 2011].

This layer above the Homosphere is called ‘Heterosphere’ [Bergmann and Schäfer, 2001]. Between Homosphere and the Heterosphere one can find a boundary layer (Homopause), after the ‘Homopause’ the separation of the gases takes place [Klose, 2008b]. Above the separation layer, gases with different molecular weights start to build layers until the lightest ones are at the upper limit of the atmosphere [Klose, 2008a].

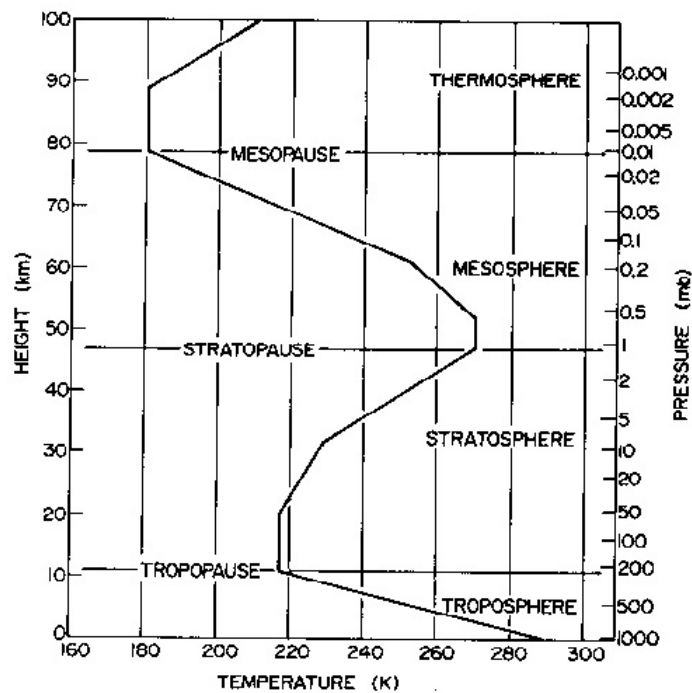


Figure 3.9: Temperature Profile of the Earth's Atmosphere, vertical layers are sketched in [Mun, 1998]

The 'Homosphere' and 'Heterosphere' are natural consequences between the proper motion of molecules and the gravitational force [Klose, 2008b]. If the gravitation would be too weak the gases would diffuse into the space due to their thermal motion [Klose, 2008b]. Indeed the decreasing air pressure and air density have to be taken into account [Klose, 2008b]. Above 500 km the thermal velocity of the air-molecules is high enough to allow them to escape into the space [Klose, 2008b].

The third possibility is the classification by ionisation:

One can differentiate between three layers with varying grades of ionization: the 'Neutrosphere', 'Ionosphere', and 'Protosphere' [Klose, 2008b]. We learned before that the density decreases with height and at ca 70 km above the surface the recombination becomes slower which leads to layers with more electrons, so that they become conductive [Klose, 2008b]. Between the surface and 50 km to approximately 90 km there is a neutral respectively partly ionized layer, followed by the ionized layer [Klose, 2008b]. Naturally the borders are blurred. The ionized layer can be divided into sublayers (for the following list see [Klose, 2008b]):

- **D-layer:** 50 – 90 km, caused by cosmic rays, lowered during night via recombination
- **E-layer:** 90 – 130 km, extenuated during night via recombination
- **F1-layer and F2-layer:** 170 – 300 km, two maxima (during day-time)
F1 and F2 are merging during night
- **Helium-Ion-layer:** 600 – 1000 km

The whole sphere will be enveloped by a Proton-layer (from 2500 km), containing just hydrogen nuclei [Klose, 2008b].

3.2.2 Aerosols

Aerosols are a suspension, which means that they are a mixture of solid and/or fluid components [Klose, 2008b]. They are not a mixture of air and particles [Bergmann and Schäfer, 2001], but they have to be dissolved in a medium and this medium is the air [Klose, 2008b].

Aerosols can also vary greatly in size, between 10^{-3} - $10^2 \mu\text{m}$ [Klose, 2008b] which implies that they can be divided into different groups according to size [Bergmann and Schäfer, 2001].

For the following see P. V. Hobbs (2000), page 87:

- **Nucleus mode:** diameter $\approx 0.01 \mu\text{m}$
Condensation of gases
- **Aitken nuclei:** 0.2 to $0.02 \mu\text{m}$
- **Accumulation mode:** diameter $\approx 0.1 \mu\text{m}$
Coagulation
- **Coarse particle mode:** diameter $\approx 1 \mu\text{m}$
Dust, ashes, sea salt

Aerosols are also very important for the climate, but to describe their effect is complicated since there exists just inaccurate information about their concentration [Klose, 2008b]. What is definitely known is that this suspension has absorbing and scattering properties [Klose, 2008b] and a lifetime of about days to weeks in the Troposphere [Bergmann and Schäfer, 2001].

The particle density decreases with high but has an secondary maximum at 20 km due to the fact that a volcanic eruption can reach this stratospheric high [Bergmann and Schäfer, 2001].

In determining the aerosol concentration in the atmosphere one has to distinguish between the concentrations above different areas and their particle radius involved. For details see the following list. This example shows the wide range of possible fluctuations and also the particle size.

- **Antarctica and Ocean** [Bergmann and Schäfer, 2001]:
Low fluctuations (about $1 \mu\text{g}/\text{m}^3$)
Particle density: $25 - 600 \text{ cm}^{-3}$
Particle radius: $0.16 - 0.17 \mu\text{m}$
- **Outbursts of dust in the desert or forest fire (smoke)** [Bergmann and Schäfer, 2001]:
Fluctuations up to $1 \text{ mg}/\text{m}^3$
Particle density of smoke: 10^6 cm^{-3}
Radius dust particles: $3 - 30 \mu\text{m}$, Radius smoke particles: $0.003 \mu\text{m}$

- As the output of aerosols is only estimated, an amount of 3×10^{12} kg/a is assumed [Bergmann and Schäfer, 2001].

The final important information about aerosols is their formation and origin. Here, again, many classifications are possible.

The primary particles ascend directly from their source into the atmosphere and secondary particles have their origin in the atmosphere via merging or nucleation [Klose, 2008b]. This means that aerosols can be produced via condensation from the gas phase (secondary) or via dispersion from the Earth's surface (primary) [Klose, 2008b].

The sources can be divided into natural, geogenic or anthropogenic sources [Klose, 2008b].

Natural sources stem from biochemical matter cycles, like the sulphur cycle [Klose, 2008b].

Geogenic sources produce particles by volcanic eruptions or by combustion of biomass and disperse them with the wind [Klose, 2008b].

The anthropogenic resource can be divided into two subgroups, in the way of generation and in the scope of application [Klose, 2008b]. The way of generation can be burning, industrial handling or traffic and the scope of application be, e.g. farming or industry [Klose, 2008b].

Furthermore, the sources that play an important role like the wind, the volcanoes, the terrestrial biosphere and the burning of biomasses, have to be mention separately.

Wind: The wind blows the particles along the Earth's surface, they collide with other particles, or obstacles and receive a vertical impulse that they require to stream into the turbulent layer [Klose, 2008b]. The particles we are talking about are e.g. dust and sea salt and have a size of 1 to 100 μm [Klose, 2008b]. Indeed the sea salt is very spatially limited (horizontal: sea level up to a hight of 3 km, vertical: 1 km from the sea the density drops to 10% of the original value) [Klose, 2008b].

Volcanoes: Here the ash particles are made of various components and can reach a height up to the Stratosphere and the ejected gases will be converted into droplets of sulphuric acid within a few weeks [Klose, 2008b].

The terrestrial Biosphere is also a provider of aerosols, especially the plants (seeds, pollens, resin and spurs) and microorganisms (size: $< 1 \mu\text{m}$) [Klose, 2008b].

Burning of biomass: The burning can occur in a naturally way (lightning or meteor strike) and anthropogenic (forest fire or forest clearing) [Klose, 2008b]. The anthropogenic ratio produces particles in a size range of 0.1 to 0.3 μm with an fraction of $\frac{1}{6}$ to $\frac{1}{2}$ of the whole organic material released into the atmosphere [Klose, 2008b].

Also interesting is the fact that the sodium chloride cores play a minor role in the aerosol production [Bergmann and Schäfer, 2001]. More important is Dimethylsulfid, something that forms as a decay product of Dimethylsulforporpionat which originates whether seaweed die off [Bergmann and Schäfer, 2001].

The reason for discussing all this details of the formation of aerosols and their properties is simple. They are very important for cloud formation which will be discussed in the next chapter.

3.2.3 Clouds

'Cloud' is just a generalized term for a few different kinds of clouds, e.g. *stratus*, *cirrus*, *cumulus*,..., which are formed via different processes or at different heights [Houghton, 2002].

They have a great influence on our climate since they increase the planetary albedo and minimize the irradiation flux [Roedel and Wagner, 1991, 1994, 2000, 2011]. This leads to a cooling effect [Roedel and Wagner, 1991, 1994, 2000, 2011]. On the other side the Earth emits infrared radiation which will be absorbed by clouds, 'back radiated' to Earth and minimized the radiation into the space [Roedel and Wagner, 1991, 1994, 2000, 2011]. This leads to a heating effect [Roedel and Wagner, 1991, 1994, 2000, 2011].

The whole weather process takes place in the Troposphere, which means also the cloud formation and the precipitation formation [Klose, 2008b]. The Stratosphere is more or less free from clouds [Klose, 2008b].

There are two important things that have to be present to form clouds or even fog or haze. One requires supersaturated air and particles in the air [Roedel and Wagner, 1991, 1994, 2000, 2011]. The most common way to get supersaturated air is to cool the air with an constant water content [Roedel and Wagner, 1991, 1994, 2000, 2011]. Not that prominent is to add more vapour to the air by evaporation over sea and lakes [Roedel and Wagner, 1991, 1994, 2000, 2011].

Now there are two way of condensation to form a raindrop, homogenous and heterogenic condensation [Roedel and Wagner, 1991, 1994, 2000, 2011].

1. Condensation of water vapour to droplets. For that form of condensation ones need several hundred percent of saturation [Roedel and Wagner, 1991, 1994, 2000, 2011].
2. Condensation on particles. Here the saturations just have to be a few tents percent but the so called 'cloud condensation nuclei (CCN)' do not have to be smaller than $0.1 \mu\text{m}$ [Roedel and Wagner, 1991, 1994, 2000, 2011].

J. Houghton (2002) explains the cloud formation in a relatively simple way. He claims that cloud particles with an approximately diameter of $10 \mu\text{m}$ has to increase in size until a diameter of $\approx 1 \text{ mm}$ [Houghton, 2002]. The formation process he follows starts with the grow of particles by the accumulation of water vapour, followed by condensation [Houghton, 2002]. Here the cloud particles grow to a size of $\approx 30 \mu\text{m}$, from then the collision process is more efficient [Houghton, 2002]. The particles get larger and 'heavier' so that they get a fall speed and sink through the cloud [Houghton, 2002]. This leads to more collisions and merging of droplets [Houghton, 2002].

P. V. Hobbs (2000) defines this process more detailed. For the following explanation of cloud formation see: Hobbs, P. V. (2000), Introduction to Atmospheric Chemistry, Cambridge University Press, pp. 111-134.

The whole process is divided into four topics:

CCN and nucleation scavenging:

As mentioned before, one of the most important things is the supersaturation of the air which surrounds a CCN. As a basic rule for the relevant percentage of the supersaturation can be stated, that the larger the size of the particle is the lower the supersaturation has to be. The second point is the dissolubility of the CCN's. At a given supersaturation the insoluble particles have to be larger than the soluble particles to form a CCN. But it has to be mentioned that most particles are composed from 'mixed nuclei'

Example: 1% of supersaturation $\rightarrow$ insoluble: $r = 0.1 \mu\text{m}$, soluble: $r = 0.01 \mu\text{m}$

This criterion of exclusion leads to the fact that only 1 % of aerosols are able to be CCNs within the continental air, but 10 % to 20 % in the marine air. In the marine air the droplets also have a larger mean size so it is more probable that those vary clouds precipitate than clouds of the same type over land masses.

Dissolution of gasses:

Gases, present in the air, start to suspend into the droplets, resulting from the condensation explained before.

Aqueous-phase:

Droplets in clouds consist of different chemical substances (CCN + water vapour) and dissolved gasses which can drive chemical reactions $\rightarrow$ 'Aqueous-phase chemical reactions'. An example of such a chemical reaction is the conversion of sulphur dioxide to sulphate. This leads to the fact that the final droplet-times have another composition than the primary CCN.

Precipitation scavenging:

The last step cleans the air via precipitation. The scavenging will be achieved by the usage of aerosols as CCN, the liquidation of gasses and also by diffusional and inertial collisions.

Diffusional collisions means that the pollutant drifts to the hydrometeor. Here the smaller pollutants clearly have an advantage over larger pollutants. In contrast, the inertial collision is more efficient for larger pollutants ($> \text{few } \mu\text{m}$) because the larger ones fall relatively to the hydrometeors, and larger particles have a greater fall velocity, which in turn makes a collision more likely. For smaller particles it is not easy to inertial by collide due to the fact that they would just follow the airstream of the hydrometeor. This prevent collisions.

All this leads to the removal of aerosols by precipitation. These aerosols are not useful as CCN and are particles called 'cloud interstitial aerosols (CIA)', located in the air between the CCN that will form the droplets.

This was the explanation of the cloud formation according P. V. Hobbs, see [Hobbs, 2000].

The reason why the discussion is all given here in detail is that clouds have a significant influence on the climate and the radiative distribution on the surface of a planet. This explanation is specially adapted to the procedures on Earth. The cloud forming processes e.g. on Venus, are quite

different and much less understood than it is in the case of Earth.

3.2.4 Radiation

The processes that occur in an atmosphere are a consequence of several factors, where the radiation from the host star, which is spatially and temporally fluctuating, is the most important. [Roedel and Wagner, 1991, 1994, 2000, 2011].

The basic properties of the radiation, that is emanated from the host star and arriving at the top of the atmospheres (TOA) of the sample planets, can be calculated with the following assumptions and equations:

The Stefan Boltzmann law describes the power radiated from a body depending on its temperature [Roedel and Wagner, 1991, 1994, 2000, 2011]:

$$\overline{F} = \epsilon \cdot \sigma \cdot T^4 \quad (2)$$

$\overline{F}$... radiant flux (Irradiance) [W/m²]

ϵ ... relative emission, $0 \leq \epsilon \leq 1$

σ ... Stefan Boltzmann constant = 5.7×10^{-8} [W m⁻² K⁻⁴].

To calculate the irradiance on the surface of the star one has only to fill in its effective temperature. The strong dependence on the temperature to the fourth power can be easily seen in the Stefan Boltzmann law [Klose, 2008b]. This leads to the obvious fact that the irradiance is heavily depending on temperature. Everything that has not reached absolute zero temperature is sending out irradiation [Klose, 2008b].

The ϵ is defined as the relative emission by Kirchhoff's law which implies that a thermal emitter always emits the equal amount that he absorbs [Roedel and Wagner, 1991, 1994, 2000, 2011], such that

$$\epsilon = \alpha, \quad (3)$$

where α is defined as the absorbed irradiance divided by the incident radiation, $0 \leq \alpha \leq 1$ [Roedel and Wagner, 1991, 1994, 2000, 2011].

For the following calculations ϵ was set to 1, which means that we assume that the star is a black body. A black body only depends on the temperature [Bergmann and Schäfer, 2001] and absorbs 100 % of the radiation, which means that it also emits 100% ($\alpha = 1 = \epsilon$) [Roedel and Wagner, 1991, 1994, 2000, 2011].

The total luminosity of the star (L) is derived by multiplying the Stefan Boltzmann law with the surface area ($4 \cdot \pi \cdot R^2$) of the star.

$$L = \sigma \cdot T^4 \cdot 4 \cdot \pi \cdot R^2 \quad (4)$$

In the next step, we want to calculate the flux density of the star at a specific planetary distance r (radius of the mean elliptic orbit), the so-called 'solar constant' $S_0(r)$. By consideration that all radiated power must radially traverse a virtual sphere, such that the power-flux there is defined by:

$$S_0 = \frac{4 \cdot \pi \cdot R^2}{4 \cdot \pi \cdot r^2} \cdot \sigma \cdot T^4 \quad (5)$$

R ... Radius of the star

r ... Distance star to planet.

The term 'constant' is only an approximation, as planetary orbits are ellipsoidal and therefore the radius (r) is not constant.

$S_0(r)$ is defined on a projection surface (Earth cross section) at a distance r [Roedel and Wagner, 1991, 1994, 2000, 2011]. To calculate the irradiance referring to the whole surface of the planet the solar constant has to be divided by 4 [Roedel and Wagner, 1991, 1994, 2000, 2011]. The factor originates from the difference between the Earth's cross section (πR^2) which was used for the calculation, and the definition of a spherical surface ($4 \pi R^2$) on which the integral flux has to be distributed. This leads to the division factor of 4.

The average computed value of the solar constant is verified with 1368 W/m^2 , and the irradiance referring to the whole surface of the planet is verified with 342 W/m^2 [Roedel and Wagner, 1991, 1994, 2000, 2011].

The solar-constant can also be calculated for different radii, like the inner or outer edge or the mean of a zone where water can stay liquid.

Indeed the radiation will not reach the surface of the planet without undergoing some modifications, given that habitable planets are surrounded by an atmosphere. Therefore, the interaction of irradiance with matter has to be considered.

The processes are called reflection (ρ), absorption (α) (= emission) and transmission (τ) $\rightarrow \rho + \alpha + \tau = 1$ [Bergmann and Schäfer, 2001]. The processes are wavelength dependent [Roedel and Wagner, 1991, 1994, 2000, 2011]. At the TOA about 30% of the radiation are immediately reflected [Bergmann and Schäfer, 2001] and have to be subtracted from the irradiance that is referring to the whole surface which leads to a net radiation input at the TOA of approximately 240 W/m^2 .

Another situation can be calculated if one considers that the planet is a spheroid so that the radiation reaches on the surface at different angles.

The irradiance, as well as the solar constant, is always referring to a vertical beam [Bergmann and Schäfer, 2001]. This leads to the definition of the radiance, defined as the irradiance per solid angle [$\text{W/m}^2 \text{ sr}$] [Bergmann and Schäfer, 2001].

This means that the star is visible under a flat angle which leads to less power deposited per unit area on the surface, following

$$d\bar{F} = F \cdot \cos(\theta) d\omega \quad (6)$$

$\bar{F}$... Irradiance

$F...$ Radiance (surface brightness) [$\text{W m}^{-2} \text{sr}^{-1}$]

$d\omega...$ solid angle, $0 \leq \omega \leq 4\pi$ $\theta...$ angle between the direction and the normal direction to the surface area.

The two extreme cases are easily explained.

For $\theta = 0$, $\cos(\theta) = 1$, which implies that the incoming radiation is at the maximum due to the fact that the radiation is vertical [Bergmann and Schäfer, 2001].

For $\theta = \pi/2$, $\cos(\theta) = 0$, which means that the beam only touches the surface of the planet slightly [Bergmann and Schäfer, 2001].

The radiation from a star can always be seen as 'parallel radiation' which implies that the solid angle is small [Bergmann and Schäfer, 2001]. The other way round the sky is a 'diffuse emitter' and emits over an entire half sphere ($\omega = 2\pi$) [Bergmann and Schäfer, 2001].

The next radiation law was established by Max Planck. He calculated the intensity distribution of an black body [Roedel and Wagner, 1991, 1994, 2000, 2011]:

$$F_\lambda(T) \cdot d\lambda = \frac{2 \cdot h \cdot c^2}{\lambda^2} \cdot \frac{d\lambda}{\left(\exp \frac{h \cdot c}{\lambda \cdot k \cdot T}\right) - 1} \quad (7)$$

$h...$ Planck constant, 6.6×10^{-34} Js

$k...$ Boltzmann constant, 1.38×10^{-23} J/K

$c...$ velocity of light.

The law is dependent on the temperature, as well as the wavelengths that the black body is emitting [Klose, 2008b]. On the basis of the plotted radiation law one can also see how much irradiance [W/m^2] a wavelength is contributing to the total radiation [$\text{W/m}^2 \mu\text{m}$] [Klose, 2008b].

The last important radiation law is the Wien's displacement law:

$$\lambda_{max} \cdot T = b \quad (8)$$

$b...$ constant, $= 2898$ [$\mu\text{m K}$].

It yields information about the wavelength at the maximum radiation at the Planck radiation curve. If one look at the radiation curves plotted at different temperatures it is easy to see that the maximum wavelengths get shifted to lower energy the lower the temperature of the black body gets.

This are all simplified assumptions. Stars are no perfect black bodies. Moreover the irradiation can also be changed by the tilted planetary axis and the eccentricity [Roedel and Wagner, 1991, 1994, 2000, 2011].

If the radiation impact onto the TOA is 30% reflected then the Albedo is 0.3 while the other 70%

penetrate into the atmosphere and undergo changes by the constituent parts (gases and aerosols). Energy of the radiation can be removed by extinction [Hobbs, 2000], which is defined as followed:

$$b_{e\lambda} = b_{s\lambda} + b_{a\lambda} \quad (9)$$

$b_{e\lambda}$... Extinction coefficient of the air [m^{-1}]
 $b_{s\lambda}$... Scattering coefficient of the air [m^{-1}]
 $b_{a\lambda}$... Absorption coefficient of the air [m^{-1}].

The coefficients can differ due to the concentration and the size of the particles in the atmosphere [Hobbs, 2000]. Moreover, the chemical composition of the particle, the shape and the polarisation of the beam exert influence on the extinction [Bohren and Huffman, 1983].

Consequently the process and general differences between the two major types of scattering and absorption will be explained:

- Scattering

The fundamental principle of scattering is based on the fact that matter consists of electrons and protons [Bohren and Huffman, 1983]. The electromagnetic wave encounters the particles (can be seen as an obstacle) and set them into vibration via the electromagnetic field [Bohren and Huffman, 1983]. The electric charges get accelerated and produce "secondary radiation" via radiant emittance of the energy in all directions [Bohren and Huffman, 1983]. This leads to a cancellation of the original direction of the radiation and to a new direction of propagation [Klose, 2008b]. A precondition for scattering is also that the refractive index of the particle and the medium is different [Klose, 2008b].

Scattering can be divided into two subcategories. The Rayleigh scattering can be seen as a limiting case of the Mie scattering, so both types show an elastic scattering behaviour, which means that the frequency (or wavelength) won't be changed during the scattering process [Klose, 2008b].

- Rayleigh scattering (RS): This is the scattering on particles that are much smaller than the wavelength [Hobbs, 2000].

$$2\pi r \ll \lambda \quad (10)$$

r ... Radius of the particle

This kind of scattering is proportional to the density of the atmosphere, which leads to the fact that scattering decreases with height [Hobbs, 2000].

The scattered irradiance is proportional to $\frac{1}{\lambda^4}$ and has an angular distribution [Bohren and Huffman, 1983], which shows an spheric symmetrically shape [Klose, 2008b]. Which in turn means that forward scattering is identical to backward scattering [Hobbs, 2000].

The Raleigh scattering (RS) can be calculated via the scattering coefficient σ [Houghton, 2002].

$$\sigma_R = \frac{32 \cdot \pi i^3}{3 \cdot N_0 \cdot \lambda^4 \cdot \rho_0} \cdot (n - 1)^2. \quad (11)$$

Scattering is defined along an atmospheric path ($\int \sigma \rho dz$) and changes the initial intensity of the beam and is calculated by the Lambert's Law [Houghton, 2002]:

$$I = I_0 \cdot \exp(-\int \sigma \rho dz). \quad (12)$$

When the radius of the particle is increasing forward scattering becomes more important and backward scattering is decreasing [Klose, 2008b].

The peak of forward scattering is also getting more defined [Bohren and Huffman, 1983].

- Mie scattering: This is the scattering on particles that are larger than the wavelength considered [Hobbs, 2000]:

$$2\pi r > \lambda \quad (13)$$

r ... Radius of the particle.

It belongs to the same principles as RS [Bohren and Huffman, 1983]. The main particles that belong to Mie scattering are Aerosols [Hobbs, 2000].

If the scattering parameter α is located between approximately 0.1 and 50 Mie scattering prevails [Hobbs, 2000]:

$$\alpha = \frac{2 \cdot \pi i \cdot r}{\lambda} \quad (14)$$

r ... Radius of the particle

λ ... Wavelength.

If the particles become even larger (droplets, rain drops, ice particles) then the calculations follow the laws of geometrical optics [Hobbs, 2000].

Results for of the Mie-Theory are only possible with computer-assisted calculations.

Figure 3.10 shows a schematic illustration of the three types of scattering processes explained above.

The process of scattering is more complicated based on the fact that the scattering particles are no spheres as assumed in the explanations before. In the atmosphere the particles do not have a regular shape [Bohren and Huffman, 1983], which makes it impossible to derive scattering without this assumption.

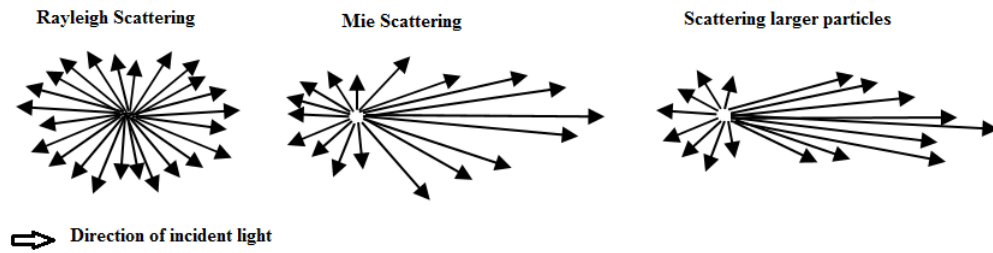


Figure 3.10: Three types of scattering, 1. Rayleigh scattering, 2. Mie scattering, 3. Scattering on larger particles [Alkholidi and Altowij, 2014]

For the Earth's atmosphere the RS is more important than the Mie scattering [Houghton, 2002].

- Absorption: Another change in the intensity occurs by absorption of energy. Absorption occurs in individual lines of discrete energy levels (vibration- and rotation states) that can be combined to vibration-rotation bands [Houghton, 2002].

Gases: They absorb discrete values of energy [Hobbs, 2000] by absorbing specific wavelengths [Klose, 2008b]. The particular wavelengths are defined by the material constant of several materials [Klose, 2008b].

The amount of different absorber in the atmosphere is large. Consequently one will find a few of the most important values [Hobbs, 2000]

O_3 : $0.2 - 0.3 \mu\text{m} \rightarrow$ near UV

Ozone $\rightarrow O_3$: absorption area is called Hartley band and converts the absorbed energy into kinetic energy, which leads to an increasing temperature of the atmosphere [Houghton, 2002]

N_2 : $< 0.2 \mu\text{m} \rightarrow$ UV

O_2 : $0.7 \mu\text{m} \rightarrow$ visible radiation (only rare absorption)

Water vapour: a lot of bands in the IR (rotation and vibration energy transitions)

CO_2 : weak absorption bands at $1.4 \mu\text{m}$, $1.6 \mu\text{m}$ and $2.0 \mu\text{m}$

Aerosols: The absorption of energy leads to an increase of temperature of the atmosphere, due to increasing vibration energy, rotation energy and electron energy [Hobbs, 2000].

Clouds: They consist of water, water vapour and aerosols and this leads to many different properties. Clouds cover approximately 50% of the sky and have a large effect on the incoming and outgoing radiation [Houghton, 2002].

Top of the cloud: a part of the radiation gets directly reflected (cloud albedo) [Houghton, 2002]

Bottom of the cloud: a part of the radiation penetrates through the cloud without any interaction (transmission) [Houghton, 2002]

The difference between the reflected and the transmitted radiation is defined as the absorbed

radiation [Houghton, 2002]:

$$F(1 - A - \tau) \quad (15)$$

F ... Flux

A ... Albedo (reflection) [%]

τ ... Transmission [%].

Beside this, water and ice are good absorbers in the IR, not only of the incoming radiation, but also of the terrestrial emitted thermal radiation [Houghton, 2002].

The absorption can be calculated similar to the scattering.

The main difference lies in the absorption coefficient (in the following called κ) [Houghton, 2002].

The absorption coefficients have to be taken from literature on the basis that they are depending on the material.

$$I = I_0 \cdot \exp\left(-\int \kappa \rho dz\right) \quad (16)$$

- Reflection: Reflection in this case implies the back radiation from a surface and that the energy won't reach the surface of a planet [Klose, 2008b]. Optically thick surface have the characteristic to reflect radiance [Bergmann and Schäfer, 2001]. For astronomical purposes the reflection is called 'Albedo'.

By summing up all these atmospheric effects, the calculations lead to the 'global radiation budget' and yield to the surface temperature of a planet. For the Earth the global radiation budget is well-known and on other test planets with fixed atmospheric parameters this process can be adapted. Therefore the principle basis of computation should be outlined:

The transformation of the incoming radiation is important for the climate. The net energy gain in the system has to be zero to keep it in balance [Bergmann and Schäfer, 2001].

The 'system Earth' is given by a combination of the three different surfaces that dominate our surface appearance; oceans, landmass and ice [Bergmann and Schäfer, 2001].

The incoming radiation is defined as $\frac{1}{4}$ of S_0 whereby 30% get immediately reflected by the planetary albedo. [Bergmann and Schäfer, 2001].

$$\Rightarrow 432 \text{ W/m}^2 (100\%) - 103 \text{ W/m}^2 (30\%) = 239 \text{ W/m}^2 (70\%)$$

In comparison with Figure 3.11 one can easily pursue the reflection, absorption and scattering processes in the system.

30% of the incoming radiation get directly lost to space:

- 4% reflected by the Earth's surface
- 6% scattered in the atmosphere

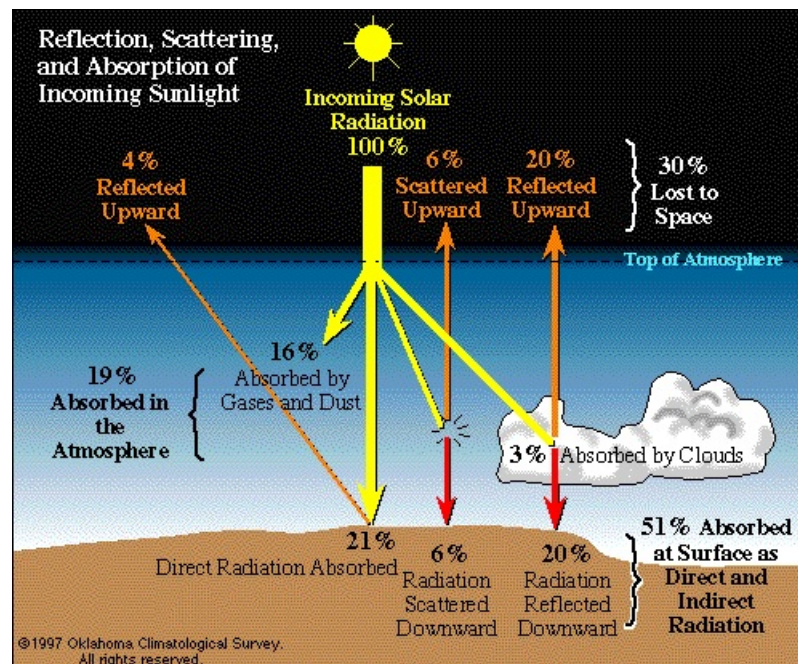


Figure 3.11: Earth's Energy Budget [O.C.S., 1996-2005]

- 20% reflected from the clouds

19% of the incoming radiation get absorbed in the atmosphere:

- 16% absorption by gases and dust
- 3% absorption by clouds

51% of the incoming radiation becomes absorbed by the Earth's surface:

- 21% of the incoming radiation is directly absorbed
- 6% from the downward scattering
- 20% radiation reflected downward from clouds

The absorbed 70% have to be emitted via thermal radiation to guarantee the energy balance.

This leads to the radiation budget, in terms of the initial energy it is equal to the reflected and emitted long wavelength radiation [Ramanathan et al., 1989].

With the Boltzmann law (see equation 2) the surface temperature can be calculated [Bergmann and Schäfer, 2001]. This calculations lead to a temperature of 255 K, which is 33 K less than the observed 288 K [Ramanathan et al., 1989]. These 33 K can be attributed to the greenhouse effect [Ramanathan et al., 1989]. This is the generalised radiation budget.

Several factors have to be considered to calculate the energy budget for a particular region:

The energy flux is not the same for each region [Bergmann and Schäfer, 2001]. The Tropics have

larger gain than loss [Bergmann and Schäfer, 2001].

The season:

In summer the radiation is for all latitudes almost steady [Bergmann and Schäfer, 2001].

In winter the radiation drops from the equator to the poles [Bergmann and Schäfer, 2001].

The cloud coverage is the another uncertainty given that the coverage is varying in time and spatial distribution. Water vapour is rising up, transported by circulations and turbulences, and is condensed in other latitudes [Ramanathan et al., 1989]

The last chapter describes the properties of the Earth's atmosphere and the especially how radiation can be effected by an atmosphere. The modifications are the fundamental parameters that have to be taken into account for the SED calculations for atmospheres with different compositions and different aerosol quantities. Therefore the processes of scattering and absorption have to be exactly comprehended for the further computations and the interpretation of the following results.

3.3 Different Atmospheres

To answer the question if photosynthesis works on other planets around M-, and G-stars with different distances to their host star it seems unreasonable to do the calculations only for one strictly well defined atmospheric composition. Therefore three other specific compositions were selected to answer the scientific question.

The selected mixture will be identical or similar to the composition of Venus, Titan and Earth's atmosphere listed below. If there will be any changes in the mixture they will be explained in detail in the chapter 5.4.

3.3.1 Earth's Atmosphere

The most important properties were already discussed in the chapters before. So only another important item is worth mentioning: The values of the properties and the composition of the atmosphere.

Properties of the atmosphere:

Surface pressure	1014 mb
Surface density	1.217 kg/m ³
Total mass of atmosphere	5.1×10^{18} kg
Total mass of hydrosphere	1.4×10^{21} kg
Average temperature	288 K
Wind speeds	0 to 100 m/s

Table 3.3: Properties of the Earth's atmosphere [Williams, 2015a]

The composition will be a very important topic for the calculations, since this variables are a critical parameter for the radiative transfer program.

Atmospheric composition (by volume, dry air):

Major composition	[%]
Nitrogen	78.08
Oxygen	20.95
Minor composition	[ppm]
Argon	9340
Carbon Dioxide	400
Neon	18.18
Helium	5.24
CH ₄	1.7
Krypton	1.14
Hydrogen	0.55

Table 3.4: Composition of the Earth's atmosphere [Williams, 2015a]

3.3.2 Venus Atmosphere

Venus will be one of the scenarios this treatise will deal with. The most important facts needed are the composition of the atmosphere to input them into the radiation transfer software. Nevertheless, some basic facts about this dim planet have to be displayed.

So first of all a few important informations.

Venus is the 2nd planet of our solar system and is also called the 'sister planet' of the Earth. However, in reality Venus is a really uncomfortable place, especially for life-as-we-know-it.

Venus and Earth are called sister planets by reason that they show similarities in their size and structure [Dunbar, 2015]. Because of the runaway greenhouse effect Venus is covered in a poisonous gas envelope with a surface temperature of 735 K [Dunbar, 2015].

The following tables give a quick overview about the general properties of Venus and the composition of its atmosphere.

Properties of the atmosphere:

Surface Pressure	92 bar
Surface density	$\approx 65 \text{ kg/m}^3$
Total mass of atmosphere	$\approx 4.8 \times 10^{20} \text{ kg}$
Average temperature	737 K
Wind speeds	0.3 to 1.0 m/s (surface)

Table 3.5: Properties of the Venus atmosphere [Williams, 2015b]

Atmospheric composition (near surface, by volume):

The atmosphere can also be divided into several layers but at about 60 km height one can find a really impressive cloud layer with a depth of approximately 20 km which surrounds the whole planet [European Space Agency, 2015]. The interesting part is the upper level of this cloud layer, because

Major components	[%]
Carbon Dioxide	96.5
Nitrogen	3.5
Minor components	[ppm]
Sulfur Dioxide	150
Argon	70
Water	20
Carbon Monoxide	17
Helium	12
Neon	7

Table 3.6: Composition of the Venus atmosphere (near surface) [Williams, 2015b]

it consist of droplets of H_2SO_4 [European Space Agency, 2015]. This leads to the assumption that lightning is possible because sulphuric acid is a good conductor [European Space Agency, 2015].

Clouds are as important on Venus as on Earth. The do not consist of water vapour but they also absorb and scatter radiation and this has to be taken into account for further calculations. With the radiation transfer program these important H_2SO_4 clouds can be taken into consideration.

3.3.3 Titan Atmosphere

The third atmosphere was chosen because of the great difference to the other ones. This leads to a greater diversity.

Due to the fact that Titans atmosphere is composed mainly of N_2 [Dunford and McKissick, 2016] an scenario with an atmosphere consisting of one gas is also covered . The second component (CH_4) only present in slight traces [Dunford and McKissick, 2016].

3.4 Atmosphere of Tidally Locked Planets

Related to atmospheres, another important point has to be clarified. Due the fact that the test planets have to be located in the LW-Zone of the M-star it is probable that the planet will be synchronously rotating. As mentioned in chapter 2.2.4.1 it is considered very likely that it is not possible for tidally locked planets to keep an atmosphere. Accordingly, the simulations of M. Joshi (2003) and Johsi et al. (1997) have to be mentioned.

In this model he calculated the circulation of an atmosphere of synchronously rotating planets. The ‘simplified global circulation model’ (SGCM) was used for these calculations [Joshi et al., 1997]. An important factor for this model was the surface energy balance, because this factor gives the surface temperature [Joshi et al., 1997]. Which in turn is fundamental for the consideration that the atmosphere is collapsing when CO_2 is condensing on the surface [Joshi et al., 1997]. It was taken into account that the frost point of CO_2 is depending on pressure [Joshi et al., 1997]. For that divers runs with different pressure and different optical depth were done [Joshi et al., 1997]. Here the results show that for a CO_2/H_2O atmosphere the atmospheric collapse takes place when the surface pressure is ≈ 30 mb and the pressure can be even lower for N_2 atmospheres (calculated with terrestrial irradiation) [Joshi et al., 1997].

M. Joshi (1997) modelled the atmospheres and got also as a result that a heat transporting cell exists. The cell is situated near the ground in a longitudinal direction and is able to transport heat from the substellar point to the antistellar point [Joshi et al., 1997]. At low altitudes the mass from the night side is able to circulate back by winds to the day side across the polar regions [Joshi et al., 1997]. The atmosphere was warmer than expected from M. Joshi et al. (1997), especially on the far side of the planet which was leading to more lower surface temperatures than considered just from radiative reflections[Joshi et al., 1997].

An interesting minor point is that if the partial pressure of CO_2 in the atmosphere is controlled by the carbonate-silicate cycle the planet should have at least a surface pressure of 1000 to 1500mb [Joshi et al., 1997]. For these pressure values it is also possible to keep water in a liquid form on the planet's surface [Joshi et al., 1997].

A few years later M. Joshi did the calculation again with a more complex atmospheric circulation model, where he took clouds into consideration on the fact that clouds have a great influence on the global climate especially on the incoming radiation and the outgoing thermal radiation from the planet's surface [Yang et al., 2013].

The following subchapter follows the explanations of M. Joshi (2003) in the study of 'Climate Model Studies of Synchronously Rotating Planets'.

The authors used the so-called 'Intermediate General Circulation Model' (IGCM) which was already used to study the Earth's climate and the changes it undergoes. It is a 3D global atmospheric circulation model. The difference between this model and the models that M. Joshi et al. (1997) used before, is the simple fact that the effects of clouds could be taken into consideration.

The IGCM was used for three runs, each with major differences in the topography of the planet's surface. Aquaplanet run, northern continent run and a dry land run.

To prevent an oceanic influence to the heat transport, the fluxes were set to zero. This will generate a heat flux only caused by the atmosphere.

The results show that the existence of clouds leads to a cooler surface temperature at the day side of the planet

What M. Joshi (2003) also claims is that theoretically all water should evaporate on the dayside and condense out on the far side of the planet. This would never happen in the aquaplanet run, due to infinite reservoir. In fact, a thick ice cap would exist on the dark side. In a regular ocean, the thickness of the cap is limited by the existing heat flow of the hydrological cycle, which was excluded in this model.

The northern hemisphere run shows that it is possible that the land mass is covered by ice.

If there is land mass on the far side, the northern hemisphere run shows that it is possible that the available water is stored as ice on this side. To prevent this a hydrological cycle is necessary.

Another, very unlikely, scenario is a landmass covering the whole terminator, whereas the melting water could return to the day light side.

Even the lowest temperature measured in these simulations (203.15 K) is above the temperature where CO₂ would freeze out. M. Joshi (2003) also concluded that the terminator would be the most habitable place on a rotationally bound planet. This area would obtain less direct radiation.

The results in this publication of M. Joshi (2003) are similar to that of his earlier work in 1997 [Joshi, 2003].

All three model runs and calculations lead M. Joshi et al. (1997), and finally also M. Joshi (2003), to the following assumption: *"We finally conclude that planets orbiting M stars can support atmospheres over a large range of conditions and, despite constraints such as stellar activity, are very likely to be habitable [Joshi et al., 1997]."*

4 Photosynthesis

4.1 Evolution of Photosynthesis

We really know very little about the beginning of the oxygenic photosynthesis. However, it was not the first metabolism that evolved on Earth to support photosynthesis.

The primordial metabolism of the protocell, a cell which could be seen as ancestor to unicellular life, is assumed to be chemolithoautotroph [Weiler and Nover, 2008]. Moreover there was a lack of O_2 in the primordial atmosphere [Weiler and Nover, 2008]. Hence, chemosynthesis was one of the first metabolisms [Weiler and Nover, 2008]. The oxygenic form of photosynthesis arose much later than the anoxygenic photosynthesis, which was the earliest form of photosynthesis [Blankenship, 2010]. 3-4 billion years ago the atmosphere contained little to no molecular oxygen [Weiler and Nover, 2008]. Methane, carbon dioxide and nitrogen were the principal constituents of the first atmosphere [Hohmann-Marriott and Blankenship, 2011]. Organisms that lived at that time were not up to oxygen so that they had to have an anaerobic biochemistry [Hohmann-Marriott and Blankenship, 2011].

Stromatolites were found in 3.4 billion years old layers, which were interpreted as remains of cyanobacteria-colonies [Weiler and Nover, 2008]. Due to that, Weiler & Nover concluded that the anoxygenic photosynthesis was perhaps raised more than 3 billion years ago [Weiler and Nover, 2008].

It is possible that the evolution of the oxygenic photosynthesis began in the shallower water between 3.5 (3.6 respectively) and 2.3 billion years ago [Kiang et al., 2007b]. Cyanobacteria-colonies formed under water, because there they were protected from UV radiation until O_2 and hence, O_3 built up in the atmosphere [Kiang et al., 2007b].

However, there is evidence of changes to the primordial atmosphere, which can be found in 2.7 billion years old rock formations [Weiler and Nover, 2008]. In these deposits iron oxide as a first indicator for the release of O_2 has been found [Weiler and Nover, 2008]. This period became known as the 'Great Oxidation Event' (between 2.4 - 2.0 billion years ago) [Holland, 2006].

This means that when O_2 appeared in the atmosphere, oxygenic organisms were better adapted than anoxygenic organisms [Kiang et al., 2007b].

After the significant rise of O_2 in the primordial atmosphere the organisms with aerobic biochemistry were in a disadvantageous position [Hohmann-Marriott and Blankenship, 2011]. M. F. Hohmann-Marriott and R. E. Blankenship concluded: "(...) and organisms were either forced to adapt to oxygen, retreat to anaerobic ecological niches, or become extinct" ([Hohmann-Marriott and Blankenship, 2011] p.517).

4.2 Fundamental Information

Actually 'Photosynthesis' just implies 'synthesis with light' and for this reason it includes all processes that form something new with light as the source of energy [Blankenship, 2002].

M. T. Madigan et al. went one step further and wrote in their book: *"The most important biological process on Earth is photosynthesis, the conversion of light energy to chemical energy"* ([Madigan et al., 2012], p. 341)

Bacteria, algae and plants are phototrophic organisms with the capability to practice photosynthesis in two different types, the oxygenic and anoxygenic [Blankenship, 2002].

Bacteria use anoxygenic photosynthesis (exclusion: Cynobacteria), and probably the oxygenic photosynthesis has evolved from this kind of phototrophy [Madigan et al., 2012]. Therefore, Bacteriochlorophylls are also taken into consideration but the focus will lay on the oxygenic photosynthesis and therefore the Chlorophylls and Carotenoides.

The basic idea of photosynthesis is to use water and carbon dioxide in combination with energy (light) to produce, directly or indirectly, sugar, carbohydrates, lipids and proteins [Ke, 2003]. Therefore photosynthesis represent an important link between the energy of electromagnetic radiation and living creatures [Ke, 2003].

Oxygenic photosynthesis is the procedure of creating organic molecules (from inorganic molecules) which are needed to build up phototrophic organisms [Amesz, 1987], with O_2 as by-product.

Nearly all organic substances on Earth are produced by photosynthesis as well as all of the oxygen provided by the atmosphere [Weiler and Nover, 2008]. Finally this implies that the heterotrophic organisms depend on this process [Weiler and Nover, 2008].

The universal principal of photosynthesis is to assemble ATP (Adenosintriphosphat) [Weiler and Nover, 2008]. Certainly there is a difference between two types of photosynthesis related to the substrate they use as an electron and hydrogen-ion source, as well as the light absorbing pigments and the photosystems (type and number) [Weiler and Nover, 2008].

Photosynthesis can be subdivided into two stages [Weiler and Nover, 2008]. In the following text these two phases will be explained more precisely.

The first subdivision, and the major one for this work, is the light-dependent reaction. The fundamental function of this part for the organism is to provide ATP and reduced co-substrates [Weiler and Nover, 2008].

This means that the phototrophic organisms need light.

Electromagnetic radiation can be absorbed from several materials [Weiler and Nover, 2008].

The excerpt of the following table shows the full electromagnetic (EM) spectrum of our sun.

An important factor of the light reaction is the absorption of electromagnetic radiation. However, the Chlorophyll molecules and Carotinoids just absorb the so called photosynthetically active radiation (PAR) [Holst et al., 2000].

Description	Wavelength	Frequency [HZ]
γ radiation	$\leq 10^{-4} \mu\text{m}$	$\geq 3 \times 10^{19}$
x-ray	$10^{-5} - 10^{-2} \mu\text{m}$	$2 \times 10^{20} - 7 \times 10^{16}$
UV-radiation	$0.1 - 0.380 \mu\text{m}$	$3 \times 10^{15} - 7.9 \times 10^{14}$
UV-C	$0.1 - 0.280 \mu\text{m}$	
UV-B	$0.280 - 0.315 \mu\text{m}$	
UV-A	$0.315 - 0.380 \mu\text{m}$	
visible light	$0.380 - 0.780 \mu\text{m}$	$7.9 \times 10^{14} - 3.85 \times 10^{14}$
violet	$0.380 - 0.436 \mu\text{m}$	
blue	$0.436 - 495 \mu\text{m}$	
green	$0.495 - 0.566 \mu\text{m}$	
yellow	$0.566 - 0.589 \mu\text{m}$	
orange	$0.589 - 0.627 \mu\text{m}$	
red	$0.627 - 0.780 \mu\text{m}$	
IR	$0.780 \mu\text{m} - 1 \text{ mm}$	$3.85 \times 10^{14} - 3 \times 10^{11}$
IR-A	$0.780 \mu\text{m} - 1.4 \mu\text{m}$	
IR-B	$1.4 \mu\text{m} - 3.0 \mu\text{m}$	
IR-C	$3.0 \mu\text{m} - 1 \text{ mm}$	
microwave	$0.1 - 100 \text{ cm}$	$300 - 0.3 \times 10^9$
radio waves	$1 \text{ m} - 10 \text{ km}$	$3 \times 10^8 - 3 \times 10^4$
UKW	$1 - 10 \text{ m}$	
KW	$10 - 100 \text{ m}$	
MW	$100 - 1000 \text{ m}$	
LW	$1 - 10 \text{ km}$	

Table 4.7: EM spectrum of the solar radiation [Klose, 2008a]

Different types of Chlorophylls and Carotenoids with diverse absorption areas are the absorbing molecules that have to be taken into consideration [Weiler and Nover, 2008]. With the action spectrum of Chlorophyll molecules (see Figure 4.12) one can see the efficiency of different spectral regions [Weiler and Nover, 2008].

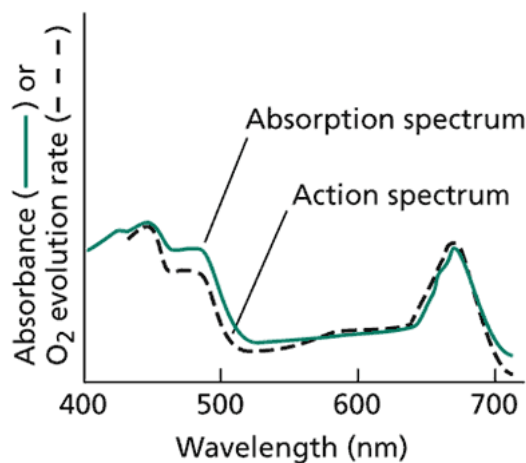


Figure 4.12: Action spectrum compared to an absorption spectrum [Sinauer Associates, 2015]

As can be seen above the PAR covers the entire visible range from 400 to 700 nm, sometimes up till the near-IR region (1000 nm) [Blankenship, 2002], with a drop at about 500 nm where the peak of the spectrum of our sun lies.

First of all the photons have to be absorbed by the pigments of the Antenna system [Blankenship, 2002]. The most prominent example of an absorbing pigment is Chlorophyll which changes to a cat-ion after the absorption of a Quantum of energy [Weiler and Nover, 2008].



A single pigment can only use a small amount of PAR, so this system has the function to increase the quantity of absorbed energy [Blankenship, 2002].

The absorption in organic molecules is not along a single line but over an area due to the rotation and vibration transition [Weiler and Nover, 2008]. This is very important for phototrophic organisms as it increases the absorbent wavelength range.

Figure 4.13 shows the absorption of red and blue light, which are the preferred wavelengths of the Chlorophyll pigments [Weiler and Nover, 2008].

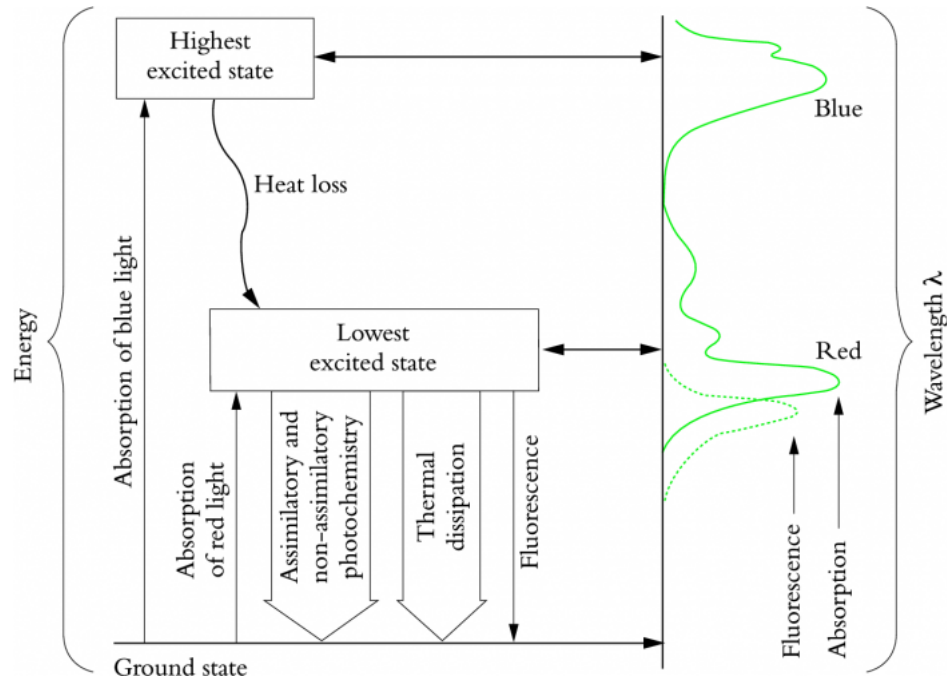


Figure 4.13: Absorption behaviour of Chlorophyll of blue and red light [Australian Society of Plant Scientists, 1999]

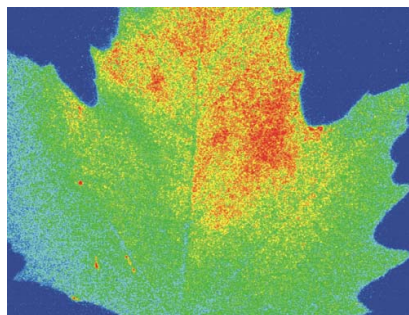
Chlorophyll molecules possess two states of excitation (S^1 and S^2) [Weiler and Nover, 2008].

$S^1 \rightarrow$ equivalent to the absorption of red light

$S^2 \rightarrow$ equivalent to the absorption of blue light

The Chlorophyll molecule is able to transport the excitation energy to another Chlorophyll pigment only with the so-called S^1 state [Weiler and Nover, 2008]. This process is called excitation-transfer [Weiler and Nover, 2008]. It can be concluded that the S^1 state is the more stable one [Weiler and Nover, 2008]. Which means that the state is long-lived enough to transfer the energy (energy transfer occurs radiation-less) [Weiler and Nover, 2008]. The S^2 state is more energetic and has to be disexcited to the S^1 state per releasing energy as vibration or EM radiation (fluorescence) [Weiler and Nover, 2008]. The vibration of the Chlorophyll molecules caused by the higher energetic blue radiation leads to a heating effect [Weiler and Nover, 2008].

Radiation with red light would lead to a completely effective photosynthesis [Weiler and Nover, 2008].



This image to the left (Figure 4.14 shows an example of fluorescence of a Platanus leaf (intensity at 740 nm, false colour, increasing intensity from blue to green to yellow to red) [KIT, 2012].

Figure 4.14: Fluorescence (false colour) [KIT⁴⁵2012]

However, the thylakoid membranes (see Figure 4.15) (which is the membrane of the Chloroplast) are appropriate to the first reaction that transforms the electromagnetic energy into redox potential [Blankenship, 2002].

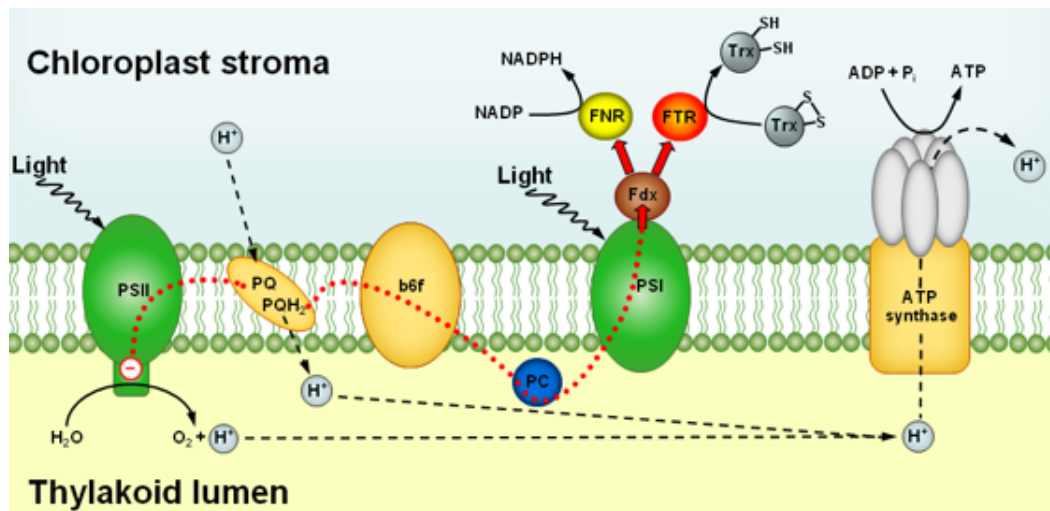


Figure 4.15: Part of the Thylakoid membrane in the model [Schuermann, 2010]

The electron transport takes place in this membrane as well as the proton transport and the ATP-Synthesis [Blankenship, 2002]. The charged particles were extracted from the excited Chlorophyll and photolysed water [Blankenship, 2002]. Photolysis of water occurs in the thylakoid membrane and is not only an electron source but also an H^+ source, which in turn is essential for the ATP-synthesis [Weiler and Nover, 2008]. During the photolysis of water the formation of molecular oxygen takes place [Weiler and Nover, 2008].

The whole transport process happens between the Photosystem II, the Cytochrome- b_6/f -complex and the Photosystem I and runs not synchronous [Weiler and Nover, 2008].

The antenna system transfers the energy, which implies that it passes the energy from one transfer molecule to the next [Blankenship, 2002].

They are arranged around the so called 'reaction centre', which consists of the special pair (primary electron donor), and both are part of the photosystems [Blankenship, 2002].

The reaction centre is to be composed of Chlorophylls and other non-protein molecules [Blankenship, 2002]. After the absorption of energy in the wavelength region of PAR, energy transfer toward the reaction centre, from higher- to lower- energy pigments, takes place [Blankenship, 2002]. Here the photochemistry occurs.

The transport through the antenna system stabilizes the energy during the transfer through the thy-

lakoid membrane [Ort and Yocum, 2003]. This leads to a separation of the oxidized and reduced species [Blankenship, 2002]. So the positive charges get separated from the negative charges and all that within a very short time [Blankenship, 2002].

Blankenship (2002) guesses, that the basic principle applies to all photosynthetic reaction centres, although the details of the process vary from one system to the next. In the following outline one can find a short explanation of the photosystems [Weiler and Nover, 2008]:

- **Photosystem II:** primarily the sequence of the electron transport, consists of a reaction centre and the antenna complex (separated inner and outer antenna), the system is also called ‘P680’ because of its absorption maximum at 680 nm
- **Cytochrom- b_6/f -complex:** following transmission of the electrons, Q-cycle takes place, Proton-pump (H^+ -ions transport to the Thylakoidlumen)
- **Photosystem I:** antenna complex and reaction center are directly connected and take the electrons from the Thylakoidlumen-side and transfer them to the Stromaside (on the iron-sulphur-protein Ferredoxin) $\rightarrow$ acceptance or release of just one electron, the system is also called ‘P700’ because of its absorption maximum at 700 nm

After removing the electrons from the water in the PS II they arrive at PS I, where the Ferredoxin transfers them on the $NADP^+$ (oxidised form of Nicotinamide adenine dinucleotide phosphate, used for the generation of carbohydrate) [Weiler and Nover, 2008].

ATP-Synthase:

ATP synthase is an important enzyme which requires energy to provide energy for the cell. It is a rotating cylinder engine powered by H^+ -ions to generate ATP from ADP (Adenosindiphosphat) [Weiler and Nover, 2008].

The ion-engine is fixed in the Thylakoid membrane and stationary [Weiler and Nover, 2008].

If there is a difference between the concentration of the H^+ on the Stroma- (above the membrane) and the Lumen-side (below the membrane) a concentration gradient is available [Weiler and Nover, 2008]. The concentration on the Thylakoidlumen side is higher so that the H^+ bind on the rotor of the lumen side and this leads to a rotation of the rotor [Weiler and Nover, 2008].

The head on the Stroma side (connected with rotor through an arm) gets in motion and passes through the 3 phases of the catalytic cycle [Weiler and Nover, 2008]. Weiler and Nover (2008) explained it that way:

1. catalytic center is not filled
2. generation of ADP and phosphate
3. generation and release of ATP [Weiler and Nover, 2008].

This leads to a formation of 3 molecules of ATP per revolution of the ATP-Synthase enzyme [Weiler and Nover, 2008].

Spatial arrangement:

The whole synthesis described above takes place in the Chloroplasts (see Figure 4.16), which occurs in all green tissues [Encyclopaedia Britannica, 2015].

Chloroplasts are just 1-2 μm thick and have a diameter of 5-7 μm [Encyclopaedia Britannica, 2015]. They are intensively structured:

1. outermost: surrounded by a double membrane (inner and outer layer) with an so-called 'inter membrane space' in between [Encyclopaedia Britannica, 2015]
2. inside: a third membrane, the thylakoid membrane forms membrane invaginations, the so-called thylakoid, this membrane surrounds the thylakoid lumen, the thylakoids form stacks of disks (Grana), Grana are interconnected through stroma lamellae [Encyclopaedia Britannica, 2015]
3. interspace: filled up with Stroma [Encyclopaedia Britannica, 2015]

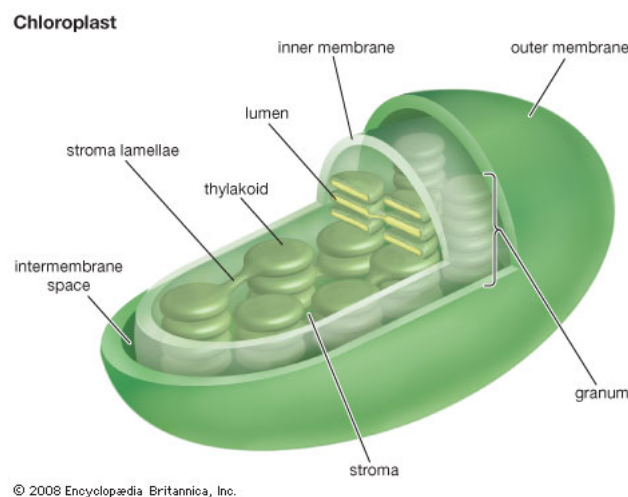


Figure 4.16: Chloroplast structure [Encyclopaedia Britannica, 2015]

Inside the Granum (see Figure 4.17): The different complexes of the light reactions are not arranged irregular inside the thylakoid membrane. [Weiler and Nover, 2008].

The following arrangement is set according to E. Weiler and L. Nover (2008) in their book 'Allgemeine und molekulare Botanik':

- **PS II, LHCII:** in the stacked area of the Grana
- **PS I, Chytochrom-b-6/f-complex:** is primarily in the stromathylakoid, on the other side of the Grana stack respectively.
- **ATP-Synthase:** completely in the stromathylakoid, on the other side of the Grana stack respectively

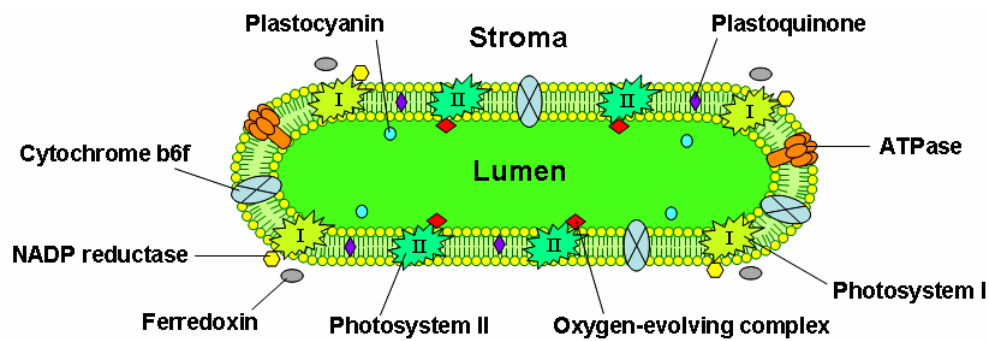


Figure 4.17: Sketch of the Thylakoid membrane [Imgarcade, no]

The second phase:

The main reason for organisms to practice photosynthesis is to produce carbohydrate, which is the end product of the carbon assimilation [Weiler and Nover, 2008].

This stage is called 'dark reaction' because one does not need light in the direct form of radiation but it needs the products created during the 'light reaction' [Blankenship, 2002]. What the organism needs is the reduced compound NADPH, and the energy of ATP, both generated in the light reaction [Blankenship, 2002].

These enzyme-catalyzed processes occur in the stroma [Blankenship, 2002].

The so-called 'Calvin cycle' can be divided into several steps. These 4 steps are set according to E. Weiler and L. Nover (2008) in their book 'Allgemeine und molekulare Botanik' and will be shortly explained. For details see E. Weiler and L. Nover (2008) in their book 'Allgemeine und molekulare Botanik':

1st step: fixation of carbon dioxide

- The most important enzyme for that is RubisCO
- The fixation rate is very low, so the organism needs a lot of RubisCO to ensure that CO_2 is not a limiting factor.
- The fixation goes along with the loss of water through the Stoma.

2nd step: reduction phase

- Needs the two products of the light reaction: ATP and NADPH
- For the reduction of one molecule O_2 2 molecules ATP and 2 molecules NADPH are needed
 - ATP is reduced to ADP with release of energy
 - NADPH is reduced to $NADP^+$ with release of hydrogen

3rd step: regeneration phase

- The ring closure of the Calvin cycle implies the regeneration of the enzyme RubisCO. Therefore a lot of complicated reaction sequences are required.
- To regenerate 6 molecules of Ribulose-1,5-bisphosphat another 2 molecules of ATP are necessary.
- That is a very important step due to the fact that the organism has to be able to fix CO_2 again.

4th step: the assimilation of the fixing profit

- The netto profit of the Calvin cycle inside the Chloroplast is glucose (monosaccharid), which is not formed in a free structure. Either Fructose-6-phosphat will be diverted from the Calvin cycle and assimilated to starch (polysaccharid) inside the Chloroplast (stroma) or G3P will be diverted and inserted into the cytoplasm and assimilated into saccharose.

Figure 4.18 shows a simplified picture of the Calvin cycle.

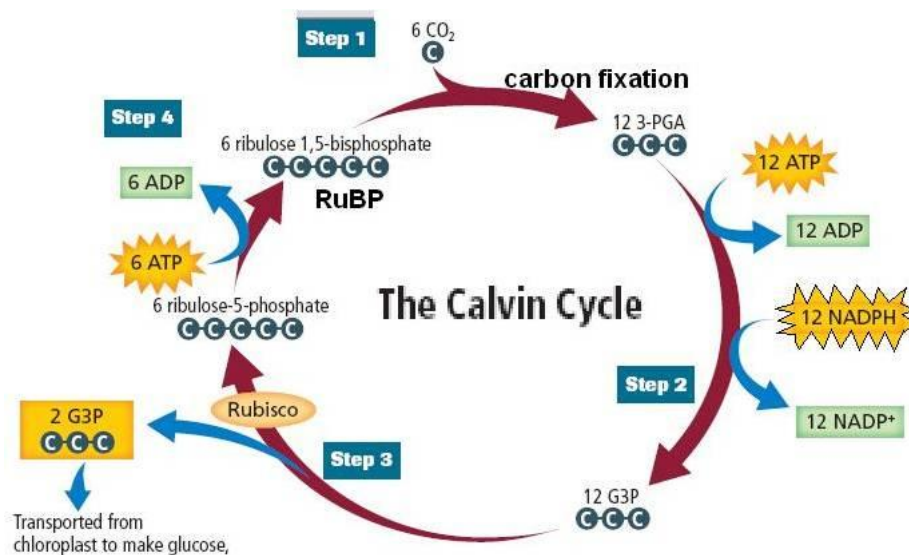
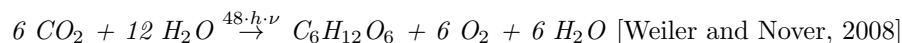


Figure 4.18: The Calvin cycle [StudyBlue, 2014]

The connection of these two stages leads to the chemical reaction equation of photosynthesis:

6 molecules CO_2 are needed to generate one molecule of glucose, based on that the point balance equation will be expressed for one molecule glucose [Weiler and Nover, 2008].



According to Weiler and Nover (2008) the light reaction needs 8 light quanta for the formation of one molecule O_2 , so for one molecule of glucose 6 molecules of O_2 are required, altogether $48 \cdot h \cdot \nu$ are needed [Weiler and Nover, 2008].

This highly complicated reaction is not completely understood until today although it is one of the most important reactions due to the fact that it produces oxygen and absorbs carbon dioxide.

4.2.1 The Emerson Effect

We already learned that 2 different photosystems are part of photosynthesis. These two systems have different preferred absorption wavelengths [Wölfinger, 2013]. PS I is also called P700 due to the fact that it absorbs at an area of 700 nm and it is also the PS where we can find a *Chlorophyll a* pigment in the centre of the antenna system (reaction centre) and PS II is called P680 and the centre contains a *Chlorophyll b* pigment [Wölfinger, 2013].

Emerson and Arnolad showed that two different kinds of pigments are working together in the process of generating glucose, in two different areas of red light and also in two different areas of blue light [Wölfinger, 2013] (see absorption spectra of Chlorophyll pigments), in a “shorter” and a “larger” wavelength range of blue and red light.

This is the reason why we can find an effect that is called “Emerson effect”. Emerson and Arnolad found out that if Phototrophs will be irradiated with two different wavelengths in the “red area of the SED” (650 nm = red, 700 nm = dark red) the photosynthetic rate will be higher [Wölfinger, 2013].

4.2.2 Limiting Factors

In the following section a short account on the limiting factors of photosynthesis, summarized from E. Weiler and L. Nover (2008) in their book ‘Allgemeine und molekulare Botanik’, will be given.

Photosynthesis is extensively dependent on external factors because of their rapidly changing characteristics. The production of photosynthetic matter will always be determined from the parameter which is located in the minimum value → law of the limiting factors!

- **Light:** The photosynthesis rate rises with the intensity of the radiation until it reaches its saturation value. After reaching the maximum the light is not the limiting factor anymore and CO_2 takes that place.

Light as limiting factor is a very important point in this work. Plants can be divided into two different living environments relating to the intensity of the irradiation they are exposed to, into the shadows or on places with a high radiation exposure [Smith and Smith, 2009], see Figure 4.19. The intensity of irradiation which is reaching the plant also differs greatly depending on time (day and season), if the plant is growing in the shadow of another plant or if the leaves are shielding each other [Smith and Smith, 2009]. This is the reason why we can find a diversity of so called “light compensation (LC) points” [Smith and Smith, 2009], see Figure 4.2.2. Naturally, shade plants have a low light compensation point and plants living in high irradiation regions have a high LC point due to the natural adaption to their habitats [Smith and Smith, 2009].

Like E. W. Smith et al. (1976) wrote in their paper about the “Variables Affecting the CO_2 Compensation Point”, page 143: “*The CO_2 equilibrium between the rate of photosynthesis and respiration of a leaf in a closed system is the CO_2 compensation point.*”

Between the light compensation point and the light saturation (LS) point the photosynthetic rate is increasing [Smith and Smith, 2009]. At the light saturation point the photosynthesis reaches its maximum value, from then onwards the photosynthetic rate is stagnating [Smith and Smith, 2009]. Sun plants have also a high light saturation point, shadow plants have a low one [Smith and Smith, 2009].

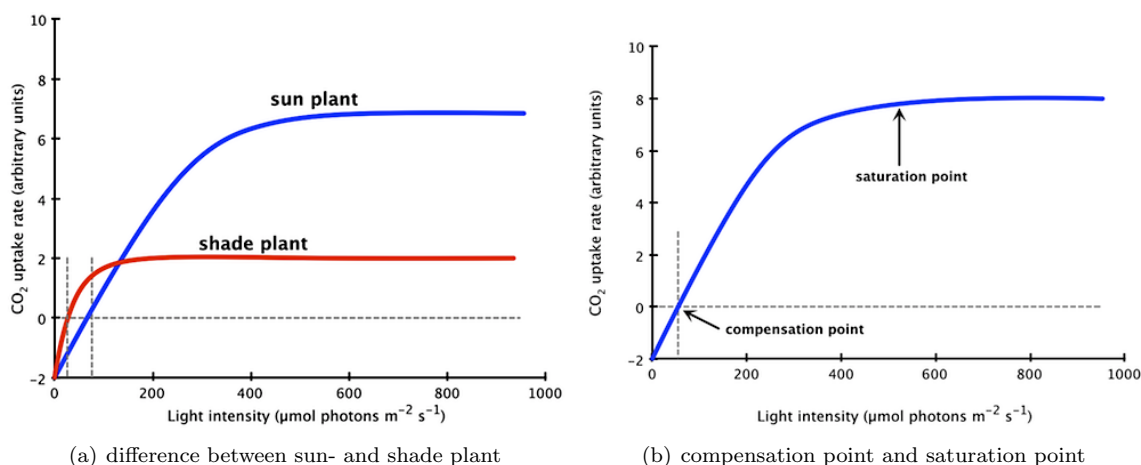


Figure 4.19: Here one can see the light intensity (axis of abscissae) against the CO_2 uptake rate (axis of ordinates), plotted are the LC point and LS point (a) and the LC points of sun- and shade plants (b) [Tiftickjian, 2013]

- **CO_2 :** This will only be a limiting factor if all other factors reach their optimum due to the relative constant percentage of carbon dioxide in the air and at the natural habitat.
- **Water:** The water content of the plants affects the photosynthesis in respect to the fact that CO_2 gets into the leaf through the stoma. The width of the gap depends on the water content.
- **Temperature:** There is a minimum temperature for the beginning of the photosynthesis process, then the rate climbs with increasing T and drops after reaching the maximum (optimum curve), provided that there is no other limiting factor.

4.2.3 C_3 -, C_4 - and CAM-Plants

"Like other physiological processes, photosynthesis differs greatly among various plant species, particularly between C_3 and C_4 plants, whether growing under normal or under stressful conditions." ([Pessarakli, 2005], quoted from preface, p. 9)

As mentioned before there are a few limiting factors according to the natural habitat of the phototrophic organisms, but adaption is a natural phenomenon.

To adapt to aride locations phototrophic organisms evolved different types of CO_2 fixation [Weiler and Nover, 2008].

C_4 : Normally the carbon dioxide assimilation and the Calvin cycle takes place in the same area

[Weiler and Nover, 2008] but in C_4 plants the assimilation and the Calvin cycle are spatially separated [Evert and Eichhorn, 2012].

Comparing the CO_2 fixation of C_3 and C_4 plants one important thing was noticed, the C_4 fixation needs more energy [Evert and Eichhorn, 2012]. As mentioned before the predominant way to assimilate CO_2 (C_3) uses 3 molecules of ATP to fix one molecule of CO_2 , C_4 needs 5 ATP molecules [Evert and Eichhorn, 2012].

A few examples [Evert and Eichhorn, 2012]:

- Maize, sugarcane and sorghum are C_4 grasses
- Wheat, rye, oats and rice are C_3 plants

The advantage of C_4 plants due to the fact that their way of CO_2 fixation is more efficient [Evert and Eichhorn, 2012]. They possess only one third to one sixth of RubisCO compared to C_3 plants for the same fixation rate [Evert and Eichhorn, 2012]. The rate of productivity of photosynthesis is the same as for C_3 but the plants do not have to open the Stoma that much for the assimilation [Evert and Eichhorn, 2012]. This leads to less water loss and a better adaptation to tropical regions (high temperature, dry, high radiation) [Evert and Eichhorn, 2012].

CAM: CAM means crassulacean acid metabolism and plants using this type of photosynthesis are called CAM plants [Evert and Eichhorn, 2012]. Only a small percentage of plants belong to this category [Dodd et al., 2002]. The difference between C_3 and C_4 plants was the spatial differentiation of the CO_2 fixation and the Calvin Cycle [Evert and Eichhorn, 2012]. The primary contrast here is that we have a very important differentiation in time [Evert and Eichhorn, 2012]. CAM plants have the ability to keep their stomata closed at day time [Dodd et al., 2002]. The fixation of the CO_2 molecules takes place at night [Dodd et al., 2002], when it is not too hot. As a result, this plant species is able to flourish in arid habitats, with high levels of solar radiation due to the fact that they can drop the water loss to a minimum [Evert and Eichhorn, 2012].

4.3 Two Types of Photosynthesis

We can distinguish between two types of photosynthesis:

Oxygenic and anoxygenic photosynthesis [Weiler and Nover, 2008].

4.3.1 Oxygenic Photosynthesis

Most important for life is the oxygenic way, due to the simple fact that it produces the oxygen that animals and human beings need to breathe.

As explained in detail in the chapters above, oxygen is the byproduct produced while water becomes fissioned during the light reaction [Ke, 2003].

4.3.1.1 Oxygenic Phototrophs and Oxygenic Photosynthesis in the Deep Sea Plants: Green plants are autotrophs, which means that they use CO_2 and light energy to produce carbohydrate [Smith and Smith, 2009].

Bacteria: Cyanobacteria are the only group of bacteria which are able to pursue oxygenic photosynthesis [Blankenship, 2002]. The reason why they are so important is easily explained. First of all the Earth was anoxygenic, a really forbidding world for creatures which are dependent on oxygen, but Cyanobacteria were able to produce O_2 and changed the Earth into a life sustaining planet [Madigan et al., 2012].

Photosynthesis in the deep sea: From logical deduction it is easy to understand that if a light beam saturates the water surface and goes a distance through the water, the characteristics of the light beam will be changed through absorption and scattering [Kirk, 1994].

The two major changes are in colour and intensity, the deeper the light penetrates the more change will occur until all of the photons are absorbed [Kirk, 1994]. The blue colour of water is derived from the poor absorption properties of water in the blue and green wavelengths [Kirk, 1994].

J. T. Kirk (1994) wrote: “[...] but its absorption begins to rise as wavelength increases above 550 nm and is quite significant in the red region: a 1-m thick layer of pure water will absorb about 35% of incident light of wavelength 680 nm.”

As one can see in Figure 4.20, the absorption of PAR is fundamental in the part over 500 nm in the SED [Kirk, 1994].

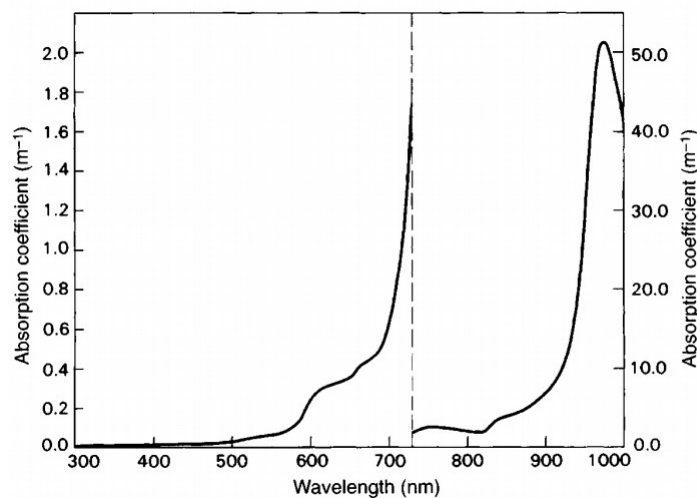


Figure 4.20: Here the absorption spectrum of water is shown on the basis of the absorption coefficients [Kirk, 1994]

What the picture also shows is that the absorption coefficient drops after the 700 nm mark. At 900 nm the coefficient rises again. The absorptions drop between 700 nm and 900 nm could be very important for photosynthesis under water for phototrophs on planets around M-stars due to their SED.

Algae: Algae is just an general term for several phyla, so they can be subdivided into a huge amount of categories referring to the differences in their photosynthetic apparatus, which is clearly seen in

the variety of colours [Falkowski and Raven, 2007]. They vary in size between solitary cells and algae of up to 100 m [Happe, last change from the autor: 15.09.2015].

Algae are the main oxygen provider of Earth and perfectly adapted to exclusive life in water [Happe, last change from the autor: 15.09.2015]. Very interesting is also the fact, that the form of organisation concerning their shape varies between cell complexes and cell spiremes [Happe, last change from the autor: 15.09.2015]. The algae which is closest to green plants (has *Chlorophyll a* and *b* and Carotenoids) is called green alga and consists of single cells from which each cell has an own photosynthetic apparatus [Happe, last change from the autor: 15.09.2015].

Lichen: Lichen are an interesting example of a partnership between two organisms to profit from the special characteristics of the other symbiont, in this special case between a fungus and a cyanobacteria or an algae [Madigan et al., 2012]. As we learned before both, cyanobacteria and algae, are able to practice oxygenic photosynthesis and are therefore the so called “primary producer”, while the fungus can be seen as the skeleton of the organism (inclusive the fixation on the ground, absorption of nutritive substance [Madigan et al., 2012]. If the symbiont is an algae, the colour comes from the Carotenoids in the algae (yellow, green, red, orange, purple or brow) [Madigan et al., 2012].

4.3.2 Anoxygenic Photosynthesis

Five families of Bacteria are known to practice anoxygenic photosynthesis [Madigan et al., 2012] (see list below [Madigan et al., 2012]):

- proteobacteria (purple bacteria)
- green sulfur bacteria
- green nonsulfur bacteria
- gram-positive bacteria (heliobacteria)
- acidobacteria

Here the anoxygenic photosynthesis will be explained shortly based on the example of purple bacteria.

The whole photosynthetic apparatus can be found in the intracytoplasmic membrane system [Madigan et al., 2012], so the phototrophic bacteria have no Chloroplasts like plants.

The reaction centers are surrounded by the antenna system and consist of polypeptides which are ingrained in the photosynthetic membrane [Madigan et al., 2012].

The antenna pigments catch the energy and hand it off to the reaction center [Madigan et al., 2012], equally to the oxygenic photosynthesis. Another difference to oxygenic photosynthesis is the fact, that these bacteria do not have *Chlorophyll a* pigments, they have Bacteriochlorophyll and Carotenoids pigments for excitation [Weiler and Nover, 2008], which is followed by the electron transfer to conserve the energy [Madigan et al., 2012]. The electron transfer is a cycle in the membrane through multiprotein complexes (cytochrome bc1 and cytochrome c2) to activate the ATPase to produce ATP [Madigan et al., 2012]. To finish the cycle the cytochrome c2 has to give one electron back to the

reaction center to allow the pigments to fall back into the ground-state [Madigan et al., 2012].

The next difference is that the anoxygenic photosynthesis do not use H_2O as reduction substance of the CO_2 [Madigan et al., 2012] and this is also the reason why this type of phototrophy does not produce oxygen.

The power comes from the electron donors (e.g. H_2S , S , $S_2O_3^{2-}$, Fe^{2+} , NO_2^- , AsO_3^{2-}) and each of them is used by another family of bacteria [Madigan et al., 2012].

To produce the required NADH (reducing power), instead of NADPH (oxygenic Photosynthesis), it is necessary to oxydize the NADH to NAD^+ via the reverse electron transport (electrons travel backwards against the thermodynamic gradient $\rightarrow$ energy is needed) ([Weiler and Nover, 2008] and [Madigan et al., 2012]).

This is what happens in purple bacteria and if one wants to adopt it on other bacteria one has to bear in mind that there are certain differences in the details. For example differences in the reaction center (e.g. between green sulfur bacteria and purple bacteria) lead to some contrast in the electron transfer [Madigan et al., 2012]. These are the major differences between oxygenic and anoxygenic photosynthesis but to discuss this in more detail would go beyond the scope of this work.

4.3.2.1 Anoxygenic Phototrophs Bacteria (the following informations can be found in [Blankenship, 2002]):

- **Purple bacteria (sulfur or nonsulfur):** The following applies: bacteria relying on anoxygenic photosynthesis contain *Bacteriochlorophyll a* or rather *Bacteriochlorophyll b* and Carotenoids
- **Green sulfur bacteria:** *Bacteriochlorophyll a* and *c*, *d* or *e* in the antenna system (principal pigment), *Bacteriochlorophyll a* in the reaction centre
- **Green nonsulfur bacteria:** *Bacteriochlorophyll a* and *c*
- **Heliobacteria:** *Bacteriochlorophyll g*

4.4 Different Types of Photosynthetic Pigments

The pigments of the organisms are very important. They are needed to collect radiation, to absorb it [Blankenship, 2002] and thereby start the process called "light reaction". During a long period of research, scientists discovered a lot of different pigments [Blankenship, 2002].

Each of the numerous pigments can be discerned by its absorption spectrum [Madigan et al., 2012]. This list will give short overview about the most important pigments of both types of photosynthesis, but for sure these are not all pigments that are found until now.

- **Chlorophyll a:** This pigment is part of every phototroph organism [Weiler and Nover, 2008]. It has a green-blue colour [Habermehl et al., 2008], which can be easily explained by its absorption (maxima at 680 nm and 430 nm) and transmission spectra [Madigan et al., 2012].
- **Chlorophyll b:** The absorption maximum of this pigment can be found at 660 nm [Madigan et al., 2012]. The colour is more yellow to green [Habermehl et al., 2008] and it just occurs in green organisms [Weiler and Nover, 2008].

- **Chlorophyll c_1 and c_2 :** These types of Chlorophyll are the replacements of *Chlorophyll b* in different kinds of algae [Weiler and Nover, 2008].
- **Chlorophyll d:** This one is found in prokaryotes [Madigan et al., 2012].
- **Carotenoids:** Peak at 480 nm [Madigan et al., 2012]. They have two very important properties. The first one is that they increase the absorption spectrum of the Chlorophyll molecules into the yellow and orange area because they are part of the reaction centre [Weiler and Nover, 2008]. The second and also very important characteristic is that they destroy the singlet oxygen via “quenching” [Habermehl et al., 2008]. Carotinoide itself can be divided into two subcategories: Carotines and Xanthopylles [Weiler and Nover, 2008].
- **Bacteriochlorophylls:** These pigments belong to the anoxygenic photosynthesis of different kind of bacteria [Madigan et al., 2012]. A distinction is drawn between *Bacteriochlorophyll a*, *b*, *c*, *d*, *e* [Weiler and Nover, 2008] and *g* and *c_s* [Madigan et al., 2012]. The list below is an excerpt of Figure 13.4, page 343, in the book “Biology of Microorganisms” of M. T. Madigan et al. (2012), and will give a short overview about the different kinds of Bacteriochlorophylls in different bacteria and their absorption maxima.

Pigment	Bacteria	Absorption maxima (in vivo) [nm]
Bchl a	purple bacteria	805, 830-890
Bchl b	purple bacteria	835-850, 1020-1040
Bchl c	green sulfur bacteria	745-755
Bchl c_s	green nonsulfur bacteria	740
Bchl d	green sulfur bacteria	705-740
Bchl e	green sulfur bacteria	719-726
Bchl g	heliobacteria	670-788

Table 4.8: In vivo absorption maxima of Bacteriochlorophylls, an absorption spectrum can be developed via dissolving the cells in a semifluid liquid (e.g. 60% sucrose) and running the spectra Madigan et al. [2012], excerpt of Figure 13.4, page 343

The following Figure of a table will give a quick overview about the pigments and where they occur (see Figure 4.21).

4.5 PAR and Quantum Efficiency

As explained before there exists a certain kind of radiation absorbed by the photosynthetic pigments called photosynthetic active radiation, which is the part of the EM spectrum usable for photosynthesis as can be seen in the absorption spectrum [Holst et al., 2000]. PAR is the part of the spectrum between approximately 400 and 700 nm where absorption takes place [Holst et al., 2000]. The absorption spectrum can be seen as a weighted part of the total radiation [Holst et al., 2000]. It has to be taken into account that the PAR is not always the same. It depends on a few factors like the location of the plant, the season, the air ratio and a lot more [Holst et al., 2000].

The question to ask is: How much irradiation does a green plant/bacteria/algae need to practice photosynthesis?

Table 4.1 Distribution of chlorophylls and bacteriochlorophylls

Type of Organism	Chl <i>a</i>	Chl <i>b</i>	Chl <i>c</i>	Chl <i>d</i>	BChl <i>a</i>	BChl <i>b</i>	BChl <i>c, d, e</i>	BChl <i>g</i>	Carotenoids	Bilins
Purple bacteria					^a	^a			+	
Green sulfur bacteria					+		+		+	
Green nonsulfur bacteria					+		+		+	
Heliobacteria								+	+	
Cyanobacteria	+	^b	^b	^c					+	+
Green algae	+	+							+	
Diatoms	+		+						+	
Brown algae	+		+						+	
Dinoflagellates	+		+						+	
Cryptomonads	+		+						+	+
Red algae	+			⁺ ?					+	+
Plants	+	+							+	

^a Purple bacteria contain either BChl *a* or *b*, but not both in the same species.

^b Most cyanobacteria contain Chl *a* as their only chlorophyll-type pigment. Prochlorophytes contain in addition Chl *b*. Some types also contain Chl *c*.

^c The cyanobacterium *Acaryochloris marina* contains mainly Chl *d*, with minor amounts of Chl *a*.

Figure 4.21: Different kinds of Chlorophylls and Bacteriochlorophylls in different organisms [Blankenship, 2002], page 46, table 4.1

First two important definitions:

- **Quantum requirement:** Is defined by the number of quanta that have to be absorbed to produce one molecule of O_2 or deoxidise one molecule of CO_2 [Buschmann and Grumbach, 1985]. This value is larger for CAM and C_4 plants as for C_3 plants [Wölflinger, 2013].
- **Quantum yield:** The quantum yield explains how active the photosynthesis is. It depends on the number of quanta that are absorbed and on the wavelength considered [Buschmann and Grumbach, 1985] (see absorption spectrum and spectrum of activity). Naturally this yield can be expressed as the required quantum number to deoxidise one molecule of CO_2 or to produce one molecule of O_2 [Wölflinger, 2013]. It is the inverse value of the quantum requirement [Buschmann and Grumbach, 1985]:

$$\text{Quantum requirement} = \frac{\text{number of absorbed quanta}}{\text{molecule of fixed } CO_2 \text{ or produced } O_2} \quad (17)$$

$$\text{Quantum yield} = \frac{\text{molecule of fixed } CO_2 \text{ or produced } O_2}{\text{number of absorbed quanta}}. \quad (18)$$

The spectrum of the maximum quantum yield looks interesting because it does not show a gap in the green area of the SED as in this spectrum the activity of the photosynthesis will be measured at a very low light intensity [Buschmann and Grumbach, 1985].

A closer look on the different sources show variable values of quantum yield and quantum requirement:

E. Loos (1967) gives a historical view on the quantum requirement. He mentioned, that Warburg and Negelein (1922, 1923) measured a value of at least $4 - 5 (h \cdot \nu)/CO_2$ and other authors later concluded more than $8 (h \cdot \nu)/CO_2$ [Loos, 1967].

E. Weiler and L. Nover (2008) tell us, that we need 48 quanta for one molecule of $C_6 H_{12} O_6$.

This comes from the balance equation: 8 quanta for one O_2 (which means also for one CO_2), and 6 CO_2 for one molecule glucose result in 48 quanta for the process [Weiler and Nover, 2008].

C. Buschmann and K. Grumbach (1985) mentioned in their book "Physiologie der Photosynthese", that the (theoretical) effectiveness of photosynthesis is about 35% and lower. For blue light it is about 20% [Buschmann and Grumbach, 1985].

Calculation of the quantum efficiency of the photosynthetic process leads to [Buschmann and Grumbach, 1985]:

9 quanta à 177 kJ (at 680 nm) to fix one mol CO_2 are 1593 kJ.

$$\frac{2860kJ(1molGlucose)}{6(1molCO_2)} = 1/6Glucose)) = 478kJ(promolCO_2produced)$$

[Buschmann and Grumbach, 1985]. 478 kJ are about 30 % of 1593 kJ [Buschmann and Grumbach, 1985].

This implies that a plant needs 1593 kJ energy from the light to fix one CO_2 and needs 478 kJ to build up 1 mol of Glucose, this means that just 30% of the absorbed energy are used to build up $C_6H_{12}O_6$ and the other 70% are dissipated during the process [Buschmann and Grumbach, 1985].

C. Buschmann and K. Grumbach (1985) also stated that measurements were performed, which showed that 2500 Chl molecules have to be excited to produce one O_2 and due to the fact that 8 quanta are needed they found out that there are about 312 Chl molecules in one photosynthetic unit [Buschmann and Grumbach, 1985].

As one can see there are many differences in parameters, not only depending on the author but also depending on the phototrophic organism. It is not easy to make a final statement about the required parameters for effective photosynthesis or even to make a statement about whether the process works.

Nevertheless, the last pages explained the general process of photosynthesis and the most important characteristics which will be needed for the calculations and the results.

5 Model Scenario

5.1 Introduction

The first part of the scientific question is to answer whether it is possible for phototrophic organisms to use the radiation of M-type stars for photosynthesis if the test planet is situated in a zone around the planet where water can stay liquid.

The second part will discuss the radiation of G-type stars. Indeed it is known that the plants on Earth use the light of the sun for photosynthesis. But here the test planet will be located outside of the zone where water can be liquid.

To configure a model various assumptions need to be taken into account and computations have to be performed.

1. The comparison of the SED of M-type and G-type stars will give a first impression of the difference between these two spectral classes. Here the Planck formula will be used to generate a black body spectrum of two stars with different effective temperatures. See section 5.2.
2. It has to be taken into account that a habitable planet has to have an atmosphere. Therefore the influence of different gases (absorption, reflection, scattering) on the incoming radiation has to be derived. To derive the spectral energy distribution (SED) on the surface of a test planet at different distances from the star a special model is required (see section 5.3). Therefore the code Streamer © was used.
3. The next step is to choose different atmospheric compositions which are required for the program code (see section 5.4). Here 3 different compositions with varying main components are chosen to cover a broad range of possible changes of radiation in the atmosphere. Also clouds can be added into the atmosphere with the applied software. As explained in chapter 3.2.4 clouds can have a great impact on the incoming radiation.
4. With these 3 compositions the LW zone can be modelled (see section 5.5). Here also the code described in section 5.3 will be applied.
5. After the computation of the inner and outer borders of the LW zone for M- and G-stars, with 3 different compositions of the atmosphere and with and without clouds the exact position of the test planet for each scenario can be chosen. See section 5.6.
 - G-star: outside of the LW zone, one scenario closer to the star (red zone), a second one farther from the star (green zone)
 - M-star: in the center of the LW zone (blue zone)
6. The spectral energy distribution on the surface of the test planets is modelled with the modified Streamer © code. The output of the model is power per square meter (flux) which can be represented graphically against 24 frequency bands for short wavelengths (0.2 – 5 μm).

7. The last step was to interpolate between the 24 wavelength bands and calculate the radiation that is absorbed from the photosynthetic pigments. The absorption spectra of different photosynthetic pigments can be matched with the computed SEDs.

5.2 Planck Spectra

To determine the difference in the spectral energy distribution of M-type stars and G-type stars in general the Plack formula was used to generate a plot of the black body radiation with the given temperature of a M- and G-star.

For this presentation the software QtiPlot, an analysis and visualisation program, was used.

The Planck formulae was coded as a function into the QtiPlot diagram input:

$$((2 * h * c * c)/(x^5)) * (1/((exp((h * c)/(x * k * t))) - 1)) \quad (19)$$

h ... Planck constant, 6.6×10^{-34} Js

k ... Boltzmann constant, 1.38×10^{-23} J/K

c ... velocity of light t ... temperature in K x ... was defined as wavelength λ in m.

Therefore the subsequent diagrams can be drawn to compare the SED of M- and G-type stars and investigate the differences as well as the overlapping area in the optical light region especially the PAR and the possibility for usage as energy source for photosynthesis. The maximum wavelength of the two stars can be calculated according to Wien's displacement law (see equation 8).

The first selected star is the sun with an effective temperature of 5778 K as exemplar for a G-type-star, which is also used as host star for the model scenarios for the radiation transfer model. The second star which is chosen for the RTM and to model the Planck spectrum is Gliese 581.

Properties of Gl 581 (see [Roques and Schneider, 2016]):

- Distance: 6.21 pc
- Mass: $0.31 M_{\odot}$
- Radius: $0.3 R_{\odot}$
- Spectral type: M2.5V
- Age: 8×10^9 yr
- T_{eff} : 3498 K

For the results and more details see chapter 6 (subchapter 6.1).

5.3 Radiation Transfer Model

To derive the spectral energy distribution on the surface of a test planet at different distances from the host star (M- or G-type), after the radiation passed through atmospheres with different compositions and the LW zone around a host star a, specific code is required.

The code used for the model scenarios is based on the software Streamer ©. Streamer © is a public domain code invented by J. R. Key and A.J. Schweiger (1998) [Ludwig et al., 2015].

It was modified by D. Neubauer in his doctoral thesis ‘Modellierung des indirekten Strahlungseffekts des Hintergrundaerosols in Österreich’ (2009) (see [Neubauer, 2009]). D. Neubauer expanded the code with a cloud model and a radiative convective model.

The following description of the cloud model and a radiative convective model is based on the thesis of D. Neubauer (2009), see [Neubauer, 2009].

- **Code Description:** The cloud nuclei growth model describes the rising of air parcels consisting of dry air, steam and water droplets. The input parameters for the simulation are dry aerosol distributions. D. Neubauer made the assumption, that the particles consist of ammonium sulphate and a percentage of black carbon. The model is described as a eulerian model for droplets and aerosols (in the following summarized as ‘particles’), where the particles are divided into size ranges. Each particle in the range has the same properties. The important topic here is the fact, that one range can be described by one representative particle. A second size range characterizes the diameter of the original cloud condensation nuclei.

The kinematic of the air parcel is described via a constant velocity and an exchange of air between the cloud and its surroundings. The movement of the droplets is derived from random walk. The clouds are specified in the way that they have boundaries (upper and lower limit) and those boundaries act as a barrier. Droplets that move over the absorbing barrier get immediately replaced by a none active droplet that has the same condensation nuclei. As a consequence the liquid water content gets modified. In contrast to the modified water content the number of droplets and aerosol mass stays constant during the turbulent diffusion.

The model of growth also includes micro physical processes:

- **Nucleation:** Particles that grow via diffusion, even if the air is not supersaturated, are hygroscopic.
- **Diffusion:** Includes the solving of the condensation and evaporation equation. Growth via diffusion is not directly proportional to the radius of the particle. Particles with smaller radius, which means that they are just now activated, grow faster and need smaller time steps. Some particles get activated during the simulation, grow and then become cloud droplets. Those particles that will not get activated remains in a domain of equilibrium diameter and compose the ‘interstellar aerosol particles’. Water droplets are able to coagulate with this interstellar aerosol particles.
- **Coagulation:** Can be divided into continuous (very large or very small particles) and

stochastic (similar sized particles) coagulation. Therefore the number concentration in the size ranges changes due to the newly originated particles which have to be newly classified. Furthermore the merging of the condensation nuclei also leads to a new categorisation into other size ranges.

- Influence of radiation: Additionally the absorption coefficient for the droplets has to be known to include the influence of the long and short wavelength on the growth of the cloud droplets. For that a ‘Mie table’ is used, where the absorption coefficients for every particle at every time step with different size and black carbon content are listed. Then the radiation transport equation has to be solved to generate the influence of the radiation flux on the derived droplet distribution. The calculation of the radiation flux takes place every 10 seconds.

The results of the numerical modelling will be saved in a data base. The data base consists of data files with droplet size distributions for different liquid water contents. During the simulation for certain values of liquid water content the size of the condensation nuclei of the cloud droplet (inclusive the volume fraction of black carbon) and the number size distribution of the droplet get written into these data files.

At the end of the simulation the output corresponds to the time course of the particle concentration of the simulation of growth (droplets, interstellar particles, activated particles and large droplets). Also part of the data file is the time course of the environment variables like pressure, temperature and saturation.

For each fluid-water-content of the cloud an associated cloud droplet distribution exists. The radiation transfer program uses these values to calculate the radiative forcing of the clouds.

- The radiation transfer model consists also of two parts. The first one calculates the scattering parameter for the Mie theory. The second one is the public domain code Streamer ©.
 - To solve the radiation transfer equation it is important to know the single scattering parameters of the Mie theory. More specifically, the absorption and scattering efficiency and the asymmetry parameter are needed to know, so that the optical depth of the cloud and the single scattering albedo can be modelled for 60 wavelengths. The original Mie routine BHMIE and BHCOAT was written by C. F. Bohren and D. F. Huffman [Bohren and Huffman, 1983]. B. T. Draine from Princeton University extended BHMIE so that it also derives the asymmetric parameter. BHCOAT was also completed by D. Neubauer in his thesis ‘Modellierung des indirekten Strahlungseffekts des Hintergrundaerosols in Österreich’ (2009) (see [Neubauer, 2009]).

The mean values of the single scattering parameters for every droplet for every separate wavelength have to be computed. An important assumption here is the single scattering.

- For the calculation of the radiative forcing the radiation transfer equation has to be solved with Streamer © (see [Key and Schweiger, 1998]). This code evaluates the radiation transfer through the whole atmosphere. The code was adapted from D. Neubauer, in the

way that Streamer © automatically uses the single scattering parameter from the Mie routine.

The equation can be solved with two numerical methods. DISORT for up to 48 zenith angles (more accurate but slower) and a ‘two-stream-method’ (faster, only for small zenith angles and thin clouds at small wavelength values it is less accurate).

The fluxes and intensities for short and long wavelengths can be numerically modelled. 24 frequency bands for short wavelengths ($0.2 - 5 \mu\text{m}$) and 105 bands for long wavelengths ($4 - 500 \mu\text{m}$). Different atmospheric composition and albedos can be chosen as input parameters.

The data base, created by D. Neubauer, was used to adapt Streamer © in order that also indirect effects can be evaluated.

The following description of Streamer © follows the description of D. Neubauer (2009), which is summarized from J. Key and A. J. Schweiger (1998) (see [Key and Schweiger, 1998]).

‘Atmospheric gases: The amount of gases can be varied. Different gases effects the incoming radiation in variable ways due to the different absorption lines.

Solar radiation: The flux corresponds to the total flux for a certain distance.

Optical properties of the clouds: The radiation flux can also be modelled with clouds in the atmosphere. For this purpose the data base has to be used.

Aerosols: For the aerosols that are not part of the clouds one can choose between 6 different models that are included into Streamer © (Tropospheric, Rural, Urban, Maritime, Arctic haze or Smoke, see also [Key, 2002]). The vertical concentration can also be described via 4 profiles.

Numerical method: DISORT (‘Discrete Ordinates Radiative Transfer Program for a Multi-Layered Plane-Parallel Medium’) solves the radiative transfer equation for a plan-parallel atmosphere. DISORT is also used for other radiative transfer programs.

The fluid water content and the corresponding droplet size distribution from the growth model will be handed over to Streamer ©. As well as the definition file for e.g. the atmospheric gases, information about the clouds, albedo and the distance to the star.

The output file contains the time course of the netto flux at the TOA and at the Tropopause, which is the most important one for this study.’

13 different scenarios were numerically modelled with the code to modify the radiation that passed through an atmosphere and reached the surface.

To decide in which distance the planet is located to the host star the liquid water (LW) zone has to be derived (see 5.5). Therefore the atmospheric compositions as input parameters for the code have to be decided on.

Three different atmospheres with slight modifications in the compositions to the original atmosphere were selected: Earth, Venus and Titan. In chapter 5.4 the percentage fraction of gases in the atmosphere are listed.

5.3.1 Application to Earth

To verify the accuracy of the modified Streamer © code with the two-stream approximation (an alternative method to solve the radiation transport equation), an Earth-like scenario was modelled. Concerning further information on the topic of the two stream approximation, I refer to the publication of J.I. Jiménez-Aquino and J.R. Varela [Jiménez-Aquino and Varela, 2005]

The planet was modelled with the same properties as the other 8 G-type star scenarios, see chapter 5.6.1. The atmospheric composition is Earth-like, see chapter 5.4.

Figure 5.22 shows scenario 0 without clouds and figure 5.23 shows scenario 0 with clouds.

The modified Streamer © code calculated the incoming radiation on the surface of the planet at 24 wavelength bands. The original data (appendix A.63), as well as the original full spectra of both models (appendix C.1), can be found in the appendix.

The maximum intensity for the model without clouds amounts to 327 W/m^2 (see figure 5.22) and was measured at 570 nm. With clouds, the maximum intensity was computed as 389.4 W/m^2 at 570 nm (see figure 5.23). The mean irradiance referring to the whole surface of the present Earth is verified with 342 W/m^2 [Roedel and Wagner, 1991, 1994, 2000, 2011].

Therefore, the model with clouds is more accurate. The deviation is less than 5%. Considering today's Earth and, therefore, the cloud covering, the higher irradiation without clouds is a logical consequence.

For scenario 0 with clouds, the photosynthetic photon fluxes for the 4 *Bacteriochlorophyll a* and the 2 *Chlorophyll a* and *Chlorophyll b* absorption maxima were calculated (see table 5.9, 5.10 and 5.11). The values can be used as reference values.

Absorption maximum [nm]	# of Photons [$\text{m}^{-2}\text{s}^{-1}$]	PPF [$\mu\text{mol}/\text{m}^2\text{s}$]
361.2	7.76267×10^{19}	129
396.4	7.47069×10^{19}	124
580.2	8.87721×10^{19}	147
780.2	2.26024×10^{20}	375

Table 5.9: This table shows the wavelength λ of the four absorption maxima of *Bacteriochlorophyll a*, the number of photons (# Photons) and the photosynthetic photon flux (PPF [$\mu\text{mol}/\text{m}^2\text{s}$]) of scenario 0 with clouds

5.4 Atmospheric Composition

The composition of the Earth's atmosphere was chosen because it is the most habitable world that we know. Therefore the compounds that are entered into the input file of the radiation transfer model are listed in table 5.12. The humidity content is set to 100%.

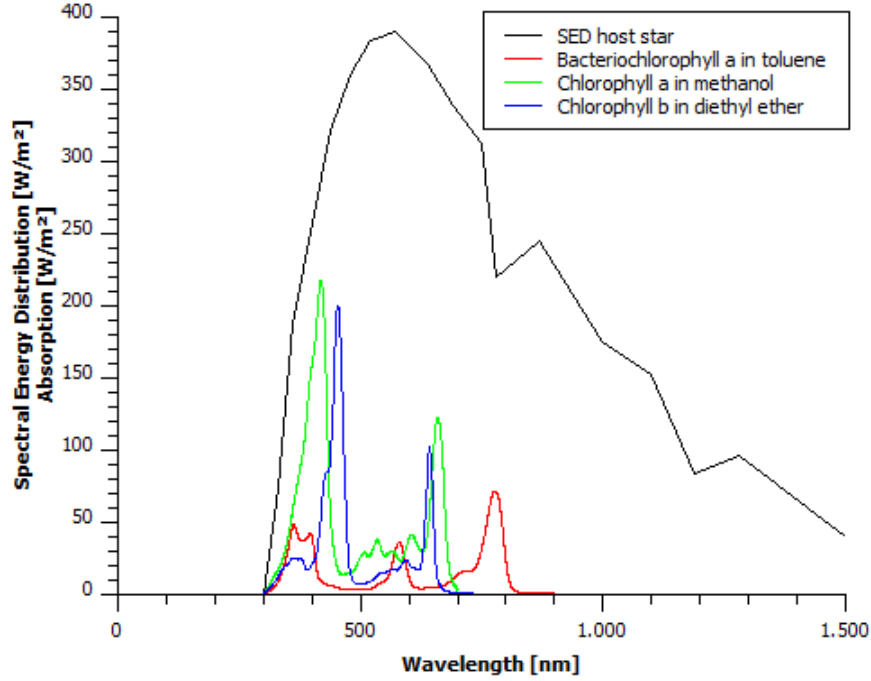


Figure 5.22: G-star, Scenario 0, without clouds, zoomed in

Absorption maximum [nm]	# of Photons [$\text{m}^{-2}\text{s}^{-1}$]	PPF [$\mu\text{mol}/\text{m}^2\text{s}$]
417.75	3.97392×10^{20}	660
654.25	3.1532×10^{20}	524

Table 5.10: This table shows the wavelength λ of the two absorption maxima of *Chlorophyll a*, the number of photons (# Photons) and the photosynthetic photon flux (PPF [$\mu\text{mol}/\text{m}^2\text{s}$]) of scenario 0 with clouds

Absorption maximum [nm]	# of Photons [$\text{m}^{-2}\text{s}^{-1}$]	PPF [$\mu\text{mol}/\text{m}^2\text{s}$]
453	3.92751×10^{20}	652
643	2.76451×10^{20}	459

Table 5.11: This table shows the wavelength λ of the two absorption maxima of *Chlorophyll b*, the number of photons (# Photons) and the photosynthetic photon flux (PPF [$\mu\text{mol}/\text{m}^2\text{s}$]) of scenario 0 with clouds

First atmospheric composition:

Gases	Fraction [%]
N ₂	78
O ₂	21
CO ₂	0.038

Table 5.12: Atmospheric Composition for Earth Scenarios, M- and G-type stars, with/without clouds

The further two compositions are chosen to cover a wide field of atmospheric gases and represent the

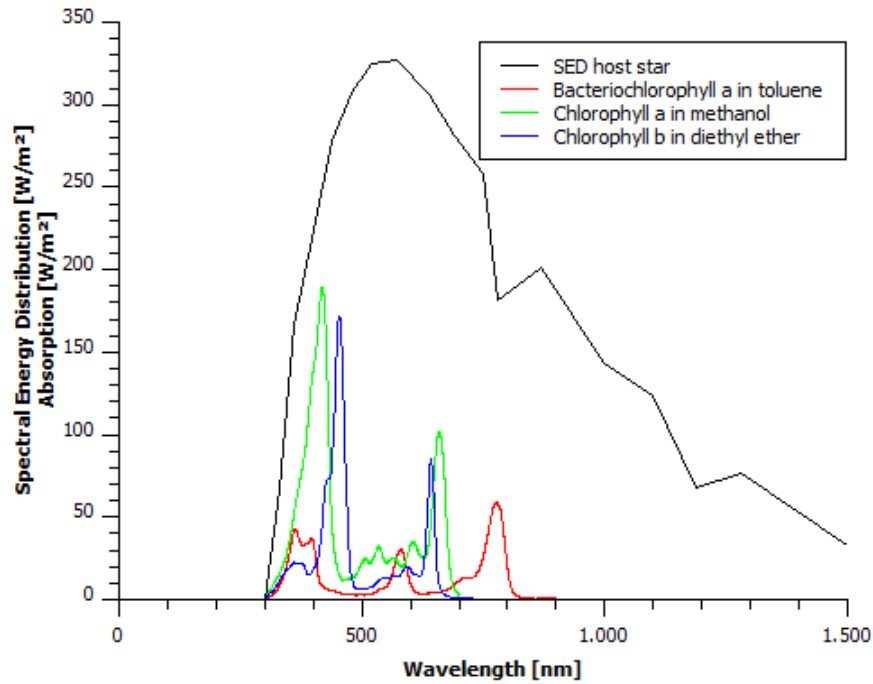


Figure 5.23: G-type star, Scenario 0, with clouds, zoomed in

compositions of a planetary body and the only known moon with an atmosphere in the Solar System.

Table 5.13 shows the components for the Venus atmosphere runs.

Second atmospheric composition:

Gases	Fraction [%]
CO ₂	96.5
N ₂	3.5
SO ₂	0.015
water vapour	0.002
CO	0.0017

Table 5.13: Atmospheric Composition for Venus Scenarios, M- and G-type stars, with/without clouds

Table 5.14 shows the components for the Titan atmosphere runs.

Third atmospheric composition:

Gases	Fraction[%]
N ₂	99.96
CO ₂	0.04

Table 5.14: Atmospheric Composition for Titan Scenarios, M- and G-type stars, without clouds

5.5 Liquid Water (LW) Zone

The liquid water zone describes an area around a star where water can stay liquid. Therefore a temperature region between ≈ 273 K and ≈ 373 K has to be observed. The LW zone should not be confused with the habitable zone. The habitable Zone depends on the distance to the host star, whereas the LW zone depends on the atmosphere of the test planet.

The position of the test planet was modified until the surface temperature of the planet reached the required value.

For all thirteen scenarios (see 5.6) that were modelled the inner borders and the outer borders of the LW zone were derived.

Difference between the G-type and M-type star scenarios:

- For the M-type star scenarios the planet will be located in the middle of the LW zone. Here an earth sized habitable planet (rotationally bound or not) with an atmosphere and liquid water on the surface is assumed. The LW zone can also be called 'blue zone'.
- For the G-type star scenarios the planet will be located outside of the liquid water zone. Outside implies closer to the star than the inner border of the liquid water zone would predicts ('red zone') as well as farther outside from the liquid water zone than the outer border of the liquid water zone ('green zone').

For a better understanding figure 5.24 illustrates the planetary system and the different configurations. Sketched in 5.24 is the liquid water zone (blue, 'blue zone') around a host star (yellow circle). Also drawn is the middle of the liquid water zone (black circle).

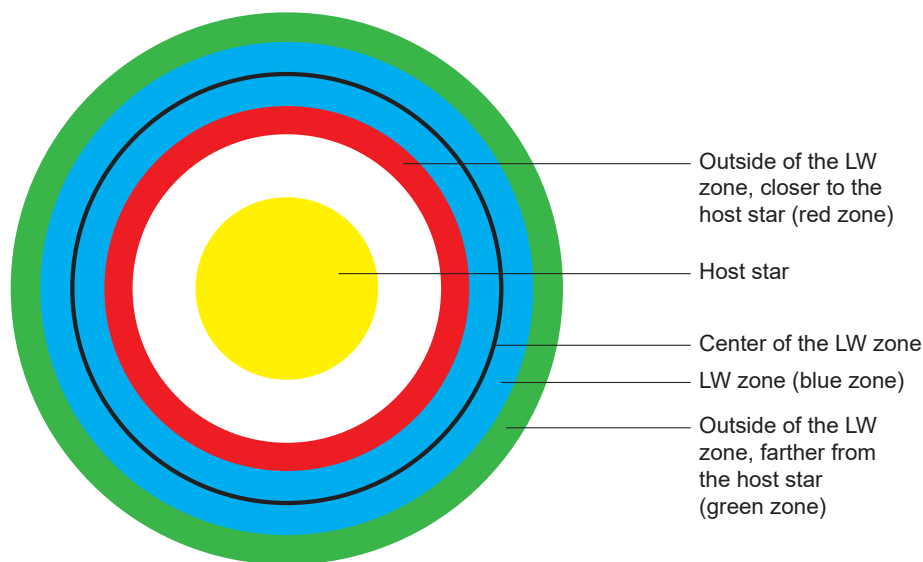


Figure 5.24: Planetary system configuration, Credit: own diagram

The plants have to be the same as we know them on Earth. A special evolution of the plants to adapt to the environment on a planet around M-stars will be excluded. Thus a closer look can be taken

on the irradiation of an M-star. The analysis and comparison of the absorption spectra of different photosynthetic pigments and the SEDs, as well as the examination of the remaining PAR, help to make an assessment of the possibility of photosynthesis.

To model the borders of the LW zone the modified version of the Streamer © code was used. Here first of all the stellar spectra of an M- or G-star have to be inputted into the code. Then the planet has to be modelled. This includes the selection of the atmospheric composition, as well as the surface pressure, aerosol concentration, albedo and if the run is made with or without clouds (see chapter 5.6).

The test planets were shifted inwards and outwards by changing the distance to the star via the input file until the surface temperatures on the planets reached the freezing point of water for the outer border and the boiling point for the inner border.

The runs had to be repeated several times until this adequate temperature was reached.

The results can be found in chapter 6, subchapter 6.2, table 6.19 and table 6.20.

5.6 Scenarios and Set Up

The following tables provide more specific information about the planetary conditions and the proper scenarios. For the runs the built-in spectrum of Streamer © of the G-type star will be the Sun and for the M-type scenarios the spectrum of AD Leonis will be used.

Table 5.15 and 5.17 present the general properties of the planets and table 5.16 and table 5.18 characterise the modelled scenarios in detail. To simulate an Earth-like planet the acceleration of gravity was set to 1 for all scenarios.

For the cloud model, explained in chapter 5.3, a 'thick cloud layer' between 180 mbar and 430 mbar was chosen. The original cloud model is defined for water clouds on Earth [Neubauer et al., 2012]. This was changed by D. Neubauer (2011) to include other solvents into the cloud model, e.g. H₂SO₄ clouds [Neubauer et al., 2011]. The alternative solvent sulphuric acid is needed for the Venus atmosphere runs.

Not known is the formation process of clouds on other planets or extrasolar planets. Therefore it has to be assumed that this procedure follows the same natural laws as on Earth [Neubauer et al., 2011]. This also holds for the aerosol formation process Neubauer et al. [2012].

Also no specifications are existing about the size distribution of aerosols on other planets [Neubauer et al., 2012]. This leads to a typical size distribution taken from the terrestrial situation of background aerosols as values for Venus are not known up to now [Neubauer et al., 2012].

5.6.1 G-star

In table 5.15 the properties of the 5 test planets are listed.

Surface Pressure: This variable can be adjusted in the definition file. To generate an Earth-like

Scenario	SF pressure [bar]	Aerosols	Albedo
Earth with clouds	1	Modus: 'rural', Vertical Distribution: Tropospheric	0.2
Earth without clouds	1	Modus: 'rural', Vertical Distribution: Tropospheric	0.2
Venus with clouds	1	Modus: 'rural', Vertical Distribution: Tropospheric	0.2
Venus without clouds	1	Modus: 'rural', Vertical Distribution: Tropospheric	0.2
Titan without clouds	1	Modus: 'rural', Vertical Distribution: Tropospheric	0.2

Table 5.15: Selected parameter to describe the planet

situation the surface pressure was set to 1 bar in all runs.

Aerosols: The optical properties (Modus) of the aerosol particles was set to 'rural'. The vertical distribution was set to 'tropospheric', which means 50 km visibility, background tropospheric aerosols and background stratospheric amounts [Key, 2002].

Albedo: The albedo describes the reflectivity of a surface (see chapter 3.2.4). In this case the albedo was set to 0.2.

The following table 5.16 shows the 8 selected G-type star scenarios which were modelled with the extended Streamer © code.

Scenario	Atmosphere	Clouds	Position
1	Earth	Yes	green zone
2	Earth	No	green zone
3	Venus	No	red zone
4	Venus	No	green zone
5	Venus	Yes	green zone
6	Venus	Yes	red zone
7	Titan	No	green zone
8	Titan	No	red zone

Table 5.16: Numerically modelled G-star Scenarios

Scenario 1 and 2 regard to the Earth-like atmosphere runs. Both planets are located in the green zone. There are no runs where the test planet is located closer to the star. This is due to the fact that the planet is modelled with 100% humidity which would lead immediately to a runaway greenhouse effect if the planet is positioned in an orbit that is closer than the inner border of the LW zone.

Therefore the inner borders generally have to be modelled carefully because it can easily come to a runaway greenhouse effect if the planet is located just a bit too close to the host star. The code finishes a run when all layers reach a dynamic equilibrium which is not obtained for a runaway greenhouse effect. The water vapour increases and the layers heat up. Thereby a temperature will be reached where the code is not able to proceed because the data base for the absorption coefficients

provides only coefficients for a certain temperature range. Therefore the Earth-like atmosphere runs were not computed for the positions closer to the star (red zone).

Scenario 2 - 6 simulate a Venus-like atmosphere. Run 3 and 4 are modelled without clouds, while the atmospheres in scenario 5 and 7 have clouds. The test planets with clouds and without clouds were located outside the LW zone (green and red zone).

Scenario 7 and 8 belongs to the Titan atmosphere. This two runs were modelled without clouds because there is no water or water vapour programmed in the atmospheric composition (see 5.14). This leads to two runs without clouds where the planets are located in the green and red zone.

5.6.2 M-star

In table 5.17 the properties of the 5 test planets for the M-star runs are listed. They have the same properties as for the 5 G-star test planets to provide comparable results.

Scenario	SF pressure [bar]	Aerosols	Albedo
Earth with clouds	1	Modus: 'rural', Vertical Distribution: Tropospheric	0.2
Earth without clouds	1	Modus: 'rural', Vertical Distribution: Tropospheric	0.2
Venus with clouds	1	Modus: 'rural', Vertical Distribution: Tropospheric	0.2
Venus without clouds	1	Modus: 'rural', Vertical Distribution: Tropospheric	0.2
Titan without clouds	1	Modus: 'rural', Vertical Distribution: Tropospheric	0.2

Table 5.17: Selected parameters to describe the planet

The following table 5.18 shows the 5 selected M-type star scenarios which were modelled with the extended Streamer © code.

Scenario	Atmosphere	Clouds	Position
1	Earth	Yes	center of the LW zone
2	Earth	No	center of the LW zone
3	Venus	Yes	center of the LW zone
4	Venus	No	center of the LW zone
5	Titan	No	center of the LW zone

Table 5.18: Numerically modelled M-star Scenarios

All planets are located in the center of the LW zone. The scenarios 1 - 4 were modelled either with or without clouds. Scenario 5, Titan, was only modelled without clouds because there is no water or water vapour input into the atmospheric composition (see 5.14).

5.7 Photosynthetic Pigments

To make a definite statement whether photosynthesis is possible with the radiation of M-stars or with the radiation of G-stars if the planet is located outside the LW zone more information about

photosynthetic pigments are needed.

As explained in chapter 4 photosynthesis only takes place if a few factors are fulfilled, whereas the absorption of PAR is the most important for this thesis. For this purpose it has to be clarified if M-stars irradiate in the wavelength range of PAR and also if enough photons are emitted to exceed the light compensation point and meet the quantum requirement.

The light absorbing pigments of phototrophic organisms are Chlorophylls for oxygenic photosynthesis and Bacteriochlorophylls for anoxygenic photosynthesis.

The oxygenic form of photosynthesis arose much later in the evolution path than the anoxygenic photosynthesis, which was the earliest form of photosynthesis [Blankenship, 2010]. Bacteria use anoxygenic photosynthesis (exclusion: Cyanobacteria), and probably the oxygenic photosynthesis has evolved from this kind of phototrophy [Madigan et al., 2012].

That is why the absorbing characteristics of *Chlorophyll a*, *Chlorophyll b* and *Bacteriochlorophyll a* will be analysed.

The absorption terms of Lambert's law (see equation 12, considering the entire integral), also called extinction, of the different pigments were taken from the website of the 'Oregon Medical Laser Center' (see [Prahl and Jacques, 2014]). This website offers an easy access to the absorption and also the emission data for a lot of compounds. Originally the data are existing in the PhotochemCAD program (see [Lindsey, 2014]). It is a free available software to approach the science of photochemistry [Lindsey, 2014].

A detailed description of the photochemCAD program and the generated results can be found in the two articles given below [Lindsey, 2014]:

- 'PhotochemCAD. A Computer-Aided Design and Research Tool in Photochemistry and Photobiology,' Du, H.; Fuh, R.-C. A.; Li, J.; Corkan, L. A.; Lindsey, J. S. Photochem. Photobiol. 1998, 68, 141-142
- 'PhotochemCAD 2. A Refined Program with Accompanying Spectral Databases for Photochemical Calculations,' Dixon, J. M.; Taniguchi, M.; Lindsey, J. S. Photochem. Photobiol. 2005, 81, 212-213,

(see [Lindsey, 2014]).

The data S. Prahl (2012) needed for the spectra, available on the 'Oregon Medical Laser Center' website (see [Prahl, 2012]), were obtained from the database belonging to the PhotochemCAD software (see [Lindsey, 2014]) [Prahl, 2012]. On this website S. Prahl (2012) offers also links to the raw data of the optical absorption values [Prahl, 2012] which were used to match with the spectral energy distributions of the test planets modelled in this thesis.

The tables of the dimensionless extinction related to the wavelength (original data, ε in equation 22 and 23) of the photosynthetic pigments can be found in the Appendix (chapter B):

Extinction (E) of *Bacteriochlorophyll a* from 900 nm - 300 nm... Appendix B.1, table B.69 to table

B.81

Extinction (E) of *Chlorophyll a* from 700 nm - 219.75 nm... Appendix B.2, table B.82 to table B.90

Extinction (E) of *Chlorophyll b* from 300 nm - 800 nm... Appendix B.3, table B.91 to table B.93

Arithmetic with the dimensionless extinction:

The absorption term indicates the reduction of the incoming radiation during the transit through a medium.

Therefore the following correlations apply:

$$I_0 = I_{abs} + I_{trans} \quad (20)$$

I_0 ... incoming radiation

I_{abs} ... absorbed radiation

I_{trans} ... transmitted radiation.

Lambert-Beer's law:

$$I_{trans} = I_0 \cdot e^{-\varepsilon} \quad (21)$$

ε ... absorption term = extinction, defined as $\exp(-\int \sigma \rho dz)$ (see equation 12 [Houghton, 2002]).

Following from this:

$$Absorption = e^{-\varepsilon} = \frac{I_0}{I_{trans}}. \quad (22)$$

Therefore the absorbed intensity can be calculated with the following equation:

$$I_{abs} = I_0 - I_{trans} = I_0 \cdot (1 - e^{-\varepsilon}). \quad (23)$$

The term $(1 - e^{-\varepsilon})$ describes the percentage of absorbed radiation. By multiplying $(1 - e^{-\varepsilon})$ with the incoming radiation the radiation that becomes absorbed by the photosynthetic pigment can be calculated. Important here is that ε depends on the wavelength. This leads to a required exact subdivision of the incoming radiation (I_0) into several wavelength bands, the same bands as the extinction ε requires (see tables B.69 - B.93).

5.8 Spectral Energy Distribution

The output file of the radiative transfer model contains 5 fluxes:

1. SW-down TOA [W/m^2]: short wavelength down to the top of the atmosphere
2. SW-down SFC [W/m^2]: short wavelength down to the surface
3. SW-up-TOA [W/m^2]: short wavelength up from the top of the atmosphere
4. LW-up-TOA [W/m^2]: long wavelength up from the top of the atmosphere

5. LW-up-SFC [W/m^2]: long wavelength up from the surface

The flux needed for the further calculations is number 2, short wavelengths down to the surface.

The flux by itself is modelled between the following 24 wavelength bands of Streamer ©:

$4 \mu\text{m} \longleftrightarrow 3.42 \mu\text{m} \longleftrightarrow 2.91 \mu\text{m} \longleftrightarrow 2.38 \mu\text{m} \longleftrightarrow 2.13 \mu\text{m} \longleftrightarrow 1.64 \mu\text{m} \longleftrightarrow 1.53 \mu\text{m} \longleftrightarrow$
 $1.28 \mu\text{m} \longleftrightarrow 1.19 \mu\text{m} \longleftrightarrow 1.10 \mu\text{m} \longleftrightarrow 1.00 \mu\text{m} \longleftrightarrow 0.87 \mu\text{m} \longleftrightarrow 0.78 \mu\text{m} \longleftrightarrow 0.75 \mu\text{m} \longleftrightarrow 0.69$
 $\mu\text{m} \longleftrightarrow 0.64 \mu\text{m} \longleftrightarrow 0.57 \mu\text{m} \longleftrightarrow 0.52 \mu\text{m} \longleftrightarrow 0.48 \mu\text{m} \longleftrightarrow 0.44 \mu\text{m} \longleftrightarrow 0.40 \mu\text{m} \longleftrightarrow 0.36 \mu\text{m}$
 $\longleftrightarrow 0.33 \mu\text{m} \longleftrightarrow 0.30 \mu\text{m}.$

Therefore the gap between the nearby wavelength bands is declared as ('gap between λ bands'):

$0.58 \mu\text{m}, 0.51 \mu\text{m}, 0.53 \mu\text{m}, 0.25 \mu\text{m}, 0.49 \mu\text{m}, 0.11 \mu\text{m}, 0.25 \mu\text{m}, 0.09 \mu\text{m}, 0.09 \mu\text{m}, 0.1 \mu\text{m},$

$0.13 \mu\text{m}, 0.09 \mu\text{m}, 0.03 \mu\text{m}, 0.06 \mu\text{m}, 0.05 \mu\text{m}, 0.07 \mu\text{m}, 0.05 \mu\text{m}, 0.04 \mu\text{m}, 0.04 \mu\text{m}, 0.04 \mu\text{m},$

$0.04 \mu\text{m}, 0.03 \mu\text{m}, 0.03 \mu\text{m}, 0.3 \mu\text{m}.$

To derive the differential flux (for results see tables A.64 - A.68) the integrated flux modelled by Streamer © at 24 wavelength bands has to be divided by the equivalent gap between the nearby wavelength bands (see passage 'gap between λ bands').

The already computed output data (fluxes) of the different scenarios can be found in the tables A.64 - A.68, the wavelengths are indicated in μm and the Intensity (SED) in W/m^2 .

1. G-type star:

- Table A.64: Scenario 3, Scenario 4, Scenario 6
- Table A.65: Scenario 5, Scenario 2, Scenario 1
- Table A.66: Scenario 7, Scenario 8

2. M-type star:

- Table A.67: Scenario 4, Scenario 3
- Table A.68: Scenario 2, Scenario 1, Scenario 5

As mentioned before the extinction (ε) is defined for single wavelengths. The extinction for *Bacteriochlorophyll a* was measured from 900 nm to 300 nm in steps of 0.2 nm, for *Chlorophyll a* from 700 nm to 219.75 nm in steps of 0.25 nm and for *Chlorophyll b* from 300 nm to 800 nm in steps of 1 nm.

Thus the calculated flux has to be converted from μm to nm and interpolated between the 24 existing wavelength bands to obtain the needed wavelengths and intensity for every available extinction for the three photosynthetic pigments. The interpolation has to model the intensities between the 24 wavelength bands given by Streamer © for the wavelengths given by the extinction value ε . The

interpolated intensities can then be used as I_0 in equation 23. The factor ε can be taken from the database website 'Oregon Medical Laser Center' (see [Prahl and Jacques, 2014]) or from the original database supplied by the PhotochemCAD program (see [Lindsey, 2014]).

This leads to the absorbed irradiation (I_{abs}) of the photosynthetic pigments given in $[\text{W}/\text{m}^2]$.

The interpolated flux can than be plotted against the absorbed irradiation of *Bacteriochlorophyll a*, *Chlorophyll a* and *Chlorophyll b*.

The results will be discussed in chapter 6.4.

6 Results

The following pages show the results of the previously described model scenarios.

1. Chapter 6.1 illustrates the major differences between two often cited typical G-type and M-type stars.
2. Chapter 6.2 comprises the results of the modelled liquid water zone (LW zone). The borders were derived and decisions were taken in which scenario the planet will be located in the green, blue or red zone.
3. Chapter 6.3 examines the comparison of several scenarios. Not all runs are comparable but the most interesting ones show the difference between the runs with and without clouds.
4. Chapter 6.4 answers the main questions of this scientific thesis. Here the previously described scenarios were numerically modelled. The modelled fluxes are compared with the calculated absorbed intensity of *Bacteriochlorophyll a*, *Chlorophyll a* and *Chlorophyll b*.

6.1 Planck Spectra

Figure 6.25 shows the spectral energy distribution of Gliese 581. This star is considered as a typical M-type star and shows the properties of the M2.5V category. It has less than one third of the mass of the sun and is also more than three times smaller in its radius [Roques and Schneider, 2016]. The effective temperature of the star is determined to be about 3498 K. With this value the calculated spectral energy distribution calculated according to the Planck-law show the shape of the graph in figure 6.25.

It can easily be seen that especially this star, but also M-stars in general, show a lack of radiation in the UV and blue part of their spectra. The spectrum of Gliese 581 starts at about 250 nm. At about 200 nm the range of weak UV radiation begins. This means that no strong UV and XUV radiation is measured. Between 250 nm and 2000 nm the emitted spectral radiance is very weak in contrast to G-type stars (see figure 6.26).

The maximum emitted radiation of Gliese 581 is up to 828.42 nm, which is near IR radiation.

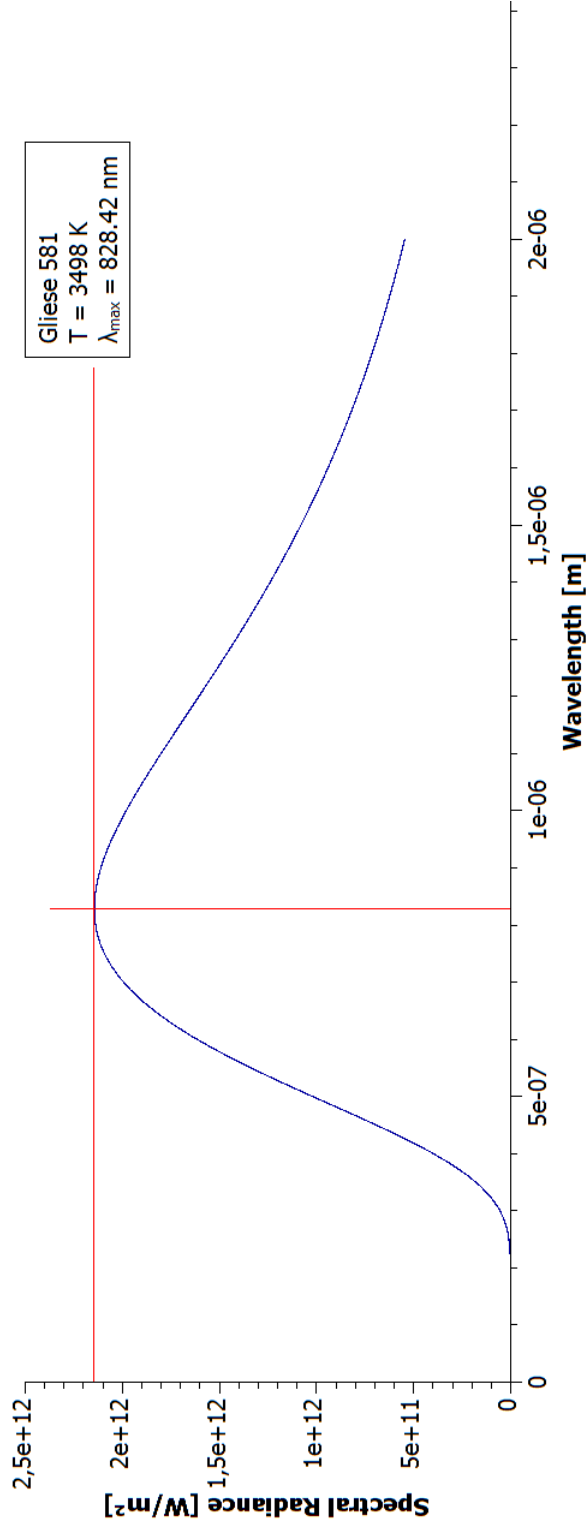


Figure 6.25: Planck spectrum of Gliese 581, a M2.5V star with a T_{eff} of 3498 K, the marked lines show the maximum wavelength of an M-star with $T_{eff} = 3498$ K

Figure 6.26 shows a comparison between the spectral energy distribution of an M-type star (sun, red line) and a G-type star (Gliese 581, blue line). It can clearly be seen that the spectral radiance of stars with larger masses is higher than for lower mass stars. Also the peak of maximum radiation is shifted to longer wavelengths. The peak emission of the sun is located at about 501 nm, which falls within the optical green light range.

Here the differences are obvious. This leads to the question if there exists radiation that is useful for photosynthetic pigments and, if so, if there are enough photons emitted by the M-star to reach the light compensation point.

G-type stars are known to emit radiation in the PAR region. Here it is questionable how the atmospheric composition affects the incoming radiation and whether these impacts are strong enough to prevent potential photosynthesis of plants and bacteria on this planet.

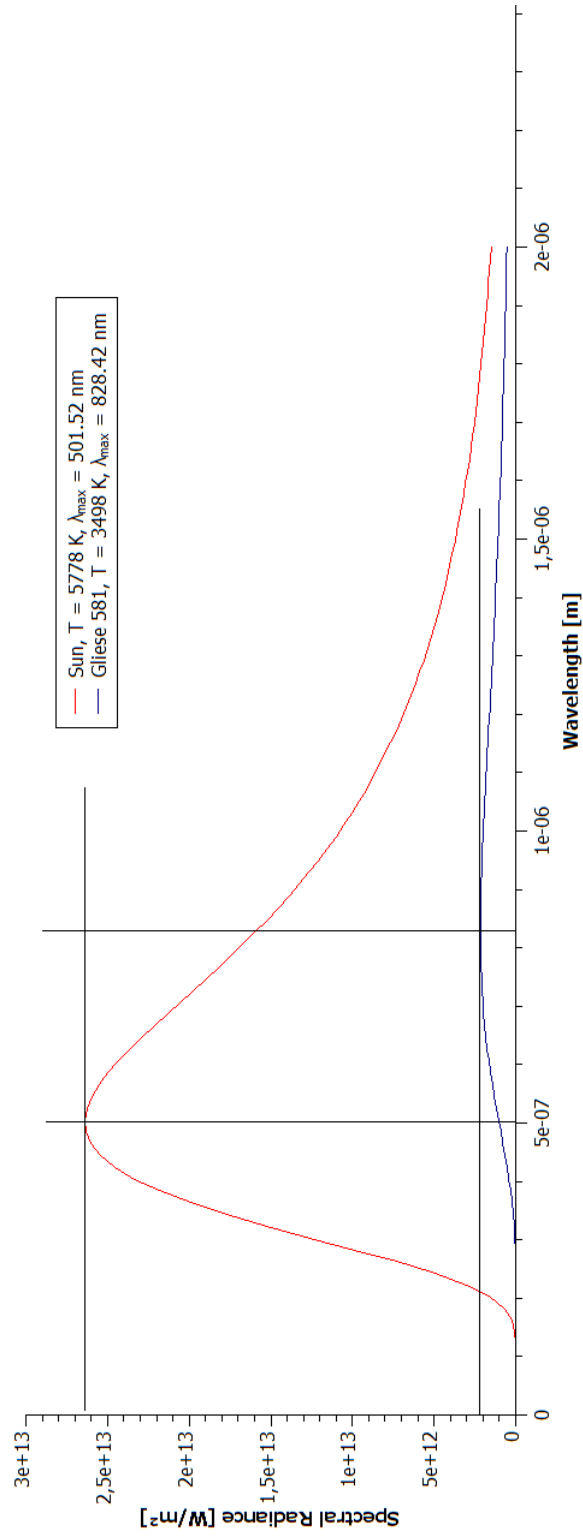


Figure 6.26: Comparison of the Planck spectra of the sun ($T_{eff} = 5778$ K, G-type star) and Gliese 581 ($T_{eff} = 3498$ K, M-type star), the marked lines show the maximum wavelength of the stars

6.2 Liquid Water (LW) Zone

6.2.1 G-Star

The calculation of the borders of the LW zone with a G-type star as host star shows the results that are achieved in table 6.19.

Table 6.19 shows that there are no calculations for the inner border of the 'Earth with clouds' and 'Earth without clouds' scenarios. This is motivated by the runaway greenhouse effect. The high humidity in these scenarios would lead to an imminently arising runaway greenhouse effect if the planet will be situated slightly closer to the host star. This effect causes that the computer code runs a loop finishes because the dynamic equilibrium in all layers is never attained.

It has to be noted that the LW zone is not equal to the habitable zone, whose definition was established by Kasting et al. a few years ago. The classical habitable zone is not only defined by liquid water on the surface of the planet but also by fact that the planet is Earth-like. Here the plate tectonics and the CO₂-cycle also taken into account. If the orbit of the Earth will be shifted outward (blue zone to green zone), more CO₂ will be created and since CO₂ is a good greenhouse gas the surface temperature of the planet won't drop as fast as it would drop without the new CO₂ content. These facts (plate tectonics, powered CO₂ cycle) were not taken into account. Therefore the term 'habitable zone' will not be used in this thesis. The calculations are only related to the a zone where water can be fluid. This is basically given in an area around the host star were the surface temperature of the planet ranges between ~ 273 K and ~ 373 K.

The outer border of the LW zone is distinguished by 0.03 AU between the Earth with and without cloud scenarios. The difference of the outer borders between the Venus scenario with and without clouds is with 0.27 AU greater than for the Earth scenarios.

In both cases the planets with clouds show an outer border that is closer to the star then the scenarios without clouds. This is because of the clouds, which in total have a cooling effect.

The same reasoning can be applied for the inner borders of the Venus atmosphere scenarios with and without clouds.

The Titan atmosphere scenario was just modelled without clouds because the atmospheric composition was simulated without water and hydrogen and oxygen only in form of CO₂ induced.

To examine the influence of the position of the planet and the atmospheric composition on the incoming radiation and therefore on the photosynthetic pigments the decision was made to shift the test planet closer to the star than the inner border indicates respectively farther outside than the outer border indicates.

The position (see row 'calculated at' in table 6.19) for the 'closer' and 'farther' position was chosen by means of the calculated borders, but the exact position was chosen randomly.

	Earth with clouds	Earth without clouds	Venus with clouds	Venus without clouds	Titan without clouds
LW zone, outer border [AU]	1.12	1.15	1.03	1.3	0.96
T at LW zone, outer border [K]	~ 300	273	272.61	273	273.12
Calculated at (farther) [AU]	1.27	1.3	1.2	1.4	1.1
T at planets position (farther) [K]	260.43	260.4	252.58	263.25	255.16
LW zone, inner border [AU]	-	-	0.535	0.715	0.49
T at LW zone, inner border [K]	-	-	373.78	372.94	374.17
Calculated at (closer) [AU]	-	-	0.4	0.6	0.4
T at planets position (closer) [K]	-	-	428.69	408	409.07

Table 6.19: Modelled borders of the LW zone of the scenarios with a G-type star as host star and the selected position for the test planet runs

6.2.2 M-Star

For the M-star scenarios the inner and outer borders of the LW zone were modelled. The limits are much closer to the host star due to the weak emitted radiation than for G-type stars (see chapter 6.1).

The planets will be located in the center of the LW zone. The center is also very close to the host star, which indicates that the planet might be tidally locked or shows a resonance between the orbital period and rotation period like Mercury in our own Solar System.

The borders of the Venus scenario with clouds are also closer to the host star than the scenario without clouds just as the G-type star calculations.

For the Earth atmosphere scenarios the position of the planet indicated in table 6.20 is the same for the run with and without clouds. Here only the run with clouds was modelled and the borders were also taken for the run without clouds because there is no difference to be complied with.

For the model runs the planets were located in the center of the LW zone (see table 6.20, last row 'calculated at').

	Venus with clouds	Venus without clouds	Earth with clouds	Earth without clouds	Titan without clouds
LW zone, outer border [AU]	0.145	0.203	0.169	0.169	0.15
T at LW zone, outer border [K]	273.49	273	273.74	~ 273.74	274.8
LW zone, inner border [AU]	0.075	0.111	0.154	0.154	0.08
T at LW zone, inner border [K]	373.99	372	~ 300	~ 300	374.5
Calculated at (middle) [AU]	0.11	0.157	0.1615	0.1615	0.115

Table 6.20: Modelled borders of the LW zone of the scenarios with a M-type star as host star and the selected position for the test planet runs

In the following chapters 6.3.1 (6.3.1, 6.3.2) and 6.4 the input data were provided by the present author while the actual computer runs were performed by W. Ludwig who also is a member of the EXO-Life-group.

6.3 Comparison of Spectra

In the following chapters 6.3.1 and 6.3.2 different scenarios will be compared to examine the influence of clouds and the different atmospheric composition on the incoming radiation.

6.3.1 G-Star

Figure 6.27 shows the comparison of the G-type star scenarios 1 and 2. Here the planets with an Earth-like atmospheric composition with (black) and without (red) clouds were located outside the LW zone, farther away from the star. The difference between the received intensities between the two scenarios at longer and shorter wavelengths is approximately equidistant. Scenario 1 (with clouds) shows lower intensities due to the clouds in the atmosphere, $\sim 30 \text{ W/m}^2$ at 570 nm. At shorter wavelengths (optical part of the spectra) clouds are opaque and scattering occurs along air particles and cloud droplets. At longer wavelengths (IR) humidity of the atmosphere plays an important role due to the fact that water is a strong absorber in the IR region.

The received flux of both scenarios is lower than the flux the Earth receives in their normal position around the sun.

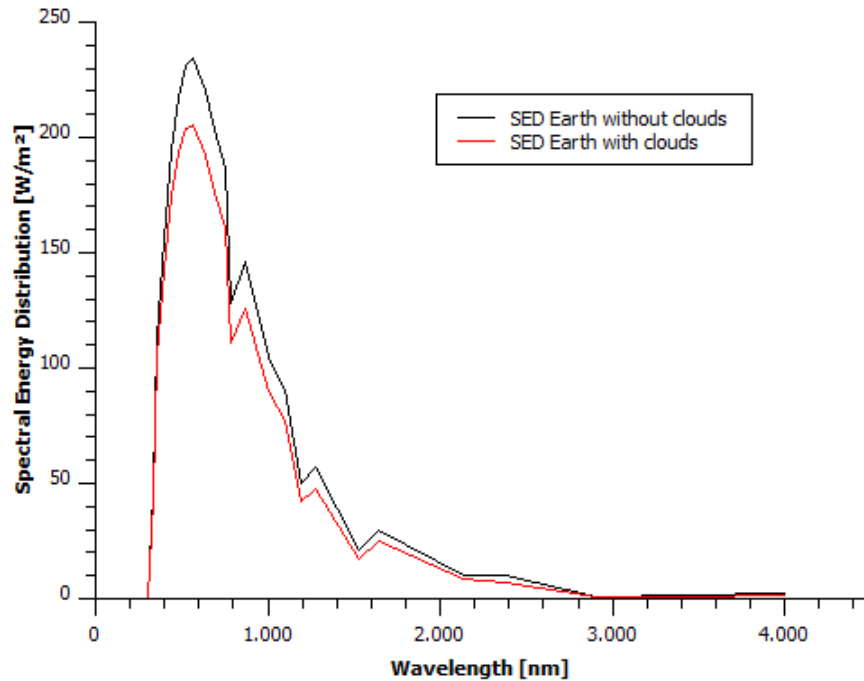


Figure 6.27: Comparison of Scenario 1 and 2 - Earth with and without clouds, green zone

Diagram 6.28 shows a comparison between Scenario 2, 4 and 7. Here the radiation of the G-type star saturates atmospheres with different compositions. All three are without clouds and the planets are located in the green zone. The set up meant that the reasons for the different intensities on the surface of the planet can not be justified by clouds. The generally lower intensities are also motivated by the greater distance to the host star.

The atmosphere of Titan (black) mainly consists of N_2 (99.96 %). N_2 is not a good absorber in all wavelength ranges, except the UV region of the spectrum, which is not present in our runs. This is the reason why the surface of the planet in scenario 7 receives more W/m^2 than the Earth (red) - and Venus-like (green) planets. This could be an advantage for plants on the planet's surface.

Scenario 2 and 4 show similar shaped graphs. The Earth-like planet sustains more flux due to the high N_2 content in the atmospheric composition. The Venus atmosphere contains 96.5 % CO_2 which is a good greenhouse gas and allows the shorter wavelengths to pass but absorbs parts of the IR.

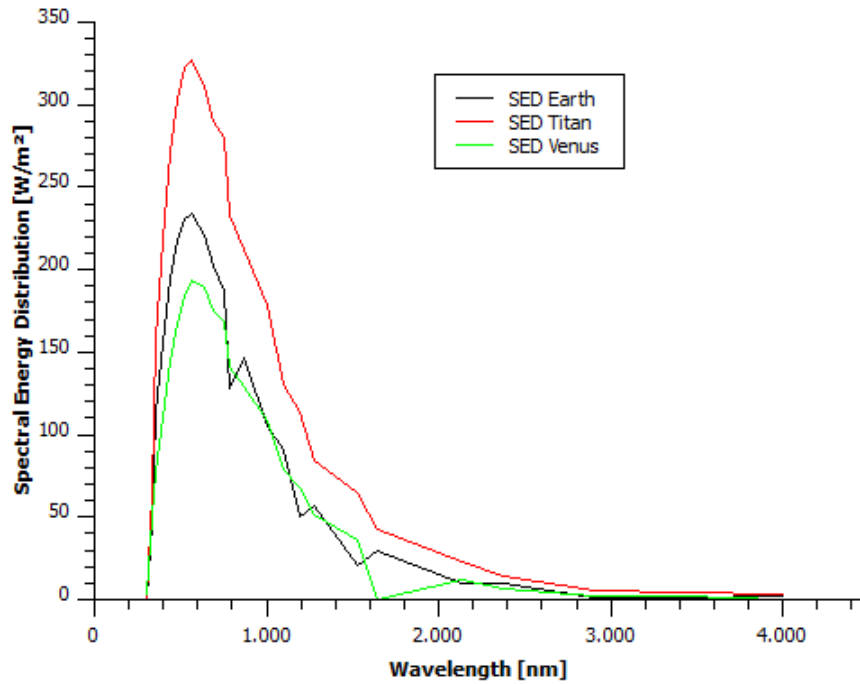


Figure 6.28: Comparison of Scenario 2, Scenario 7 and Scenario 4 - Earth, Titan and Venus without clouds, green zone

Figure 6.29 compares the Venus (red) and Earth (black) scenario, both with clouds and located in the green zone. The relative difference between the two graphs is equal over the whole wavelength range.

The received intensity of both scenarios is lower due to the greater distance to the host star. The Earth-like atmosphere is not as opaque as the Venus-like atmosphere due to the high content of transparent N_2 which leads to a higher photon flux on the surface of the test planet. The easily visible three drops in the SED from the Earth-like atmosphere belong to absorption bands of water and O_2 .

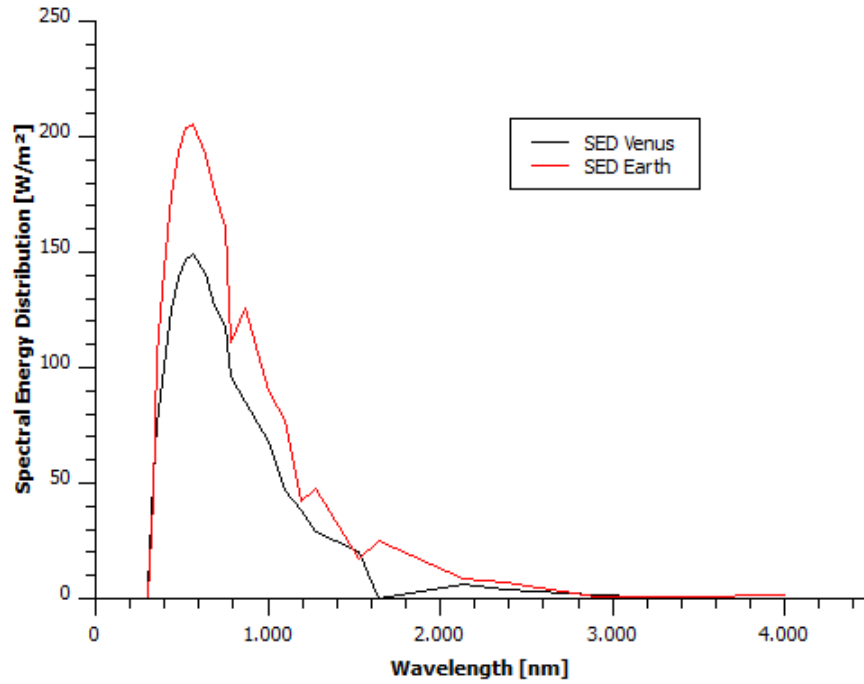


Figure 6.29: Comparison of Scenario 1 and Scenario 5 - Earth and Venus with clouds, green zone

The following figure 6.30 shows the difference between the Venus atmosphere with (black) and without (red) clouds. Scenarios 4 and 5 show the same relative difference between the photon flux measured on the surface of the test planet to the entire wavelength range.

The planet with the Venus-like atmosphere with clouds is situated closer to the star but the surface still receives less radiation. This is most likely explained by the presence of clouds, which means that larger particles for scattering processes are available in the optical region and above 1000 nm the high CO_2 content causes the IR absorption, especially the 1640 nm line.

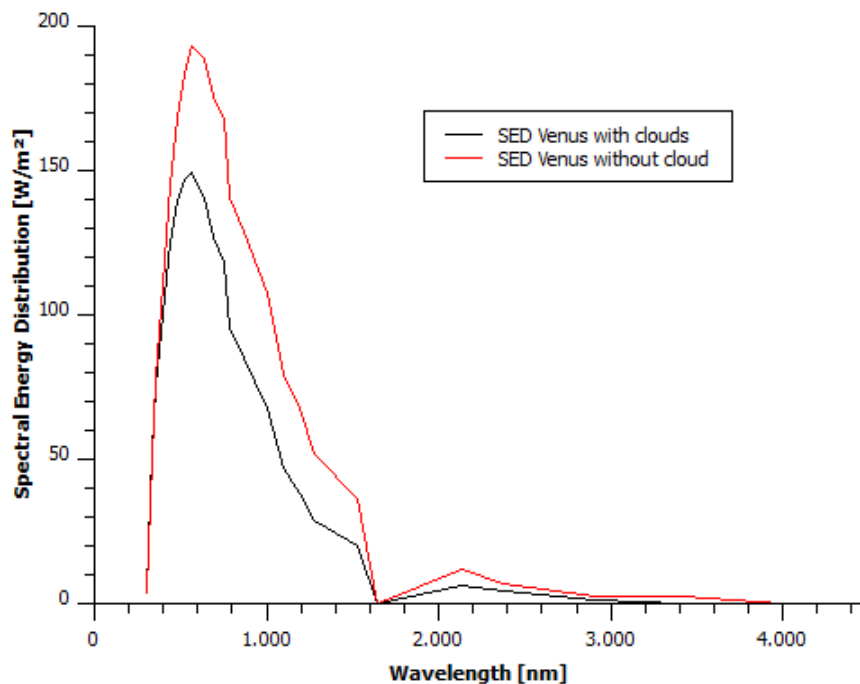


Figure 6.30: Comparison of Scenario 4 and Scenario 5 - Venus without and with clouds, green zone

Figure 6.31 shows the first comparison of two G-type star scenarios where the planet is located in the red zone. Scenario 6, Venus with clouds coloured in black and scenario 3, Venus without clouds coloured in red. The intensity reaching the surface of the planet is extremely high compared to the scenarios farther from the star. Here the clouds have no great influence on the radiation in the optical part of the spectrum. A difference is observable where the IR region is starting. Here the planet with an atmosphere with clouds receives less radiation than the planet without clouds. This is based on the reflective and absorbing properties of clouds as well as the absorbing properties of CO_2 in the IR. The comparison of scenario 8, Titan without clouds (black), and scenario 3, Venus without clouds (red), is shown in figure 6.32.

Both atmospheres show no clouds and the planets are located in the red zone. The general preservation of incoming radiant for the Titan scenario is approximately twice as intense as for the Venus scenario. This can be attributed to the high N_2 concentration of 99.92 % in the Titan atmosphere. N_2 only absorbs radiation of shorter wavelength, and high energies.

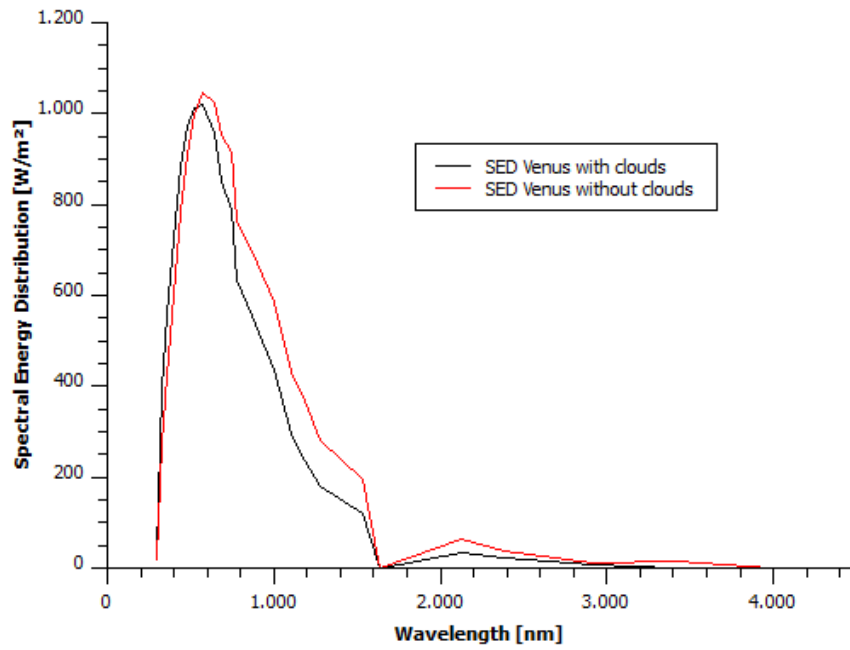


Figure 6.31: Comparison of Scenario 6 and Scenario 3 - Venus with and without clouds, red zone

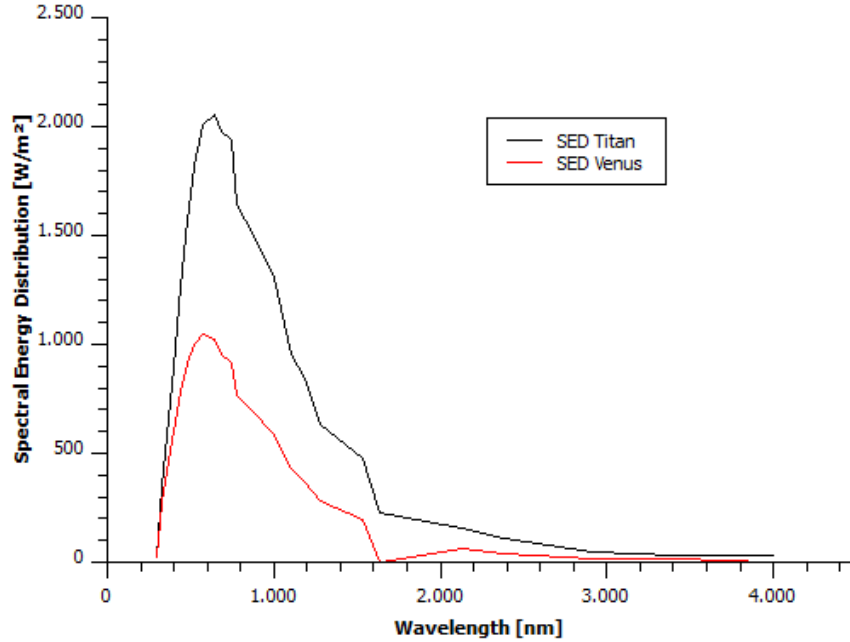


Figure 6.32: Comparison of Scenario 8 and Scenario 3 - Titan and Venus without clouds, red zone

6.3.2 M-Star

The following diagrams compare the scenarios on which an M-type star is a host star.

The graph of the Earth-like atmosphere (black) shows the mandatory shape of a spectrum after passing an atmosphere (see figure 6.33). The graph of the Venus-like atmosphere (red) shows the same shape as known from the diagrams before but the maximum intensity here is situated at wavelengths ≥ 1000 nm (IR) while the maximum of the spectra calculated with G-type stars is located in the optical range. Both scenarios were modelled with clouds.

The strong absorption lines given in the Earth spectra are not present in the Venus spectra which leads to the assumption that they are caused by O_2 or the high humidity of the Earth's atmosphere. The maximum intensity of the runs are located around $\sim 170 \text{ W/m}^2$ and $\sim 210 \text{ W/m}^2$ which is comparable to the intensities of the G-type star runs where the planet is located in the green zone. Here the planet is situated in the center of the LW zone but because of the low luminosity of M-stars the LW zone is by far closer to the host star.

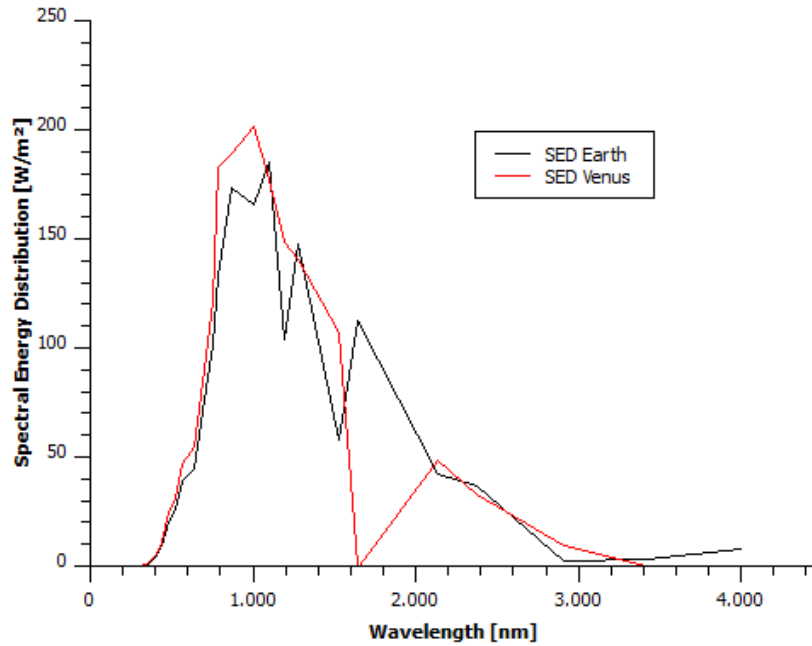


Figure 6.33: Comparison of Scenario 1 and Scenario 3 - Earth and Venus with clouds, center of the LW zone

Figure 6.34: The graphs of the Earth (red) and Venus (green) scenarios are modelled without clouds. Both runs show higher peaks of the SED than in the scenarios with clouds, what is a natural effect deduced from the reflection and absorbing properties of clouds. The maxima of the Earth-, Venus- and Titan-like scenarios are all located around ~ 1000 nm which lies in the nature of M-type stars. The Titan (black) run shows twice as much flux at the maximum wavelength than the other two scenarios. This can be explained by the N_2 rich atmosphere. The Titan atmosphere shows also no significant absorption lines in all runs (both G-type and M-type star as host star scenarios).

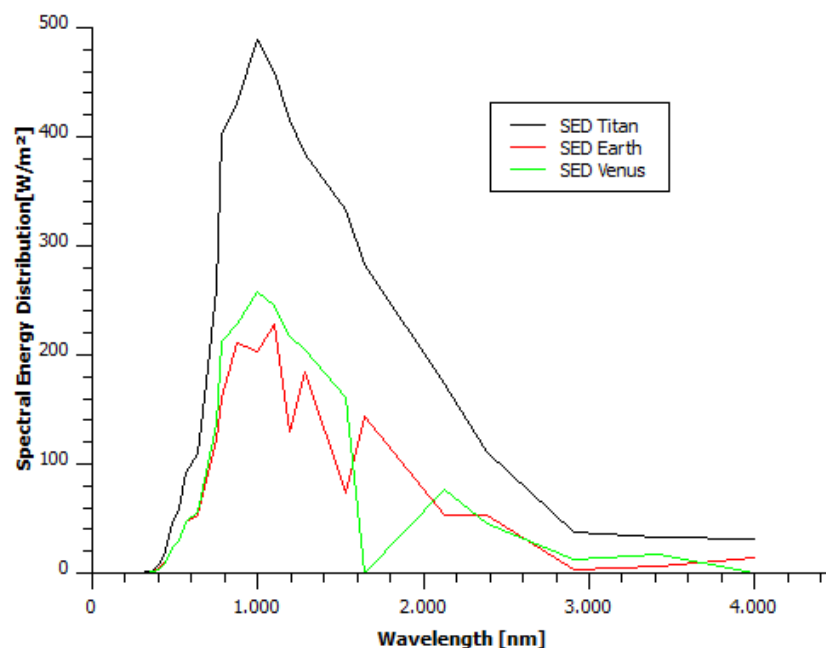


Figure 6.34: Comparison of Scenario 5, Scenario 2 and Scenario 4 - Titan, Earth and Venus without clouds, center of the LW zone

The comparison of the different scenarios that were modelled show that the composition of the atmospheres has a great influence. N_2 does not effect the incoming radiation highly, while water vapour shows detailed absorption lines.

Absorption also mainly occurs in the IR region due to the properties of the molecules present in the atmospheres. The optical part of the spectra is mainly unaffected by the atmospheric composition.

The host star itself effects the conditions on the surface of the test planets in a large-scale. The LW zone is much closer situated to the M-star than to the G-star. This on the one hand leads to appropriate surface temperatures but planets could become rotationally bound. This on the one hand could lead to an atmosphere loss but on the other hand possible plants would receive more photons for photosynthesis.

6.4 Radiation Transfer Model

The following diagrams show the final results of the 13 G- and M-type star scenarios with different atmospheric compositions, with and without clouds, modelled with the modified Streamer code and plotted together with the derived absorption spectra of *Bacteriochlorophyll a*, *Chlorophyll a* and *Chlorophyll b*.

It has to be stated that the values of the maximum intensities of the scenarios mentioned in the following and previous sections are approximate values. The modified Streamer code calculates the flux only for 24 wavelength bands. Therefore the maximum intensity is measured at a certain wavelength band available in the code but the true maximum will be located between bands given by Streamer.

Scenario 1, 2 and 3 show their maximum intensity at the 1100 nm band of the Streamer code. The true maxima will be located between 1000 nm and 1100 nm. Scenario 4 and 5 show the maxima at 1000 nm therefore the true maxima will also be located between 1000 nm and 1100 nm.

So the obtained intensity maxima will be related to the maximum at the wavelength band used by the modified Streamer code. The error of the values remain within the error limits of the Streamer code.

Thus it is possible to see if the spectral range of PAR is existing in the spectra of M-stars, in this case of AD Leonis.

Otherwise the G-star scenarios show how the distance to the star and the different atmospheric compositions effect the spectral energy distribution on the planet's surface.

Furthermore it can be calculated how many photons reach the surface at an accurately defined wavelength. Here the absorption maxima of the photosynthetic pigments can be taken and the attained number of photons can be compared with the hypothetical light compensation point. Resulting from the idea a statement about the possibility and the effectiveness of photosynthesis can be made.

$$I = N \cdot E \quad (24)$$

I... received intensity [W/m²]

N... number of photons

E... energy of a photon at a given wavelength = $h \cdot \frac{c}{\lambda}$.

$$N = I \cdot \frac{\lambda}{h \cdot c} \quad (25)$$

With equation 25 the number of photons per square meter and second can be calculated.

Composed graphs 6.35 to figure 6.47 are given 'zoomed in'. The fully derived spectra of all runs show the energy distribution from 300 nm to 4000 nm. The absorbed radiation from the pigment is situated between ~ 220 nm and ~ 900 nm. This leads to optically compacted absorption spectra and prevents a high visibility of the details of the spectra. Therefore the SEDs were terminated at 1300 nm or 1500 nm. The original full spectra of all runs can be found in the appendix. For the complete G-star spectra with absorption spectra of the photosynthetic pigments see figure C.50 to figure C.57. For the full M-star spectra with absorption spectra of the photosynthetic pigments see figure C.58 to figure C.62.

A possible eccentricity of the orbits is not included into the calculations. Therefore circular orbits are assumed and the intensity should be approximately the same during the whole orbit around the host star.

Moreover the maxima of the photosynthetic pigments were selected with the help of ε . The tables 6.21 to table 6.59 show the wavelength (λ [nm]) at which the maximum absorption takes place. The second columns show the incoming intensity of the spectra (I_0 [W/m²]) and the third one the intensity that is absorbed by the pigments (I_{abs} [W/m²]). With equation 25 the number of photons that will be absorbed were calculated (see table 6.21 - 6.59, column 4: # Photons [m⁻²s⁻¹]).

6.4.1 G-Star

As for all G-stars the bandwidth of PAR is covered, equally for the runs 'closer' or 'farther' from the star outside the LW zone. Therefore photosynthesis is not prohibited by a lack of radiation in the optical part of the spectra. The great difference lies in the flux received.

It can be summarized for all runs that *Chlorophyll a* absorbs the largest amount of photons, followed by *Chlorophyll b* and the smallest amount by *Bacteriochlorophyll a*. *Chlorophyll a* shows higher absorption properties in the green range than the other pigments and the maxima are shifted to lower wavelengths for the maximum in the blue and to longer wavelengths for the maximum in the red in contrast to *Chlorophyll b*. The maxima of *Chlorophyll b* are located closer together but also in the blue and the red range of the spectrum. *Bacteriochlorophyll b* reveals the lowest absorption efficiency. The advantage are the 4 absorption maxima. A double maximum is located between ~ 300 nm and ~ 400 nm, one around ~ 580 nm and the highest at ~ 780 nm. Therefore *Bacteriochlorophyll* absorbs also IR radiation. It is also the only probed pigment which has a maximum in the yellow range at 580.2 nm, but with only ~ 9 % of absorption efficiency the peak is only little above the absorption efficiency of the green drop of *Chlorophyll a*.

Bacteriochlorophyll a (red) shows 4 maxima (see table 6.21). A double maximum is located between ~ 360 nm and ~ 400 nm, the third one at 580.2 nm and the highest at 780.2 nm.

It is important to know that photosynthesis is not controlled by the absorbed energy [Nobel, 2009]. It depends a lot more on the portion of absorbed photons [Nobel, 2009].

In the scientific field of biology the light compensation point is defined in a 'photosynthetic photon

flux (PPF)' [Nobel, 2009]. P. S. Nobel (2009) wrote in his book, that for C₃ plants the light compensation point sets in at 8 - 16 $\frac{\mu\text{mol}}{\text{m}^2\text{s}}$ and for C₄ plants at 6 - 14 $\frac{\mu\text{mol}}{\text{m}^2\text{s}}$ [Nobel, 2009]. Shade plants generally have a lower light compensation point [Nobel, 2009].

Here the number of photons per square meter and second was calculated. This means that for the number of photons have to be divided by the Avogadroconstant to obtain the photon flux in $\frac{\mu\text{mol}}{\text{m}^2\text{s}}$.

$$F_{\text{photon}} = \frac{N_p}{N_A} \quad (26)$$

F_{photon} ... Photon flux [$\frac{\mu\text{mol}}{\text{m}^2\text{s}}$]

N_p ... Number of Photons

N_A ... Avogadro constant - $6.022 \times 10^{23} \text{ mol}^{-1} = 6.022 \times 10^{17} \mu\text{mol}^{-1}$

Scenario 1

The first G-type star scenario is modelled with an Earth-like atmosphere with clouds, depicted in figure 6.35). The planet is situated in the green zone.

The maximum intensity of $\sim 205.472 \text{ W/m}^2$ is received at about 570 nm.

For the Earth the average computed value of the solar constant is verified with 1368 W/m^2 , and the irradiance referring to the whole surface of the planet is verified with 342 W/m^2 [Roedel and Wagner, 1991, 1994, 2000, 2011]. Based on the fact that the G-type runs have the sun as their host star the difference between these two values is due to the diverse distance to the host star. The test planet in run 1 is 0.27 AU farther outside than the Earth at her natural position in the solar system.

Figure 6.35 shows the results of the modified Streamer code (black) the absorbed intensities calculated with the absorption (ε) and the interpolated flux.

The lowest number of photons is given for *Bacteriochlorophyll a* at 396.4 nm with $4.7189 \times 10^{19} \frac{\text{photons}}{\text{m}^2\text{s}^1}$ which leads to an absorbed photon flux of $78.36 \frac{\mu\text{mol}}{\text{m}^2\text{s}}$. This leads to the assumption that the absorbed photon flux is high enough to exceed the light compensation point. The highest absorbed photon flux is given for *Chlorophyll a* at 417.75 nm with $415 \frac{\mu\text{mol}}{\text{m}^2\text{s}}$.

The largest absorption takes place at the 780.2 nm line, where about 32 % of the incoming radiation will be absorbed.

The absorption area of *Bacteriochlorophyll a* is spread over a large part of the spectrum given the fact that 780 nm are already situated in the IR, which will be important for the M-type scenarios where optical blue radiation is hardly available. A disadvantage is that *Bacteriochlorophyll a* is obviously a bad absorber in general. Furthermore there is drop at $\sim 780 \text{ nm}$ visible in the SED. This is exactly the wavelength range near one of the maximum absorption peaks of *Bacteriochlorophyll a*.

Indeed this is negligible because the light compensation point will certainly exceeded.

Table 6.22 shows the two absorption maxima of *Chlorophyll a* (green) in the first G-type star scenario. The maxima are located in the violet-blue (717.75 nm) and red (654.25 nm) range of the spectrum. The number of absorbed photons are higher than they are for *Bacteriochlorophyll a*, therefore the

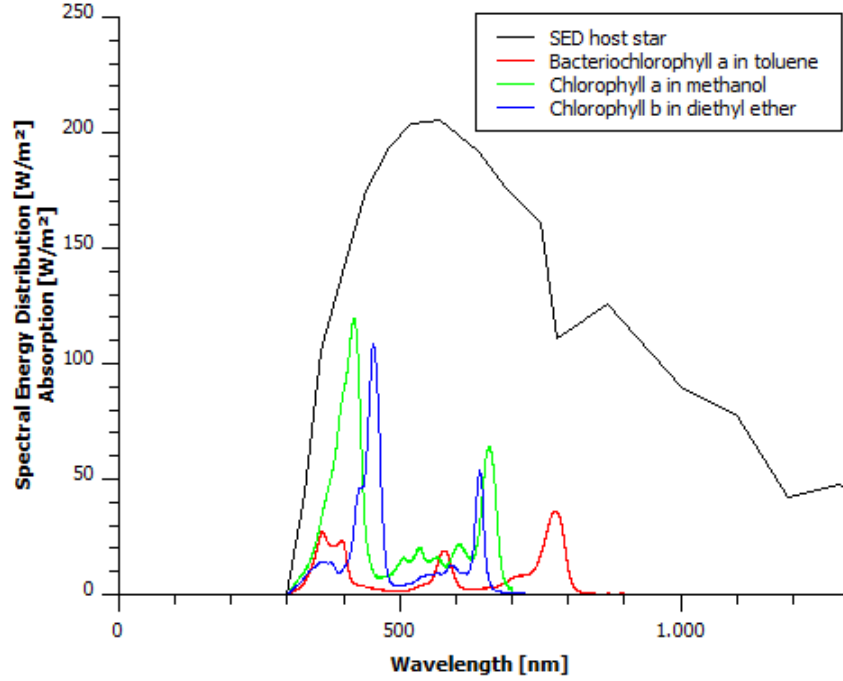


Figure 6.35: Scenario 1, G-star, Earth atmosphere, with clouds, green zone, zoomed in

λ [nm]	I_0 [W/m ²]	I_{abs} [W/m ²]	# Photons [m ⁻² s ⁻¹]
780.2	110.601	35.0439	1.37639×10^{20}
580.2	203.57	19.0902	5.57585×10^{19}
396.4	138.615	23.6474	4.7189×10^{19}
361.2	106.412	27.0214	4.91337×10^{19}

Table 6.21: This table shows the wavelength λ of the four absorption maxima of *Bacteriochlorophyll a*, the intensity of the incoming radiation I_0 , the absorbed intensity I_{abs} and the number of photons (# Photons) of the first G-type scenario.

light compensation point is also surmounted. The digram also shows that the green graph generally is higher than the absorption spectra of *Bacteriochlorophyll a* and *Chlorophyll b*. Therefore it can be assumed that *Chlorophyll a* is the photosynthetic pigment with the best absorbing properties of the three selected pigments. The absorbing spectrum of *Chlorophyll a* shows also a minor drop in the green range, which indicates that this pigments also better absorbs 'green' photons than the other pigments.

λ [nm]	I_0 [W/m ²]	I_{abs} [W/m ²]	# Photons [m ⁻² s ⁻¹]
654.25	187.712	60.0112	1.97651×10^{20}
417.75	156.535	119.249	2.5078×10^{20}

Table 6.22: This table shows the wavelength λ of the four absorption maxima of *Chlorophyll a*, the intensity of the incoming radiation I_0 , the absorbed intensity I_{abs} and the number of photons (# Photons) of the first G-type scenario.

Table 6.23 shows the two absorption maxima of *Chlorophyll b*. Both maxima are located in the blue and red range of the spectrum.

Chlorophyll b absorbs less efficient than *Chlorophyll a* with ~ 60 % in contrast to ~ 76 %.

λ [nm]	I_0 [W/m ²]	I_{abs} [W/m ²]	# Photons [m ⁻² s ⁻¹]
453	180.971	108.541	2.47524×10^{20}
643	191.427	53.5797	1.73434×10^{20}

Table 6.23: This table shows the wavelength λ of the four absorption maxima of *Chlorophyll b*, the intensity of the incoming radiation I_0 , the absorbed intensity I_{abs} and the number of photons (# Photons) of the first G-type scenario.

Scenario 2

Figure 6.36 demonstrates the results of the second run. The black graph indicates the modelled SED, red the absorption spectrum of *Bacteriochlorophyll a*, green the absorption spectrum of *Chlorophyll a* and blue the absorption spectra of *Chlorophyll b*.

This scenario is modelled with an Earth-like atmosphere without clouds. This explains the higher received intensity on the surface of the planet. The maximum lies at 570 nm with 234.21135 W/m². Like scenario 1 there is a difference between the irradiance that is referring to the whole surface of the Earth at its common distance and the modelled intensity.

The whole absorption spectra of the photosynthetic pigments are covered by the modelled SED and the incoming number of photons of all pigments is higher than $5.1661 \times 10^{19} \frac{\text{photons}}{\text{m}^2\text{s}}$. This value refers to *Bacteriochlorophyll a* at a wavelength of 396.4 nm. The absorbed photon flux of this number of photons is $88.02 \frac{\mu\text{mol}}{\text{m}^2\text{s}}$, and therefore higher as the required photon flux to exceed the light compensation point.

Like in run 1 there is drop at ~ 780 nm visible in the SED. This is exactly the wavelength range near one of the maximum absorption peaks of *Bacteriochlorophyll a*. But even with this drop the absorption at the 780.2 nm line is still the highest.

Table 6.24 summarizes the 4 absorption maxima of *Bacteriochlorophyll a*. At the 780.2 nm line about 32 % intensity is absorbed while at the 580.2 nm line about 9 % intensity is absorbed.

λ [nm]	I_0 [W/m ²]	I_{abs} [W/m ²]	# Photons [m ⁻² s ⁻¹]
780.2	128.048	40.5719	1.59351×10^{20}
580.2	232.237	21.7785	6.36106×10^{19}
396.4	151.751	25.8884	5.1661×10^{19}
361.2	114.802	29.1519	5.30076×10^{19}

Table 6.24: This table shows the wavelength λ of the four absorption maxima of *Bacteriochlorophyll a*, the intensity of the incoming radiation I_0 , the absorbed intensity I_{abs} and the number of photons (# Photons) of the second G-type scenario.

The properties of the *Chlorophyll a* maxima are described in table 6.25. Here the absorption maximum at 654.25 is half as high as for the 417.75 nm line. This implies that blue photons are superiorly absorbed. The highest absorbed photon flux is given for *Chlorophyll a* at 417.75 nm with $\sim 458 \frac{\mu\text{mol}}{\text{m}^2\text{s}}$.

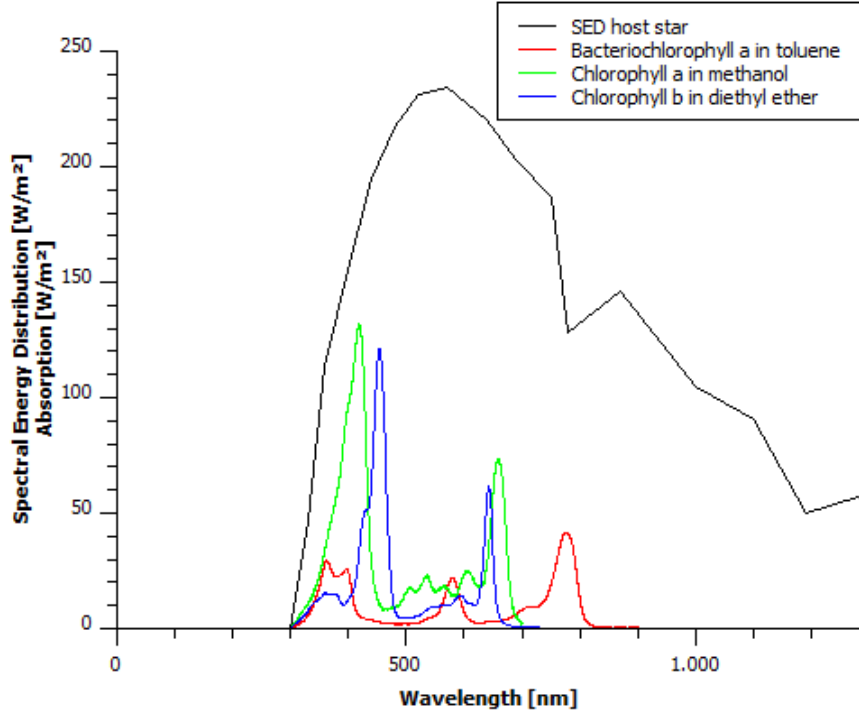


Figure 6.36: Scenario 2, G-star, Earth atmosphere, without clouds, green zone, zoomed in

λ [nm]	I_0 [W/m ²]	I_{abs} [W/m ²]	# Photons [m ⁻² s ⁻¹]
654.25	215.548	68.9104	2.26961×10^{20}
417.75	172.682	131.549	2.76648×10^{20}

Table 6.25: This table shows the wavelength λ of the absorption maxima of *Chlorophyll a*, the intensity of the incoming radiation I_0 , the absorbed intensity I_{abs} and the number of photons (# Photons) of the second G-type scenario.

Table 6.26 illustrates the absorption maxima of *Chlorophyll b* at 453 nm and 643 nm. The blue range of the spectrum is stronger absorbed than the red part. The difference of the absorbed photon flux between the two maxima is $127.84 \frac{\mu\text{mol}}{\text{m}^2\text{s}}$.

λ [nm]	I_0 [W/m ²]	I_{abs} [W/m ²]	# Photons [m ⁻² s ⁻¹]
453	201.739	120.997	2.75928×10^{20}
643	219.576	61.4586	1.98938×10^{20}

Table 6.26: This table shows the wavelength λ of the absorption maxima of *Chlorophyll b*, the intensity of the incoming radiation I_0 , the absorbed intensity I_{abs} and the number of photons (# Photons) of the second G-type scenario.

Scenario 3

Scenario 3, given in figure 6.37, displays a Venus-like atmosphere without clouds. The planet is located in the red zone. The intensity received on the surface of the test planet is highest at 570 nm and amounts to 1047.99 W/m^2 . The solar irradiance for Venus at its original mean position at

0.7 AU with the primary conditions is about 2613.9 W/m^2 [Williams, 2015b]. The solar irradiance divided by 4 gives 653.475 W/m^2 , approximately 37.6 % less than it receives in the present computer simulation runs.

With a surface temperature of 428.69 K the planet would be not habitable for life-as-we-know it. However the modelled spectrum shows a perfect match with the calculated absorption spectra of the photosynthetic pigments. Like in the other G-type star scenarios the absorption peaks in the red segment fit perfectly within the modelled SED without getting affected by possibly too weak high energetic radiation. The SED itself shows no significant absorption lines that could impact the absorption of the pigments.

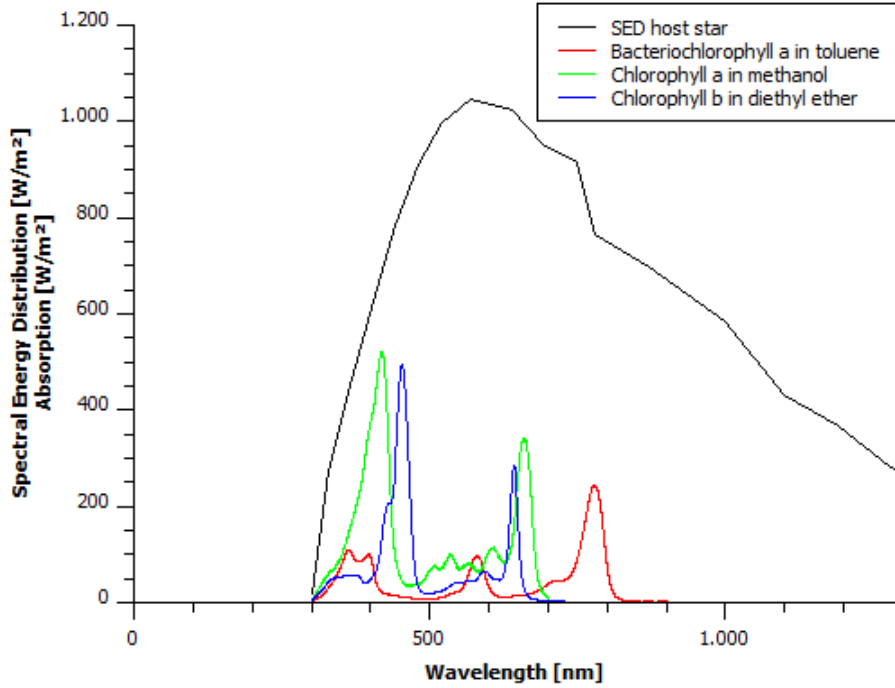


Figure 6.37: Scenario 3, G-star, Venus atmosphere, without clouds, red zone, zoomed in

The four absorption maxima of *Bacteriochlorophyll a* can be found in table 6.27. At blue wavelengths there is less absorption than at red wavelengths, at least in the yellow range at 580.2 nm. This is contrary to *Chlorophyll a* and *Chlorophyll b*, being both oxygenic photosynthesis pigments. It is already visible in the SED that the light compensation point at all maxima will be exceeded. The minimal number of absorbed photons for *Bacteriochlorophyll a* is given at 361.2 nm with $1.97438 \times 10^{20} \text{ m}^{-2}\text{s}^{-1}$. The number of photons can be converted to mol like explained before, which leads to $327.85 \frac{\mu\text{mol}}{\text{m}^2\text{s}}$, far above the light compensation point.

In table 6.28 both absorption maxima of *Chlorophyll a* are listed. The values of the absorbed photons are nearly identical but the absorbed intensity of the red wavelength is about 38.3 % lower than the intensity in the blue range. This is because the absorption ability in the red is lower than in the blue but the received intensity I_0 is about one third higher in the red range of the spectrum.

The absorption maxima, intensities and number of photons of *Chlorophyll b* are specified in table

λ [nm]	I_0 [W/m ²]	I_{abs} [W/m ²]	# Photons [m ⁻² s ⁻¹]
780.2	764.574	242.255	9.51485×10^{20}
580.2	1044.56	97.9557	2.86108×10^{20}
396.4	584.966	99.7939	1.99141×10^{20}
361.2	427.603	108.583	1.97438×10^{20}

Table 6.27: This table shows the wavelength λ of the four absorption maxima of *Bacteriochlorophyll a*, the intensity of the incoming radiation I_0 , the absorbed intensity I_{abs} and the number of photons (# Photons) of the third G-type scenario.

λ [nm]	I_0 [W/m ²]	I_{abs} [W/m ²]	# Photons [m ⁻² s ⁻¹]
654.25	1003.87	320.937	1.05703×10^{21}
417.75	682.594	520	1.09356×10^{21}

Table 6.28: This table shows the wavelength λ of the absorption maxima of *Chlorophyll a*, the intensity of the incoming radiation I_0 , the absorbed intensity I_{abs} and the number of photons (# Photons) of the third G-type scenario.

6.29. Here the absorbed intensity of the red maximum is 42.4 % lower than the absorbed intensity of the blue maximum, but the number of absorbed photons is only 18 % lower due to the different absorbed wavelengths.

Also if one observes the proportion between the maximum in the blue and the red of *Chlorophyll a* and *Chlorophyll b* one can see that *Chlorophyll b* absorbs proportionally less red photons. In the blue range about 60 % of the incoming radiation at this wavelength will be absorbed and about 28 % in the red range.

However, the light compensation points at both maxima are reached.

λ [nm]	I_0 [W/m ²]	I_{abs} [W/m ²]	# Photons [m ⁻² s ⁻¹]
453	825.646	495.199	1.12928×10^{21}
643	1020.11	285.524	9.24223×10^{20}

Table 6.29: This table shows the wavelength λ of the absorption maxima of *Chlorophyll b*, the intensity of the incoming radiation I_0 , the absorbed intensity I_{abs} and the number of photons (# Photons) of the third G-type scenario.

Scenario 4

Scenario 4, see figure 6.38, describes a planet with Venus-like atmosphere without clouds in the green zone. Because of the great distance of 1.4 AU the maximum intensity at 570 nm is only 193.078 W/m². This distance is possible because the run was done without clouds. Clouds show a cooling effect, this leads to the assumption that a planet without clouds could be situated farther outside in the planetary system and nevertheless exhibit surface temperatures above 273 K.

The spectral energy distribution covers the absorption spectra of the three photosynthetic pigments and offers enough intensity even in the blue range. Beginning at 300 nm the SED shows a clear increase of intensity until it reaches its maximum at 570 nm. No significant absorption lines are visible in the SED.

Table 6.30 gives the most important informations about the absorption spectra of *Bacteriochlorophyll a*. Like in the other scenarios the peak in the yellow range of the spectrum at 580.2 nm shows the

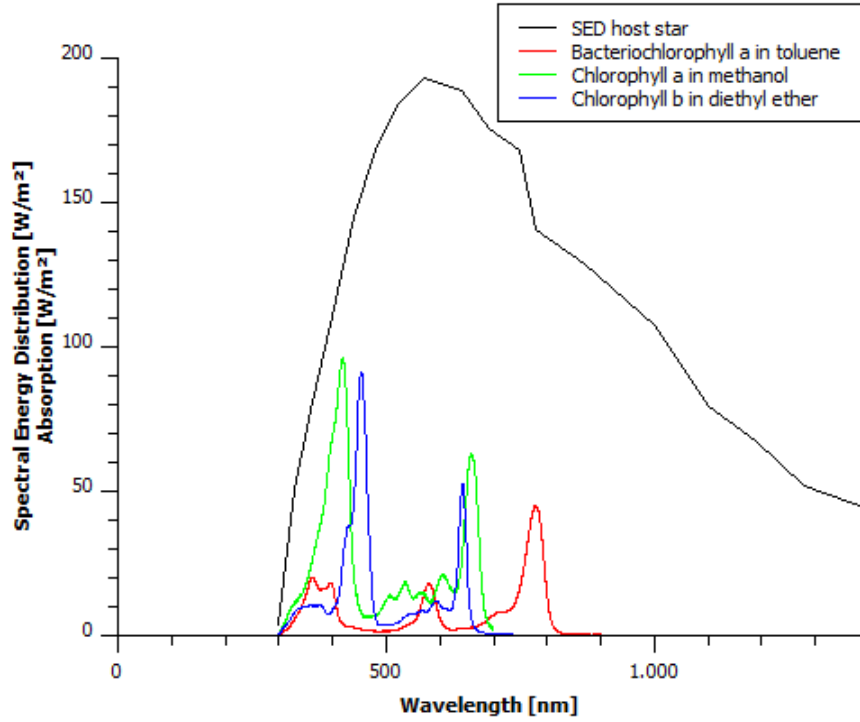


Figure 6.38: Scenario 4, G-star, Venus atmosphere, without clouds, green zone, zoomed in

least absorbed radiation. Because of the maximum of received intensity at 570 nm the the absorbed number of photons is higher than at 396.4 nm and 361.2 nm.

The least number of photons are received at 361.2 nm with $3.64 \times 10^{19} \text{ m}^{-2}\text{s}^{-1}$. These are $\sim 60.5 \frac{\mu\text{mol}}{\text{m}^2\text{s}}$, more than the required 8 - 16 $\frac{\mu\text{mol}}{\text{m}^2\text{s}}$ for C_3 plants and 6 - 14 $\frac{\mu\text{mol}}{\text{m}^2\text{s}}$ for C_4 plants [Nobel, 2009] for the light compensation point to be reached.

λ [nm]	I_0 [W/m^2]	I_{abs} [W/m^2]	# Photons [$\text{m}^{-2}\text{s}^{-1}$]
780.2	140.733	44.5913	1.75138×10^{20}
580.2	192.436	18.0461	5.27089×10^{19}
396.4	107.881	18.4043	3.67262×10^{19}
361.2	78.8645	20.0263	3.64143×10^{19}

Table 6.30: This table shows the wavelength λ of the four absorption maxima of *Bacteriochlorophyll a*, the intensity of the incoming radiation I_0 , the absorbed intensity I_{abs} and the number of photons (# Photons) of the fourth G-type scenario.

Table 6.31 shows the two absorption maxima of the *Chlorophyll a* absorption spectrum. At 654.25 nm more W/m^2 are incoming than at 417.75 nm but the absorbed intensity is higher in the blue range as well as the number of absorbed photons per square meter and second. Both numbers of absorbed photons exceed the required absorbed photon flux by far.

The highest absorbed photon flux for this scenario is given for *Chlorophyll b* at 453 nm with $\sim 346 \frac{\mu\text{mol}}{\text{m}^2\text{s}}$, pointed in table 6.32.

λ [nm]	I_0 [W/m ²]	I_{abs} [W/m ²]	# Photons [m ⁻² s ⁻¹]
654.25	184.871	59.103	1.9466×10^{20}
417.75	125.877	95.8932	2.01664×10^{20}

Table 6.31: This table shows the wavelength λ of the two absorption maxima of *Chlorophyll a*, the intensity of the incoming radiation I_0 , the absorbed intensity I_{abs} and the number of photons (# Photons) of the fourth G-type scenario.

λ [nm]	I_0 [W/m ²]	I_{abs} [W/m ²]	# Photons [m ⁻² s ⁻¹]
453	152.236	91.307	2.08221×10^{20}
643	187.873	52.5848	1.70214×10^{20}

Table 6.32: This table shows the wavelength λ of the two absorption maxima of *Chlorophyll b*, the intensity of the incoming radiation I_0 , the absorbed intensity I_{abs} and the number of photons (# Photons) of the fourth G-type scenario.

Scenario 5

Scenario 5 (see figure 6.39) describes a planet with a Venus-like atmosphere with clouds. The planet is situated outside the LW zone, farther away from the star at 1.2 AU. The received flux reaches its maximum at 570 nm with 149.322 W/m². This intensity is slightly below the intensity of Scenario 4 where the atmosphere is not modelled with clouds. This means that the incoming photon flux is lower over the whole wavelength range.

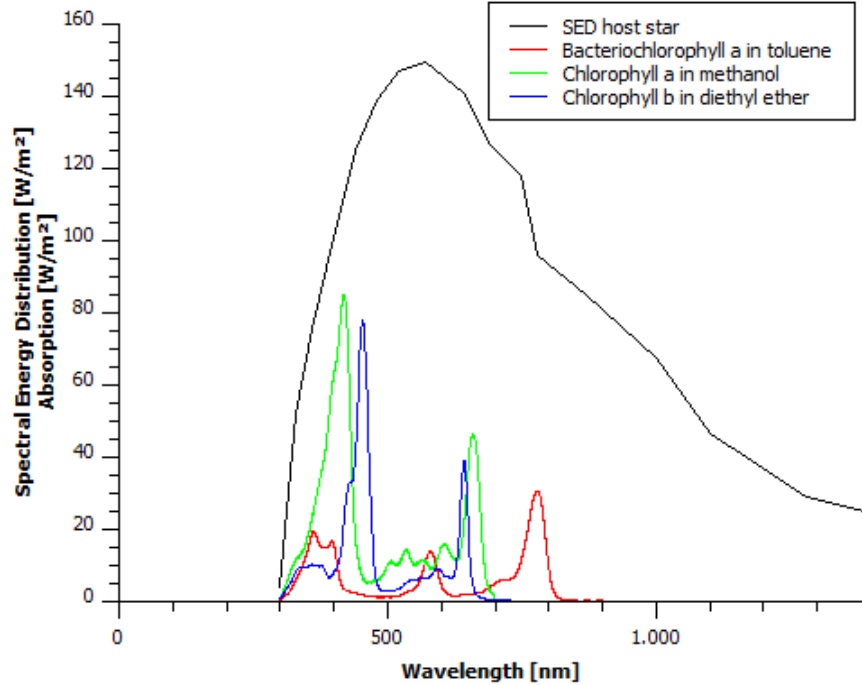


Figure 6.39: Scenario 5, G-star, Venus atmosphere, with clouds, green zone, zoomed in

Table 6.33 displays the absorption maxima of *Bacteriochlorophyll a* in scenario 5.

Just like in the other scenarios the absorption spectrum of *Bacteriochlorophyll a* extends into the IR range of the spectrum. All four maxima are clearly lower than the maxima of the other two oxygenic photosynthesis pigments. The lowest received intensity (I_0) is maintained at 361.2 nm but the lowest absorbed intensity (I_{abs}) is to be found at 580.2 nm. The lowest number of received photons per square meter and second is counted at 396.4 nm. But even with only 3.18466×10^{19} photons $m^{-2}s^{-1}$ the light compensation point is exceed because the absorbed photon flux is $\sim 53 \frac{\mu mol}{m^2 s}$.

λ [nm]	I_0 [W/m ²]	I_{abs} [W/m ²]	# Photons [m ⁻² s ⁻¹]
780.2	95.883	30.3805	1.19323×10^{20}
580.2	148.088	13.8873	4.05619×10^{19}
396.4	81.5659	17.1255	3.18466×10^{19}
361.2	76.3892	19.3978	3.52714×10^{19}

Table 6.33: This table shows the wavelength λ of the four absorption maxima of *Bacteriochlorophyll a*, the intensity of the incoming radiation I_0 , the absorbed intensity I_{abs} and the number of photons (# Photons) of the fifth G-type scenario.

The absorption maxima of *Chlorophyll a* can be found in table 6.34. The highest absorbed intensity can be found in the blue range with about 76 % of the incoming radiation. Here the number of absorbed photons is also higher, but only about 24 %.

λ [nm]	I_0 [W/m ²]	I_{abs} [W/m ²]	# Photons [m ⁻² s ⁻¹]
654.25	136.804	43.736	1.44048×10^{20}
417.75	111.635	85.0435	1.78847×10^{20}

Table 6.34: This table shows the wavelength λ of the two absorption maxima of *Chlorophyll a*, the intensity of the incoming radiation I_0 , the absorbed intensity I_{abs} and the number of photons (# Photons) of the fifth G-type scenario.

Table 6.35 shows the most important data of the *Chlorophyll b* spectrum.

With $294.5 \frac{\mu mol}{m^2 s}$ and $210.6 \frac{\mu mol}{m^2 s}$ both absorbed photon fluxes exceed the light compensation point and photosynthesis gets effective.

λ [nm]	I_0 [W/m ²]	I_{abs} [W/m ²]	# Photons [m ⁻² s ⁻¹]
453	129.681	77.7791	1.77372×10^{20}
643	139.999	39.1852	1.2684×10^{20}

Table 6.35: This table shows the wavelength λ of the two absorption maxima of *Chlorophyll b*, the intensity of the incoming radiation I_0 , the absorbed intensity I_{abs} and the number of photons (# Photons) of the fifth G-type scenario.

Scenario 6

Also in scenario 6 (see figure 6.40), a Venus-like atmosphere with clouds, the spectral energy distribution fits well with the absorption data. In the UV/blue range of the spectra the SED shows no cutoff.

The planet is located in the red zone. This also explains the high measured irradiance. This amounts to 1021.46 W/m^2 at 570 nm.

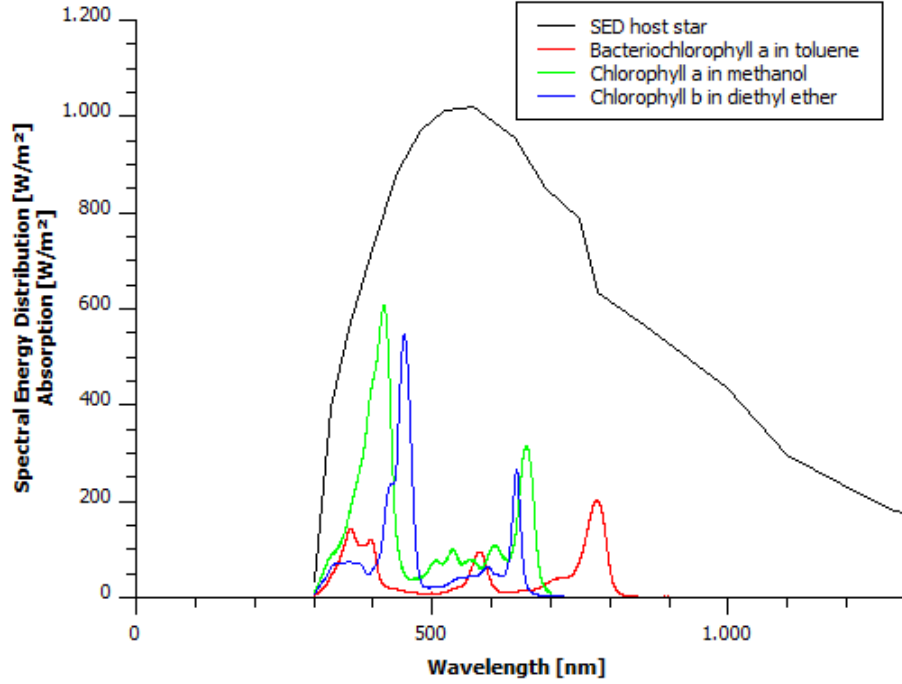


Figure 6.40: Scenario 6, G-star, Venus atmosphere, with clouds, red zone, zoomed in

The absorbed intensity I_{abs} of *Bacteriochlorophyll a* (see table 6.36) in contrast to the received irradiation (I_0) at a maximum of a specific wavelength on the surface of the planet is lowest at 580 nm, like for all scenarios because of the low absorption properties. The highest absorption takes place at 780 nm (32 %). On the basis of the good absorption properties of *Bacteriochlorophyll* in the IR. The least number of absorbed photons per square meter and second is found at 396.4 nm, $2.42 \times 10^{20} \text{ m}^{-2}\text{s}^{-1}$. With a value of $401.2 \frac{\mu\text{mol}}{\text{m}^2\text{s}}$ this value exceeds the needed photosynthetic photon flux by far.

λ [nm]	I_0 [W/m ²]	I_{abs} [W/m ²]	# Photons [m ⁻² s ⁻¹]
780.2	633.397	200.692	7.8824×10^{20}
580.2	1011.68	94.8726	2.77103×10^{20}
396.4	709.713	121.075	2.41609×10^{20}
361.2	562.257	142.776	2.59612×10^{20}

Table 6.36: This table shows the wavelength λ of the four absorption maxima of *Bacteriochlorophyll a*, the intensity of the incoming radiation I_0 , the absorbed intensity I_{abs} and the number of photons (# Photons) of the sixth G-type scenario.

Table 6.37 shows the key data of *Chlorophyll a* in Scenario 6.

The number of photons per square meter and second of the 417.75 nm line converted into the photosynthetic photon flux in mol results in $2071.27 \frac{\mu\text{mol}}{\text{m}^2\text{s}}$, which is the highest PPF of Scenario 6.

Table 6.38 shows the key data of *Chlorophyll b* in Scenario 6.

This pigment also absorbs enough $\frac{\mu\text{mol}}{\text{m}^2\text{s}}$ to provide effective photosynthesis relating to the radiation

λ [nm]	I_0 [W/m ²]	I_{abs} [W/m ²]	# Photons [m ⁻² s ⁻¹]
654.25	924.751	295.642	9.73716×10^{20}
417.75	795.304	605.862	1.27413×10^{21}

Table 6.37: This table shows the wavelength λ of the two absorption maxima of *Chlorophyll a*, the intensity of the incoming radiation I_0 , the absorbed intensity I_{abs} and the number of photons (# Photons) of the sixth G-type scenario.

available.

λ [nm]	I_0 [W/m ²]	I_{abs} [W/m ²]	# Photons [m ⁻² s ⁻¹]
453	911.969	546.973	1.24735×10^{21}
643	948.126	265.377	8.59009×10^{20}

Table 6.38: This table shows the wavelength λ of the two absorption maxima of *Chlorophyll b*, the intensity of the incoming radiation I_0 , the absorbed intensity I_{abs} and the number of photons (# Photons) of the sixth G-type scenario.

Scenario 7

Scenario 7 is the first Titan atmosphere scenario. The SED of the planet was modelled with a Titan-like atmosphere without clouds, see figure 6.41. Here the planet is situated outside the LW zone, farther away from the host star. The maximum of the SED is at about 570 nm with 326.92 W/m^2 . From all investigated planets located outside the LW zone farther away from the host star this model receives the highest irradiance at the surface of the planet.

This is because of the special composition of the atmosphere. The atmosphere is modelled after the Saturn moon Titan which has an high N_2 content. N_2 just absorbs in the UV range of the spectrum at high energy levels. This is not given in the case of G-stars. This leads to less absorption. The run was also calculated without clouds. This leads to reduced reflection and scattering.

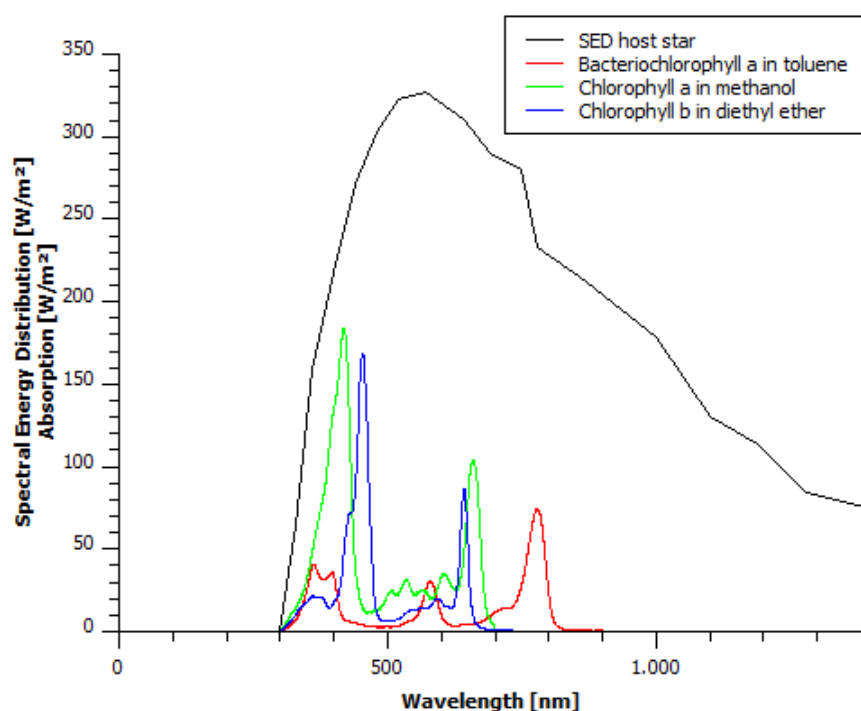


Figure 6.41: Scenario 7, G-star, Titan atmosphere, without clouds, green zone, zoomed in

Table 6.39 shows the four absorption maxima of the *Bacteriochlorophyll* a graph coloured in green in figure 6.41. Although the atmospheric composition is different from the other 6 scenarios, the basic principle is the same as for all of them. The photosynthetic pigments show the same general percentage of absorption of the incoming radiation and the same energy distribution.

This scenario also gives no evidence that it could not be possible for plants to use the remaining radiation, after passing through an Titan-like atmosphere, for photosynthesis.

The lowest absorption of radiation takes place at 580 nm with $\sim 9 \%$ of the incoming radiation. The

lowest number of photons is measured at 396.4 nm. Converted into a PPF it results in $\sim 199 \frac{\mu\text{mol}}{\text{m}^2\text{s}}$, far above the light compensation point of C_3 and C_4 plants.

λ [nm]	I_0 [W/m ²]	I_{abs} [W/m ²]	# Photons [m ⁻² s ⁻¹]
780.2	232.794	73.7607	2.89704×10^{20}
580.2	324.609	30.4409	8.89115×10^{19}
396.4	211.815	36.1352	7.21086×10^{19}
361.2	160.175	40.6736	7.39578×10^{19}

Table 6.39: This table shows the wavelength λ of the four absorption maxima of *Bacteriochlorophyll a*, the intensity of the incoming radiation I_0 , the absorbed intensity I_{abs} and the number of photons (# Photons) of the seventh G-type scenario.

The properties of the maxima of *Chlorophyll a* are listed in detail in table 6.40. Regarding the incoming radiation intensity and the absorbed intensity, at blue wavelengths about 44 % more radiation becomes absorbed. But at the maximum of 417.75 nm there are only 18 % more photons absorbed than at 654.25 nm. Nevertheless at both maxima the PPF exceeds $530 \frac{\mu\text{mol}}{\text{m}^2\text{s}}$ and therefore also the light compensation point.

λ [nm]	I_0 [W/m ²]	I_{abs} [W/m ²]	# Photons [m ⁻² s ⁻¹]
654.25	305.063	97.5282	3.21216×10^{20}
417.75	241.037	183.622	3.86157×10^{20}

Table 6.40: This table shows the wavelength λ of the two absorption maxima of *Chlorophyll a*, the intensity of the incoming radiation I_0 , the absorbed intensity I_{abs} and the number of photons (# Photons) of the seventh G-type scenario.

The properties of the maxima of *Chlorophyll b* are shown in table 6.41.

At the blue maximum there is a higher percentage absorbed than in the red maximum. ~ 60 % at the blue maximum and ~ 28 at the red maxima. Both PPFs exceed the light compensation point.

λ [nm]	I_0 [W/m ²]	I_{abs} [W/m ²]	# Photons [m ⁻² s ⁻¹]
453	281.591	168.891	3.85147×10^{20}
643	309.793	86.7098	2.80674×10^{20}

Table 6.41: This table shows the wavelength λ of the two absorption maxima of *Chlorophyll b*, the intensity of the incoming radiation I_0 , the absorbed intensity I_{abs} and the number of photons (# Photons) of the seventh G-type scenario.

Scenario 8

Scenario 8 is the second Titan atmosphere scenario. The run was modelled with a Titan-like atmosphere without clouds, see figure 6.42. Here the planet is situated in the red zone. The maximum of the SED is at about 640 nm with 2056.21 W/m^2 . From all runs this is the only one where the maximum is located at 640 nm and not at 570 nm. With 2056.21 W/m^2 this scenario exhibits the highest incoming radiation of all G-type star scenarios.

This is not only due to the close distance to the host star but also because of the special composition of the atmosphere. The main atmospheric component N_2 just absorbs in the UV range

of the spectrum at high energy levels. This leads to less absorption. The run was also calculated without clouds which decreases reflection and scattering.

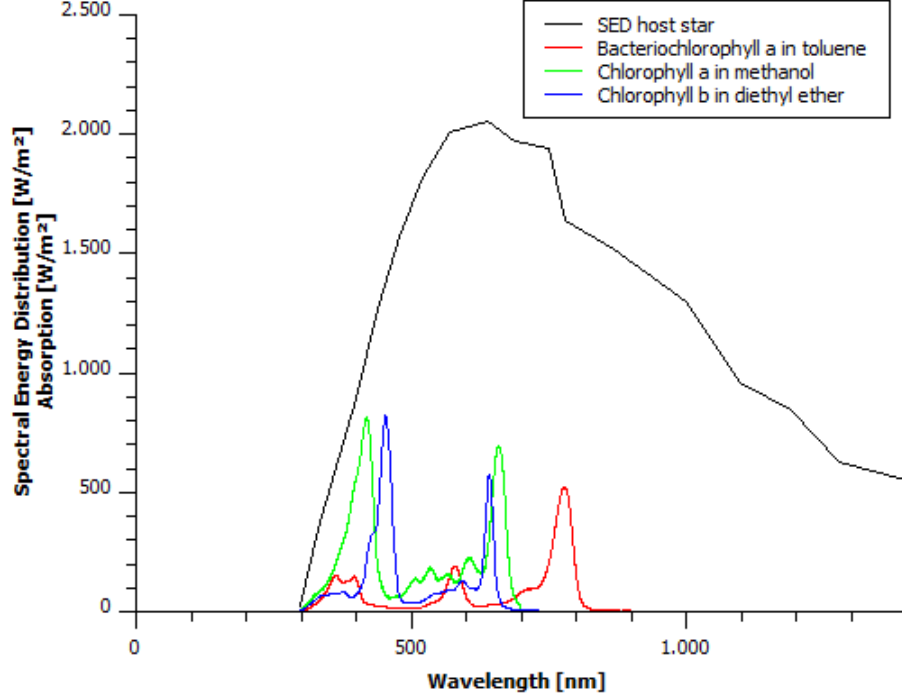


Figure 6.42: Scenario 8, G-star, Titan atmosphere, without clouds, red zone, zoomed in

Table 6.42 shows the four absorption maxima of *Bacteriochlorophyll a*.

This scenario also shows no evidence that it could not be possible for plants to use the remaining radiation for photosynthesis after passing through an Titan-like atmosphere. But it is possible that due to the high PPF the light saturation point is exceeded. This would lead to another limiting factor than light, like e.g. water.

The lowest absorption takes place at 580.2 nm with $\sim 9\%$ of the incoming radiation. The lowest number of photons is measured at 361.2 nm. Converted into a PPF it results in $\sim 451 \frac{\mu\text{mol}}{\text{m}^2\text{s}}$.

λ [nm]	I_0 [W/m ²]	I_{abs} [W/m ²]	# Photons [m ⁻² s ⁻¹]
780.2	1638.95	519.301	2.03962×10^{21}
580.2	2014.65	188.928	5.51821×10^{20}
396.4	866.423	147.81	2.94958×10^{20}
361.2	588.46	149.429	2.71711×10^{20}

Table 6.42: This table shows the wavelength λ of the four absorption maxima of *Bacteriochlorophyll a*, the intensity of the incoming radiation I_0 , the absorbed intensity I_{abs} and the number of photons (# Photons) of the eighth G-type scenario.

The properties of the maxima of *Chlorophyll a* are illustrated in table 6.43 and the properties of the maxima of *Chlorophyll b* are illustrated in table 6.44. Both pigments show a high absorbed number of photons that exceed the light compensation point by far.

Chlorophyll a shows the highest absorption of photons at 654.25 nm with $2.1407 \times 10^{21} \text{ m}^{-2} \text{ s}^{-1}$ and the lowest at 417.75 nm with $1.69875 \times 10^{21} \text{ m}^{-2} \text{ s}^{-1}$. Converted into PPF this produces $3554.21 \frac{\mu\text{mol}}{\text{m}^2\text{s}}$ and $2819.6 \frac{\mu\text{mol}}{\text{m}^2\text{s}}$. Both fluxes are high enough to cover the light compensation point and are probably high enough to exceed the light saturation point.

λ [nm]	I_0 [W/m ²]	I_{abs} [W/m ²]	# Photons [m ⁻² s ⁻¹]
654.25	2033.05	649.963	2.1407×10^{21}
417.75	1060.35	807.774	1.69875×10^{21}

Table 6.43: This table shows the wavelength λ of the two absorption maxima of *Chlorophyll a*, the intensity of the incoming radiation I_0 , the absorbed intensity I_{abs} and the number of photons (# Photons) of the eighth G-type scenario.

λ [nm]	I_0 [W/m ²]	I_{abs} [W/m ²]	# Photons [m ⁻² s ⁻¹]
453	1367.26	820.041	1.87007×10^{21}
643	2051.33	574.16	1.85852×10^{21}

Table 6.44: This table shows the wavelength λ of the two absorption maxima of *Chlorophyll b*, the intensity of the incoming radiation I_0 , the absorbed intensity I_{abs} and the number of photons (# Photons) of the eighth G-type scenario.

6.4.2 M-Star

Scenario 1

The first scenario, given in figure 6.43, shows the results of the SED (black) plotted together with the absorption spectra of *Bacteriochlorophyll a* (red), *Chlorophyll a* (green) and *Chlorophyll b* (blue). As one can easily see from figure 6.43 the outcome from the M-star Streamer models are different from the G-type star scenarios due to their different spectral energy distribution. This has great impact of the absorption spectra of the photosynthetic pigments because the absorption term ε depends on the incoming radiation (I_0) at the required wavelength.

Scenario 1 deals with an Earth-like atmosphere with clouds. The planet is located in the middle of the LW zone at 0.1615 AU. This is a very short distance to a star but in the case of M-stars the emitted flux is very low, which means that the LW zone is shifted closer to the host star to obtain a moderate surface temperature. This is the case for all 5 M-star scenarios and would lead in most instances to tidal locking or a resonance of the orbital period with the rotation period.

Rotationally bound planets have advantages and disadvantages for habitability and photosynthesis. It is supposed that it is not possible for tidally locked planets to keep an atmosphere, see chapter 2.2.4. But there were also simulations done that suppose that the formation and preservation of atmospheres of tidally locked planets could be possible, see chapter 3.4.

An advantage could be the fact that one side of the planet always is exposed to the host star. This means that one side receives no photons and therefore on this side it would not be possible for plants to grow and live. But on the other side, where it is always 'day' more photons are incoming because this side would never, or seldomly, be in the dark. This increases the amount of incoming photons and could lead to a high enough photosynthetic photon flux to exceed the light compensation point.

One fact that was visible in the Planck-spectra of Gliese 581 and is also visible in the simulated scenarios is that the maximal intensity is shifted from the optical range into the IR range of the spectrum. This applies for all scenarios and also for all further scenarios that were calculated with different M-stars than AD Leonis. This is a general property of this category of stars. Only the maximum could be shifted a few nanometres towards the optical red range for the upper mass limit of M-stars or forward into the IR range for the lower mass limit. Therefore the UV- and blue range of the spectrum is scarcely or not at all available. This is the greatest disadvantage of M-stars as host stars for planets that host green plants and phototroph bacteria as we know them from Earth.

This fact is clearly visible in figure 6.43.

The diagram shows a lack of blue radiation. Between 300 nm and 480 nm (edge of the blue range) approximately 0 to 10 W/m² are reaching the surface. Taking into consideration the fact that the photosynthetic pigments also just absorb a certain percentage of the incoming radiation the absorbed photon flux and therefore the PPF will be very low.

The maximum intensity in this scenario is reached at 1100 nm, clearly in the near IR. The highest received radiation at this wavelength is 184.94 W/m^2 . Even when the planet is located in the middle of the LW zone the received flux is very low compared to the fluxes in the G-type star scenarios.

But the LW zone in the Earth-like atmosphere models is also very narrow due to the fact that the inner borders of scenario 1 and 2 only could be calculated until the surface temperature reached $\sim 300 \text{ K}$ and not $\sim 373 \text{ K}$. If the planet was shifted closer to the star than 0.154 AU the runaway greenhouse effect would start taking over and the used modified Streamer code would run in an endless loop.

The modelled SED shows strong absorption lines between 1000 nm and 2000 nm (NIR). They can be explained by the high humidity of the atmosphere. However, the absorption lines do not effect the absorption spectra of the photosynthetic pigments. The absorption properties of the pigments are the same as for the other scenarios. They absorb the same percentage of incoming radiation. But in the M-star scenarios this could lead to problems because the incoming radiation (I_0) for the shorter wavelengths, which is needed for the calculations of the absorbed intensity, is minimal. Therefore absorbed intensity and the number of photons received per square meter and second is always smaller in the blue range of the spectra than in the red and IR range.

Looking closer at figure 6.43 it is also visible that the double peak of *Bacteriochlorophyll a* is no longer visible. The peaks of *Chlorophyll a* at 417.75 nm and *Chlorophyll b* at 453 nm are hardly visible but still apparent.

The peaks of all three pigments look higher in the red range of the spectrum, but this is a optical illusion. The absorption here has the same percentage amount than in the 8 G-type star scenarios before. But the incoming radiation has its maximum at red and IR wavelengths.

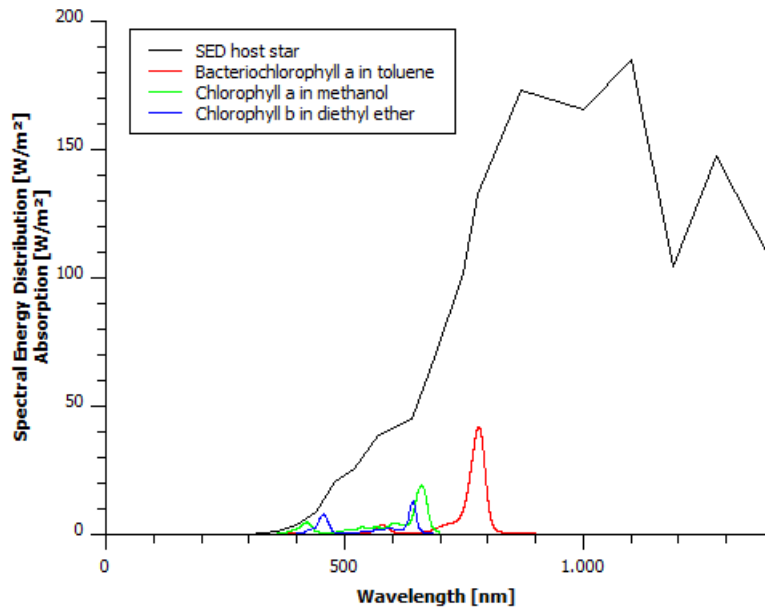


Figure 6.43: Scenario 1, M-star, Earth atmosphere, with clouds, zoomed in

Table 6.45 shows the maximum wavelength of the absorption spectrum of *Bacteriochlorophyll a* as well as the intensity of the incoming radiation, the absorbed intensity and the number of photons.

General absorbing properties of *Bacteriochlorophyll*:

780.2 nm $\rightarrow \sim 32$ % of the incoming radiation will be absorbed

580.2 nm $\rightarrow \sim 9$ % of the incoming radiation will be absorbed

396.4 nm $\rightarrow \sim 17$ % of the incoming radiation will be absorbed

361.2 nm $\rightarrow \sim 25$ % of the incoming radiation will be absorbed.

At 361.2 nm 25 % of the incoming radiation will be absorbed but that are only 0.278 W/m² and therefore 5.061×10^{17} photons m⁻²s⁻¹. This leads to a PPF of only $0.84 \frac{\mu\text{mol}}{\text{m}^2\text{s}}$. For C₃ plants the light compensation point lies at 8 - 16 $\frac{\mu\text{mol}}{\text{m}^2\text{s}}$ and for C₄ plants at 6 - 14 $\frac{\mu\text{mol}}{\text{m}^2\text{s}}$ [Nobel, 2009]. Shade plants generally have a lower light compensation point [Nobel, 2009]. But none of them will be reached with $0.84 \frac{\mu\text{mol}}{\text{m}^2\text{s}}$.

However the antenna system, responsible for the collection of photons, is always described as a funnel. This leads to the assumption that the energy of photons, once captured, can never be lost again. As a result light would be the limiting factor. As explained in chapter 4.2.2 the light compensation point with regard to CO₂ describes a balance of the amount of CO₂ fixed for photosynthesis and the amount of CO₂ exhaled during the respiration [Smith et al., 1976].

If this point is not be reached, which means that the illuminance is to low, the plants will die.

At 396.4 nm there are more photons available. The amount of the number of photons per square meter and second is $1.88 \frac{\mu\text{mol}}{\text{m}^2\text{s}}$. Here the light compensation point is also not exceeded. But at 580.2 nm and above the spectral energy distribution of this scenario rises. Here one comes into a range were M-stars, in this case AD Leonis, emit greater amounts of radiation. The PPF at 580.2 nm amounts $18 \frac{\mu\text{mol}}{\text{m}^2\text{s}}$ and at 780.2 nm $274.5 \frac{\mu\text{mol}}{\text{m}^2\text{s}}$. Both values exceed the light compensation point and show that enough radiation is available in the red range of the spectra.

As expected not enough photons are available in the blue range of the spectrum for *Bacteriochlorophyll a*.

λ [nm]	I_0 [W/m ²]	I_{abs} [W/m ²]	# Photons [m ⁻² s ⁻¹]
780.2	132.85	42.0935	1.65327×10^{20}
580.2	39.6458	3.71787	1.08591×10^{19}
396.4	3.33972	0.569749	1.13695×10^{18}
361.2	1.096	0.278311	5.06059×10^{17}

Table 6.45: This table shows the the wavelength λ of the four absorption maxima of *Bacteriochlorophyll a*, the intensity of the incoming radiation I_0 , the absorbed intensity I_{abs} and the number of photons (# Photons) of the first M-type scenario.

As expected *Chlorophyll a*, see table 6.46, shows less absorbed photons at shorter wavelengths. At 417.47 nm the PPF values are $\sim 16 \frac{\mu\text{mol}}{\text{m}^2\text{s}}$. This value nearly covers the light compensation point. Therefore the point is also exceeded at 654 nm with $\sim 91 \frac{\mu\text{mol}}{\text{m}^2\text{s}}$.

λ [nm]	I_0 [W/m ²]	I_{abs} [W/m ²]	# Photons [m ⁻² s ⁻¹]
654.25	52.1666	16.6776	5.49288×10^{19}
417.75	5.98545	4.55972	9.58909×10^{18}

Table 6.46: This table shows the the wavelength λ of the four absorption maxima of *Chlorophyll a*, the intensity of the incoming radiation I_0 , the absorbed intensity I_{abs} and the number of photons (# Photons) of the first M-type scenario.

Table 6.47 presents the most important properties of the absorption maxima of the *Chlorophyll b* absorption spectrum. At 453 nm a larger absorption of radiation takes place but the number of absorbed photons is lower than at 643 nm because of the lack of radiation in the blue range of the spectrum.

At both maxima the light compensation point is exceeded ($453 \text{ nm} \rightarrow \sim 29 \frac{\mu\text{mol}}{\text{m}^2\text{s}}$, $643 \text{ nm} \rightarrow \sim 70 \frac{\mu\text{mol}}{\text{m}^2\text{s}}$).

λ [nm]	I_0 [W/m ²]	I_{abs} [W/m ²]	# Photons [m ⁻² s ⁻¹]
453	12.7103	7.62328	1.73846×10^{19}
643	46.264	12.9491	4.19155×10^{19}

Table 6.47: This table shows the wavelength λ of the four absorption maxima of *Chlorophyll b*, the intensity of the incoming radiation I_0 , the absorbed intensity I_{abs} and the number of photons (# Photons) of the first M-type scenario.

Scenario 2

Scenario 2, figure 6.44, is similar to scenario 1 and shows the same general properties in the shape of the diagram. This run deals also with a planet with an Earth-like atmosphere that is located at the same distance to the host star than in the first scenario. The difference here is that the atmosphere was modelled without clouds. This leads to a higher maximum intensity at 1100 nm. 228.347 W/m² were measured.

The lack of 'blue' radiation in these simulation is also clearly visible. The difference between the incoming radiation between 300 nm and 480 nm between scenario 1 and scenario 2 is insignificantly small, about 3.4 W/m² (480 nm) to 1.5×10^{-5} W/m² (300 nm).

The double peak of *Bacteriochlorophyll a* is not visible. The peaks of *Chlorophyll a* at 417.75 nm and *Chlorophyll b* at 453 nm are hardly visible but still apparent due to their good absorption abilities. In the red wavelength range are also more photons available than in the blue range which has an impact on the PPF and therefore on the photosynthetic ability.

Among other things table 6.48 exhibits the number of photons absorbed by *Bacteriochlorophyll a*. Because of the low absorption ability of *Bacteriochlorophyll a* the single PPFs of the single absorption maximum will be listed below:

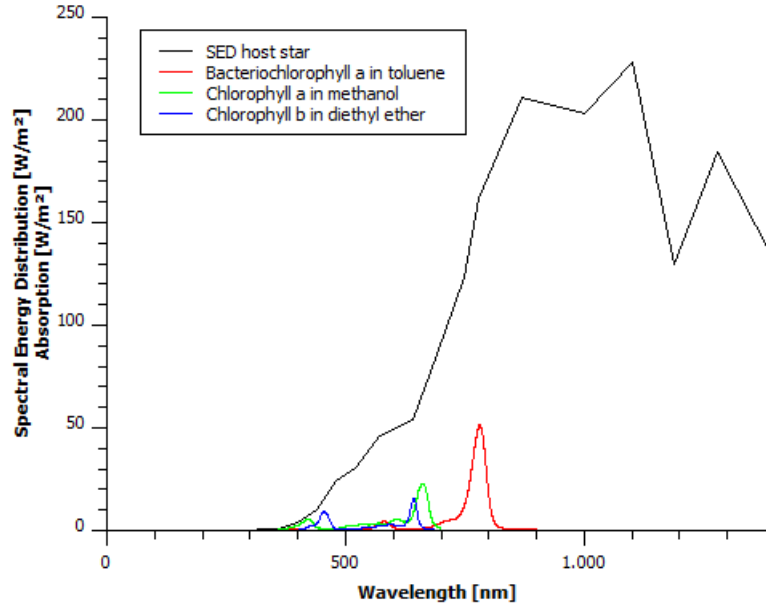


Figure 6.44: Scenario 2, M-star, Earth atmosphere, without clouds, zoomed in

$$\begin{aligned}
 780.2 \text{ nm} &\rightarrow \sim 334 \frac{\mu\text{mol}}{\text{m}^2\text{s}} \\
 580.2 \text{ nm} &\rightarrow \sim 21.5 \frac{\mu\text{mol}}{\text{m}^2\text{s}} \\
 396.4 \text{ nm} &\rightarrow \sim 2.2 \frac{\mu\text{mol}}{\text{m}^2\text{s}} \\
 361.2 \text{ nm} &\rightarrow \sim 0.95 \frac{\mu\text{mol}}{\text{m}^2\text{s}}
 \end{aligned}$$

As in scenario 1 the light compensation points at 361.2 nm and 396.4 nm have not been achieved. If changing to longer wavelengths the photon rate starts to increase and the limit will be overstepped.

λ [nm]	I_0 [W/m ²]	I_{abs} [W/m ²]	# Photons [m ⁻² s ⁻¹]
780.2	161.641	51.2159	2.01156×10^{20}
580.2	47.3342	4.43886	1.2965×10^{19}
396.4	3.82459	0.652466	1.30201×10^{18}
361.2	1.23732	0.314197	5.71311×10^{17}

Table 6.48: This table shows the wavelength λ of the four absorption maxima of *Bacteriochlorophyll a*, the intensity of the incoming radiation I_0 , the absorbed intensity I_{abs} and the number of photons (# Photons) of the second M-type scenario.

Since the oxygenic photosynthetic pigments show better absorption abilities it seems to be easier for plants-as-we-know-them to exceed the light compensation point even at lower wavelengths. Table 6.49 declares the most important informations about the *Chlorophyll a* absorption spectrum.

Most of the radiation gets absorbed in the blue range but premiere fact that only a few photons are available the number of absorbed photons in the red range go beyond the number of photons ab-

sorbed in the blue range. However with $18.4 \frac{\mu\text{mol}}{\text{m}^2\text{s}}$ at 417.75 nm the LC point will be barely exceeded and with ~ 110 by fare at 654.25 nm.

λ [nm]	I_0 [W/m ²]	I_{abs} [W/m ²]	# Photons [m ⁻² s ⁻¹]
654.25	62.7604	20.0644	6.60835×10^{19}
417.75	6.91799	5.27012	1.10831×10^{19}

Table 6.49: This table shows the wavelength λ of the absorption maxima of *Chlorophyll a*, the intensity of the incoming radiation I_0 , the absorbed intensity I_{abs} and the number of photons (# Photons) of the second M-type scenario.

Table 6.50 shows the absorption maxima of the *Chlorophyll b* absorption spectra.

The *Chlorophyll b* absorption spectrum shows a similar shape to *Chlorophyll a* with the difference that the maxima are lower and are shifted closer together. Therefore the photosynthetic photon flux at 453 nm is $33.7 \frac{\mu\text{mol}}{\text{m}^2\text{s}}$ and for $83.6 \frac{\mu\text{mol}}{\text{m}^2\text{s}}$ at 643 nm.

λ [nm]	I_0 [W/m ²]	I_{abs} [W/m ²]	# Photons [m ⁻² s ⁻¹]
453	14.8421	8.9019	2.03004×10^{19}
643	55.5619	15.5516	5.03394×10^{19}

Table 6.50: This table shows the wavelength λ of the absorption maxima of *Chlorophyll b*, the intensity of the incoming radiation I_0 , the absorbed intensity I_{abs} and the number of photons (# Photons) of the second M-type scenario.

Scenario 3

Scenario 3 describes a planet with Venus-like atmosphere with clouds, see figure 6.45. The planet is located in the center of the LW zone at 0.11.

In the area of absorption no significant absorption lines are visible, but at 1640 nm the received power falls off significantly to 2.52×10^{-19} W/m², close to zero.

The maximal received intensities are 201.33 W/m² at 1100 nm. This is the first big difference to the first two Earth-like atmosphere scenarios where the peak was situated around 1000 nm.

Looking closer to between 900 nm and 1100 nm there is a drop at about 1000 nm visible followed by rising of the SED until it drops again at 1100 nm. This can be caused by the high water content of the Earth-like atmosphere and the lower CO₂ content.

The absorption maxima data of *Bacteriochlorophyll a* (see table 6.51) show no major differences between the Earth-like atmosphere and the Venus-like atmosphere without clouds. The values of Scenario 1, Earth-like atmosphere with clouds show slightly smaller values.

Comparable with the first two scenarios the blue range of the spectrum in scenario 3 offers also not enough photons to exceed the LC point: at 361.2 nm $\rightarrow 1.07 \frac{\mu\text{mol}}{\text{m}^2\text{s}}$ and at 396.4 nm $\rightarrow 2.32 \frac{\mu\text{mol}}{\text{m}^2\text{s}}$.

In the red range at both maxima the LC point is exceeded: at 580.2 nm $\rightarrow 22 \frac{\mu\text{mol}}{\text{m}^2\text{s}}$ and at 780.2 nm $\rightarrow 378 \frac{\mu\text{mol}}{\text{m}^2\text{s}}$.

Table 6.52 declares the most important informations about the *Chlorophyll a* absorption spectrum.

With $19.5 \frac{\mu\text{mol}}{\text{m}^2\text{s}}$ at 417.75 nm the LC point will be barely exceeded but with $\sim 109.8 \frac{\mu\text{mol}}{\text{m}^2\text{s}}$ at 654.25 nm the limit will be surpassed far enough.

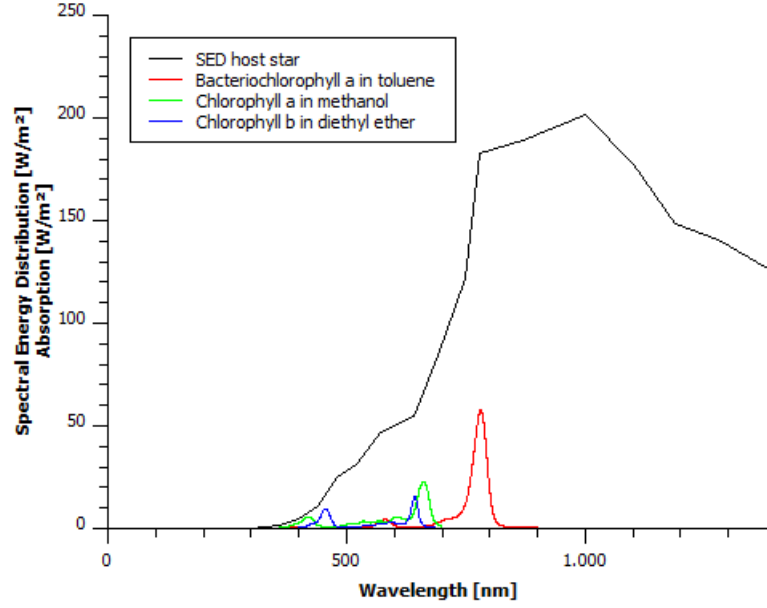


Figure 6.45: Scenario 3, M-star, Venus atmosphere, with clouds, zoomed in

λ [nm]	I_0 [W/m ²]	I_{abs} [W/m ²]	# Photons [m ⁻² s ⁻¹]
780.2	182.751	57.9045	2.27427×10^{20}
580.2	48.1921	4.51932	1.32×10^{19}
396.4	4.10742	0.700716	1.3983×10^{18}
361.2	1.37954	0.350311	6.36979×10^{17}

Table 6.51: This table shows the wavelength λ of the four absorption maxima of *Bacteriochlorophyll a*, the intensity of the incoming radiation I_0 , the absorbed intensity I_{abs} and the number of photons (# Photons) of the third M-type scenario.

λ [nm]	I_0 [W/m ²]	I_{abs} [W/m ²]	# Photons [m ⁻² s ⁻¹]
654.25	62.817	20.0825	6.61431×10^{19}
417.75	7.33269	5.58605	1.17475×10^{19}

Table 6.52: This table shows the wavelength λ of the absorption maxima of *Chlorophyll a*, the intensity of the incoming radiation I_0 , the absorbed intensity I_{abs} and the number of photons (# Photons) of the third M-type scenario.

Table 6.53 shows the most important information of the *Chlorophyll b* absorption spectra.

The number of received photons per square meter and second converted into the PPF results in: $35.2 \frac{\mu\text{mol}}{\text{m}^2\text{s}}$ at 453 nm and $84.4 \frac{\mu\text{mol}}{\text{m}^2\text{s}}$ at 643 nm.

These values show the same order of magnitude as the PPF of *Chlorophyll b* in the Earth-like models.

Scenario 4

Figure 6.46 is similar to scenario 3. A planet with a Venus-like atmosphere (without clouds) is situated in the center of the LW zone. The planet is situated at 0.157 AU. The main reason for this is the lack of clouds. The planet can not be shifted farther inside without clouds because it is getting

λ [nm]	I_0 [W/m ²]	I_{abs} [W/m ²]	# Photons [m ⁻² s ⁻¹]
453	15.5137	9.30467	2.12189×10^{19}
643	56.1321	15.7112	5.08561×10^{19}

Table 6.53: This table shows the wavelength λ of the absorption maxima of *Chlorophyll b*, the intensity of the incoming radiation I_0 , the absorbed intensity I_{abs} and the number of photons (# Photons) of the third M-type scenario.

too hot too fast on its surface.

Looking at the general properties of the diagram it is visible that the maximum intensity is also located around 1000 nm but the intensity received itself at this wavelength with 258.21 nm is higher compared to the Venus-like scenario with clouds.

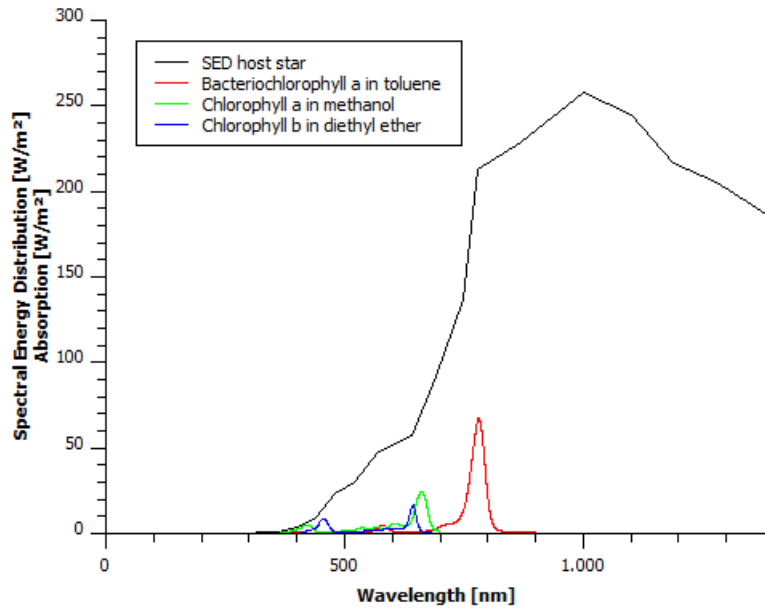


Figure 6.46: Scenario 4, M-star, Venus atmosphere, without clouds, zoomed in

The four absorption maxima, their intensities and number of photons per square meter and second of *Bacteriochlorophyll a* are displayed in table 6.51.

The maximum absorption at blue wavelengths hardly offers photons for photosynthesis. With $0.82 \frac{\mu\text{mol}}{\text{m}^2\text{s}}$ (361.2 nm) and $1.92 \frac{\mu\text{mol}}{\text{m}^2\text{s}}$ (396.4 nm) the number of photons is not even enough to exceed the LC point of shade plants. But at 580.2 nm ($22.2 \frac{\mu\text{mol}}{\text{m}^2\text{s}}$) and 780.2 nm ($440 \frac{\mu\text{mol}}{\text{m}^2\text{s}}$) enough photons are available to keep the plants alive.

λ [nm]	I_0 [W/m ²]	I_{abs} [W/m ²]	# Photons [m ⁻² s ⁻¹]
780.2	212.834	67.4364	2.64864×10^{20}
580.2	48.737	4.57041	1.33492×10^{19}
396.4	3.39878	0.579825	1.15705×10^{18}
361.2	1.06516	0.27048	4.9182×10^{17}

Table 6.54: This table shows the wavelength λ of the four absorption maxima of *Bacteriochlorophyll a*, the intensity of the incoming radiation I_0 , the absorbed intensity I_{abs} and the number of photons (# Photons) of the fourth M-type scenario.

Table 6.55 shows the absorption maxima of *Chlorophyll a*

With $16.8 \frac{\mu\text{mol}}{\text{m}^2\text{s}}$ at 417.75 nm the LC point will be barely exceeded. The absorption maximum in the red range shows a larger absorption of photons with $116.7 \frac{\mu\text{mol}}{\text{m}^2\text{s}}$.

λ [nm]	I_0 [W/m ²]	I_{abs} [W/m ²]	# Photons [m ⁻² s ⁻¹]
654.25	66.7245	21.3317	7.02575×10^{19}
417.75	6.33637	4.82705	1.01513×10^{19}

Table 6.55: This table shows the wavelength λ of the two absorption maxima of *Chlorophyll a*, the intensity of the incoming radiation I_0 , the absorbed intensity I_{abs} and the number of photons (# Photons) of the fourth M-type scenario.

The maxima of *Chlorophyll b*, see table 6.56, show both that the LC point will be passed.

$$453 \text{ nm} \rightarrow \sim 31.9 \frac{\mu\text{mol}}{\text{m}^2\text{s}}$$

$$643 \text{ nm} \rightarrow \sim 88.7 \frac{\mu\text{mol}}{\text{m}^2\text{s}}$$

λ [nm]	I_0 [W/m ²]	I_{abs} [W/m ²]	# Photons [m ⁻² s ⁻¹]
453	14.0343	8.41735	1.91954×10^{19}
643	58.9527	16.5006	5.34115×10^{19}

Table 6.56: This table shows the wavelength λ of the two absorption maxima of *Chlorophyll b*, the intensity of the incoming radiation I_0 , the absorbed intensity I_{abs} and the number of photons (# Photons) of the fourth M-type scenario.

Scenario 5

The last scenario modelled with the modified Streamer code was a M-star scenario with a Titan-like atmosphere without clouds. The planet is also located in the center of the LW zone at 0.115 AU.

The SED shows no prominent absorption lines and the maximum intensity of 489,75 W/m² was measured at 1000 nm. This is the highest intensity of all five M-star runs.

The transmission of the Titan-like atmosphere in this case is an advantage for plants. The radiant flux received at 300 nm is just about 0.213 W/m², and increases to 46.90 W/m² at 480 nm. This is approximately twice as much as in the other four M-type star scenarios, where the flux at 480 nm only amount between 20 W/m² and 25 W/m².

The absorption spectrum of the photosynthetic pigments shows the same general shape like in run 1 to 4 and also like in the G-type star scenarios with the difference that the incoming intensity up to the 650 nm line is very weak so that the blue peaks are hardly present and the red peaks of *Chlorophyll a* and *Chlorophyll b* seem to be weaker than the red peak of *Bacteriochlorophyll a*.

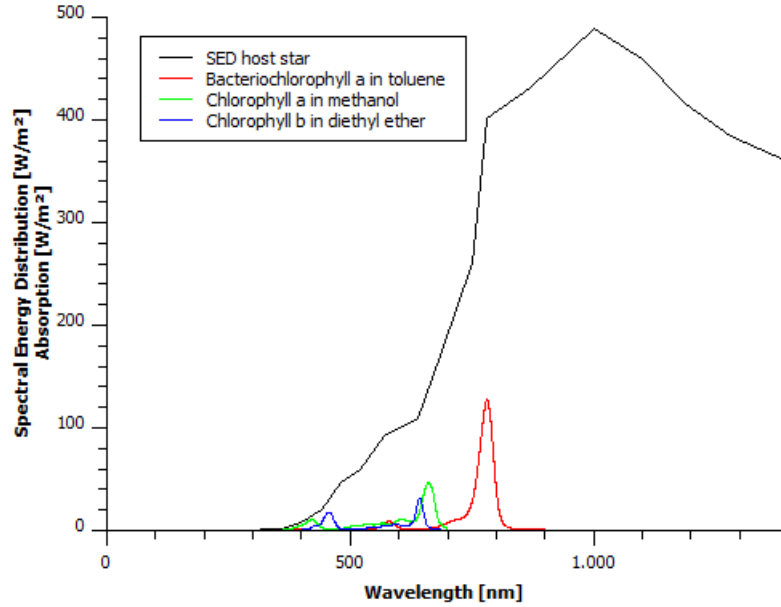


Figure 6.47: Scenario 5, M-star, Titan atmosphere, without clouds, zoomed in

Table 6.57 shows the absorption data of the maxima of *Bacteriochlorophyll a*.

Converted into a PPF the maxima show the following properties:

$$\begin{aligned}
 780.2 \text{ nm} &\rightarrow \sim 831.12 \frac{\mu\text{mol}}{\text{m}^2\text{s}} \\
 580.2 \text{ nm} &\rightarrow \sim 43.34 \frac{\mu\text{mol}}{\text{m}^2\text{s}} \\
 396.4 \text{ nm} &\rightarrow \sim 4.21 \frac{\mu\text{mol}}{\text{m}^2\text{s}} \\
 361.2 \text{ nm} &\rightarrow \sim 1.86 \frac{\mu\text{mol}}{\text{m}^2\text{s}}
 \end{aligned}$$

This means that in the blue range the LC point is not exceeded although the Titan-like atmosphere is very transparent. But in the red range of the spectra the maxima show a twice as high absorption than in the models. Going to longer wavelengths the LC point is passed by the received photons at 580.2 nm and 780.2 nm.

λ [nm]	I_0 [W/m ²]	I_{abs} [W/m ²]	# Photons [m ⁻² s ⁻¹]
780.2	402.191	127.434	5.00512×10^{20}
580.2	95.2857	8.93562	2.60991×10^{19}
396.4	7.44126	1.26946	2.53324×10^{18}
361.2	2.42345	0.615394	1.11898×10^{18}

Table 6.57: This table shows the wavelength λ of the four absorption maxima of *Bacteriochlorophyll a*, the intensity of the incoming radiation I_0 , the absorbed intensity I_{abs} and the number of photons (# Photons) of the fifth M-type scenario.

Table 6.58 shows the absorption data of the maxima of *Bacteriochlorophyll a*. With $224.44 \frac{\mu\text{mol}}{\text{m}^2\text{s}}$ at 654.25 nm and $35.8 \frac{\mu\text{mol}}{\text{m}^2\text{s}}$ at 417.75 nm both maxima obtain enough photons to pass the LC point.

λ [nm]	I_0 [W/m ²]	I_{abs} [W/m ²]	# Photons [m ⁻² s ⁻¹]
654.25	128.24	40.9982	1.35031×10^{20}
417.75	13.4883	10.2754	2.16092×10^{19}

Table 6.58: This table shows the wavelength λ of the two absorption maxima of *Chlorophyll a*, the intensity of the incoming radiation I_0 , the absorbed intensity I_{abs} and the number of photons (# Photons) of the fifth M-type scenario

The properties of the absorption maxima of *Chlorophyll b* are pointed in table 6.59.

The converted number of photons per square meter and second at the two absorption maxima of *Chlorophyll b* at 453 nm yield to $65.94 \frac{\mu\text{mol}}{\text{m}^2\text{s}}$ and at 643 nm to $170.99 \frac{\mu\text{mol}}{\text{m}^2\text{s}}$. At both maxima the PPF overstep the LC point.

λ [nm]	I_0 [W/m ²]	I_{abs} [W/m ²]	# Photons [m ⁻² s ⁻¹]
453	29.0309	17.4119	3.9707×10^{19}
643	113.658	31.8125	1.02975×10^{20}

Table 6.59: This table shows the wavelength λ of the two absorption maxima of *Chlorophyll b*, the intensity of the incoming radiation I_0 , the absorbed intensity I_{abs} and the number of photons (# Photons) of the fifth M-type scenario.

7 Discussion

Thirteen scenarios were modelled with the modified radiation transfer code Streamer.

The following assumptions were made:

- Each planet has an atmosphere. Chosen were an Earth-like atmosphere with or without clouds, a Venus-like atmosphere with or without clouds and a Titan-like atmosphere without clouds. The Titan runs were not done with clouds because no humidity is assumed in the atmosphere.
- The planets have circular orbits so that they stay in the LW zone or outside, but do not cross into or out of the LW zone. The liquid water zone was defined here as the area around the host star where water can be fluid on the planet's surface, which means that the surface temperature has to be approximately between 273 K and 373 K.
- All planets are 'Earth-like', which means that they are terrestrial and experience a gravitational acceleration of 1 g.

Discussion G-Type Stars

The 2 Earth-like runs, the 4 different Venus scenarios, and the 2 Titan-like models show no evidence that contradicts the theory that leftover radiation after passage through the atmosphere could be used for photosynthesis. In all eight G-type star scenarios, enough radiation in the blue and the red range of the spectrum was left after passing through the atmosphere. The existence of clouds only influenced the amount of radiation that reached the surface of the planet. The clouds also shifted the borders of the LW zone because they have a cooling effect.

Comparable are the Venus runs:

The LW zone for the 'Venus with clouds' simulation shows a width of 0.495 AU. Calculated without clouds, the width amounts 0.585 AU.

No significant absorption lines were measured that could influence the absorption spectra of the photosynthetic pigments.

The distance of the planet to its host star changes the amount of incoming photons on the surface. An increase is observable in the red zone and a decrease in the green zone.

The photosynthetic photon fluxes are immensely high for both of the Titan-like runs. The atmosphere is composed largely of N_2 , which does not show absorption properties in the wavelength ranges emitted by G-type stars. This means that a great amount of radiation passes unhindered through the atmosphere. The Venus- and Earth-like atmospheres show absorption lines according to their atmospheric compositions.

The lowest measured photosynthetic photon flux is given in scenario 5 (Venus-like atmosphere with

clouds, green zone). Here, the absorption spectrum of *Bacteriochlorophyll a* shows only 3.18466×10^{19} absorbed photons per square meter and second at 396.4 nm. But, even here, the light compensation point is exceeded because the conversion leads to $\sim 53 \frac{\mu\text{mol}}{\text{m}^2\text{s}}$.

In scenario 8, the highest PPF for all G-type star models is measured at 654.25 nm. 2.1407×10^{21} photons $\text{m}^{-2} \text{s}^{-1}$ yield $3554.21 \frac{\mu\text{mol}}{\text{m}^2\text{s}}$.

There is no value found in the literature for the light saturation point of photosynthesis, but it could be possible that this point will be exceeded in this scenario. The only disadvantage of exceeding the light saturation point is that other factors, like water on the surface or the CO_2 content of the atmosphere, could become the limiting factor of photosynthesis.

In summary, the LCP of the photosynthetic pigments was exceeded for all G-type scenarios. Compared with the received PPF of the present-day Earth (see chapter 5.3.1), the planets located in the green zone show less PPF and in the red zone far more for every absorption maximum.

Discussion M-type stars

The general opinion was that it is not possible for plants (as we know them on Earth) to conduct photosynthesis with radiation from M stars. This opinion was based on the fact that the radiation shows a deficiency in the blue range of the spectral energy distribution.

The five runs were modelled with different atmospheres. The test planet is always located in the center of the LW zone. The first four scenarios are comparable to each other.

The first and the third runs were modelled with an Earth-like atmosphere and a Venus-like atmosphere, respectively, and clouds. The SEDs show similar maxima at 1100 nm with 184.94 W/m^2 and 177.39 W/m^2 . The most obvious difference between these two runs, and also for the Earth- and Venus-like run without clouds, is the presence of strong absorption lines in the Earth-like scenario SEDs.

Scenario 1, Earth-like atmosphere with clouds: at 1190 nm a drop to $\sim 104 \text{ W/m}^2$ and at 1530 nm to 57.9 W/m^2

Scenario 2, Earth-like atmosphere without clouds: at 1190 nm a drop to 129.57 W/m^2 and at 1530 nm to 72.95 W/m^2

Both drops in both runs are at wavelengths far longer than the PAR.

Scenarios 3 and 4, Venus-like atmosphere with and without clouds, show a significant drop in intensity at 1620 nm, where the received energy is close to zero W/m^2 . This drop is also not important for the photosynthetic pigments. Scenario 5, Titan-like atmosphere without clouds, shows no significant absorption lines.

Earth-like atmospheres show the typical broad absorption bands of H_2O and O_2 , where one of these at $\sim 780 \text{ nm}$ decreases the number of absorbed photons for *Bacteriochlorophyll a*. The Venus-like atmospheres exhibit only weak absorption in general but one extreme absorption band at about 1620

nm where almost no radiation reaches the surface. No absorption spectra of the photosynthetic pigments are located at this wavelength, so this lack of radiation will not harm photosynthesis. The Titan-like atmospheres show hardly any sign of absorption.

However, the absorption lines start to become pronounced above 1000 nm and the absorption spectrum of *Bacteriochlorophyll a* drops to zero between 800 nm and 900 nm. Therefore, the absorption spectra of all photosynthetic pigments are not influenced by the absorption properties of Venus- and Earth-like atmospheres.

Comparisons of scenarios 2 and 4 (2 = Earth-like, 4 = Venus-like, each without clouds) show higher received intensities. The Earth-like run shows the maximum intensity at 1100 nm to be 228.35 W/m² and the Venus-like run shows the maximum intensity at 1000 nm to be 201.33 W/m².

With regard to the different maxima, I would like to point out what I explained at the beginning of chapter 6.4:

It has to be mentioned that the values of the maximum intensities of the scenarios mentioned in the following and previous sections are approximate values. The modified Streamer code calculates the flux only for 24 wavelength bands. Therefore, the maximum intensity is measured at a certain wavelength band available in the code, but the true maximum will be located between bands given by Streamer. In the following, the mentioned intensity maxima will be related to the maximum at the wavelength band used by the modified Streamer code.

This leads to the assumption that the maxima of all scenarios are less far apart than it seems when only looking at the wavelength bands of the modified Streamer code.

Comparing runs 2 and 4, the maximum intensities show similar values. Therefore, the models with Venus- and Earth-like scenarios with clouds show no great difference. This is also true for the scenarios without clouds. But, comparing the models with and without clouds, it can be shown that planets without clouds receive more W/m² on their surfaces. The difference between the received intensity of the Earth-like scenarios with and without clouds is about 23.5 %. For the Venus-like runs, the difference between the received intensity with and without clouds is 13.5 %.

The planet with the Titan-like atmosphere receives the most flux on the surface. The atmosphere is N₂-rich and therefore exhibits no significant absorption lines or scattering properties.

The interesting aspect here is the question if enough photons are available to exceed the light compensation point and ensure that the amount of CO₂ fixed for photosynthesis and the amount of CO₂ exhaled during the respiration are at least equal [Smith et al., 1976].

Here, it should also not be forgotten that photosynthesis is ruled by the absorbed energy and therefore the wavelength [Nobel, 2009]. But the pigments show areas where photons are more likely absorbed (absorption maxima). It depends a lot more on the portion of absorbed photons [Nobel, 2009]. The number of received photons per square meter and second converted to a photosynthetic photon flux [$\frac{\mu\text{mol}}{\text{m}^2\text{s}}$] makes it possible to compare the received photons with the PPF needed to exceed the light compensation point of C₃ and C₄ plants.

Summarizing the PPF of the five scenarios, the following situation emerges:

P. S. Nobel (2009) wrote in his book that, for C_3 plants, the light compensation point set in at $8 - 16 \frac{\mu\text{mol}}{\text{m}^2\text{s}}$ and for C_4 plants at $6 - 14 \frac{\mu\text{mol}}{\text{m}^2\text{s}}$ [Nobel, 2009]. Shade plants generally have lower light compensation points [Nobel, 2009].

Bacteriochlorophyll a

Scenario	Absorption maxima [nm]	Significantly higher	Just above	Beneath
Scenario 1	361.2			x
	396.2			x
	580.2		x	
	780.2	x		
Scenario 2	361.2			x
	396.2			x
	580.2		x	
	780.2	x		
Scenario 3	361.2			x
	396.2			x
	580.2		x	
	780.2	x		
Scenario 4	361.2			x
	396.2			x
	580.2		x	
	780.2	x		
Scenario 5	361.2			x
	396.2			x
	580.2		x	
	780.2	x		

Table 7.60: This table shows if the LC point is: significantly exceeded ($83.6 \frac{\mu\text{mol}}{\text{m}^2\text{s}} - 831.12 \frac{\mu\text{mol}}{\text{m}^2\text{s}}$), slightly exceeded ($16 \frac{\mu\text{mol}}{\text{m}^2\text{s}} - 43.34 \frac{\mu\text{mol}}{\text{m}^2\text{s}}$) or not exceeded ($\leq 4.21 \frac{\mu\text{mol}}{\text{m}^2\text{s}}$) for all models and absorption maxima of *Bacteriochlorophyll a*

First, it looked like photosynthesis works better for *Bacteriochlorophyll a* for radiation from M-type stars. But only two of four absorption maxima exceed the LC point.

As expected, the lack of radiation at short wavelengths affects the photosynthesis of bacteria. At 361.2 nm and 396.2 nm, not enough photons are received to pass the light compensation point. Looking beyond 580 nm, the number of photons received per square meter and second is high enough to exceed the LC point.

This leads to the assumption that enough red photons are available for anoxygenic photosynthesis, but not enough blue photons.

Now, two facts about photosynthesis have to be taken into account, the excitation states (see chapter 4.2) and the Emerson effect (see chapter 4.2.1).

Therefore, the possibility of anoxygenic photosynthesis of bacteria with *Bacteriochlorophyll a* cannot be excluded, even if there are not enough photons of short wavelengths (blue range) present in the

spectra of M-type stars (AD Leonis).

The spectra show that there is far less radiation at shorter wavelengths but, contrary to the *Bacteriochlorophyll a* spectra, the peaks of the *Chlorophyll a* and *Chlorophyll b* spectra are visible. Table 7.61 shows that, at the absorption maxima of *Chlorophyll a* and also of *Chlorophyll b* (table 7.62), these pigments receive enough photons to pass the LC point.

Scenario	Absorption maxima [nm]	Significantly higher	Just above	Beneath
Scenario 1	417.75		x	
	654.25	x		
Scenario 2	417.75		x	
	654.25	x		
Scenario 3	417.75		x	
	654.25	x		
Scenario 4	417.75		x	
	654.25	x		
Scenario 5	417.75		x	
	654.25	x		

Table 7.61: This table shows if the LC point is: significantly exceeded ($83.6 \frac{\mu\text{mol}}{\text{m}^2\text{s}} - 831.12 \frac{\mu\text{mol}}{\text{m}^2\text{s}}$), slightly exceeded ($16 \frac{\mu\text{mol}}{\text{m}^2\text{s}} - 43.34 \frac{\mu\text{mol}}{\text{m}^2\text{s}}$) or not exceeded ($\leq 4.21 \frac{\mu\text{mol}}{\text{m}^2\text{s}}$) for all models and absorption maxima of *Chlorophyll a*

Scenario	Absorption maxima [nm]	Significantly higher	Just above	Beneath
Scenario 1	453		x	
	643	x		
Scenario 2	453		x	
	643	x		
Scenario 3	453		x	
	643	x		
Scenario 4	453		x	
	643	x		
Scenario 5	453	x		
	643	x		

Table 7.62: This table shows if the LC point is: significantly exceeded ($83.6 \frac{\mu\text{mol}}{\text{m}^2\text{s}} - 831.12 \frac{\mu\text{mol}}{\text{m}^2\text{s}}$), slightly exceeded ($16 \frac{\mu\text{mol}}{\text{m}^2\text{s}} - 43.34 \frac{\mu\text{mol}}{\text{m}^2\text{s}}$) or not exceeded ($\leq 4.21 \frac{\mu\text{mol}}{\text{m}^2\text{s}}$) for all models and absorption maxima of *Chlorophyll b*

Compared to the present-day Earth (Scenario 0, see chapter 5.3.1), all *Chlorophyll a* and *Chlorophyll b* maxima show lower received photon fluxes. The PPF of *Bacteriochlorophyll a* at 361.2 nm, 396.4 nm and 580.2 nm are below the present-day Earth values. However, at 780.2 nm in scenarios 1 and 3, the received flux is near the flux in scenario 0. Scenarios 3, 4, and 5 show a higher PPF at 780.2 nm than the Earth.

8 Summary

This Master's thesis deals with the possibility of photosynthesis on planets with different atmospheric compositions around G-type and M-type stars.

The main idea of developing scenarios with G-type stars as host star was to create conditions that differ from present Earth and examine if it could serve as a habitat for phototroph organisms as-we-know-them. Therefore, several model planets were simulated with different atmospheric composition to investigate the influence of the atmosphere on the radiation that reaches the surface of the test planets. In order to cause a large range of scenarios, the planets were not located at their present positions in the Solar System, but inside and outside the liquid water zone.

The 3 most important pigments, *Bacteriochlorophyll a* for anoxygenic photosynthesis and *Chlorophyll a* and *Chlorophyll b* for oxygenic photosynthesis, were chosen for this study.

M-type stars exhibit different spectral energy ranges than G-type stars. The maximum intensity is not located in the optical range of the spectrum but in the IR. This leads to the situation that even through the absorption properties are known, it is unclear whether there is enough energy provided to perform photosynthetic reactions.

All scenarios show that the atmosphere has an influence on the spectral energy received at the planet's surface, but the influence on the photosynthetic pigments is not present on a scale that prohibits photosynthesis.

What is observable is the change in the intensity if the atmosphere of the test planet is modelled with or without clouds, which consequently also influences the position of the liquid water zone. For models with cloud, the intensity received at the surface is generally lower due to the scattering and absorption property of the clouds. Therefore, the borders of the liquid water zone are shifted.

The liquid water zone itself is expanded, in the G-type as well as in the M-type scenarios, for runs without clouds.

For G-type stars, as the Sun, it was supposed that the required radiation for photosynthesis would be sufficiently supplied by the host star, at least for planets with Earth-like atmospheres. It has been proven that after the radiation passed Venus- and Titan-like atmospheres (with and without clouds) the test planets perceives a large amount of radiation in the short and long wavelength range.

All scenarios show amounts of received photons in the required wavelength areas that are high enough to cover the light compensation point.

Five M-type star scenarios were numerically modelled to investigate if the photosynthetic active radiation wavelength range is covered by the emitted radiation of an M-type star. All planets were situated in the centre of the liquid water zone around the M-type host star.

The spectral energy distributions of the scenarios show the expected behaviour and a shift of the maximum wavelength from the optical range to the IR.

It was demonstrated that M-type stars offer a lack of radiation in the optical wavelength range. Here, it was questionable if the emitted number of photons [$\text{m}^{-2} \text{s}^{-1}$] is high enough to exceed the light compensation point and provide sufficient amounts of radiation in the PAR area.

At first glance, it seems that the absorption spectrum of *Bacteriochlorophyll a* offers the best absorption efficiency to enable photosynthesis on planets around M-type stars due to the fact that *Bacteriochlorophyll a* absorbs energy in the IR range as well as the optical range. Indeed, *Bacteriochlorophyll a* absorbs best at red wavelengths, in contrast to *Chlorophyll a* and *Chlorophyll b*, which absorb best at blue wavelengths.

This leads to the result that *Bacteriochlorophyll a* absorbs a similar percentage of radiation but needs a large amount of photons because of the position of the absorption maxima.

In fact, *Bacteriochlorophyll a* owns the worst absorption properties of the three examined pigments. This becomes clear when looking at the number of absorbed photons (per square meter and second) at the absorption maxima.

In all scenarios, the light compensation point of *Bacteriochlorophyll a* is not passed at the blue maximum. Shifting to yellow, the point is slightly exceeded, and at the border of optical red and NIR the light compensation point is passed by far. In contrast, at the blue maxima of *Chlorophyll a* and *Chlorophyll b* the light compensation point is passed, even if only modestly. At the blue absorption maxima the point is also exceeded by a greater amount of photosynthetic photon flux.

Considering the received radiation at the maxima of absorption of the pigments, the results calculated with the modified Streamer © code indicate that oxygenic photosynthesis would be possible. These pigments not only absorb at the maxima, they also absorb between the maxima. Taking the Emerson effect and the excitation states of photosynthetic pigments into account, anoxygenic photosynthesis with *Bacteriochlorophyll a* on planets around M-type stars could be feasible.

Furthermore, the planets are potentially tidally locked, which leads to a higher irradiation and longer periods of absorbing, CO_2 fixation, water absorption, and O_2 production. J. Schreiber (2006) noted that radiation between 400 and 720 nm is barely available in the spectral energy distribution of M-type stars but that could compensate for the lack of radiation at all [Schreiber, 2006].

This leads to the already adopted assumption that photosynthesis is feasible around G-type stars, even with atmospheres of different compositions and with different distances to the host stars.

N. Kiang et al. (2007) performed simulations (featuring F2V, K2V, M1V, and M5V stars along with Earth-like planets) to derive the photon flux density and concluded that for different stars, different radiation bands could be relevant for photosynthesis [Kiang et al., 2007a]. The photosynthetic

photon flux density (calculated between 400-700 nm, 400-1100 nm until 400-2500 nm) on planets around M-type stars is higher in the NIR region [Kiang et al., 2007a]. Therefore, N. Kiang et al. determined that an expansion of the PAR to 1800 nm (or even to 2500 nm) could be beneficial [Kiang et al., 2007a].

An interesting fact, mentioned in [Kiang, 2008], is the evolutionary adaption of photosynthesis to other environments. phototrophic organisms might evolve with different kinds of photosynthetic pigments and might therefore appear black. [Kiang, 2008].

The investigations featured in this thesis agree with the statements of [Kiang et al., 2007b] and [Lissauer, 2007].

It was shown that the emitted number of photons exceeds the light compensation point for pigments of oxygenic photosynthesis in the blue and red part of the optical spectrum. For *Bacteriochlorophyll a*, the blue light compensation point is not exceeded but the light harvesting complex should minimize the negative effects and maximize the collected number of photons.

N. Kiang et al. (2007) indicated in their graphs the spectral energy distribution on the surface of the Earth and on top of the atmosphere plotted together with absorption spectra of photosynthetic pigments, which examines the same general shape as calculated in this thesis [Kiang et al., 2007b]. The main objectives in the work of N. Kiang (2007) were the reflectance spectra of photosynthetic organisms (see [Kiang et al., 2007b]). The light compensation point is also mentioned for green plants and red macro-algae [Kiang et al., 2007b], but no computations were established with M-type star spectra.

J.J. Lissauer (2007) emphasizes the fact that marine photosynthesis only uses a fractional amount of the received flux from the sun [Lissauer, 2007]. As one can see, most of the authors refer to photosynthesis in the marine environment due to the low received fluxes and therefore low light compensation points. The light compensation points are generally assumed to be lower than in this thesis.

This model was created to estimate the potential for photosynthesis on terrestrial planets with different atmospheric compositions and distances to their host stars. Therefore, it was possible to prove that photosynthesis is possible on planets around M-type stars.

In addition, the model can be used for further studies with different atmospheric qualities, planets and host stars.

A Spectral Energy Distribution Data

A.1 Scenario 0

Table A.63 shows the output of the G-type star model with an Earth-like atmosphere with and without clouds. The planet is located at 1 AU.

Earth without clouds		Earth with clouds	
λ [μm]	SED [W/m^2]	λ [μm]	SED [W/m^2]
4.00	3.72563509	4.00	2.26475561
3.42	2.00720144	3.42	0.96735916
2.91	1.10960918	2.91	0.77442674
2.38	16.6944732	2.38	11.4532239
2.13	16.8548086	2.13	13.3186385
1.64	50.4046982	1.64	39.9020803
1.53	33.6370691	1.53	26.8605343
1.28	95.7595854	1.28	76.8965413
1.19	83.5535717	1.19	67.4096276
1.10	152.319543	1.10	123.898639
1.00	174.580865	1.00	143.21142
0.87	244.844205	0.87	201.536499
0.78	220.472802	0.78	181.579621
0.75	312.217097	0.75	258.297564
0.69	339.035613	0.69	281.453068
0.64	367.292685	0.64	306.642313
0.57	389.359904	0.57	327.077393
0.52	383.764538	0.52	324.754101
0.48	360.545844	0.48	307.560493
0.44	321.425351	0.44	277.32334
0.40	256.983242	0.40	224.696774
0.36	187.122566	0.36	166.370759
0.33	73.9339327	0.33	66.8216769
0.30	0.0159801	0.30	0.0145019

Table A.63: Spectral Energy distribution (SED) in [W/m^2] in dependence of the wavelength (λ) in [μm] calculated by means of the extended Streamer © code - Scenario 0, current Earth scenario with and without clouds, located at 1 AU

A.2 G-Star

Table A.64, table A.65 and table A.66 show the output of the G-type star models.

Venus without clouds, red zone		Venus without clouds, green zone		Venus with clouds, red zone	
λ [μm]	SED [W/m^2]	λ [μm]	SED [W/m^2]	λ [μm]	SED [W/m^2]
4.00	0.168940764	4.00	0.031322862	4.00	0.000318705
3.42	14.22307166	3.42	2.663357623	3.42	0.02221527
2.91	11.71523161	2.91	2.358849755	2.91	7.405653765
2.38	37.2312812	2.38	6.846606954	2.38	23.95486892
2.13	62.63169225	2.13	11.78751734	2.13	35.33791647
1.64	1.14229×10^{-20}	1.64	9.09016×10^{-23}	1.64	2.87922×10^{-18}
1.53	193.6473886	1.53	36.19519128	1.53	119.2653668
1.28	281.0466599	1.28	51.69488265	1.28	181.5823113
1.19	368.0617389	1.19	67.74644603	1.19	237.9934784
1.10	430.8081471	1.10	79.25910122	1.10	296.2865224
1.00	585.2165121	1.00	107.7555288	1.00	436.221474
0.87	698.330634	0.87	128.5247696	0.87	555.3695998
0.78	764.7219256	0.78	140.7606811	0.78	633.5711633
0.75	914.9320195	0.75	168.3951493	0.75	786.3707209
0.69	952.2898384	0.69	175.3330287	0.69	850.4708865
0.64	1024.434505	0.64	188.6730175	0.64	954.3597105
0.57	1047.990874	0.57	193.0778625	0.57	1.021.459479
0.52	998.5947994	0.52	184.0489899	0.52	1.012.06357
0.48	910.4818672	0.48	167.8563216	0.48	970.7017535
0.44	784.7984693	0.44	144.7155126	0.44	883.6900137
0.40	601.0601282	0.40	110.8488359	0.40	724.7932059
0.36	422.2382104	0.36	77.87529958	0.36	557.2301591
0.33	275.1892053	0.33	50.78888787	0.33	393.7765441
0.30	19.75633674	0.30	3.691445991	0.30	32.99772629

Table A.64: Spectral Energy distribution (SED) in [W/m^2] in dependence of the wavelength (λ) in [μm] calculated by means of the extended Streamer © code - Scenario 3, Scenario 4 and Scenario 6

A SPECTRAL ENERGY DISTRIBUTION DATA

Venus with clouds, green zone		Earth without clouds, green zone		Earth with clouds, green zone	
λ [μm]	SED [W/m^2]	λ [μm]	SED [W/m^2]	λ [μm]	SED [W/m^2]
4.00	0.000731237	4.00	2.23893599	4.00	1.425710534
3.42	0.054227687	3.42	1.317706165	3.42	0.657089771
2.91	1.452482966	2.91	0.71805182	2.91	0.51927098
2.38	4.164178244	2.38	9.951262807	2.38	7.143625358
2.13	6.319153566	2.13	10.27379791	2.13	8.469457565
1.64	4.3382×10^{-21}	1.64	29.95793842	1.64	24.80489464
1.53	19.94478736	1.53	20.76790744	1.53	17.25285535
1.28	28.949226	1.28	57.06799046	1.28	47.91195436
1.19	37.98425468	1.19	50.34464072	1.19	42.38461026
1.10	46.61794619	1.10	90.8301044	1.10	77.23892224
1.00	67.58461863	1.00	104.8854107	1.00	89.85178403
0.87	84.81614318	0.87	146.2883489	0.87	125.8625113
0.78	95.9076889	0.78	128.0071191	0.78	110.5670076
0.75	118.0609363	0.75	186.5197482	0.75	161.2845468
0.69	126.6507856	0.69	202.7477041	0.69	175.9064675
0.64	140.8510174	0.64	220.6504866	0.64	192.4178184
0.57	149.32247	0.57	234.2135038	0.57	205.4719513
0.52	146.7577917	0.52	231.1073441	0.52	204.2144219
0.48	139.171184	0.48	217.434078	0.48	193.6419022
0.44	125.1118689	0.44	194.1814872	0.44	174.8705176
0.40	100.8837615	0.40	155.5301998	0.40	141.9085813
0.36	75.63168461	0.36	113.5419178	0.36	105.3137947
0.33	52.19473067	0.33	46.67660519	0.33	43.83177374
0.30	4.222121805	0.30	0.011620741	0.30	0.010839903

Table A.65: Spectral Energy distribution (SED) in [W/m^2] in dependence of the wavelength (λ) in [μm] calculated by means of the extended Streamer © code - Scenario 5, Scenario 2 and Scenario 1

Titan without clouds, green zone		Titan without clouds, red zone	
λ [μm]	SED [W/m^2]	λ [μm]	SED [W/m^2]
4.00	3.553641784	4.00	27.50501161
3.42	4.411163315	3.42	34.45223685
2.91	5.737663129	2.91	43.14595609
2.38	14.59609617	2.38	108.147122
2.13	23.18549287	2.13	154.4440114
1.64	42.20319172	1.64	229.1908711
1.53	64.78214043	1.53	478.5087414
1.28	84.51617252	1.28	629.0287461
1.19	113.7039719	1.19	842.8724901
1.10	129.8002729	1.10	956.2834124
1.00	178.7746999	1.00	1300.820663
0.87	212.3939602	0.87	1516.139835
0.78	232.8396303	0.78	1639.226129
0.75	279.6230165	0.75	1940.929815
0.69	290.0339631	0.69	1974.95082
0.64	311.0538125	0.64	2056.2076
0.57	326.920637	0.57	2007.564381
0.52	322.5085144	0.52	1823.098527
0.48	303.4913564	0.48	1573.802403
0.44	271.0469124	0.44	1267.806298
0.40	217.0964659	0.40	894.8509459
0.36	158.4140925	0.36	578.9838887
0.33	64.05180294	0.33	348.5352612
0.30	0.078424084	0.30	19.98517227

Table A.66: Spectral Energy distribution (SED) in [W/m^2] in dependence of the wavelength (λ) in [μm] calculated by means of the extended Streamer © code - Scenario 7 and Scenario 8

A.3 M-Star

Table A.67 and table A.68 show the output of the M-type star models.

Venus without clouds		Venus with clouds	
4.00	0.235264497	4.00	0.001701783
3.42	16.92077253	3.42	0.104101455
2.91	12.9098853	2.91	9.21744837
2.38	45.47112666	2.38	32.58899757
2.13	76.99299907	2.13	48.2819796
1.64	1.62155e-21	1.64	2.52365e-19
1.53	160.9913133	1.53	106.7203827
1.28	205.3799591	1.28	140.4677086
1.19	216.6548474	1.19	148.3270687
1.10	245.0120468	1.10	177.3901103
1.00	258.2140935	1.00	201.3266879
0.87	228.5239967	0.87	189.0494403
0.78	212.7993396	0.78	182.736735
0.75	137.0420717	0.75	121.6827718
0.69	91.42164454	0.69	84.0597639
0.64	56.88017608	0.64	54.34953488
0.57	47.3480042	0.57	47.14188865
0.52	29.97480429	0.52	30.92350251
0.48	22.99562224	0.48	24.83439468
0.44	9.719527537	0.44	11.02593474
0.40	3.637449083	0.40	4.386402547
0.36	0.985608323	0.36	1.286545435
0.33	0.587917311	0.33	0.822956585
0.30	0.077677457	0.30	0.123373405

Table A.67: Spectral Energy distribution (SED) in $[\text{W}/\text{m}^2]$ in dependence of the wavelength (λ) in $[\mu\text{m}]$ calculated by means of the extended Streamer © code - Scenario 4 and Scenario 3

Earth without clouds		Earth with clouds		Titan without clouds	
λ [μm]	SED [W/m^2]	λ [μm]	SED [W/m^2]	λ [μm]	SED [W/m^2]
4.00	13.51064508	4.00	8.183814259	4.00	31.43774928
3.42	6.175571151	3.42	2.958609756	3.42	33.39427228
2.91	3.041891247	2.91	2.109772206	2.91	37.29659666
2.38	53.68371057	2.38	36.68444505	2.38	111.5096517
2.13	53.74002815	2.13	42.27018879	2.13	173.2825306
1.64	143.2355508	1.64	112.8265629	1.64	283.0464686
1.53	72.95026732	1.53	57.94120429	1.53	332.1110696
1.28	184.4961143	1.28	147.4843204	1.28	384.5341343
1.19	129.5714643	1.19	104.0629857	1.19	416.3361888
1.10	228.3473962	1.10	184.9411816	1.10	459.0445804
1.00	202.7899428	1.00	165.7400946	1.00	489.7477507
0.87	210.9321693	0.87	173.0938408	0.87	431.1776911
0.78	161.5313214	0.78	132.7604192	0.78	402.1267297
0.75	123.0770576	0.75	101.5553204	0.75	260.5977609
0.69	85.63576535	0.69	70.92384261	0.69	174.579982
0.64	53.64225515	0.64	44.68998119	0.64	109.7693725
0.57	46.25819665	0.57	38.78539542	0.57	92.81525767
0.52	30.28248667	0.52	25.58401802	0.52	59.81222153
0.48	23.93531512	0.48	20.38668552	0.48	46.90428393
0.44	10.46394682	0.44	9.014275283	0.44	20.4251427
0.40	4.089194179	0.40	3.569196456	0.40	7.954444674
0.36	1.149118378	0.36	1.01950911	0.36	2.25238566
0.33	0.41641338	0.33	0.375271815	0.33	1.406848154
0.30	0.000166949	0.30	0.00015195	0.30	0.212407137

Table A.68: Spectral Energy distribution (SED) in [W/m^2] in dependence of the wavelength (λ) in [μm] calculated by means of the extended Streamer © code - Scenario 2, Scenario 1 and Scenario 5

B Extinction - Original Data

B.1 Bacteriochlorophyll a

λ [nm]	E.	λ [nm]	E.	λ [nm]	E.	λ [nm]	E.	λ [nm]	E.
900	0.00192	892.2	0.00312	884.4	0.00172	876.6	0.00264	868.8	0.00287
899.8	0.00316	892	0.0016	884.2	0.00184	876.4	0.00283	868.6	0.00286
899.6	0.00295	891.8	0.0016	884	0.00232	876.2	0.00233	868.4	0.00261
899.4	0.00365	891.6	0.00241	883.8	0.00238	876	0.00283	868.2	0.00279
899.2	0.00307	891.4	0.00174	883.6	0.00214	875.8	0.0029	868	0.00274
899	0.00184	891.2	0.00214	883.4	0.00195	875.6	0.00277	867.8	0.0029
898.8	0.00304	891	0.00214	883.2	0.00216	875.4	0.00275	867.6	0.003
898.6	0.00094	890.8	0.00202	883	0.00192	875.2	0.00284	867.4	0.00272
898.4	0.0015	890.6	0.00179	882.8	0.00211	875	0.00279	867.2	0.00265
898.2	0.00229	890.4	0.0012	882.6	0.00191	874.8	0.00268	867	0.00291
898	0.00267	890.2	0.0015	882.4	0.00175	874.6	0.0026	866.8	0.00241
897.8	0.00232	890	0.00172	882.2	0.00211	874.4	0.0029	866.6	0.00245
897.6	0.00202	889.8	0.00307	882	0.00179	874.2	0.00251	866.4	0.00256
897.4	0.00214	889.6	0.00284	881.8	0.00135	874	0.00323	866.2	0.00265
897.2	0.00113	889.4	0.00144	881.6	0.00124	873.8	0.00238	866	0.00222
897	0.00084	889.2	0.00206	881.4	0.0021	873.6	0.00311	865.8	0.00259
896.8	0.00259	889	0.00226	881.2	0.0017	873.4	0.00233	865.6	0.00265
896.6	0.00257	888.8	0.00132	881	0.002	873.2	0.00292	865.4	0.00261
896.4	0.00342	888.6	0.00135	880.8	0.00169	873	0.0032	865.2	0.00251
896.2	0.00297	888.4	0.00214	880.6	0.00232	872.8	0.00304	865	0.00206
896	0.00244	888.2	0.00198	880.4	0.00167	872.6	0.00292	864.8	0.00235
895.8	0.0018	888	0.00207	880.2	0.00204	872.4	0.00277	864.6	0.00236
895.6	0.00264	887.8	0.00242	880	0.00155	872.2	0.00282	864.4	0.00262
895.4	0.00249	887.6	0.00206	879.8	0.00194	872	0.00289	864.2	0.00202
895.2	0.00184	887.4	0.0023	879.6	0.00181	871.8	0.00258	864	0.00234
895	0.00257	887.2	0.00176	879.4	0.0015	871.6	0.0028	863.8	0.00203
894.8	0.00124	887	0.00259	879.2	0.00193	871.4	0.00268	863.6	0.00255
894.6	0.00226	886.8	0.00269	879	0.00223	871.2	0.00305	863.4	0.00241
894.4	0.00157	886.6	0.00288	878.8	0.00202	871	0.00316	863.2	0.00235
894.2	0.00174	886.4	0.00256	878.6	0.00238	870.8	0.00303	863	0.00236
894	0.00247	886.2	0.00195	878.4	0.00237	870.6	0.00287	862.8	0.00217
893.8	0.00319	886	0.00154	878.2	0.00277	870.4	0.00258	862.6	0.00197
893.6	0.00354	885.8	0.0022	878	0.00268	870.2	0.00285	862.4	0.00232
893.4	0.00195	885.6	0.00244	877.8	0.00268	870	0.00297	862.2	0.00215
893.2	0.0032	885.4	0.00171	877.6	0.00241	869.8	0.003	862	0.00219
893	0.00229	885.2	0.00236	877.4	0.00236	869.6	0.00288	861.8	0.00246
892.8	0.00212	885	0.00286	877.2	0.00253	869.4	0.0027	861.6	0.00212
892.6	0.00136	884.8	0.00138	877	0.00262	869.2	0.00315	861.4	0.0022
892.4	0.00191	884.6	0.00145	876.8	0.00292	869	0.00293	861.2	0.00271

Table B.69: Extinction ε (E.) from *Bacteriochlorophyll a* related to the wavelength [Prahl, 2012]

λ [nm]	E.	λ [nm]	E.	λ [nm]	E.	λ [nm]	E.	λ [nm]	E.
861	0.00254	851.6	0.00268	842.2	0.00316	832.8	0.00487	823.4	0.00825
860.8	0.00226	851.4	0.00284	842	0.00376	832.6	0.00518	823.2	0.00853
860.6	0.00219	851.2	0.00272	841.8	0.00384	832.4	0.0051	823	0.00828
860.4	0.00237	851	0.00263	841.6	0.0035	832.2	0.00534	822.8	0.00868
860.2	0.00223	850.8	0.00255	841.4	0.00349	832	0.00546	822.6	0.00867
860	0.00254	850.6	0.00275	841.2	0.0037	831.8	0.00522	822.4	0.00889
859.8	0.0025	850.4	0.00303	841	0.00363	831.6	0.00508	822.2	0.00878
859.6	0.00225	850.2	0.00289	840.8	0.00355	831.4	0.00514	822	0.00924
859.4	0.00223	850	0.00292	840.6	0.00349	831.2	0.0052	821.8	0.00939
859.2	0.00249	849.8	0.00287	840.4	0.00365	831	0.00531	821.6	0.0094
859	0.0022	849.6	0.00277	840.2	0.00366	830.8	0.0055	821.4	0.00973
858.8	0.00218	849.4	0.00306	840	0.00367	830.6	0.00556	821.2	0.00963
858.6	0.00216	849.2	0.0028	839.8	0.00352	830.4	0.00547	821	0.00977
858.4	0.00218	849	0.003	839.6	0.00396	830.2	0.00576	820.8	0.01007
858.2	0.00257	848.8	0.00284	839.4	0.00401	830	0.00558	820.6	0.01019
858	0.00204	848.6	0.00282	839.2	0.00395	829.8	0.00598	820.4	0.01021
857.8	0.00257	848.4	0.00306	839	0.00413	829.6	0.00574	820.2	0.01043
857.6	0.00234	848.2	0.00303	838.8	0.00384	829.4	0.00597	820	0.0107
857.4	0.00221	848	0.00286	838.6	0.00399	829.2	0.00593	819.8	0.01073
857.2	0.00206	847.8	0.00302	838.4	0.00393	829	0.00579	819.6	0.01101
857	0.00246	847.6	0.00305	838.2	0.00412	828.8	0.00605	819.4	0.01093
856.8	0.00229	847.4	0.00308	838	0.00391	828.6	0.00622	819.2	0.01139
856.6	0.00233	847.2	0.00266	837.8	0.00436	828.4	0.00628	819	0.01131
856.4	0.00221	847	0.00288	837.6	0.00405	828.2	0.00622	818.8	0.01157
856.2	0.0023	846.8	0.00282	837.4	0.00419	828	0.00618	818.6	0.01164
856	0.00214	846.6	0.00289	837.2	0.00384	827.8	0.00638	818.4	0.01198
855.8	0.00251	846.4	0.0033	837	0.00392	827.6	0.00642	818.2	0.01212
855.6	0.00207	846.2	0.00276	836.8	0.0042	827.4	0.00633	818	0.0124
855.4	0.00234	846	0.00311	836.6	0.00427	827.2	0.00678	817.8	0.01261
855.2	0.00244	845.8	0.00309	836.4	0.0043	827	0.00661	817.6	0.0128
855	0.00264	845.6	0.0029	836.2	0.00424	826.8	0.00645	817.4	0.0131
854.8	0.00237	845.4	0.00312	836	0.00437	826.6	0.00708	817.2	0.01317
854.6	0.00215	845.2	0.0032	835.8	0.00441	826.4	0.0069	817	0.01342
854.4	0.00226	845	0.00284	835.6	0.00429	826.2	0.00703	816.8	0.01376
854.2	0.00225	844.8	0.0032	835.4	0.00445	826	0.00695	816.6	0.01387
854	0.00239	844.6	0.00298	835.2	0.00444	825.8	0.0072	816.4	0.01401
853.8	0.00266	844.4	0.00307	835	0.00459	825.6	0.00716	816.2	0.01459
853.6	0.00268	844.2	0.00308	834.8	0.00441	825.4	0.00723	816	0.01469
853.4	0.00251	844	0.0032	834.6	0.00471	825.2	0.00725	815.8	0.01497
853.2	0.00249	843.8	0.00308	834.4	0.00481	825	0.00755	815.6	0.01544
853	0.0025	843.6	0.00348	834.2	0.00492	824.8	0.00755	815.4	0.01544
852.8	0.00251	843.4	0.00333	834	0.00459	824.6	0.00772	815.2	0.01608
852.6	0.00269	843.2	0.00356	833.8	0.00437	824.4	0.00775	815	0.01602
852.4	0.00265	843	0.00359	833.6	0.00496	824.2	0.00783	814.8	0.01665
852.2	0.00277	842.8	0.0032	833.4	0.00467	824	0.00792	814.6	0.01684
852	0.00249	842.6	0.00345	833.2	0.00493	823.8	0.00801	814.4	0.01708
851.8	0.00278	842.4	0.00358	833	0.00516	823.6	0.00809	814.2	0.01766

Table B.70: Extinction ε (E.) from *Bacteriochlorophyll a* related to the wavelength [Prahl, 2012]

B EXTINCTION - ORIGINAL DATA

λ [nm]	E.	λ [nm]	E.	λ [nm]	E.	λ [nm]	E.	λ [nm]	E.
814	0.01798	804.6	0.05766	795.2	0.18549	785.8	0.34792	776.4	0.36969
813.8	0.01824	804.4	0.05932	795	0.18941	785.6	0.35027	776.2	0.36832
813.6	0.01853	804.2	0.06098	794.8	0.1931	785.4	0.35236	776	0.36693
813.4	0.01918	804	0.06271	794.6	0.19697	785.2	0.35451	775.8	0.36577
813.2	0.01957	803.8	0.06438	794.4	0.20087	785	0.35647	775.6	0.36433
813	0.02006	803.6	0.06608	794.2	0.2047	784.8	0.35854	775.4	0.36295
812.8	0.02057	803.4	0.06805	794	0.20872	784.6	0.36027	775.2	0.3613
812.6	0.02093	803.2	0.06959	793.8	0.21227	784.4	0.36197	775	0.36012
812.4	0.02122	803	0.07174	793.6	0.21625	784.2	0.36385	774.8	0.35825
812.2	0.02205	802.8	0.07373	793.4	0.22022	784	0.36546	774.6	0.35665
812	0.02226	802.6	0.07559	793.2	0.22386	783.8	0.36703	774.4	0.35492
811.8	0.0229	802.4	0.07768	793	0.2278	783.6	0.36859	774.2	0.3533
811.6	0.02348	802.2	0.07974	792.8	0.23162	783.4	0.3699	774	0.3515
811.4	0.02388	802	0.08206	792.6	0.23551	783.2	0.37129	773.8	0.34965
811.2	0.02471	801.8	0.0842	792.4	0.23962	783	0.37242	773.6	0.34783
811	0.02528	801.6	0.08668	792.2	0.24315	782.8	0.37341	773.4	0.34595
810.8	0.02587	801.4	0.08896	792	0.24722	782.6	0.37447	773.2	0.34398
810.6	0.02644	801.2	0.09116	791.8	0.25089	782.4	0.37566	773	0.34212
810.4	0.027	801	0.09362	791.6	0.25456	782.2	0.37649	772.8	0.34015
810.2	0.0276	800.8	0.09609	791.4	0.25849	782	0.37726	772.6	0.33815
810	0.02832	800.6	0.09871	791.2	0.2624	781.8	0.37802	772.4	0.33593
809.8	0.02904	800.4	0.10127	791	0.26617	781.6	0.37882	772.2	0.33409
809.6	0.02982	800.2	0.104	790.8	0.26976	781.4	0.37903	772	0.33205
809.4	0.03032	800	0.10643	790.6	0.27358	781.2	0.37979	771.8	0.32993
809.2	0.03132	799.8	0.10948	790.4	0.27741	781	0.37995	771.6	0.32781
809	0.03217	799.6	0.11215	790.2	0.28116	780.8	0.38034	771.4	0.3256
808.8	0.03296	799.4	0.11509	790	0.28459	780.6	0.38072	771.2	0.32334
808.6	0.03393	799.2	0.11779	789.8	0.28812	780.4	0.38087	771	0.32114
808.4	0.03483	799	0.12085	789.6	0.29167	780.2	0.38104	770.8	0.31896
808.2	0.03573	798.8	0.1237	789.4	0.29519	780	0.38096	770.6	0.31644
808	0.03682	798.6	0.12707	789.2	0.29882	779.8	0.38098	770.4	0.31427
807.8	0.0376	798.4	0.13002	789	0.30187	779.6	0.38079	770.2	0.31224
807.6	0.03858	798.2	0.13337	788.8	0.30521	779.4	0.38087	770	0.30966
807.4	0.03976	798	0.13637	788.6	0.3086	779.2	0.38056	769.8	0.30737
807.2	0.04062	797.8	0.13967	788.4	0.31183	779	0.37993	769.6	0.30506
807	0.04168	797.6	0.14297	788.2	0.31515	778.8	0.37943	769.4	0.30265
806.8	0.0428	797.4	0.14649	788	0.31802	778.6	0.37901	769.2	0.30033
806.6	0.0441	797.2	0.14964	787.8	0.32131	778.4	0.37853	769	0.298
806.4	0.04526	797	0.15305	787.6	0.32423	778.2	0.37793	768.8	0.29572
806.2	0.04652	796.8	0.15648	787.4	0.32737	778	0.37729	768.6	0.29314
806	0.04775	796.6	0.15983	787.2	0.33	777.8	0.3764	768.4	0.29067
805.8	0.04913	796.4	0.16345	787	0.33297	777.6	0.37555	768.2	0.28832
805.6	0.05051	796.2	0.16719	786.8	0.33563	777.4	0.37453	768	0.28573
805.4	0.05167	796	0.17049	786.6	0.3378	777.2	0.37378	767.8	0.28321
805.2	0.0534	795.8	0.17441	786.4	0.34058	777	0.37286	767.6	0.2808
805	0.05464	795.6	0.17831	786.2	0.34303	776.8	0.37185	767.4	0.27841
804.8	0.05603	795.4	0.18179	786	0.34545	776.6	0.37076	767.2	0.27596

Table B.71: Extinction ε (E.) from *Bacteriochlorophyll a* related to the wavelength [Prahl, 2012]

λ [nm]	E.	λ [nm]	E.	λ [nm]	E.	λ [nm]	E.	λ [nm]	E.
767	0.27349	757.6	0.1662	748.2	0.09846	738.8	0.06562	729.4	0.05234
766.8	0.27106	757.4	0.16437	748	0.0975	738.6	0.0649	729.2	0.05234
766.6	0.26845	757.2	0.1626	747.8	0.09659	738.4	0.06503	729	0.05205
766.4	0.26592	757	0.16064	747.6	0.09554	738.2	0.06448	728.8	0.05199
766.2	0.26334	756.8	0.15883	747.4	0.09458	738	0.06423	728.6	0.05179
766	0.26107	756.6	0.15674	747.2	0.09383	737.8	0.06387	728.4	0.05162
765.8	0.25859	756.4	0.15483	747	0.09279	737.6	0.06323	728.2	0.05165
765.6	0.25633	756.2	0.15332	746.8	0.09186	737.4	0.06307	728	0.05137
765.4	0.25348	756	0.15143	746.6	0.09096	737.2	0.06257	727.8	0.05139
765.2	0.25103	755.8	0.14963	746.4	0.09002	737	0.06224	727.6	0.05128
765	0.24864	755.6	0.14789	746.2	0.08909	736.8	0.06173	727.4	0.05118
764.8	0.24605	755.4	0.14631	746	0.08853	736.6	0.06134	727.2	0.05098
764.6	0.24367	755.2	0.14453	745.8	0.08764	736.4	0.06114	727	0.05093
764.4	0.2414	755	0.14311	745.6	0.08677	736.2	0.06047	726.8	0.05101
764.2	0.23876	754.8	0.14128	745.4	0.08586	736	0.06044	726.6	0.05129
764	0.23619	754.6	0.13981	745.2	0.08511	735.8	0.06022	726.4	0.05141
763.8	0.23407	754.4	0.13831	745	0.08434	735.6	0.05985	726.2	0.05099
763.6	0.23182	754.2	0.13664	744.8	0.08366	735.4	0.05931	726	0.05086
763.4	0.22929	754	0.13508	744.6	0.08282	735.2	0.05905	725.8	0.05109
763.2	0.22688	753.8	0.13367	744.4	0.08196	735	0.05876	725.6	0.05082
763	0.22444	753.6	0.13208	744.2	0.08143	734.8	0.05828	725.4	0.05069
762.8	0.22199	753.4	0.13045	744	0.08066	734.6	0.05788	725.2	0.05065
762.6	0.21961	753.2	0.1289	743.8	0.08014	734.4	0.05764	725	0.05057
762.4	0.21768	753	0.1276	743.6	0.07929	734.2	0.05743	724.8	0.05063
762.2	0.215	752.8	0.126	743.4	0.07863	734	0.05724	724.6	0.05043
762	0.21279	752.6	0.12466	743.2	0.07805	733.8	0.05669	724.4	0.05054
761.8	0.21053	752.4	0.12337	743	0.07709	733.6	0.05655	724.2	0.0504
761.6	0.20825	752.2	0.12175	742.8	0.0763	733.4	0.05628	724	0.05043
761.4	0.20586	752	0.12062	742.6	0.07577	733.2	0.05615	723.8	0.05041
761.2	0.20382	751.8	0.11931	742.4	0.07512	733	0.05597	723.6	0.05021
761	0.20154	751.6	0.11801	742.2	0.07458	732.8	0.0556	723.4	0.05034
760.8	0.19934	751.4	0.11672	742	0.07384	732.6	0.05549	723.2	0.0503
760.6	0.19694	751.2	0.11565	741.8	0.07315	732.4	0.05555	723	0.05037
760.4	0.19497	751	0.1141	741.6	0.0728	732.2	0.05499	722.8	0.05018
760.2	0.19271	750.8	0.11282	741.4	0.07205	732	0.05489	722.6	0.05011
760	0.19075	750.6	0.11164	741.2	0.07159	731.8	0.05457	722.4	0.05023
759.8	0.18859	750.4	0.11015	741	0.07104	731.6	0.05448	722.2	0.05006
759.6	0.18657	750.2	0.10917	740.8	0.07057	731.4	0.05415	722	0.0502
759.4	0.18424	750	0.10777	740.6	0.06996	731.2	0.054	721.8	0.05013
759.2	0.18214	749.8	0.10669	740.4	0.06961	731	0.05379	721.6	0.04997
759	0.18029	749.6	0.10569	740.2	0.06888	730.8	0.05379	721.4	0.05
758.8	0.17809	749.4	0.10451	740	0.0684	730.6	0.05345	721.2	0.05021
758.6	0.17614	749.2	0.10361	739.8	0.068	730.4	0.05349	721	0.04992
758.4	0.17407	749	0.10254	739.6	0.06757	730.2	0.05314	720.8	0.04993
758.2	0.17218	748.8	0.10177	739.4	0.06708	730	0.05316	720.6	0.04997
758	0.16984	748.6	0.10069	739.2	0.06657	729.8	0.0531	720.4	0.04995
757.8	0.1682	748.4	0.09966	739	0.06616	729.6	0.05253	720.2	0.04986

Table B.72: Extinction ε (E.) from *Bacteriochlorophyll a* related to the wavelength [Prahl, 2012]

B EXTINCTION - ORIGINAL DATA

λ [nm]	E.	λ [nm]	E.	λ [nm]	E.	λ [nm]	E.	λ [nm]	E.
720	0.05019	710.6	0.04855	701.2	0.04271	691.8	0.03355	682.4	0.02516
719.8	0.05005	710.4	0.04846	701	0.04267	691.6	0.03343	682.2	0.0249
719.6	0.05007	710.2	0.04852	700.8	0.04242	691.4	0.03314	682	0.02484
719.4	0.05002	710	0.04829	700.6	0.04208	691.2	0.0328	681.8	0.02453
719.2	0.05002	709.8	0.04803	700.4	0.04203	691	0.03279	681.6	0.02441
719	0.05011	709.6	0.04826	700.2	0.04168	690.8	0.03253	681.4	0.02426
718.8	0.04981	709.4	0.04792	700	0.04162	690.6	0.03231	681.2	0.02415
718.6	0.04987	709.2	0.04795	699.8	0.04142	690.4	0.0322	681	0.02417
718.4	0.04953	709	0.04778	699.6	0.04127	690.2	0.03203	680.8	0.02393
718.2	0.04954	708.8	0.04767	699.4	0.04093	690	0.03163	680.6	0.02364
718	0.04971	708.6	0.04764	699.2	0.04088	689.8	0.03151	680.4	0.02355
717.8	0.04951	708.4	0.04737	699	0.0407	689.6	0.03131	680.2	0.02339
717.6	0.04952	708.2	0.0472	698.8	0.04049	689.4	0.0312	680	0.02337
717.4	0.04939	708	0.04718	698.6	0.04042	689.2	0.03114	679.8	0.02324
717.2	0.04942	707.8	0.04707	698.4	0.04015	689	0.03097	679.6	0.02314
717	0.04953	707.6	0.04713	698.2	0.0398	688.8	0.03063	679.4	0.02297
716.8	0.04953	707.4	0.04687	698	0.03959	688.6	0.03025	679.2	0.0227
716.6	0.04928	707.2	0.04718	697.8	0.0396	688.4	0.03032	679	0.02286
716.4	0.04955	707	0.04695	697.6	0.03925	688.2	0.03002	678.8	0.02266
716.2	0.0496	706.8	0.04695	697.4	0.03901	688	0.02966	678.6	0.02242
716	0.04957	706.6	0.04667	697.2	0.03909	687.8	0.02957	678.4	0.02241
715.8	0.04954	706.4	0.04639	697	0.03872	687.6	0.0294	678.2	0.02207
715.6	0.04969	706.2	0.04644	696.8	0.03841	687.4	0.02937	678	0.02207
715.4	0.04954	706	0.04626	696.6	0.03833	687.2	0.02901	677.8	0.02188
715.2	0.0497	705.8	0.04606	696.4	0.03802	687	0.02919	677.6	0.02198
715	0.04941	705.6	0.04613	696.2	0.03805	686.8	0.02874	677.4	0.02165
714.8	0.04962	705.4	0.04584	696	0.03768	686.6	0.02861	677.2	0.02153
714.6	0.04948	705.2	0.04579	695.8	0.03729	686.4	0.02858	677	0.02155
714.4	0.0494	705	0.04548	695.6	0.03707	686.2	0.02812	676.8	0.02149
714.2	0.0494	704.8	0.04568	695.4	0.03687	686	0.02808	676.6	0.02112
714	0.04916	704.6	0.04529	695.2	0.03673	685.8	0.0278	676.4	0.02123
713.8	0.0493	704.4	0.04523	695	0.0363	685.6	0.02776	676.2	0.02089
713.6	0.04933	704.2	0.04519	694.8	0.03626	685.4	0.02744	676	0.02089
713.4	0.0493	704	0.045	694.6	0.03602	685.2	0.02726	675.8	0.02076
713.2	0.04933	703.8	0.04478	694.4	0.03591	685	0.02709	675.6	0.02053
713	0.04925	703.6	0.04458	694.2	0.03576	684.8	0.02697	675.4	0.02055
712.8	0.04926	703.4	0.04431	694	0.03549	684.6	0.02679	675.2	0.02041
712.6	0.04934	703.2	0.04433	693.8	0.0351	684.4	0.02658	675	0.0202
712.4	0.04895	703	0.04424	693.6	0.03516	684.2	0.02644	674.8	0.02016
712.2	0.04907	702.8	0.04402	693.4	0.03497	684	0.02639	674.6	0.01999
712	0.04904	702.6	0.04395	693.2	0.0345	683.8	0.02627	674.4	0.01985
711.8	0.04894	702.4	0.04342	693	0.03445	683.6	0.026	674.2	0.01983
711.6	0.04877	702.2	0.0436	692.8	0.03429	683.4	0.02585	674	0.01962
711.4	0.04874	702	0.04348	692.6	0.03384	683.2	0.02567	673.8	0.01964
711.2	0.04881	701.8	0.04314	692.4	0.03386	683	0.02566	673.6	0.01967
711	0.04859	701.6	0.04318	692.2	0.03362	682.8	0.02533	673.4	0.01953
710.8	0.0487	701.4	0.04315	692	0.03377	682.6	0.02538	673.2	0.01945

Table B.73: Extinction ε (E.) from *Bacteriochlorophyll a* related to the wavelength [Prahl, 2012]

λ [nm]	E.	λ [nm]	E.	λ [nm]	E.	λ [nm]	E.	λ [nm]	E.
673	0.01929	663.6	0.0159	654.2	0.01492	644.8	0.01368	635.4	0.01236
672.8	0.01938	663.4	0.01573	654	0.01489	644.6	0.01366	635.2	0.01212
672.6	0.01901	663.2	0.01586	653.8	0.01496	644.4	0.01386	635	0.01201
672.4	0.01902	663	0.0159	653.6	0.01485	644.2	0.0138	634.8	0.01215
672.2	0.0188	662.8	0.01574	653.4	0.01458	644	0.01358	634.6	0.01208
672	0.01872	662.6	0.01595	653.2	0.01497	643.8	0.01348	634.4	0.01206
671.8	0.01865	662.4	0.0158	653	0.01465	643.6	0.01352	634.2	0.01197
671.6	0.01869	662.2	0.01581	652.8	0.01471	643.4	0.01353	634	0.01205
671.4	0.01874	662	0.01594	652.6	0.01487	643.2	0.01353	633.8	0.01204
671.2	0.01834	661.8	0.01578	652.4	0.01484	643	0.01356	633.6	0.01204
671	0.01848	661.6	0.01586	652.2	0.01455	642.8	0.01337	633.4	0.01203
670.8	0.01843	661.4	0.0157	652	0.01497	642.6	0.01347	633.2	0.01201
670.6	0.01799	661.2	0.01542	651.8	0.01453	642.4	0.01352	633	0.01188
670.4	0.01824	661	0.01602	651.6	0.01468	642.2	0.01335	632.8	0.0118
670.2	0.01834	660.8	0.01572	651.4	0.0146	642	0.01326	632.6	0.01191
670	0.01808	660.6	0.01579	651.2	0.01465	641.8	0.01339	632.4	0.01178
669.8	0.01803	660.4	0.01584	651	0.01449	641.6	0.01325	632.2	0.0117
669.6	0.01802	660.2	0.01566	650.8	0.01456	641.4	0.01316	632	0.01179
669.4	0.01796	660	0.01548	650.6	0.01429	641.2	0.01315	631.8	0.01175
669.2	0.01786	659.8	0.01561	650.4	0.01443	641	0.01317	631.6	0.0117
669	0.01778	659.6	0.01552	650.2	0.01431	640.8	0.01305	631.4	0.01156
668.8	0.01804	659.4	0.0156	650	0.01442	640.6	0.0132	631.2	0.01173
668.6	0.01777	659.2	0.01558	649.8	0.01466	640.4	0.01304	631	0.01153
668.4	0.01749	659	0.01554	649.6	0.01442	640.2	0.01303	630.8	0.01162
668.2	0.01745	658.8	0.01561	649.4	0.01432	640	0.01283	630.6	0.01167
668	0.01731	658.6	0.01555	649.2	0.01425	639.8	0.01303	630.4	0.01145
667.8	0.01731	658.4	0.01548	649	0.01428	639.6	0.01297	630.2	0.01143
667.6	0.01731	658.2	0.01519	648.8	0.0143	639.4	0.01279	630	0.01159
667.4	0.01711	658	0.01531	648.6	0.01429	639.2	0.01276	629.8	0.01152
667.2	0.01734	657.8	0.01529	648.4	0.01442	639	0.01281	629.6	0.01136
667	0.01705	657.6	0.01544	648.2	0.01407	638.8	0.01278	629.4	0.0114
666.8	0.01717	657.4	0.01514	648	0.01418	638.6	0.0128	629.2	0.01127
666.6	0.01704	657.2	0.01539	647.8	0.01434	638.4	0.01279	629	0.01132
666.4	0.01698	657	0.01515	647.6	0.0143	638.2	0.01269	628.8	0.01149
666.2	0.01695	656.8	0.01512	647.4	0.01405	638	0.01277	628.6	0.01137
666	0.01673	656.6	0.01525	647.2	0.01409	637.8	0.01275	628.4	0.01125
665.8	0.01672	656.4	0.01513	647	0.01424	637.6	0.01253	628.2	0.01134
665.6	0.01682	656.2	0.01508	646.8	0.01422	637.4	0.01249	628	0.01127
665.4	0.01635	656	0.01523	646.6	0.01411	637.2	0.01251	627.8	0.01115
665.2	0.01635	655.8	0.01513	646.4	0.014	637	0.01246	627.6	0.01118
665	0.0162	655.6	0.0152	646.2	0.01389	636.8	0.01245	627.4	0.01144
664.8	0.01613	655.4	0.01504	646	0.0139	636.6	0.01245	627.2	0.01124
664.6	0.016	655.2	0.01501	645.8	0.014	636.4	0.01241	627	0.01075
664.4	0.01621	655	0.01499	645.6	0.01388	636.2	0.01245	626.8	0.01128
664.2	0.01605	654.8	0.01474	645.4	0.01389	636	0.01242	626.6	0.01137
664	0.01623	654.6	0.01499	645.2	0.01382	635.8	0.01252	626.4	0.01119
663.8	0.01585	654.4	0.01484	645	0.01385	635.6	0.01242	626.2	0.01133

Table B.74: Extinction ε (E.) from *Bacteriochlorophyll a* related to the wavelength [Prahl, 2012]

B EXTINCTION - ORIGINAL DATA

λ [nm]	E.	λ [nm]	E.	λ [nm]	E.	λ [nm]	E.	λ [nm]	E.
626	0.01114	616.6	0.01215	607.2	0.01798	597.8	0.0386	588.4	0.07901
625.8	0.0111	616.4	0.01224	607	0.01826	597.6	0.03916	588.2	0.07987
625.6	0.01119	616.2	0.01221	606.8	0.01863	597.4	0.04004	588	0.08081
625.4	0.01107	616	0.01225	606.6	0.01866	597.2	0.04071	587.8	0.08132
625.2	0.01115	615.8	0.01227	606.4	0.0192	597	0.04145	587.6	0.08223
625	0.01106	615.6	0.01242	606.2	0.01953	596.8	0.04209	587.4	0.08318
624.8	0.01105	615.4	0.01255	606	0.01958	596.6	0.04292	587.2	0.08388
624.6	0.01112	615.2	0.01262	605.8	0.02003	596.4	0.04371	587	0.08464
624.4	0.01121	615	0.01231	605.6	0.02014	596.2	0.04453	586.8	0.08529
624.2	0.01114	614.8	0.01271	605.4	0.02047	596	0.04525	586.6	0.08623
624	0.01131	614.6	0.01281	605.2	0.02069	595.8	0.04606	586.4	0.08706
623.8	0.01107	614.4	0.01285	605	0.02099	595.6	0.04674	586.2	0.08757
623.6	0.01105	614.2	0.01282	604.8	0.02142	595.4	0.04745	586	0.08832
623.4	0.01132	614	0.01295	604.6	0.02165	595.2	0.04849	585.8	0.08902
623.2	0.01111	613.8	0.0131	604.4	0.02195	595	0.04942	585.6	0.08952
623	0.01123	613.6	0.01306	604.2	0.02227	594.8	0.0501	585.4	0.09025
622.8	0.01113	613.4	0.01323	604	0.02283	594.6	0.05097	585.2	0.09081
622.6	0.01115	613.2	0.01352	603.8	0.02324	594.4	0.05167	585	0.09114
622.4	0.01109	613	0.01345	603.6	0.02352	594.2	0.05259	584.8	0.09183
622.2	0.01113	612.8	0.01341	603.4	0.02397	594	0.05341	584.6	0.09247
622	0.01126	612.6	0.01362	603.2	0.02423	593.8	0.05423	584.4	0.09298
621.8	0.01104	612.4	0.01385	603	0.02465	593.6	0.05529	584.2	0.09343
621.6	0.01123	612.2	0.01383	602.8	0.02507	593.4	0.05622	584	0.09387
621.4	0.01119	612	0.01392	602.6	0.02544	593.2	0.05702	583.8	0.09422
621.2	0.01108	611.8	0.01414	602.4	0.02577	593	0.05796	583.6	0.09479
621	0.01123	611.6	0.01432	602.2	0.02619	592.8	0.05906	583.4	0.09516
620.8	0.01151	611.4	0.01438	602	0.02692	592.6	0.05977	583.2	0.09557
620.6	0.01143	611.2	0.01449	601.8	0.02728	592.4	0.0607	583	0.09584
620.4	0.01139	611	0.0146	601.6	0.02796	592.2	0.06157	582.8	0.09627
620.2	0.01139	610.8	0.01477	601.4	0.02801	592	0.06258	582.6	0.0964
620	0.01153	610.6	0.01503	601.2	0.02864	591.8	0.06365	582.4	0.09679
619.8	0.01153	610.4	0.015	601	0.02906	591.6	0.06426	582.2	0.09708
619.6	0.0114	610.2	0.01519	600.8	0.02965	591.4	0.06536	582	0.09737
619.4	0.01145	610	0.01547	600.6	0.03023	591.2	0.06625	581.8	0.0974
619.2	0.01166	609.8	0.01548	600.4	0.03057	591	0.06732	581.6	0.09759
619	0.01167	609.6	0.01567	600.2	0.03116	590.8	0.06817	581.4	0.0979
618.8	0.01157	609.4	0.01588	600	0.03176	590.6	0.06902	581.2	0.09809
618.6	0.01174	609.2	0.01592	599.8	0.03232	590.4	0.0702	581	0.09803
618.4	0.01168	609	0.01623	599.6	0.03302	590.2	0.07103	580.8	0.09821
618.2	0.0118	608.8	0.0164	599.4	0.0335	590	0.07187	580.6	0.09834
618	0.01179	608.6	0.01662	599.2	0.03411	589.8	0.07279	580.4	0.09823
617.8	0.01174	608.4	0.01677	599	0.03494	589.6	0.07355	580.2	0.09847
617.6	0.01199	608.2	0.0168	598.8	0.03538	589.4	0.0745	580	0.09837
617.4	0.01189	608	0.0173	598.6	0.03599	589.2	0.07539	579.8	0.09833
617.2	0.0119	607.8	0.01749	598.4	0.03674	589	0.07661	579.6	0.09821
617	0.01203	607.6	0.01757	598.2	0.03731	588.8	0.07735	579.4	0.09821
616.8	0.01202	607.4	0.01777	598	0.03792	588.6	0.07801	579.2	0.09812

Table B.75: Extinction ε (E.) from *Bacteriochlorophyll a* related to the wavelength [Prahl, 2012]

λ [nm]	E.	λ [nm]	E.	λ [nm]	E.	λ [nm]	E.	λ [nm]	E.
579	0.09814	569.6	0.07314	560.2	0.04018	550.8	0.02457	541.4	0.02056
578.8	0.09785	569.4	0.07252	560	0.03973	550.6	0.02426	541.2	0.02065
578.6	0.0975	569.2	0.07176	559.8	0.03926	550.4	0.02433	541	0.02035
578.4	0.09746	569	0.07099	559.6	0.0387	550.2	0.02417	540.8	0.02027
578.2	0.09745	568.8	0.07028	559.4	0.03818	550	0.02406	540.6	0.02037
578	0.09732	568.6	0.06943	559.2	0.03779	549.8	0.02376	540.4	0.02006
577.8	0.09684	568.4	0.06868	559	0.0373	549.6	0.02373	540.2	0.02017
577.6	0.09661	568.2	0.06785	558.8	0.03678	549.4	0.02366	540	0.02002
577.4	0.09637	568	0.06718	558.6	0.03634	549.2	0.02345	539.8	0.02008
577.2	0.09611	567.8	0.0663	558.4	0.03564	549	0.02352	539.6	0.01985
577	0.09564	567.6	0.0656	558.2	0.03521	548.8	0.02319	539.4	0.01978
576.8	0.0954	567.4	0.06474	558	0.03463	548.6	0.02309	539.2	0.02001
576.6	0.09478	567.2	0.06414	557.8	0.03435	548.4	0.02303	539	0.01977
576.4	0.09477	567	0.0634	557.6	0.03407	548.2	0.02306	538.8	0.01965
576.2	0.09415	566.8	0.06263	557.4	0.03353	548	0.02286	538.6	0.01964
576	0.09389	566.6	0.0616	557.2	0.03303	547.8	0.02275	538.4	0.01954
575.8	0.09327	566.4	0.06114	557	0.03273	547.6	0.02263	538.2	0.01934
575.6	0.09293	566.2	0.06033	556.8	0.03244	547.4	0.02268	538	0.01913
575.4	0.09254	566	0.05966	556.6	0.032	547.2	0.0225	537.8	0.01905
575.2	0.09216	565.8	0.05882	556.4	0.03181	547	0.02254	537.6	0.01912
575	0.09137	565.6	0.05805	556.2	0.03132	546.8	0.02229	537.4	0.01903
574.8	0.0911	565.4	0.05728	556	0.03092	546.6	0.02234	537.2	0.0189
574.6	0.09032	565.2	0.05661	555.8	0.0307	546.4	0.02207	537	0.01871
574.4	0.0899	565	0.05594	555.6	0.03016	546.2	0.02215	536.8	0.01884
574.2	0.08929	564.8	0.0551	555.4	0.02999	546	0.02207	536.6	0.01867
574	0.08874	564.6	0.05431	555.2	0.02952	545.8	0.02206	536.4	0.01872
573.8	0.08797	564.4	0.05381	555	0.02933	545.6	0.02189	536.2	0.01861
573.6	0.08751	564.2	0.0529	554.8	0.02884	545.4	0.02191	536	0.01848
573.4	0.08687	564	0.05224	554.6	0.02881	545.2	0.02185	535.8	0.01845
573.2	0.08635	563.8	0.05144	554.4	0.02847	545	0.02175	535.6	0.01829
573	0.08579	563.6	0.0508	554.2	0.02816	544.8	0.0216	535.4	0.01812
572.8	0.0849	563.4	0.05004	554	0.02785	544.6	0.02169	535.2	0.018
572.6	0.08442	563.2	0.04928	553.8	0.02774	544.4	0.02173	535	0.01789
572.4	0.08364	563	0.04883	553.6	0.02726	544.2	0.02142	534.8	0.0178
572.2	0.08319	562.8	0.04799	553.4	0.02703	544	0.02139	534.6	0.01784
572	0.08207	562.6	0.0476	553.2	0.02672	543.8	0.02137	534.4	0.01758
571.8	0.08158	562.4	0.04701	553	0.02664	543.6	0.0212	534.2	0.01733
571.6	0.0811	562.2	0.04611	552.8	0.02644	543.4	0.02126	534	0.01745
571.4	0.08016	562	0.04557	552.6	0.02627	543.2	0.02117	533.8	0.01722
571.2	0.07947	561.8	0.04499	552.4	0.02608	543	0.02081	533.6	0.01718
571	0.07877	561.6	0.0443	552.2	0.02577	542.8	0.02097	533.4	0.01713
570.8	0.07807	561.4	0.04367	552	0.02584	542.6	0.021	533.2	0.01705
570.6	0.07737	561.2	0.04322	551.8	0.0254	542.4	0.02088	533	0.01686
570.4	0.07656	561	0.04268	551.6	0.02524	542.2	0.02097	532.8	0.01673
570.2	0.07571	560.8	0.04206	551.4	0.02499	542	0.02069	532.6	0.01671
570	0.07475	560.6	0.04156	551.2	0.02494	541.8	0.02073	532.4	0.01655
569.8	0.07382	560.4	0.04087	551	0.02477	541.6	0.02068	532.2	0.01628

Table B.76: Extinction ε (E.) from *Bacteriochlorophyll a* related to the wavelength [Prahl, 2012]

B EXTINCTION - ORIGINAL DATA

λ [nm]	E.	λ [nm]	E.	λ [nm]	E.	λ [nm]	E.	λ [nm]	E.
532	0.01646	522.6	0.01159	513.2	0.009	503.8	0.00878	494.4	0.00887
531.8	0.01623	522.4	0.01137	513	0.00922	503.6	0.00901	494.2	0.00895
531.6	0.01614	522.2	0.01124	512.8	0.00914	503.4	0.00882	494	0.009
531.4	0.016	522	0.01129	512.6	0.00909	503.2	0.00868	493.8	0.00896
531.2	0.01592	521.8	0.01116	512.4	0.009	503	0.00878	493.6	0.00893
531	0.01591	521.6	0.01106	512.2	0.00915	502.8	0.00863	493.4	0.00901
530.8	0.01554	521.4	0.01095	512	0.00888	502.6	0.00888	493.2	0.00877
530.6	0.01563	521.2	0.01095	511.8	0.00901	502.4	0.00901	493	0.00904
530.4	0.01535	521	0.01052	511.6	0.00905	502.2	0.00905	492.8	0.00892
530.2	0.01517	520.8	0.01076	511.4	0.00901	502	0.00887	492.6	0.00888
530	0.01523	520.6	0.01047	511.2	0.00883	501.8	0.00895	492.4	0.00879
529.8	0.01524	520.4	0.0106	511	0.00898	501.6	0.00914	492.2	0.00897
529.6	0.01492	520.2	0.01044	510.8	0.0092	501.4	0.00907	492	0.00895
529.4	0.01473	520	0.01058	510.6	0.00882	501.2	0.00901	491.8	0.00872
529.2	0.01467	519.8	0.01056	510.4	0.00902	501	0.00913	491.6	0.00899
529	0.01455	519.6	0.01013	510.2	0.0088	500.8	0.00892	491.4	0.00885
528.8	0.01448	519.4	0.01025	510	0.00893	500.6	0.00885	491.2	0.00886
528.6	0.01427	519.2	0.0102	509.8	0.00896	500.4	0.009	491	0.00897
528.4	0.01432	519	0.01017	509.6	0.00903	500.2	0.00902	490.8	0.00897
528.2	0.01417	518.8	0.01016	509.4	0.00891	500	0.00897	490.6	0.00899
528	0.01408	518.6	0.00999	509.2	0.0091	499.8	0.0091	490.4	0.00895
527.8	0.01401	518.4	0.00997	509	0.00871	499.6	0.00909	490.2	0.00897
527.6	0.01379	518.2	0.00996	508.8	0.009	499.4	0.00921	490	0.00878
527.4	0.01366	518	0.00992	508.6	0.00892	499.2	0.00924	489.8	0.00876
527.2	0.01367	517.8	0.01003	508.4	0.0089	499	0.00934	489.6	0.00878
527	0.01343	517.6	0.00982	508.2	0.00888	498.8	0.00936	489.4	0.00894
526.8	0.01344	517.4	0.0099	508	0.00886	498.6	0.00933	489.2	0.00879
526.6	0.01329	517.2	0.0097	507.8	0.00901	498.4	0.00932	489	0.00884
526.4	0.01335	517	0.00974	507.6	0.00894	498.2	0.00946	488.8	0.00877
526.2	0.01301	516.8	0.00963	507.4	0.009	498	0.00923	488.6	0.0088
526	0.01297	516.6	0.00974	507.2	0.00898	497.8	0.00924	488.4	0.00889
525.8	0.0129	516.4	0.00964	507	0.00889	497.6	0.0093	488.2	0.00896
525.6	0.01277	516.2	0.00956	506.8	0.00873	497.4	0.00931	488	0.00883
525.4	0.01272	516	0.00955	506.6	0.00852	497.2	0.0093	487.8	0.00878
525.2	0.01254	515.8	0.00947	506.4	0.0085	497	0.00935	487.6	0.00903
525	0.0124	515.6	0.00953	506.2	0.00871	496.8	0.00926	487.4	0.0089
524.8	0.01245	515.4	0.00929	506	0.00872	496.6	0.00922	487.2	0.00897
524.6	0.01235	515.2	0.0094	505.8	0.00886	496.4	0.00924	487	0.00885
524.4	0.01211	515	0.00945	505.6	0.00881	496.2	0.00924	486.8	0.00891
524.2	0.01204	514.8	0.00941	505.4	0.00868	496	0.00927	486.6	0.00878
524	0.01196	514.6	0.0092	505.2	0.00872	495.8	0.00893	486.4	0.00881
523.8	0.01184	514.4	0.00948	505	0.00859	495.6	0.00883	486.2	0.00875
523.6	0.0117	514.2	0.00945	504.8	0.00882	495.4	0.00922	486	0.00879
523.4	0.01183	514	0.00917	504.6	0.00867	495.2	0.0088	485.8	0.00899
523.2	0.0116	513.8	0.00927	504.4	0.00879	495	0.00904	485.6	0.00892
523	0.01169	513.6	0.00921	504.2	0.00877	494.8	0.00891	485.4	0.0089
522.8	0.0114	513.4	0.00908	504	0.0088	494.6	0.00886	485.2	0.00874

Table B.77: Extinction ε (E.) from *Bacteriochlorophyll a* related to the wavelength [Prahll, 2012]

λ [nm]	E.	λ [nm]	E.	λ [nm]	E.	λ [nm]	E.	λ [nm]	E.
485	0.00886	475.6	0.00958	466.2	0.01106	456.8	0.01315	447.4	0.01638
484.8	0.00907	475.4	0.00959	466	0.01098	456.6	0.01333	447.2	0.0165
484.6	0.00885	475.2	0.0098	465.8	0.0112	456.4	0.01331	447	0.01664
484.4	0.00895	475	0.00979	465.6	0.01121	456.2	0.01331	446.8	0.01666
484.2	0.00906	474.8	0.00959	465.4	0.01134	456	0.01334	446.6	0.01683
484	0.00897	474.6	0.00974	465.2	0.0113	455.8	0.0134	446.4	0.01664
483.8	0.00889	474.4	0.00975	465	0.01139	455.6	0.01345	446.2	0.01682
483.6	0.00891	474.2	0.00989	464.8	0.01129	455.4	0.01353	446	0.01712
483.4	0.00893	474	0.00989	464.6	0.01153	455.2	0.01361	445.8	0.017
483.2	0.00895	473.8	0.00972	464.4	0.01164	455	0.01366	445.6	0.01718
483	0.00893	473.6	0.00986	464.2	0.01137	454.8	0.01376	445.4	0.01719
482.8	0.00906	473.4	0.01006	464	0.01149	454.6	0.01391	445.2	0.01728
482.6	0.00913	473.2	0.00989	463.8	0.01168	454.4	0.01386	445	0.01693
482.4	0.00893	473	0.01009	463.6	0.01146	454.2	0.01381	444.8	0.01735
482.2	0.00905	472.8	0.01	463.4	0.01149	454	0.01395	444.6	0.01743
482	0.00921	472.6	0.00984	463.2	0.01168	453.8	0.01433	444.4	0.01754
481.8	0.00908	472.4	0.01008	463	0.01164	453.6	0.01426	444.2	0.0177
481.6	0.00904	472.2	0.01004	462.8	0.01192	453.4	0.01428	444	0.01769
481.4	0.0091	472	0.01019	462.6	0.01169	453.2	0.01423	443.8	0.01767
481.2	0.00911	471.8	0.01016	462.4	0.01193	453	0.01434	443.6	0.01814
481	0.00894	471.6	0.01021	462.2	0.01182	452.8	0.01462	443.4	0.0184
480.8	0.0091	471.4	0.01004	462	0.01178	452.6	0.0146	443.2	0.01823
480.6	0.00914	471.2	0.01018	461.8	0.01195	452.4	0.0147	443	0.01828
480.4	0.00939	471	0.01023	461.6	0.01211	452.2	0.01464	442.8	0.01825
480.2	0.00927	470.8	0.0102	461.4	0.01218	452	0.01489	442.6	0.01866
480	0.00906	470.6	0.01047	461.2	0.01197	451.8	0.01505	442.4	0.01857
479.8	0.00912	470.4	0.01034	461	0.01217	451.6	0.01491	442.2	0.01853
479.6	0.0093	470.2	0.01039	460.8	0.01205	451.4	0.01496	442	0.01878
479.4	0.00917	470	0.01043	460.6	0.01247	451.2	0.01527	441.8	0.01886
479.2	0.00912	469.8	0.01042	460.4	0.01244	451	0.01518	441.6	0.019
479	0.00915	469.6	0.01031	460.2	0.01247	450.8	0.01533	441.4	0.0189
478.8	0.0092	469.4	0.01063	460	0.01235	450.6	0.01542	441.2	0.019
478.6	0.0093	469.2	0.01062	459.8	0.01242	450.4	0.01556	441	0.01905
478.4	0.00928	469	0.01058	459.6	0.01249	450.2	0.01553	440.8	0.01931
478.2	0.0094	468.8	0.01081	459.4	0.01253	450	0.0158	440.6	0.01919
478	0.00942	468.6	0.01064	459.2	0.01262	449.8	0.01538	440.4	0.01932
477.8	0.00934	468.4	0.01056	459	0.01276	449.6	0.01536	440.2	0.01937
477.6	0.0094	468.2	0.01078	458.8	0.01259	449.4	0.01541	440	0.01946
477.4	0.00946	468	0.01074	458.6	0.01266	449.2	0.01577	439.8	0.01955
477.2	0.00939	467.8	0.0108	458.4	0.01276	449	0.0157	439.6	0.01954
477	0.00938	467.6	0.01091	458.2	0.01279	448.8	0.01569	439.4	0.01958
476.8	0.00942	467.4	0.011	458	0.01291	448.6	0.01607	439.2	0.01955
476.6	0.00954	467.2	0.01085	457.8	0.01281	448.4	0.01601	439	0.01984
476.4	0.00944	467	0.01104	457.6	0.01303	448.2	0.01617	438.8	0.01996
476.2	0.00956	466.8	0.01095	457.4	0.01301	448	0.01614	438.6	0.02011
476	0.00957	466.6	0.01102	457.2	0.01326	447.8	0.01618	438.4	0.01983
475.8	0.00935	466.4	0.01107	457	0.01292	447.6	0.0162	438.2	0.02034

Table B.78: Extinction ε (E.) from *Bacteriochlorophyll a* related to the wavelength [Prahl, 2012]

B EXTINCTION - ORIGINAL DATA

λ [nm]	E.	λ [nm]	E.	λ [nm]	E.	λ [nm]	E.	λ [nm]	E.
438	0.02045	428.6	0.02378	419.2	0.03151	409.8	0.06573	400.4	0.16874
437.8	0.02061	428.4	0.02387	419	0.03152	409.6	0.06725	400.2	0.17066
437.6	0.02048	428.2	0.02411	418.8	0.0318	409.4	0.069	400	0.1721
437.4	0.02073	428	0.02392	418.6	0.03253	409.2	0.07062	399.8	0.17367
437.2	0.02072	427.8	0.02419	418.4	0.03257	409	0.07243	399.6	0.17516
437	0.02063	427.6	0.02436	418.2	0.03294	408.8	0.07398	399.4	0.17619
436.8	0.0209	427.4	0.02443	418	0.0332	408.6	0.07583	399.2	0.17764
436.6	0.02072	427.2	0.02458	417.8	0.03359	408.4	0.07767	399	0.17906
436.4	0.02099	427	0.02457	417.6	0.03405	408.2	0.07984	398.8	0.17991
436.2	0.02107	426.8	0.02462	417.4	0.03439	408	0.08159	398.6	0.18109
436	0.0212	426.6	0.02483	417.2	0.0347	407.8	0.08364	398.4	0.18194
435.8	0.02111	426.4	0.02501	417	0.03506	407.6	0.08563	398.2	0.18295
435.6	0.02123	426.2	0.02504	416.8	0.03551	407.4	0.08749	398	0.18366
435.4	0.02137	426	0.02529	416.6	0.03615	407.2	0.08945	397.8	0.18422
435.2	0.02136	425.8	0.02542	416.4	0.03634	407	0.09152	397.6	0.18483
435	0.02132	425.6	0.02535	416.2	0.03671	406.8	0.09405	397.4	0.18546
434.8	0.02153	425.4	0.0256	416	0.03721	406.6	0.09601	397.2	0.18586
434.6	0.02148	425.2	0.02594	415.8	0.03773	406.4	0.09836	397	0.18634
434.4	0.0216	425	0.02594	415.6	0.03829	406.2	0.10079	396.8	0.18663
434.2	0.02166	424.8	0.02624	415.4	0.03896	406	0.10306	396.6	0.18696
434	0.02173	424.6	0.02615	415.2	0.03933	405.8	0.10543	396.4	0.18705
433.8	0.02186	424.4	0.02642	415	0.03984	405.6	0.10814	396.2	0.18691
433.6	0.02213	424.2	0.0265	414.8	0.0406	405.4	0.11025	396	0.18694
433.4	0.02209	424	0.02676	414.6	0.04117	405.2	0.11282	395.8	0.18691
433.2	0.02208	423.8	0.02692	414.4	0.04177	405	0.1155	395.6	0.1867
433	0.02201	423.6	0.02725	414.2	0.04253	404.8	0.11761	395.4	0.18677
432.8	0.02211	423.4	0.02686	414	0.0432	404.6	0.12029	395.2	0.18648
432.6	0.02245	423.2	0.02707	413.8	0.04403	404.4	0.1228	395	0.18656
432.4	0.02235	423	0.02738	413.6	0.04453	404.2	0.1257	394.8	0.186
432.2	0.0224	422.8	0.02762	413.4	0.04562	404	0.12835	394.6	0.18577
432	0.02228	422.6	0.02778	413.2	0.0462	403.8	0.13055	394.4	0.18547
431.8	0.02267	422.4	0.02794	413	0.04699	403.6	0.13316	394.2	0.18553
431.6	0.02273	422.2	0.02827	412.8	0.04779	403.4	0.13566	394	0.18528
431.4	0.02293	422	0.02828	412.6	0.04877	403.2	0.13801	393.8	0.18473
431.2	0.02285	421.8	0.02855	412.4	0.04971	403	0.1406	393.6	0.18456
431	0.02286	421.6	0.02871	412.2	0.05084	402.8	0.14319	393.4	0.18401
430.8	0.02275	421.4	0.02873	412	0.052	402.6	0.14545	393.2	0.1833
430.6	0.02278	421.2	0.02894	411.8	0.05283	402.4	0.14783	393	0.18318
430.4	0.02292	421	0.02913	411.6	0.05382	402.2	0.15015	392.8	0.18259
430.2	0.02293	420.8	0.02963	411.4	0.05497	402	0.1525	392.6	0.18197
430	0.02316	420.6	0.02991	411.2	0.05645	401.8	0.15456	392.4	0.18165
429.8	0.02306	420.4	0.03002	411	0.05765	401.6	0.1568	392.2	0.18135
429.6	0.02326	420.2	0.03016	410.8	0.05881	401.4	0.15895	392	0.181
429.4	0.02324	420	0.03047	410.6	0.05995	401.2	0.16107	391.8	0.18062
429.2	0.02346	419.8	0.03037	410.4	0.06151	401	0.16307	391.6	0.18058
429	0.02346	419.6	0.0309	410.2	0.063	400.8	0.16502	391.4	0.18023
428.8	0.02352	419.4	0.03127	410	0.06423	400.6	0.16687	391.2	0.17995

Table B.79: Extinction ε (E.) from *Bacteriochlorophyll a* related to the wavelength [Prahl, 2012]

λ [nm]	E.	λ [nm]	E.	λ [nm]	E.	λ [nm]	E.	λ [nm]	E.
391	0.17964	381.6	0.18339	372.2	0.21288	362.8	0.28925	353.4	0.24991
390.8	0.17935	381.4	0.18327	372	0.21428	362.6	0.29033	353.2	0.2482
390.6	0.17886	381.2	0.18363	371.8	0.2155	362.4	0.29071	353	0.24678
390.4	0.17871	381	0.18377	371.6	0.21715	362.2	0.29169	352.8	0.24486
390.2	0.17866	380.8	0.18408	371.4	0.21827	362	0.29163	352.6	0.24313
390	0.17837	380.6	0.18406	371.2	0.22008	361.8	0.2921	352.4	0.24176
389.8	0.17819	380.4	0.1843	371	0.22156	361.6	0.29266	352.2	0.24039
389.6	0.17833	380.2	0.1846	370.8	0.22286	361.4	0.29274	352	0.23928
389.4	0.17811	380	0.18499	370.6	0.22481	361.2	0.29294	351.8	0.23803
389.2	0.17804	379.8	0.1851	370.4	0.2263	361	0.29252	351.6	0.23585
389	0.17796	379.6	0.18541	370.2	0.22806	360.8	0.29277	351.4	0.23536
388.8	0.17817	379.4	0.18563	370	0.22987	360.6	0.29263	351.2	0.23338
388.6	0.17785	379.2	0.18612	369.8	0.23169	360.4	0.2924	351	0.23179
388.4	0.17748	379	0.18618	369.6	0.23379	360.2	0.29206	350.8	0.22965
388.2	0.17771	378.8	0.18642	369.4	0.23567	360	0.29174	350.6	0.22868
388	0.17766	378.6	0.18672	369.2	0.23725	359.8	0.29132	350.4	0.22716
387.8	0.17754	378.4	0.18686	369	0.23906	359.6	0.29046	350.2	0.22605
387.6	0.17759	378.2	0.18734	368.8	0.24123	359.4	0.29	350	0.2245
387.4	0.1779	378	0.18776	368.6	0.24305	359.2	0.28914	349.8	0.22288
387.2	0.17811	377.8	0.18808	368.4	0.24484	359	0.28844	349.6	0.22156
387	0.17809	377.6	0.18889	368.2	0.2469	358.8	0.28759	349.4	0.21998
386.8	0.17815	377.4	0.18895	368	0.24897	358.6	0.28684	349.2	0.21898
386.6	0.17833	377.2	0.18966	367.8	0.25079	358.4	0.28617	349	0.21772
386.4	0.17861	377	0.19007	367.6	0.25292	358.2	0.28476	348.8	0.21635
386.2	0.17869	376.8	0.19045	367.4	0.25468	358	0.28373	348.6	0.21526
386	0.17876	376.6	0.19105	367.2	0.25652	357.8	0.28228	348.4	0.21397
385.8	0.17919	376.4	0.19201	367	0.25842	357.6	0.28091	348.2	0.2126
385.6	0.17929	376.2	0.19219	366.8	0.2605	357.4	0.27969	348	0.21099
385.4	0.17953	376	0.19308	366.6	0.2626	357.2	0.27863	347.8	0.21037
385.2	0.1799	375.8	0.19385	366.4	0.26425	357	0.27733	347.6	0.20887
385	0.17989	375.6	0.19453	366.2	0.26614	356.8	0.27609	347.4	0.20778
384.8	0.18014	375.4	0.19515	366	0.2679	356.6	0.27474	347.2	0.20651
384.6	0.18038	375.2	0.196	365.8	0.26953	356.4	0.27311	347	0.20509
384.4	0.18079	375	0.19686	365.6	0.27127	356.2	0.27161	346.8	0.2039
384.2	0.18094	374.8	0.19757	365.4	0.27284	356	0.2702	346.6	0.2028
384	0.18127	374.6	0.19842	365.2	0.27437	355.8	0.26875	346.4	0.2018
383.8	0.18138	374.4	0.1995	365	0.27589	355.6	0.26719	346.2	0.20063
383.6	0.18167	374.2	0.20039	364.8	0.27742	355.4	0.26558	346	0.1993
383.4	0.1817	374	0.20146	364.6	0.27888	355.2	0.26401	345.8	0.1982
383.2	0.18187	373.8	0.20278	364.4	0.28045	355	0.26235	345.6	0.19724
383	0.18235	373.6	0.20345	364.2	0.28175	354.8	0.26095	345.4	0.19622
382.8	0.18224	373.4	0.20494	364	0.28291	354.6	0.25931	345.2	0.19493
382.6	0.18237	373.2	0.20599	363.8	0.28419	354.4	0.2578	345	0.19382
382.4	0.18274	373	0.20743	363.6	0.28535	354.2	0.25639	344.8	0.1928
382.2	0.18284	372.8	0.20856	363.4	0.28645	354	0.2547	344.6	0.19147
382	0.18311	372.6	0.20972	363.2	0.28754	353.8	0.25276	344.4	0.19096
381.8	0.1834	372.4	0.21123	363	0.28838	353.6	0.25135	344.2	0.18971

Table B.80: Extinction ε (E.) from *Bacteriochlorophyll a* related to the wavelength [Prahl, 2012]

B EXTINCTION - ORIGINAL DATA

λ [nm]	E.	λ [nm]	E.	λ [nm]	E.	λ [nm]	E.	λ [nm]	E.
344	0.18905	334.6	0.144	325.2	0.10991	315.8	0.08757	306.4	0.08885
343.8	0.18698	334.4	0.14353	325	0.1098	315.6	0.08746	306.2	0.08853
343.6	0.18628	334.2	0.14213	324.8	0.10915	315.4	0.08791	306	0.08872
343.4	0.18534	334	0.14128	324.6	0.1082	315.2	0.08743	305.8	0.08896
343.2	0.18402	333.8	0.1407	324.4	0.10786	315	0.08757	305.6	0.0883
343	0.18311	333.6	0.14005	324.2	0.1069	314.8	0.0874	305.4	0.08778
342.8	0.18188	333.4	0.1387	324	0.10656	314.6	0.08721	305.2	0.08778
342.6	0.18105	333.2	0.13822	323.8	0.10558	314.4	0.08713	305	0.08772
342.4	0.18034	333	0.1378	323.6	0.10527	314.2	0.08712	304.8	0.08795
342.2	0.17866	332.8	0.13706	323.4	0.10446	314	0.08702	304.6	0.08775
342	0.17801	332.6	0.1362	323.2	0.10432	313.8	0.08666	304.4	0.08728
341.8	0.17674	332.4	0.13546	323	0.10338	313.6	0.08673	304.2	0.08769
341.6	0.17612	332.2	0.13486	322.8	0.10317	313.4	0.08604	304	0.08747
341.4	0.17494	332	0.13453	322.6	0.1028	313.2	0.08646	303.8	0.08682
341.2	0.17376	331.8	0.13324	322.4	0.10142	313	0.08593	303.6	0.0872
341	0.17307	331.6	0.1324	322.2	0.10159	312.8	0.08637	303.4	0.08655
340.8	0.17185	331.4	0.13139	322	0.10068	312.6	0.08627	303.2	0.08619
340.6	0.17082	331.2	0.13093	321.8	0.10052	312.4	0.0865	303	0.0863
340.4	0.16991	331	0.12982	321.6	0.0999	312.2	0.08642	302.8	0.08621
340.2	0.16879	330.8	0.12983	321.4	0.09913	312	0.08661	302.6	0.08591
340	0.1677	330.6	0.12864	321.2	0.09961	311.8	0.08675	302.4	0.08588
339.8	0.16706	330.4	0.12854	321	0.09786	311.6	0.08663	302.2	0.08503
339.6	0.16593	330.2	0.12735	320.8	0.09818	311.4	0.08683	302	0.08491
339.4	0.16482	330	0.12671	320.6	0.0972	311.2	0.0867	301.8	0.08491
339.2	0.16383	329.8	0.12645	320.4	0.09653	311	0.08693	301.6	0.0844
339	0.1632	329.6	0.1256	320.2	0.09625	310.8	0.08687	301.4	0.08407
338.8	0.1625	329.4	0.12521	320	0.09589	310.6	0.08721	301.2	0.08364
338.6	0.16151	329.2	0.12405	319.8	0.09559	310.4	0.08707	301	0.08346
338.4	0.16024	329	0.12345	319.6	0.09476	310.2	0.08727	300.8	0.08272
338.2	0.15939	328.8	0.12205	319.4	0.09462	310	0.08749	300.6	0.08253
338	0.15825	328.6	0.12164	319.2	0.09393	309.8	0.08748	300.4	0.08228
337.8	0.1575	328.4	0.12108	319	0.09319	309.6	0.08718	300.2	0.08207
337.6	0.15647	328.2	0.12061	318.8	0.09354	309.4	0.08764	300	0.08163
337.4	0.15566	328	0.11977	318.6	0.09326	309.2	0.08798		
337.2	0.15462	327.8	0.11922	318.4	0.0926	309	0.08806		
337	0.1536	327.6	0.11823	318.2	0.09243	308.8	0.08801		
336.8	0.15287	327.4	0.11778	318	0.09189	308.6	0.08823		
336.6	0.15196	327.2	0.11696	317.8	0.09137	308.4	0.08783		
336.4	0.15057	327	0.11606	317.6	0.09093	308.2	0.08803		
336.2	0.15026	326.8	0.11589	317.4	0.09039	308	0.08793		
336	0.14922	326.6	0.11499	317.2	0.09022	307.8	0.08864		
335.8	0.14846	326.4	0.11463	317	0.0894	307.6	0.08836		
335.6	0.14787	326.2	0.11337	316.8	0.08932	307.4	0.08868		
335.4	0.14723	326	0.11255	316.6	0.08909	307.2	0.08836		
335.2	0.14609	325.8	0.11257	316.4	0.08869	307	0.08908		
335	0.14521	325.6	0.11143	316.2	0.08905	306.8	0.08877		
334.8	0.14451	325.4	0.1109	316	0.08829	306.6	0.08879		

Table B.81: Extinction ε (E.) from *Bacteriochlorophyll a* related to the wavelength [Prahl, 2012]

B.2 Chlorophyll a

λ [nm]	E.	λ [nm]	E.	λ [nm]	E.	λ [nm]	E.	λ [nm]	E.
700	0.011102	689	0.028801	678	0.108359	667	0.349302	656	0.406335
699.75	0.012773	688.75	0.03029	677.75	0.111201	666.75	0.359058	655.75	0.404274
699.5	0.009507	688.5	0.028092	677.5	0.115533	666.5	0.361685	655.5	0.400605
699.25	0.009055	688.25	0.029478	677.25	0.120175	666.25	0.364647	655.25	0.398444
699	0.013058	688	0.032454	677	0.122062	666	0.366547	655	0.393567
698.75	0.011323	687.75	0.0316	676.75	0.128732	665.75	0.371479	654.75	0.391089
698.5	0.016142	687.5	0.030569	676.5	0.133124	665.5	0.376122	654.5	0.387902
698.25	0.013825	687.25	0.033614	676.25	0.135289	665.25	0.382253	654.25	0.385219
698	0.014092	687	0.033056	676	0.143181	665	0.38357	654	0.384677
697.75	0.014916	686.75	0.035456	675.75	0.146728	664.75	0.386062	653.75	0.381279
697.5	0.01327	686.5	0.034371	675.5	0.154399	664.5	0.389521	653.5	0.379357
697.25	0.012718	686.25	0.034924	675.25	0.158548	664.25	0.390214	653.25	0.374082
697	0.011747	686	0.036508	675	0.162614	664	0.393439	653	0.372797
696.75	0.017019	685.75	0.038369	674.75	0.169077	663.75	0.397152	652.75	0.364104
696.5	0.014558	685.5	0.038642	674.5	0.172066	663.5	0.400513	652.5	0.358287
696.25	0.015086	685.25	0.039591	674.25	0.181865	663.25	0.4032	652.25	0.352275
696	0.015167	685	0.041711	674	0.185322	663	0.405715	652	0.349588
695.75	0.015634	684.75	0.042622	673.75	0.193457	662.75	0.40602	651.75	0.341984
695.5	0.016071	684.5	0.045786	673.5	0.197645	662.5	0.406542	651.5	0.339955
695.25	0.016243	684.25	0.042781	673.25	0.206827	662.25	0.413266	651.25	0.339943
695	0.016063	684	0.048693	673	0.214914	662	0.409955	651	0.330749
694.75	0.019114	683.75	0.049714	672.75	0.219015	661.75	0.412385	650.75	0.325653
694.5	0.014815	683.5	0.048672	672.5	0.227647	661.5	0.414946	650.5	0.323995
694.25	0.01937	683.25	0.051138	672.25	0.237066	661.25	0.415069	650.25	0.314745
694	0.019408	683	0.05574	672	0.237977	661	0.414685	650	0.313027
693.75	0.020909	682.75	0.055808	671.75	0.245361	660.75	0.41659	649.75	0.3056
693.5	0.018651	682.5	0.056038	671.5	0.254572	660.5	0.416712	649.5	0.300543
693.25	0.018581	682.25	0.059292	671.25	0.258282	660.25	0.418716	649.25	0.293029
693	0.019011	682	0.06096	671	0.265996	660	0.418444	649	0.292377
692.75	0.019164	681.75	0.063405	670.75	0.273775	659.75	0.419762	648.75	0.28253
692.5	0.020851	681.5	0.066379	670.5	0.281168	659.5	0.419157	648.5	0.280305
692.25	0.019041	681.25	0.068239	670.25	0.287697	659.25	0.421693	648.25	0.27784
692	0.02269	681	0.069303	670	0.287851	659	0.418317	648	0.27272
691.75	0.025885	680.75	0.07221	669.75	0.297664	658.75	0.416748	647.75	0.269389
691.5	0.020369	680.5	0.074414	669.5	0.299786	658.5	0.417519	647.5	0.2645
691.25	0.023341	680.25	0.077856	669.25	0.307482	658.25	0.418452	647.25	0.262931
691	0.025357	680	0.082575	669	0.310683	658	0.416993	647	0.25536
690.75	0.021725	679.75	0.084741	668.75	0.31851	657.75	0.415837	646.75	0.248513
690.5	0.025853	679.5	0.085929	668.5	0.325491	657.5	0.412837	646.5	0.245672
690.25	0.021941	679.25	0.087935	668.25	0.329617	657.25	0.414483	646.25	0.240563
690	0.026205	679	0.094452	668	0.333757	657	0.411488	646	0.236131
689.75	0.026647	678.75	0.093869	667.75	0.338083	656.75	0.408461	645.75	0.228548
689.5	0.025518	678.5	0.101954	667.5	0.346454	656.5	0.406627	645.5	0.224153
689.25	0.025972	678.25	0.104665	667.25	0.347717	656.25	0.406663	645.25	0.221201

Table B.82: Extinction ε (E.) from *Chlorophyll a* related to the wavelength [Prahl, 2012]

B EXTINCTION - ORIGINAL DATA

λ [nm]	E.	λ [nm]	E.	λ [nm]	E.	λ [nm]	E.	λ [nm]	E.
645	0.215587	633.25	0.094082	621.5	0.086506	609.75	0.114433	598	0.10362
644.75	0.210436	633	0.090191	621.25	0.086651	609.5	0.113983	597.75	0.101278
644.5	0.204103	632.75	0.091483	621	0.088165	609.25	0.112363	597.5	0.100601
644.25	0.20222	632.5	0.091885	620.75	0.08765	609	0.114534	597.25	0.099703
644	0.198686	632.25	0.091735	620.5	0.088249	608.75	0.114937	597	0.099572
643.75	0.192028	632	0.090235	620.25	0.089191	608.5	0.117118	596.75	0.097945
643.5	0.187003	631.75	0.088146	620	0.087979	608.25	0.114991	596.5	0.097989
643.25	0.184278	631.5	0.087952	619.75	0.091961	608	0.1162	596.25	0.097361
643	0.179904	631.25	0.086142	619.5	0.090404	607.75	0.115691	596	0.095347
642.75	0.178941	631	0.085785	619.25	0.090068	607.5	0.114668	595.75	0.093779
642.5	0.17289	630.75	0.086341	619	0.092649	607.25	0.113258	595.5	0.093948
642.25	0.170892	630.5	0.083849	618.75	0.092829	607	0.116552	595.25	0.094187
642	0.164152	630.25	0.085627	618.5	0.092274	606.75	0.113836	595	0.093803
641.75	0.162518	630	0.085843	618.25	0.09277	606.5	0.116119	594.75	0.091778
641.5	0.159153	629.75	0.086291	618	0.09588	606.25	0.116164	594.5	0.092033
641.25	0.154273	629.5	0.086345	617.75	0.094006	606	0.115066	594.25	0.089707
641	0.149961	629.25	0.084684	617.5	0.095666	605.75	0.115655	594	0.08863
640.75	0.149476	629	0.086249	617.25	0.095684	605.5	0.113865	593.75	0.088098
640.5	0.145542	628.75	0.084619	617	0.096138	605.25	0.116503	593.5	0.087063
640.25	0.140304	628.5	0.083928	616.75	0.097404	605	0.115775	593.25	0.086249
640	0.140924	628.25	0.08321	616.5	0.0958	604.75	0.115805	593	0.084279
639.75	0.135348	628	0.085282	616.25	0.097812	604.5	0.115906	592.75	0.083851
639.5	0.13133	627.75	0.08651	616	0.100871	604.25	0.114544	592.5	0.084919
639.25	0.130154	627.5	0.083568	615.75	0.099422	604	0.116787	592.25	0.082185
639	0.127268	627.25	0.082978	615.5	0.099783	603.75	0.114889	592	0.08105
638.75	0.125143	627	0.082409	615.25	0.099484	603.5	0.116348	591.75	0.079974
638.5	0.123646	626.75	0.083395	615	0.102614	603.25	0.115158	591.5	0.078855
638.25	0.123526	626.5	0.080476	614.75	0.101039	603	0.11379	591.25	0.076104
638	0.120109	626.25	0.08385	614.5	0.100393	602.75	0.112558	591	0.076214
637.75	0.120883	626	0.082742	614.25	0.102781	602.5	0.114567	590.75	0.076642
637.5	0.118095	625.75	0.084122	614	0.102038	602.25	0.112716	590.5	0.077156
637.25	0.115316	625.5	0.086173	613.75	0.101717	602	0.110525	590.25	0.076193
637	0.114361	625.25	0.084141	613.5	0.1051	601.75	0.110998	590	0.07379
636.75	0.11267	625	0.08351	613.25	0.105297	601.5	0.110444	589.75	0.072837
636.5	0.111127	624.75	0.085727	613	0.105811	601.25	0.108872	589.5	0.073651
636.25	0.10951	624.5	0.084642	612.75	0.106547	601	0.112487	589.25	0.072355
636	0.107053	624.25	0.086736	612.5	0.110282	600.75	0.109995	589	0.073826
635.75	0.103005	624	0.084301	612.25	0.109184	600.5	0.108771	588.75	0.071488
635.5	0.103051	623.75	0.084694	612	0.108625	600.25	0.108617	588.5	0.071529
635.25	0.102305	623.5	0.083656	611.75	0.109258	600	0.10907	588.25	0.070903
635	0.10352	623.25	0.085072	611.5	0.11145	599.75	0.107674	588	0.068795
634.75	0.103147	623	0.085157	611.25	0.110342	599.5	0.107413	587.75	0.067292
634.5	0.093638	622.75	0.086668	611	0.111509	599.25	0.107547	587.5	0.066753
634.25	0.097075	622.5	0.088713	610.75	0.110196	599	0.107795	587.25	0.067949
634	0.094975	622.25	0.086033	610.5	0.112176	598.75	0.104747	587	0.066579
633.75	0.094997	622	0.08803	610.25	0.113147	598.5	0.103906	586.75	0.065932
633.5	0.094536	621.75	0.085952	610	0.111817	598.25	0.104288	586.5	0.065633

Table B.83: Extinction ε (E.) from *Chlorophyll a* related to the wavelength [Prahl, 2012]

B EXTINCTION - ORIGINAL DATA

λ [nm]	E.	λ [nm]	E.	λ [nm]	E.	λ [nm]	E.	λ [nm]	E.
586.25	0.064599	574.5	0.069707	562.75	0.080479	551	0.070764	539.25	0.096832
586	0.066308	574.25	0.072446	562.5	0.078935	550.75	0.071346	539	0.095315
585.75	0.064852	574	0.073645	562.25	0.079412	550.5	0.071068	538.75	0.097393
585.5	0.066269	573.75	0.073067	562	0.079972	550.25	0.069478	538.5	0.098275
585.25	0.064935	573.5	0.072728	561.75	0.079551	550	0.072176	538.25	0.098107
585	0.064484	573.25	0.074193	561.5	0.078074	549.75	0.06944	538	0.100773
584.75	0.063627	573	0.071059	561.25	0.080274	549.5	0.069195	537.75	0.1024
584.5	0.064545	572.75	0.077202	561	0.079488	549.25	0.071308	537.5	0.101213
584.25	0.064069	572.5	0.073648	560.75	0.080184	549	0.073039	537.25	0.101435
584	0.062177	572.25	0.074449	560.5	0.07965	548.75	0.070568	537	0.101525
583.75	0.062741	572	0.075133	560.25	0.0799	548.5	0.071332	536.75	0.100376
583.5	0.061653	571.75	0.075551	560	0.079128	548.25	0.071357	536.5	0.102075
583.25	0.063553	571.5	0.076289	559.75	0.078372	548	0.071933	536.25	0.101854
583	0.061255	571.25	0.077404	559.5	0.078322	547.75	0.071349	536	0.103396
582.75	0.062872	571	0.079273	559.25	0.077044	547.5	0.074106	535.75	0.103939
582.5	0.061759	570.75	0.075904	559	0.077698	547.25	0.074993	535.5	0.10375
582.25	0.062559	570.5	0.080586	558.75	0.076028	547	0.073813	535.25	0.104672
582	0.061163	570.25	0.078334	558.5	0.076304	546.75	0.073528	535	0.104207
581.75	0.062267	570	0.077633	558.25	0.077002	546.5	0.074015	534.75	0.104608
581.5	0.064968	569.75	0.079963	558	0.076492	546.25	0.073854	534.5	0.102944
581.25	0.063441	569.5	0.080167	557.75	0.075138	546	0.075643	534.25	0.104355
581	0.064055	569.25	0.079517	557.5	0.077264	545.75	0.074756	534	0.103977
580.75	0.063709	569	0.080237	557.25	0.076412	545.5	0.078283	533.75	0.102259
580.5	0.064514	568.75	0.079269	557	0.074817	545.25	0.077988	533.5	0.101458
580.25	0.063025	568.5	0.080039	556.75	0.074447	545	0.078465	533.25	0.100182
580	0.062995	568.25	0.079652	556.5	0.07401	544.75	0.080239	533	0.098934
579.75	0.063191	568	0.07933	556.25	0.074059	544.5	0.079186	532.75	0.10181
579.5	0.063224	567.75	0.080657	556	0.073831	544.25	0.078848	532.5	0.09988
579.25	0.063098	567.5	0.081067	555.75	0.072264	544	0.080928	532.25	0.098536
579	0.064858	567.25	0.078014	555.5	0.075661	543.75	0.080961	532	0.098171
578.75	0.065934	567	0.079128	555.25	0.073898	543.5	0.085325	531.75	0.09955
578.5	0.067029	566.75	0.081763	555	0.075036	543.25	0.082203	531.5	0.099039
578.25	0.064807	566.5	0.081013	554.75	0.072448	543	0.085249	531.25	0.099174
578	0.065933	566.25	0.081109	554.5	0.072694	542.75	0.08394	531	0.096275
577.75	0.062987	566	0.080095	554.25	0.075372	542.5	0.085493	530.75	0.097159
577.5	0.065524	565.75	0.080914	554	0.07344	542.25	0.086162	530.5	0.095771
577.25	0.0671	565.5	0.080606	553.75	0.073651	542	0.087707	530.25	0.095899
577	0.067224	565.25	0.080408	553.5	0.072243	541.75	0.08862	530	0.095648
576.75	0.068946	565	0.080388	553.25	0.07109	541.5	0.089758	529.75	0.095261
576.5	0.068446	564.75	0.081734	553	0.072048	541.25	0.090901	529.5	0.094347
576.25	0.067295	564.5	0.081326	552.75	0.071257	541	0.091016	529.25	0.09482
576	0.069347	564.25	0.079427	552.5	0.070886	540.75	0.092756	529	0.091573
575.75	0.067839	564	0.080175	552.25	0.072161	540.5	0.091298	528.75	0.093076
575.5	0.070226	563.75	0.0816	552	0.070626	540.25	0.093349	528.5	0.091493
575.25	0.06998	563.5	0.081184	551.75	0.071924	540	0.094063	528.25	0.089789
575	0.069713	563.25	0.079729	551.5	0.071813	539.75	0.095154	528	0.088203
574.75	0.070737	563	0.080514	551.25	0.07121	539.5	0.095038	527.75	0.089263

Table B.84: Extinction ε (E.) from *Chlorophyll a* related to the wavelength [Prah, 2012]

B EXTINCTION - ORIGINAL DATA

λ [nm]	E.	λ [nm]	E.	λ [nm]	E.	λ [nm]	E.	λ [nm]	E.
527.5	0.087254	515.75	0.072487	504	0.079956	492.25	0.056036	480.5	0.041304
527.25	0.088066	515.5	0.071976	503.75	0.077701	492	0.055239	480.25	0.043411
527	0.086397	515.25	0.072196	503.5	0.076329	491.75	0.054449	480	0.04402
526.75	0.085859	515	0.074386	503.25	0.076936	491.5	0.054888	479.75	0.042329
526.5	0.087349	514.75	0.074101	503	0.077606	491.25	0.054852	479.5	0.0449
526.25	0.085754	514.5	0.073014	502.75	0.076561	491	0.055284	479.25	0.043181
526	0.083181	514.25	0.071667	502.5	0.07558	490.75	0.051544	479	0.044819
525.75	0.085269	514	0.073084	502.25	0.076544	490.5	0.051826	478.75	0.043954
525.5	0.0845	513.75	0.075118	502	0.076516	490.25	0.051735	478.5	0.044501
525.25	0.082592	513.5	0.072783	501.75	0.075059	490	0.053048	478.25	0.041563
525	0.081552	513.25	0.074726	501.5	0.074987	489.75	0.051438	478	0.040761
524.75	0.084096	513	0.073308	501.25	0.072814	489.5	0.052418	477.75	0.041953
524.5	0.081083	512.75	0.07512	501	0.074731	489.25	0.05189	477.5	0.041461
524.25	0.080593	512.5	0.07444	500.75	0.074449	489	0.050601	477.25	0.043113
524	0.079918	512.25	0.07531	500.5	0.074673	488.75	0.050464	477	0.043699
523.75	0.081262	512	0.074403	500.25	0.073865	488.5	0.04926	476.75	0.042543
523.5	0.079962	511.75	0.07482	500	0.074007	488.25	0.049631	476.5	0.042501
523.25	0.078757	511.5	0.074884	499.75	0.072493	488	0.046867	476.25	0.041436
523	0.079433	511.25	0.075471	499.5	0.072966	487.75	0.048602	476	0.042995
522.75	0.077814	511	0.077701	499.25	0.071169	487.5	0.046585	475.75	0.042592
522.5	0.078959	510.75	0.077846	499	0.070967	487.25	0.047845	475.5	0.041897
522.25	0.075683	510.5	0.078806	498.75	0.071026	487	0.046947	475.25	0.042253
522	0.078109	510.25	0.078318	498.5	0.069162	486.75	0.045901	475	0.041216
521.75	0.075919	510	0.078184	498.25	0.070202	486.5	0.04629	474.75	0.042653
521.5	0.074846	509.75	0.078763	498	0.069307	486.25	0.048265	474.5	0.041666
521.25	0.07631	509.5	0.07814	497.75	0.068671	486	0.047879	474.25	0.042709
521	0.074308	509.25	0.078457	497.5	0.067601	485.75	0.046214	474	0.041387
520.75	0.077008	509	0.079177	497.25	0.06858	485.5	0.045534	473.75	0.042602
520.5	0.07458	508.75	0.080732	497	0.066607	485.25	0.045488	473.5	0.043449
520.25	0.076566	508.5	0.079587	496.75	0.066195	485	0.044995	473.25	0.042784
520	0.074511	508.25	0.083392	496.5	0.065893	484.75	0.045988	473	0.043017
519.75	0.075034	508	0.080774	496.25	0.066829	484.5	0.044559	472.75	0.041756
519.5	0.073121	507.75	0.081308	496	0.065711	484.25	0.044252	472.5	0.042973
519.25	0.072089	507.5	0.07909	495.75	0.066386	484	0.042991	472.25	0.041447
519	0.071148	507.25	0.081005	495.5	0.062662	483.75	0.04449	472	0.040834
518.75	0.07369	507	0.081133	495.25	0.063198	483.5	0.043904	471.75	0.042886
518.5	0.073188	506.75	0.08	495	0.062376	483.25	0.043738	471.5	0.042989
518.25	0.074507	506.5	0.08059	494.75	0.062209	483	0.044113	471.25	0.042857
518	0.073446	506.25	0.080914	494.5	0.059975	482.75	0.042179	471	0.042802
517.75	0.072599	506	0.079616	494.25	0.059189	482.5	0.04361	470.75	0.043072
517.5	0.073773	505.75	0.07945	494	0.059637	482.25	0.042652	470.5	0.042385
517.25	0.074461	505.5	0.077499	493.75	0.059275	482	0.043035	470.25	0.041353
517	0.073311	505.25	0.080724	493.5	0.058718	481.75	0.043605	470	0.040729
516.75	0.070767	505	0.080544	493.25	0.059064	481.5	0.043451	469.75	0.041077
516.5	0.07256	504.75	0.079074	493	0.057349	481.25	0.044392	469.5	0.041502
516.25	0.072856	504.5	0.080184	492.75	0.058123	481	0.045651	469.25	0.042095
516	0.074705	504.25	0.081054	492.5	0.056076	480.75	0.044269	469	0.039467

Table B.85: Extinction ε (E.) from *Chlorophyll a* related to the wavelength [Prahl, 2012]

λ [nm]	E.	λ [nm]	E.	λ [nm]	E.	λ [nm]	E.	λ [nm]	E.
468.75	0.042589	457	0.044713	445.25	0.094679	433.5	0.372654	421.75	1.297066
468.5	0.042532	456.75	0.045691	445	0.10141	433.25	0.385782	421.5	1.308416
468.25	0.042593	456.5	0.046691	444.75	0.099879	433	0.399227	421.25	1.321636
468	0.041659	456.25	0.047176	444.5	0.101489	432.75	0.417863	421	1.338078
467.75	0.041425	456	0.046689	444.25	0.103875	432.5	0.431255	420.75	1.355169
467.5	0.04083	455.75	0.0492	444	0.108671	432.25	0.444204	420.5	1.36085
467.25	0.040486	455.5	0.047539	443.75	0.108818	432	0.457835	420.25	1.371746
467	0.041811	455.25	0.050277	443.5	0.109075	431.75	0.479194	420	1.374953
466.75	0.042452	455	0.049636	443.25	0.115128	431.5	0.494037	419.75	1.390728
466.5	0.041663	454.75	0.049462	443	0.115551	431.25	0.514576	419.5	1.396421
466.25	0.041075	454.5	0.050271	442.75	0.122467	431	0.529125	419.25	1.407561
466	0.041199	454.25	0.049024	442.5	0.124839	430.75	0.547862	419	1.416368
465.75	0.040986	454	0.052627	442.25	0.12352	430.5	0.564632	418.75	1.414014
465.5	0.040742	453.75	0.05427	442	0.127531	430.25	0.586565	418.5	1.42252
465.25	0.041067	453.5	0.052966	441.75	0.129455	430	0.605456	418.25	1.422329
465	0.04138	453.25	0.054229	441.5	0.133127	429.75	0.629038	418	1.422354
464.75	0.041415	453	0.055535	441.25	0.136058	429.5	0.649883	417.75	1.434644
464.5	0.041095	452.75	0.05457	441	0.141473	429.25	0.667144	417.5	1.430591
464.25	0.040375	452.5	0.056431	440.75	0.145932	429	0.687552	417.25	1.432708
464	0.042156	452.25	0.057737	440.5	0.146397	428.75	0.714125	417	1.421373
463.75	0.040776	452	0.058866	440.25	0.151923	428.5	0.733708	416.75	1.424429
463.5	0.042159	451.75	0.058744	440	0.154752	428.25	0.755026	416.5	1.416689
463.25	0.040841	451.5	0.060426	439.75	0.157134	428	0.779146	416.25	1.413341
463	0.041312	451.25	0.060616	439.5	0.163192	427.75	0.801865	416	1.413426
462.75	0.040603	451	0.062843	439.25	0.168223	427.5	0.824279	415.75	1.411218
462.5	0.04034	450.75	0.064658	439	0.17595	427.25	0.848503	415.5	1.407476
462.25	0.041143	450.5	0.064044	438.75	0.177659	427	0.873578	415.25	1.393344
462	0.039424	450.25	0.065597	438.5	0.183421	426.75	0.892989	415	1.391405
461.75	0.042819	450	0.066764	438.25	0.188556	426.5	0.91127	414.75	1.381882
461.5	0.041531	449.75	0.065925	438	0.193944	426.25	0.938729	414.5	1.37642
461.25	0.041026	449.5	0.071529	437.75	0.197521	426	0.961532	414.25	1.366967
461	0.039459	449.25	0.068758	437.5	0.205472	425.75	0.982128	414	1.35067
460.75	0.043184	449	0.070132	437.25	0.214333	425.5	1.010326	413.75	1.347816
460.5	0.042117	448.75	0.07238	437	0.220222	425.25	1.030616	413.5	1.343173
460.25	0.043045	448.5	0.075415	436.75	0.228488	425	1.051551	413.25	1.326268
460	0.041918	448.25	0.07384	436.5	0.235224	424.75	1.06803	413	1.318008
459.75	0.042611	448	0.076863	436.25	0.245794	424.5	1.093459	412.75	1.309519
459.5	0.041586	447.75	0.079933	436	0.253279	424.25	1.116436	412.5	1.29546
459.25	0.040479	447.5	0.079682	435.75	0.26249	424	1.136495	412.25	1.289708
459	0.041868	447.25	0.082235	435.5	0.274387	423.75	1.15166	412	1.27985
458.75	0.043495	447	0.084268	435.25	0.281594	423.5	1.172763	411.75	1.276736
458.5	0.043149	446.75	0.086876	435	0.294362	423.25	1.191369	411.5	1.259332
458.25	0.042746	446.5	0.086157	434.75	0.307654	423	1.210527	411.25	1.245128
458	0.044645	446.25	0.086473	434.5	0.318428	422.75	1.227507	411	1.237993
457.75	0.043729	446	0.090574	434.25	0.331725	422.5	1.248505	410.75	1.223487
457.5	0.047165	445.75	0.091252	434	0.344014	422.25	1.260407	410.5	1.213726
457.25	0.044397	445.5	0.096405	433.75	0.358213	422	1.27998	410.25	1.19907

Table B.86: Extinction ε (E.) from *Chlorophyll a* related to the wavelength [Prah, 2012]

B EXTINCTION - ORIGINAL DATA

λ [nm]	E.	λ [nm]	E.	λ [nm]	E.	λ [nm]	E.	λ [nm]	E.
410	1.191065	398.25	0.952415	386.5	0.663729	374.75	0.519511	363	0.401371
409.75	1.181276	398	0.951224	386.25	0.66084	374.5	0.519256	362.75	0.403305
409.5	1.17253	397.75	0.947127	386	0.649915	374.25	0.51331	362.5	0.400149
409.25	1.153793	397.5	0.943169	385.75	0.641044	374	0.510875	362.25	0.398641
409	1.15187	397.25	0.936181	385.5	0.642131	373.75	0.5062	362	0.393439
408.75	1.142764	397	0.932488	385.25	0.63681	373.5	0.503849	361.75	0.393218
408.5	1.130807	396.75	0.929048	385	0.632472	373.25	0.508343	361.5	0.385753
408.25	1.123879	396.5	0.923244	384.75	0.62767	373	0.499901	361.25	0.389653
408	1.114384	396.25	0.918052	384.5	0.620906	372.75	0.501612	361	0.380301
407.75	1.105854	396	0.914032	384.25	0.61978	372.5	0.495275	360.75	0.383722
407.5	1.094944	395.75	0.910927	384	0.617973	372.25	0.492159	360.5	0.383309
407.25	1.086218	395.5	0.908987	383.75	0.613612	372	0.496059	360.25	0.372064
407	1.081018	395.25	0.901331	383.5	0.605957	371.75	0.49795	360	0.373386
406.75	1.073428	395	0.894698	383.25	0.603716	371.5	0.488886	359.75	0.371658
406.5	1.066776	394.75	0.892367	383	0.599662	371.25	0.491654	359.5	0.370873
406.25	1.058985	394.5	0.88449	382.75	0.600225	371	0.4835	359.25	0.367417
406	1.055471	394.25	0.877766	382.5	0.598675	370.75	0.481534	359	0.363302
405.75	1.049306	394	0.873886	382.25	0.58905	370.5	0.48266	358.75	0.36359
405.5	1.043448	393.75	0.865306	382	0.587522	370.25	0.476762	358.5	0.355118
405.25	1.050865	393.5	0.85657	381.75	0.587931	370	0.475372	358.25	0.360074
405	1.040854	393.25	0.847011	381.5	0.579064	369.75	0.468629	358	0.356809
404.75	1.029464	393	0.839304	381.25	0.579852	369.5	0.467353	357.75	0.349997
404.5	1.024583	392.75	0.831255	381	0.576212	369.25	0.465912	357.5	0.345194
404.25	1.022514	392.5	0.82763	380.75	0.574434	369	0.468043	357.25	0.352307
404	1.018432	392.25	0.815081	380.5	0.569314	368.75	0.460166	357	0.347066
403.75	1.017809	392	0.811783	380.25	0.568541	368.5	0.460532	356.75	0.346322
403.5	1.015675	391.75	0.802845	380	0.568492	368.25	0.458279	356.5	0.339931
403.25	1.011633	391.5	0.795994	379.75	0.561826	368	0.45613	356.25	0.337553
403	1.007754	391.25	0.791864	379.5	0.565037	367.75	0.452843	356	0.334161
402.75	1.000842	391	0.77947	379.25	0.557784	367.5	0.448109	355.75	0.334263
402.5	0.993619	390.75	0.780521	379	0.559086	367.25	0.450168	355.5	0.334281
402.25	0.999313	390.5	0.765436	378.75	0.553926	367	0.444199	355.25	0.331164
402	0.995009	390.25	0.75891	378.5	0.551756	366.75	0.446414	355	0.329642
401.75	0.989586	390	0.752014	378.25	0.550526	366.5	0.442628	354.75	0.32861
401.5	0.986495	389.75	0.743258	378	0.54045	366.25	0.43835	354.5	0.328844
401.25	0.986617	389.5	0.736036	377.75	0.545503	366	0.435701	354.25	0.319968
401	0.979585	389.25	0.732356	377.5	0.541432	365.75	0.433284	354	0.324643
400.75	0.981948	389	0.724526	377.25	0.539178	365.5	0.433018	353.75	0.31663
400.5	0.982108	388.75	0.719942	377	0.535642	365.25	0.42854	353.5	0.320728
400.25	0.981142	388.5	0.709673	376.75	0.53583	365	0.429116	353.25	0.322169
400	0.96948	388.25	0.704465	376.5	0.535414	364.75	0.42426	353	0.306843
399.75	0.970268	388	0.70258	376.25	0.529838	364.5	0.421027	352.75	0.314062
399.5	0.963661	387.75	0.694521	376	0.529148	364.25	0.415941	352.5	0.315124
399.25	0.962188	387.5	0.686721	375.75	0.527179	364	0.412079	352.25	0.312081
399	0.96399	387.25	0.676887	375.5	0.522815	363.75	0.414157	352	0.309657
398.75	0.960517	387	0.670525	375.25	0.522558	363.5	0.412089	351.75	0.305153
398.5	0.957679	386.75	0.664345	375	0.519923	363.25	0.408727	351.5	0.301705

Table B.87: Extinction ε (E.) from *Chlorophyll a* related to the wavelength [Prahl, 2012]

λ [nm]	E.	λ [nm]	E.	λ [nm]	E.	λ [nm]	E.	λ [nm]	E.
351.25	0.299094	339.5	0.24833	327.75	0.260851	316	0.273436	304.25	0.229209
351	0.303327	339.25	0.256512	327.5	0.256134	315.75	0.26103	304	0.231272
350.75	0.303384	339	0.251427	327.25	0.261952	315.5	0.272929	303.75	0.233641
350.5	0.302354	338.75	0.257339	327	0.262659	315.25	0.262343	303.5	0.227107
350.25	0.295532	338.5	0.248058	326.75	0.259939	315	0.266368	303.25	0.231503
350	0.294161	338.25	0.254544	326.5	0.261319	314.75	0.266176	303	0.233745
349.75	0.291192	338	0.254885	326.25	0.264313	314.5	0.263615	302.75	0.228339
349.5	0.288129	337.75	0.252045	326	0.271873	314.25	0.266187	302.5	0.233159
349.25	0.300101	337.5	0.253488	325.75	0.270516	314	0.262314	302.25	0.231745
349	0.292089	337.25	0.251137	325.5	0.262363	313.75	0.262561	302	0.22978
348.75	0.284096	337	0.256649	325.25	0.264497	313.5	0.260643	301.75	0.228879
348.5	0.288205	336.75	0.249746	325	0.26187	313.25	0.2562	301.5	0.226076
348.25	0.289308	336.5	0.248748	324.75	0.269844	313	0.260147	301.25	0.227907
348	0.279359	336.25	0.249667	324.5	0.267211	312.75	0.256055	301	0.227544
347.75	0.284549	336	0.25378	324.25	0.270205	312.5	0.25437	300.75	0.219141
347.5	0.278217	335.75	0.242233	324	0.266274	312.25	0.260924	300.5	0.223537
347.25	0.280722	335.5	0.256858	323.75	0.271663	312	0.259376	300.25	0.219541
347	0.278606	335.25	0.253062	323.5	0.265779	311.75	0.25985	300	0.225472
346.75	0.284733	335	0.253069	323.25	0.26126	311.5	0.249471	299.75	0.220842
346.5	0.276129	334.75	0.248408	323	0.269627	311.25	0.25741	299.5	0.225857
346.25	0.271961	334.5	0.255404	322.75	0.269758	311	0.257551	299.25	0.224373
346	0.27131	334.25	0.254074	322.5	0.262273	310.75	0.254386	299	0.222472
345.75	0.26538	334	0.25608	322.25	0.265842	310.5	0.254862	298.75	0.217472
345.5	0.276935	333.75	0.242096	322	0.263762	310.25	0.255784	298.5	0.220529
345.25	0.268905	333.5	0.260244	321.75	0.266273	310	0.249368	298.25	0.220053
345	0.266981	333.25	0.257443	321.5	0.269999	309.75	0.24906	298	0.221675
344.75	0.271122	333	0.254624	321.25	0.265081	309.5	0.251402	297.75	0.218731
344.5	0.266045	332.75	0.257329	321	0.264434	309.25	0.249846	297.5	0.226187
344.25	0.263679	332.5	0.25596	320.75	0.272545	309	0.245556	297.25	0.222255
344	0.258925	332.25	0.257275	320.5	0.274533	308.75	0.252015	297	0.219103
343.75	0.263213	332	0.249483	320.25	0.275981	308.5	0.240353	296.75	0.218866
343.5	0.258849	331.75	0.256064	320	0.265662	308.25	0.248287	296.5	0.220686
343.25	0.259619	331.5	0.254935	319.75	0.275156	308	0.24678	296.25	0.218892
343	0.261966	331.25	0.2588	319.5	0.267546	307.75	0.248644	296	0.21193
342.75	0.263657	331	0.25275	319.25	0.266369	307.5	0.24238	295.75	0.217823
342.5	0.26328	330.75	0.257197	319	0.271299	307.25	0.248466	295.5	0.21966
342.25	0.254585	330.5	0.258086	318.75	0.275794	307	0.246321	295.25	0.217803
342	0.260444	330.25	0.260223	318.5	0.267725	306.75	0.241985	295	0.224319
341.75	0.258367	330	0.255827	318.25	0.275423	306.5	0.2408	294.75	0.221852
341.5	0.260505	329.75	0.259029	318	0.274949	306.25	0.2359	294.5	0.222341
341.25	0.266701	329.5	0.254218	317.75	0.27098	306	0.243965	294.25	0.220535
341	0.254702	329.25	0.261507	317.5	0.269867	305.75	0.237836	294	0.225319
340.75	0.265364	329	0.252077	317.25	0.272632	305.5	0.235257	293.75	0.229708
340.5	0.261663	328.75	0.255867	317	0.265202	305.25	0.236071	293.5	0.227614
340.25	0.254559	328.5	0.257686	316.75	0.269243	305	0.229491	293.25	0.225724
340	0.253727	328.25	0.264916	316.5	0.27337	304.75	0.234151	293	0.227432
339.75	0.259713	328	0.262818	316.25	0.270601	304.5	0.235132	292.75	0.225575

Table B.88: Extinction ε (E.) from *Chlorophyll a* related to the wavelength [Prah, 2012]

B EXTINCTION - ORIGINAL DATA

λ [nm]	E.	λ [nm]	E.	λ [nm]	E.	λ [nm]	E.	λ [nm]	E.
292.5	0.227418	280.75	0.264209	269	0.245773	257.25	0.240351	245.5	0.349862
292.25	0.230463	280.5	0.257644	268.75	0.244137	257	0.247165	245.25	0.352363
292	0.230948	280.25	0.255415	268.5	0.245904	256.75	0.242183	245	0.357957
291.75	0.230801	280	0.253545	268.25	0.24396	256.5	0.250052	244.75	0.360848
291.5	0.231427	279.75	0.258639	268	0.242616	256.25	0.248924	244.5	0.365325
291.25	0.232737	279.5	0.260479	267.75	0.239675	256	0.25126	244.25	0.365528
291	0.231488	279.25	0.258431	267.5	0.245559	255.75	0.252538	244	0.371296
290.75	0.22979	279	0.254201	267.25	0.235754	255.5	0.256214	243.75	0.370704
290.5	0.236661	278.75	0.255473	267	0.235374	255.25	0.25287	243.5	0.381458
290.25	0.23303	278.5	0.26593	266.75	0.240285	255	0.263069	243.25	0.384419
290	0.236363	278.25	0.256854	266.5	0.243968	254.75	0.25774	243	0.38786
289.75	0.240262	278	0.264375	266.25	0.243122	254.5	0.255381	242.75	0.384362
289.5	0.23903	277.75	0.26137	266	0.239636	254.25	0.266216	242.5	0.390462
289.25	0.237976	277.5	0.260318	265.75	0.24162	254	0.270564	242.25	0.398632
289	0.238829	277.25	0.26049	265.5	0.236757	253.75	0.270362	242	0.413281
288.75	0.234679	277	0.261901	265.25	0.24177	253.5	0.274496	241.75	0.40356
288.5	0.244881	276.75	0.26394	265	0.237882	253.25	0.280954	241.5	0.414738
288.25	0.242575	276.5	0.266472	264.75	0.235714	253	0.274477	241.25	0.409499
288	0.238613	276.25	0.258869	264.5	0.235919	252.75	0.278893	241	0.414259
287.75	0.235858	276	0.258684	264.25	0.237162	252.5	0.283115	240.75	0.417058
287.5	0.238943	275.75	0.25959	264	0.233339	252.25	0.289375	240.5	0.425701
287.25	0.244481	275.5	0.262584	263.75	0.234862	252	0.291213	240.25	0.428063
287	0.23887	275.25	0.265121	263.5	0.23705	251.75	0.289297	240	0.432732
286.75	0.244879	275	0.263147	263.25	0.229371	251.5	0.289812	239.75	0.430253
286.5	0.248368	274.75	0.258144	263	0.239073	251.25	0.291422	239.5	0.443009
286.25	0.246378	274.5	0.260808	262.75	0.24235	251	0.298432	239.25	0.435594
286	0.243237	274.25	0.256714	262.5	0.238706	250.75	0.298141	239	0.446354
285.75	0.242826	274	0.262469	262.25	0.240234	250.5	0.303961	238.75	0.446096
285.5	0.250242	273.75	0.258536	262	0.235247	250.25	0.304531	238.5	0.457551
285.25	0.241243	273.5	0.256582	261.75	0.240113	250	0.306751	238.25	0.460489
285	0.250641	273.25	0.258442	261.5	0.230419	249.75	0.31394	238	0.455987
284.75	0.247761	273	0.252878	261.25	0.237765	249.5	0.311109	237.75	0.471322
284.5	0.248133	272.75	0.256288	261	0.233881	249.25	0.314774	237.5	0.474682
284.25	0.24839	272.5	0.257032	260.75	0.230102	249	0.31603	237.25	0.46942
284	0.251719	272.25	0.251373	260.5	0.233853	248.75	0.316687	237	0.479875
283.75	0.25124	272	0.24808	260.25	0.231894	248.5	0.32024	236.75	0.478604
283.5	0.256957	271.75	0.25545	260	0.229944	248.25	0.325776	236.5	0.491938
283.25	0.251188	271.5	0.248757	259.75	0.233318	248	0.317128	236.25	0.496828
283	0.263056	271.25	0.252687	259.5	0.23207	247.75	0.321249	236	0.49992
282.75	0.248019	271	0.253996	259.25	0.235226	247.5	0.326997	235.75	0.508357
282.5	0.254361	270.75	0.251502	259	0.235857	247.25	0.324059	235.5	0.51045
282.25	0.252695	270.5	0.246791	258.75	0.237151	247	0.331448	235.25	0.524661
282	0.251693	270.25	0.247001	258.5	0.237187	246.75	0.329588	235	0.526887
281.75	0.253597	270	0.247281	258.25	0.238902	246.5	0.334098	234.75	0.519054
281.5	0.251609	269.75	0.252776	258	0.240203	246.25	0.337072	234.5	0.52213
281.25	0.252205	269.5	0.246229	257.75	0.243516	246	0.342422	234.25	0.534003
281	0.26202	269.25	0.249669	257.5	0.241551	245.75	0.349803	234	0.550577

Table B.89: Extinction ε (E.) from *Chlorophyll a* related to the wavelength [Prahl, 2012]

λ [nm]	E.	λ [nm]	E.	λ [nm]	E.	λ [nm]	E.	λ [nm]	E.
233.75	0.555824	230.75	0.620047	227.75	0.655799	225	0.698405	222.25	0.735236
233.5	0.556857	230.5	0.610865	227.5	0.653851	224.75	0.693225	222	0.737823
233.25	0.567973	230.25	0.628053	227.25	0.666567	224.5	0.709144	221.75	0.732109
233	0.56985	230	0.633249	227	0.669587	224.25	0.705414	221.5	0.750737
232.75	0.575586	229.75	0.635115	226.75	0.673405	224	0.710297	221.25	0.740679
232.5	0.582779	229.5	0.63066	226.5	0.68882	223.75	0.71586	221	0.749943
232.25	0.58372	229.25	0.638271	226.25	0.675661	223.5	0.726367	220.75	0.752347
232	0.595404	229	0.64011	226	0.685655	223.25	0.707757	220.5	0.751302
231.75	0.593654	228.75	0.637561	225.75	0.687755	223	0.734183	220.25	0.755899
231.5	0.601132	228.5	0.653936	225.5	0.683597	222.75	0.72973	220	0.755579
231.25	0.619766	228.25	0.653944	225.25	0.687507	222.5	0.734264	219.75	0.766642
231	0.61667	228	0.653543						

Table B.90: Extinction ε (E.) from *Chlorophyll a* related to the wavelength [Prah, 2012]

B.3 Chlorophyll b

λ [nm]	E.	λ [nm]	E.	λ [nm]	E.	λ [nm]	E.	λ [nm]	E.
300	0.20913	344	0.16572	388	0.0795	432	0.32273	476	0.06931
301	0.1657	345	0.16352	389	0.07666	433	0.32057	477	0.05932
302	0.16682	346	0.16076	390	0.07452	434	0.32002	478	0.050804
303	0.16803	347	0.15841	391	0.07287	435	0.32198	479	0.044031
304	0.16904	348	0.15623	392	0.07219	436	0.32606	480	0.038605
305	0.17005	349	0.15444	393	0.072	437	0.33428	481	0.034373
306	0.17088	350	0.15289	394	0.07293	438	0.34731	482	0.031254
307	0.17129	351	0.1516	395	0.07402	439	0.36532	483	0.028685
308	0.17164	352	0.15075	396	0.07579	440	0.38962	484	0.026415
309	0.17135	353	0.15009	397	0.07797	441	0.42137	485	0.024083
310	0.17081	354	0.14989	398	0.08	442	0.45685	486	0.022561
311	0.17036	355	0.14943	399	0.08212	443	0.49929	487	0.023891
312	0.16915	356	0.14919	400	0.08447	444	0.54731	488	0.022608
313	0.16758	357	0.14873	401	0.087	445	0.5999	489	0.021665
314	0.16626	358	0.1484	402	0.08894	446	0.65596	490	0.021512
315	0.16478	359	0.14759	403	0.09074	447	0.71053	491	0.021339
316	0.16338	360	0.14586	404	0.09303	448	0.76423	492	0.021319
317	0.1624	361	0.14339	405	0.09485	449	0.81322	493	0.02116
318	0.16169	362	0.14052	406	0.09707	450	0.85669	494	0.021087
319	0.16148	363	0.13748	407	0.10005	451	0.88773	495	0.020919
320	0.1618	364	0.13499	408	0.10313	452	0.90895	496	0.02099
321	0.16258	365	0.134	409	0.10715	453	0.91572	497	0.021238
322	0.16403	366	0.13403	410	0.11228	454	0.91047	498	0.021509
323	0.16556	367	0.13295	411	0.11806	455	0.89217	499	0.021116
324	0.16765	368	0.13136	412	0.12547	456	0.86322	500	0.021411
325	0.17	369	0.12914	413	0.13441	457	0.82384	501	0.021385
326	0.17232	370	0.12751	414	0.14472	458	0.77622	502	0.021401
327	0.17491	371	0.12579	415	0.15681	459	0.72419	503	0.021455
328	0.17711	372	0.12431	416	0.17076	460	0.67078	504	0.021403
329	0.1788	373	0.12369	417	0.18607	461	0.61476	505	0.021492
330	0.18012	374	0.12277	418	0.20291	462	0.55817	506	0.021394
331	0.18079	375	0.1222	419	0.22059	463	0.50055	507	0.021291
332	0.18123	376	0.12153	420	0.2392	464	0.44501	508	0.021328
333	0.18116	377	0.12066	421	0.25709	465	0.39519	509	0.021513
334	0.18096	378	0.11907	422	0.27352	466	0.34932	510	0.021565
335	0.18022	379	0.11651	423	0.28751	467	0.30586	511	0.02167
336	0.17927	380	0.11409	424	0.29994	468	0.26256	512	0.021445
337	0.17822	381	0.11077	425	0.31006	469	0.22663	513	0.021759
338	0.17703	382	0.10684	426	0.3176	470	0.19331	514	0.022014
339	0.17559	383	0.10221	427	0.32244	471	0.16317	515	0.022388
340	0.17391	384	0.09741	428	0.3253	472	0.13704	516	0.022493
341	0.17218	385	0.09234	429	0.32636	473	0.1149	517	0.022582
342	0.17029	386	0.08761	430	0.32561	474	0.09716	518	0.023118
343	0.16808	387	0.08337	431	0.32438	475	0.08182	519	0.023332

Table B.91: Extinction ε (E.) from *Chlorophyll b* related to the wavelength [Prahl, 2012]

λ [nm]	E.	λ [nm]	E.	λ [nm]	E.	λ [nm]	E.	λ [nm]	E.
520	0.023782	567	0.045116	614	0.048328	661	0.025247	708	0.002539
521	0.024307	568	0.045128	615	0.047741	662	0.022283	709	0.002546
522	0.024895	569	0.044974	616	0.047321	663	0.01991	710	0.00255
523	0.025163	570	0.044837	617	0.04682	664	0.017585	711	0.002602
524	0.026042	571	0.044723	618	0.04624	665	0.015684	712	0.002657
525	0.026622	572	0.044608	619	0.046311	666	0.014018	713	0.002732
526	0.027145	573	0.044609	620	0.046616	667	0.012935	714	0.002686
527	0.027835	574	0.044383	621	0.047598	668	0.011887	715	0.002601
528	0.028886	575	0.044665	622	0.048916	669	0.010919	716	0.002498
529	0.029912	576	0.044647	623	0.051114	670	0.010064	717	0.00248
530	0.030879	577	0.044989	624	0.054158	671	0.009539	718	0.002525
531	0.03168	578	0.045541	625	0.05822	672	0.00891	719	0.002407
532	0.032747	579	0.046718	626	0.06324	673	0.008557	720	0.002355
533	0.033586	580	0.047682	627	0.0696	674	0.00816	721	0.002332
534	0.034771	581	0.049173	628	0.07727	675	0.007802	722	0.002239
535	0.035413	582	0.050414	629	0.08642	676	0.00765	723	0.002218
536	0.036642	583	0.052388	630	0.09703	677	0.007287	724	0.002227
537	0.036967	584	0.054141	631	0.10969	678	0.007077	725	0.002215
538	0.037629	585	0.05566	632	0.12502	679	0.006696	726	0.002094
539	0.038463	586	0.05759	633	0.1423	680	0.006342	727	0.002017
540	0.038999	587	0.05911	634	0.16315	681	0.005996	728	0.002101
541	0.039419	588	0.0605	635	0.18642	682	0.005656	729	0.001984
542	0.039691	589	0.06192	636	0.21155	683	0.005366	730	0.001898
543	0.040165	590	0.0629	637	0.23758	684	0.004969	731	0.001881
544	0.040442	591	0.06389	638	0.26322	685	0.004685	732	0.001827
545	0.040743	592	0.0646	639	0.28629	686	0.004396	733	0.001819
546	0.040874	593	0.06468	640	0.30597	687	0.00412	734	0.001837
547	0.040905	594	0.06495	641	0.3204	688	0.003863	735	0.001623
548	0.040965	595	0.06469	642	0.32805	689	0.003764	736	0.001596
549	0.041041	596	0.06431	643	0.32836	690	0.003576	737	0.001545
550	0.041017	597	0.06334	644	0.32127	691	0.003319	738	0.001461
551	0.041007	598	0.06204	645	0.30607	692	0.003282	739	0.001469
552	0.040915	599	0.06026	646	0.28532	693	0.003095	740	0.001437
553	0.040979	600	0.05884	647	0.2599	694	0.003019	741	0.001487
554	0.041298	601	0.05708	648	0.23211	695	0.00289	742	0.001487
555	0.041448	602	0.0553	649	0.20289	696	0.002884	743	0.001503
556	0.041787	603	0.053533	650	0.17421	697	0.00285	744	0.001525
557	0.041983	604	0.052206	651	0.14702	698	0.002775	745	0.001535
558	0.042394	605	0.051066	652	0.12275	699	0.002644	746	0.001601
559	0.043019	606	0.050153	653	0.10161	700	0.002651	747	0.001682
560	0.043476	607	0.049939	654	0.08398	701	0.002653	748	0.001517
561	0.043957	608	0.049579	655	0.06663	702	0.002651	749	0.001548
562	0.044243	609	0.049432	656	0.053231	703	0.002582	750	0.001669
563	0.044514	610	0.049391	657	0.049846	704	0.002542	751	0.001562
564	0.044754	611	0.04938	658	0.040953	705	0.002473	752	0.001527
565	0.045017	612	0.049175	659	0.033813	706	0.00256	753	0.001479
566	0.045131	613	0.048821	660	0.029317	707	0.002578	754	0.001406

Table B.92: Extinction ε (E.) from *Chlorophyll g* related to the wavelength [Prah, 2012]

B EXTINCTION - ORIGINAL DATA

λ [nm]	E.	λ [nm]	E.	λ [nm]	E.	λ [nm]	E.	λ [nm]	E.
755	0.001387	765	0.001147	774	0.001004	783	0.000874	792	0.000844
756	0.001431	766	0.001136	775	0.00106	784	0.000791	793	0.000903
757	0.001338	767	0.001066	776	0.001036	785	0.000869	794	0.000968
758	0.001318	768	0.001232	777	0.000911	786	0.000901	795	0.0008
759	0.001269	769	0.001186	778	0.000913	787	0.000911	796	0.000819
760	0.001235	770	0.001067	779	0.000925	788	0.000878	797	0.000828
761	0.001204	771	0.001134	780	0.000868	789	0.000892	798	0.000803
762	0.001122	772	0.001062	781	0.000909	790	0.000861	799	0.000738
763	0.001221	773	0.00107	782	0.00092	791	0.000858	800	0.000791
764	0.001145								

Table B.93: Extinction ε (E.) from *Chlorophyll b* related to the wavelength [Prahl, 2012]

C Spectra

C.1 Application to Earth - Scenario 0

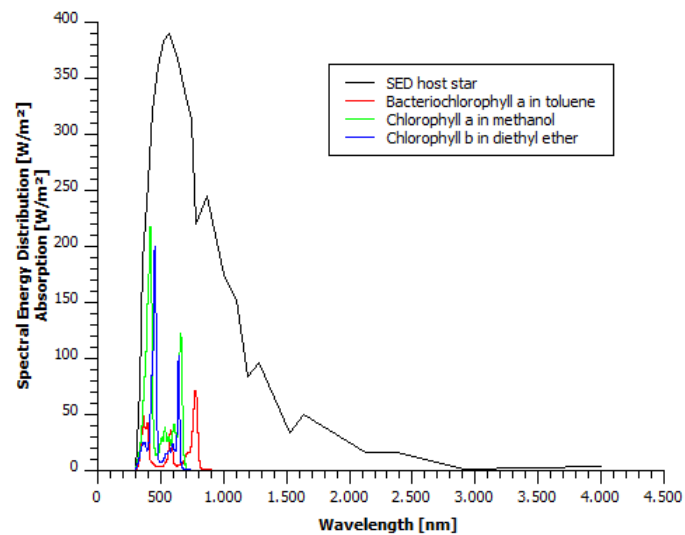


Figure C.48: Application to Earth, Scenario 0, G-star, Earth atmosphere, without clouds, 1 AU

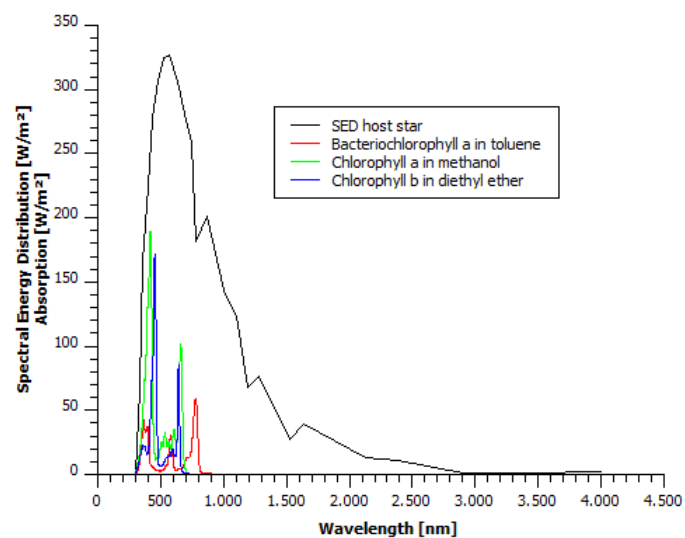


Figure C.49: Application to Earth, Scenario 0, G-star, Earth atmosphere, with clouds, 1 AU

C.2 G-Star

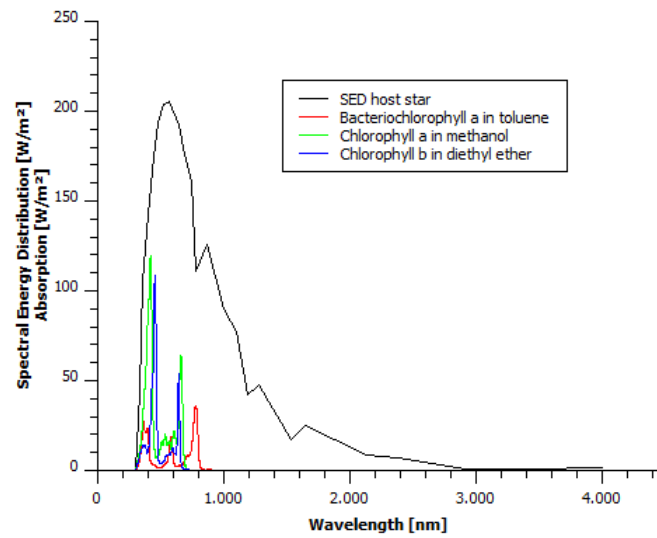


Figure C.50: Scenario 1, G-star, Earth atmosphere, with clouds, green zone

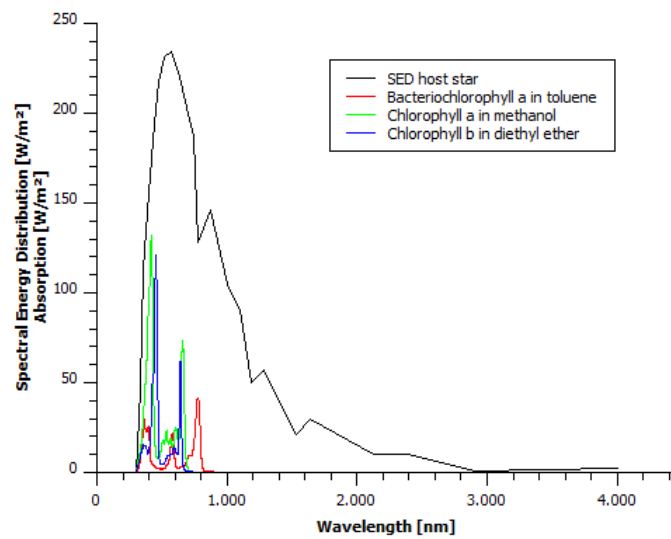


Figure C.51: Scenario 2, G-star, Earth atmosphere, without clouds, green zone

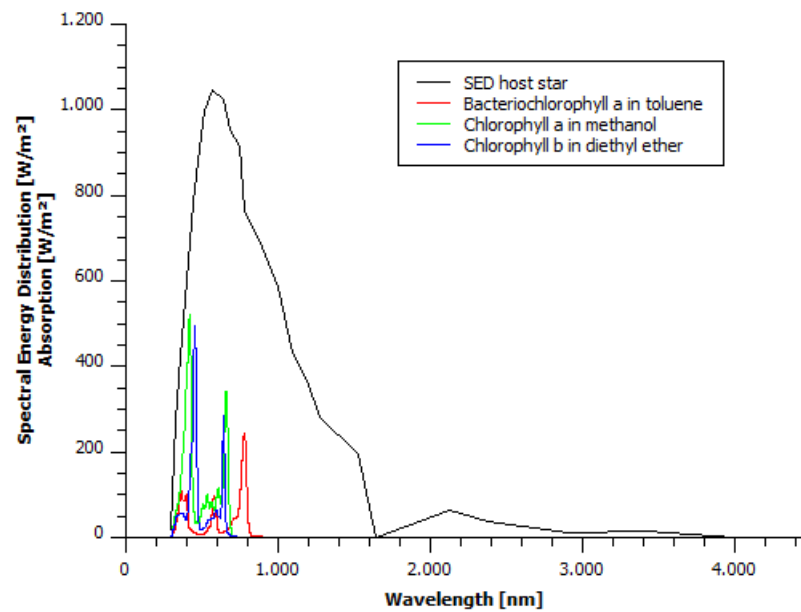


Figure C.52: Scenario 3, G-star, Venus atmosphere, without clouds, red zone

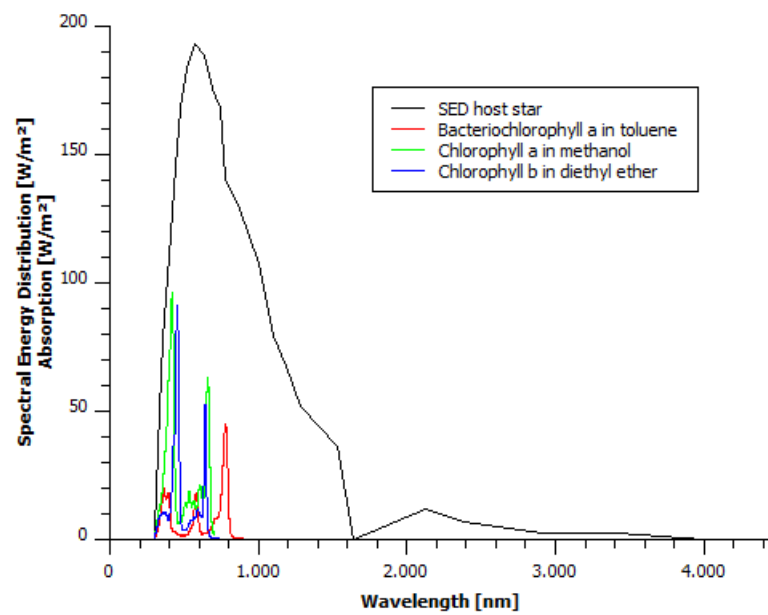


Figure C.53: Scenario 4, G-star, Venus atmosphere, without clouds, green zone

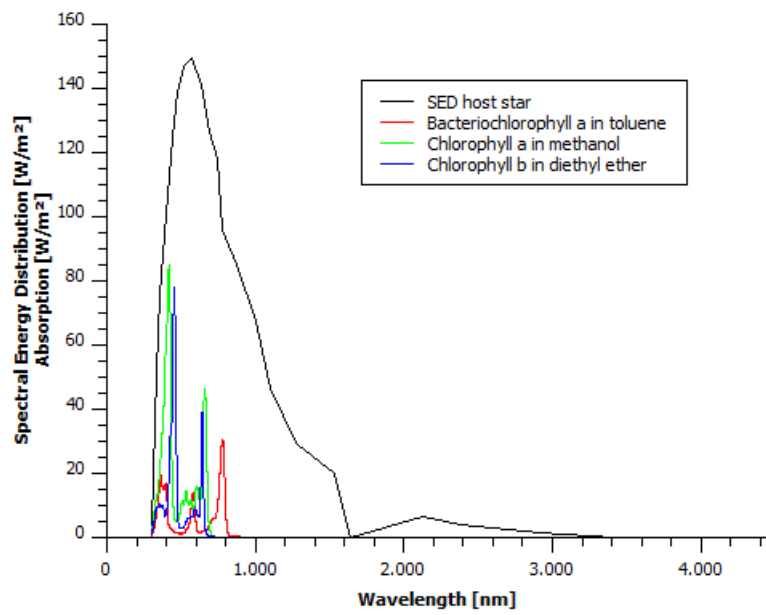


Figure C.54: Scenario 5, G-star, Venus atmosphere, with clouds, green zone

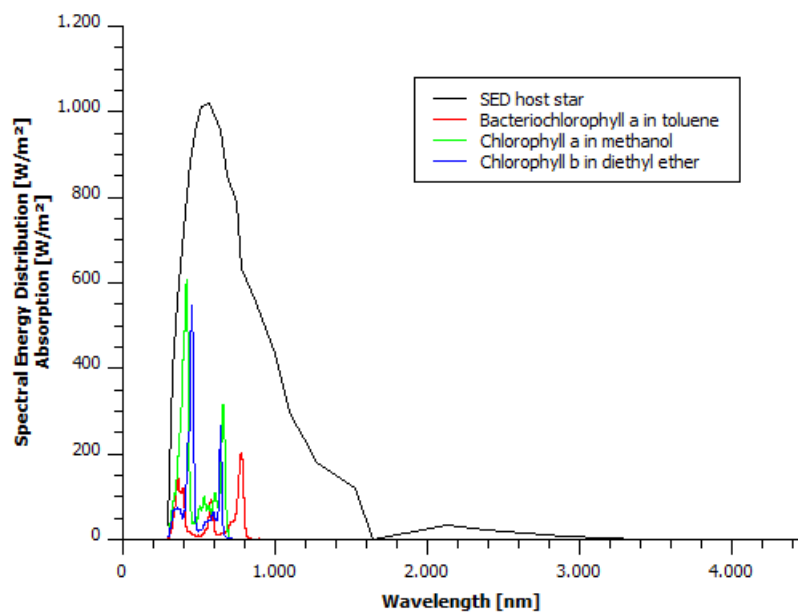


Figure C.55: Scenario 6, G-star, Venus atmosphere, with clouds, red zone

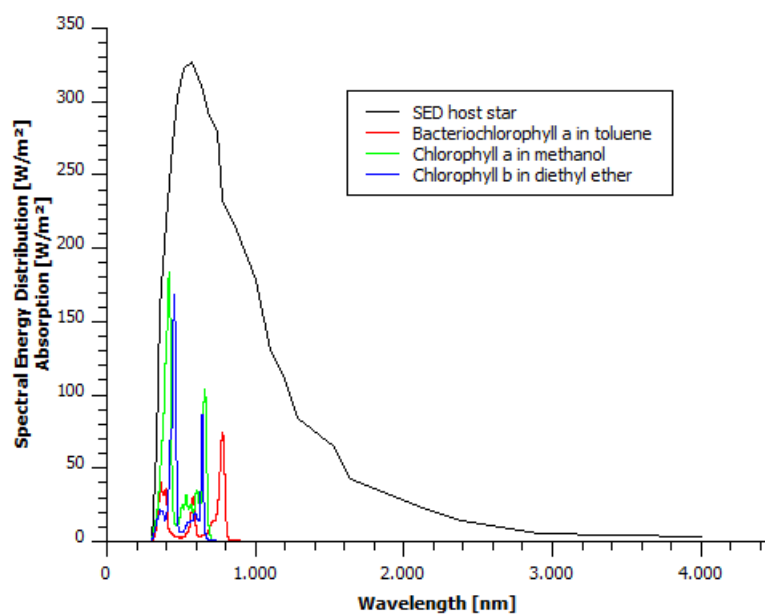


Figure C.56: Scenario 7, G-star, Titan atmosphere, without clouds, green zone

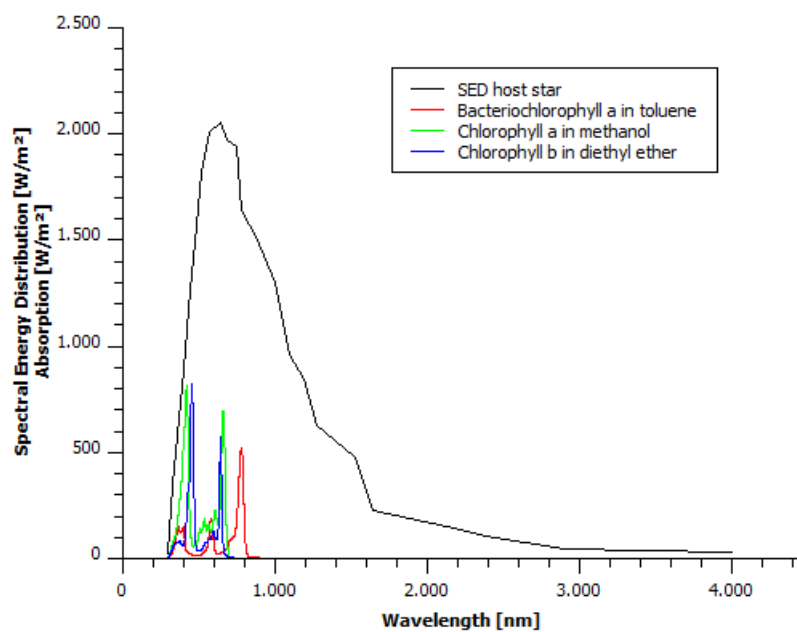


Figure C.57: Scenario 8, G-star, Titan atmosphere, without clouds, red zone

C.3 M-Star

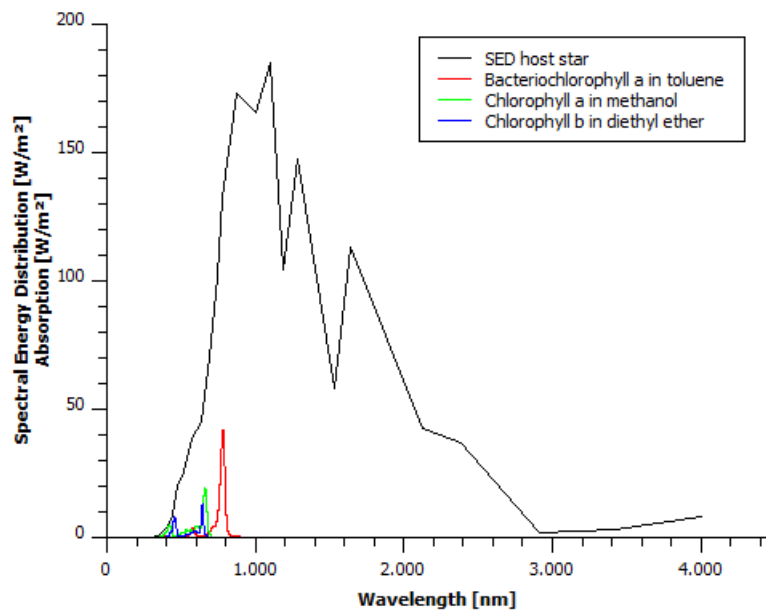


Figure C.58: Scenario 1, M-star, Earth atmosphere, with clouds

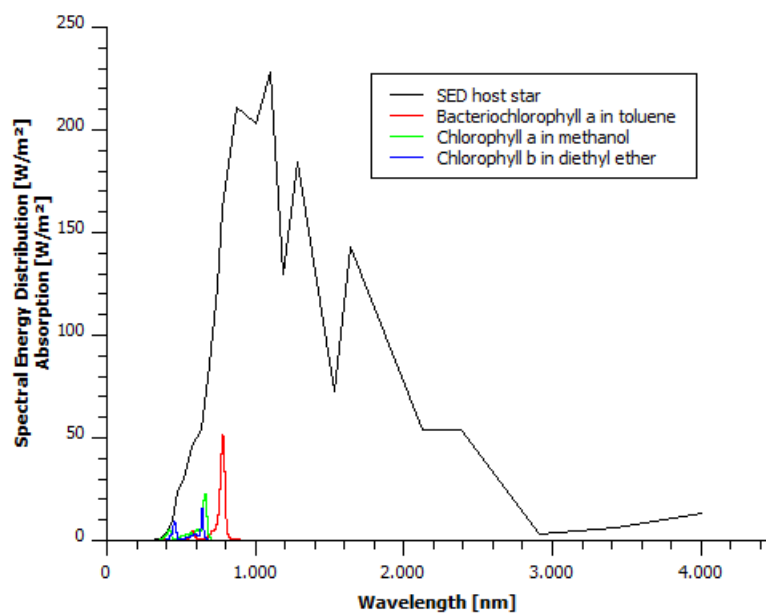


Figure C.59: Scenario 2, M-star, Earth atmosphere, without clouds

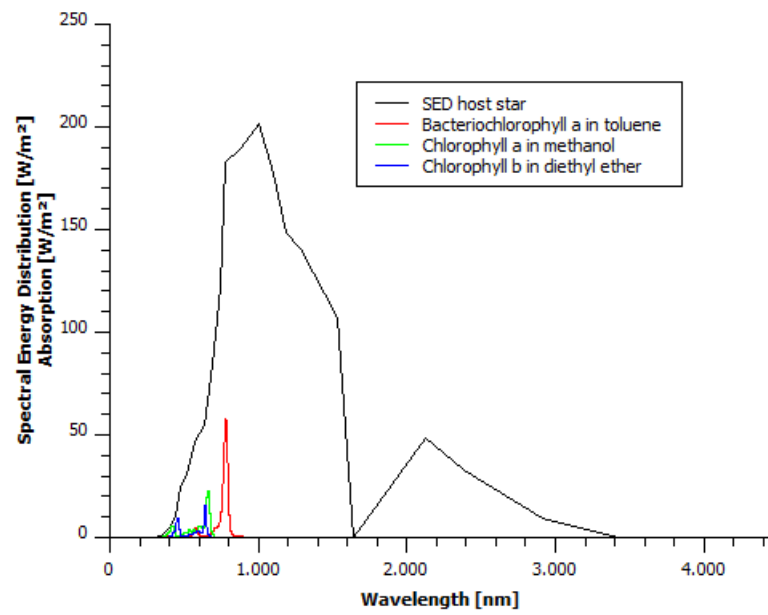


Figure C.60: Scenario 3, M-star, Venus atmosphere, with clouds

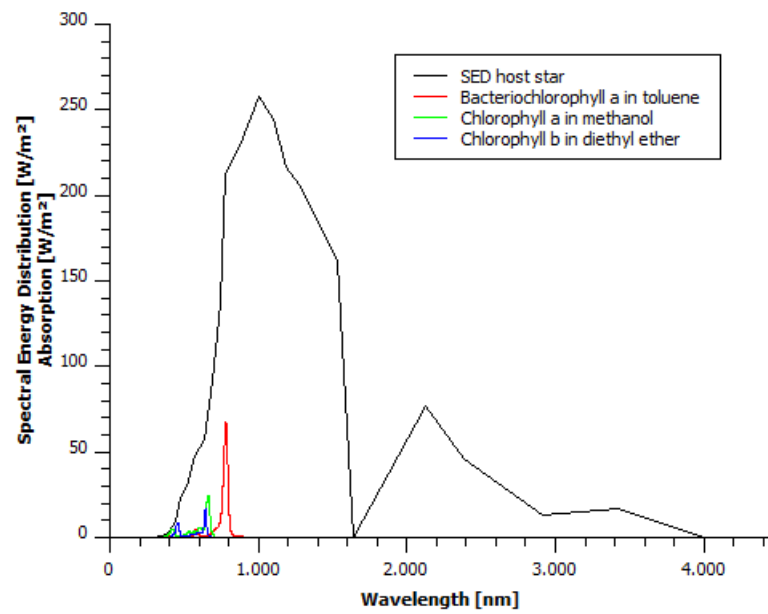


Figure C.61: Scenario 4, M-star, Venus atmosphere, without clouds

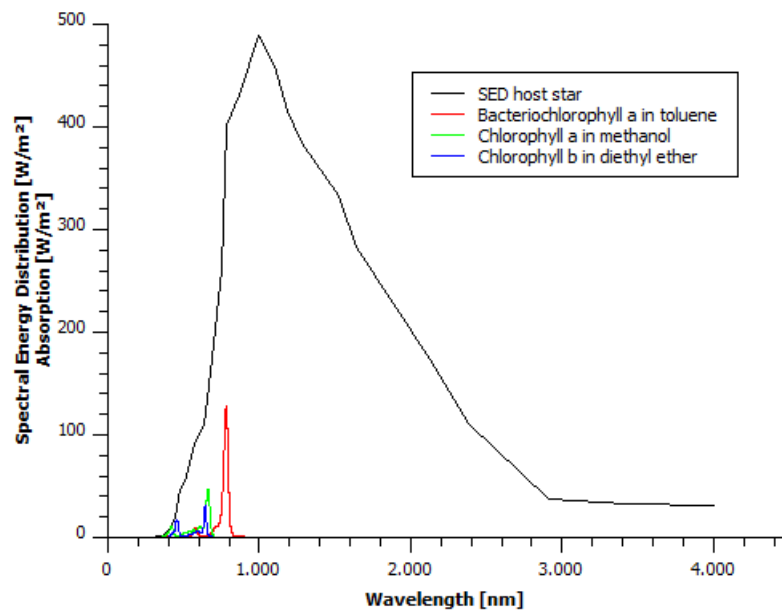


Figure C.62: Scenario 5, M-star, Titan atmosphere, without clouds

Abstract in German

Diese Arbeit beschäftigt sich mit der Habitabilität von terrestrischen Planeten in Bezug auf die Möglichkeit von Pflanzen wie wir sie kennen auf Planeten Photosynthese zu betreiben, welche unterschiedliche Atmosphärenzusammensetzung aufweisen und sich in verschiedenen Entfernung zu ihrem Zentralstern befinden.

Zu Zentralsternen welche Planetensysteme beherbergen die für Leben wie wir es kennen als am günstigsten angesehen werden zählen Sterne der G- und M Kategorie. Die Klasse der M-Sterne beinhaltet die meisten Sterne in unserer Sonnenumgebung. 75 % unserer Nachbarsterne zählen zu dieser Spektralklasse. Diese sind masseärmer als G-Sterne. Dadurch sind sie allerdings auch langlebiger, was wieder die Entwicklung höheren Lebens begünstigt.

Negativ auf etwaiges Leben könnte sich die hohe stellare Aktivität auswirken, welche auch in dieser Arbeit kurz umrissen wird um ihre Nach- aber auch Vorteile zu präzisieren.

Im Gegensatz dazu ist es offensichtlich, dass Leben wie wir es kennen auf Planeten um G-Sterne möglich ist. Die Erde mit ihren unterschiedlichen Habitaten brachte die verschiedensten Bakterien- und Pflanzenarten hervor die wichtig für die Weiterentwicklung des Planeten waren. Um die heutige lebensfreundliche Umgebung zu schaffen musste sich zunächst die oxygene Photosynthese entwickeln, welche den Großteil des heute vorhanden Sauerstoffs in unserer Atmosphäre hervorbrachte.

Es ist jedoch fraglich ob M-Sterne die für die Photosynthese notwendige Strahlung bereitstellen können. Dies bezieht sich nicht nur auf die Anzahl der Photonen um den Lichtkompensationspunkt zu überschreiten sondern auch auf den Spektralbereich. Die von den phototropen Organismen genutzte Strahlung deckt den optischen Bereich des elektromagnetischen Spektrums ab. M-Sterne dagegen zeigen ein im IR gelegenes Maximum.

Die abgegebene Strahlung trifft auf den oberen Rand einer Atmosphäre. Diese muss jedoch nicht zwingend erdähnlich sein. Der heutige Stand der Technik erlaubt es noch nicht die Zusammensetzung von Atmosphären extrasolarer Planeten zu untersuchen. Aufgrund unterschiedlicher Entstehung und Entwicklungsvorgänge kann eine solche eine vollkommen andere Zusammensetzung aufweisen als die für uns habitable Erdatmosphäre.

Daher beschäftigt sich diese Masterarbeit mit der emittierten Strahlung von M-Sternen und G-Sternen, die Auswirkungen einer Atmosphäre auf die Strahlung und möglicher Photosynthese von Pflanzen auf der Oberfläche von Planeten die sich in verschiedenen Abständen zu ihren Zentralsternen befinden.

Untersucht werden verschiedene Szenarien welche aufzeigen wie die spektrale Energieverteilung der ursprünglichen Strahlung nach dem Durchgang und der Wechselwirkung mit einer Venus-, Erd- oder Titanähnliche Atmosphäre auf der Oberfläche eines Testplaneten ankommt und ob photosynthetisch aktive Strahlung im modifizierten Spektrum vorhanden sein sollte. Die Atmosphärenberechnungen

können sowohl mit als auch ohne Wolken stattfinden um deren Einfluss auf die eintreffende Strahlung zu ermitteln.

Zunächst muss für alle Szenarien eine Zone berechnet werden in der es möglich ist, dass Wasser auf der Oberfläche des Planeten flüssig ist. Diese wurde mit Hilfe der modifizierten, frei erhältlichen Software Streamer berechnet, welche auch für die Modellierung der spektralen Energieverteilungen nach dem Durchgang durch die verschiedenen Atmosphären verwendet wurde. Die Zone wurde in einem Bereich um den Zentralstern angenommen, in dem die Oberflächentemperatur zwischen ~ 273 K und ~ 373 K beträgt.

Die M-Stern Szenarien untersuchen drei Atmosphärentypen (Venus, Erde und Titan), wobei unter anderem auch noch zwischen Berechnungen mit und ohne Wolken unterschieden werden muss. Als Zentralstern wurde ein M2.5V Stern mit dem Namen AD Leo gewählt. Der Orbit der Testplaneten wird als kreisförmig angenommen, da bei zu exzentrischen Orbits die Möglichkeit besteht, dass sich der Planet eine Zeitlang außerhalb der sogenannte 'liquid water zone (LW zone)' befindet. Diese Planeten wurden in den Modellen im Zentrum der 'LW zone' positioniert.

Hier könnte es Probleme mit rotationsgebundenen Umlaufperioden geben. Ist ein Planet seinem Zentralstern zu nahe, kommt es aufgrund von Gezeitenreibung zu einer 1:1 Umlaufperiode. Eine Seite des Planeten wird daher immer bestrahlt, während die andere immer abgewandt ist. Dies kann dazu führen, dass die Ausbildung einer Atmosphäre unmöglich wird, bzw. eine vorhandene Atmosphäre auf der einen Seite verdampft und auf der anderen ausfriert. Dass es allerdings auch möglich ist auf rotationsgebundene Planeten Atmosphären zu finden wird auch in dieser Arbeit behandelt.

Eine Annahme die allerdings getroffen werden muss, ist das Vorhandensein einer Atmosphäre.

Die G-Stern Szenarien sind ähnlich den M-Stern Szenarien aufgebaut. Als Zentralstern wurde die Sonne gewählt. Auch hier wurden eine Venus-, Erd- oder Titanähnliche Atmosphäre angenommen. Die Atmosphären wurden entweder mit oder ohne Wolken modelliert und die Orbits der Testplaneten als kreisförmig angenommen. Da bei der G-Spektralklasse im allgemeinen angenommen werden kann, dass photosynthetisch aktive Strahlung im Spektrum vorhanden ist, bezieht sich die wissenschaftliche Fragestellung auf die Veränderungen der spektralen Energieverteilung und der Intensität auf der Oberfläche des Planeten nach dem Durchgang durch Atmosphären verschiedener Zusammensetzungen. Um einen größeren Unterschied zu der bereits bekannten Sonne-Erde Konstellation zu schaffen wurden die Testplaneten nicht innerhalb der 'LW zone' positioniert, sondern außerhalb dieses Gebietes, jeweils einmal näher und einmal in größerer Distanz zum Zentralstern.

Diese Modellrechnungen sollen eine möglichst große Bandbreite an möglichen planetaren Konfigurationen abdecken. Sowohl in Bezug auf den Zentralstern selbst, die Entfernung zu diesem, als auch die möglichen Atmosphären. Hiermit soll die Möglichkeit geschaffen werden ob es für Pflanzen möglich ist auf anderen Himmelskörpern Photosynthese zu betreiben. Eine wichtige Annahme besteht darin, dass es sich um Pflanzen handelt wie wir sie hier auf der Erde vorfinden. Eine evolutionäre Entwicklung von phototrophen Organismen auf anderen Planeten muss in diesen Modellen ausgeschlossen werden, da keine Aussage über die absorbierenden Eigenschaften des Bacteriochlorophylls und Chlorophylls getroffen werden kann.

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