



universität
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MASTERARBEIT

Titel der Masterarbeit

„Census of the Molecular Gas in
Nearby Galaxies Selected from the
CALIFA Survey“

Verfasser

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angestrebter akademischer Grad

Master of Science (MSc)

Wien, 2014

Studienkennzahl lt. Studienblatt:

A 066 861

Studienrichtung lt. Studienblatt:

Masterstudium Astronomie

Betreuer:

Dipl.-Phys.Univ.Dr. Helmut Dannerbauer

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Abstract

The presented master thesis is based on the statistically representative galaxy sample of CALIFA, the “Calar Alto Legacy Integral Field Area survey” consisting of 600 local galaxies with redshifts ranging from $z=0.005$ to $z=0.03$. The CALIFA survey has been designed to obtain maps of stellar populations, ages, metallicities, ionized gas distributions, gas excitation mechanisms, chemical abundances as well as kinematic properties from stellar and ionized gas components. However, a key piece for the complete understanding and interpretation of the nature and properties of the star formation in the investigated sample is missing: the cold molecular gas reservoir, the fuel for star formation. This is subject to this work which is a preliminary study of the ultimate goal of obtaining interferometric CO maps with ALMA, PdBI and CARMA with matching spatial resolution of the optical IFU data of $2''$ (corresponding to a physical scale of 200–760 pc) to investigate molecular gas properties of local galaxies on a statistical basis. Within this thesis, an extended archival search on CO detections and non-detections of CALIFA galaxies was fulfilled and for 159 galaxies out of CALIFA’s mothersample (consisting of 939 targets), CO data was found. Infrared data from the IRAS and WISE satellites are available for 497 and 924 galaxies, respectively. These datasets were compiled in order to derive star formation rates for *all* galaxies of the mothersample. 21 cm magnitudes were taken from two different sources (Springob et al. 2005 and HYPERLEDA) in order to calculate atomic gas masses for 2/3 of the CALIFA sample. All previously published data was homogenized and molecular masses were derived by means of a sophisticated CO aperture correction. Additionally, for 26 galaxies for which metallicities were recently published by Sánchez et al. (2013), an empirical relation was used for a CO conversion factor derivation and a subsequent metallicity-dependent molecular gas mass calculation. Furthermore, all mentioned data was organized in a MySQL database, which was made accessible through a web-interface to the CALIFA collaboration. A physically motivated subsample of 65 galaxies was defined for future interferometric investigation. For that purpose, an algorithm was developed which assures that the found subsample is as homogeneous as possible in the constraining parameters of stellar mass, star formation rate and morphology. Based on that subsample, observations at several *submm* facilities such as APEX, IRAM and PdBI were proposed. All used methods and calculations are described and discussed. The Kennicutt-Schmidt relation for CALIFA galaxies was established and analyzed. Star formation efficiencies and gas depletion times based on the molecular and the total gas were derived and discussed. Finally, three conclusions could be drawn. First, the SFR scales nearly linearly with H_2 , even where most gas is atomic. Second, the star formation threshold is *independent on the scale* and coincides with an

atomic-to-molecular transition. And finally, to first order, the SFR/MH2 ratio is fixed in “normal” spiral galaxies. These findings were exhibited from *integrated*, hence *averaged* quantities. Thus, to first order, even from integrated values, basic properties of the ISM can be derived which can be an asset for high-redshift investigations.

Beside that global perspective of star formation, a comparison between the ionized and the molecular gas in the merger pair NGC2623 was performed. Based on CALIFA’s IFU data and archival SMA data, it was possible to unveil a kinematic feature confirming the prospect that during a major merger event, hot gas is most likely moving outwards, whereas cold, molecular gas streams inwards into the central region.

Constants		
c	speed of light	$2.997\,924\,58 \times 10^8 \, m \, s^{-1}$
h	Planck constant	$6.626\,075\,540 \times 10^{-34} \, J \, s$
$\hbar$	reduced Planck constant	$1.054\,572\,666 \times 10^{-34} \, J \, s$
AU	astronomical unit	$1.495\,978\,706\,6 \times 10^{11} \, m$
pc	parsec	$3.085\,677\,6 \times 10^{16} \, m$
G	constant of gravitation	$6.672\,59 \times 10^{-11} \, m^3 \, kg^{-1} \, s^{-2}$
$M_{\odot}$	solar mass	$1.989\,1 \times 10^{30} \, kg$
$L_{\odot}$	solar luminosity	$3.845\,8 \times 10^{33} \, erg \, s^{-1}$
m_H	mass of ^1H atom	$1.673\,534\,4 \times 10^{-27} \, kg$
m_e	mass of e^-	$9.109\,389\,754 \times 10^{-31} \, kg$
Conversions		
erg	energy of 1 erg	$10^{-7} \, J$
eV	energy of 1 eV	$1.602\,177\,334\,9 \times 10^{-19} \, J$
Jy	flux density in Janksy	$10^{-26} \, W \, m^{-2} \, Hz^{-1}$
λ_0	wavelength associated with 1eV	$12\,398.428\,2 \times 10^{-10} \, m$
ν_0	frequency associated with 1eV	$2.417\,988\,367\,2 \times 10^{14} \, s^{-1}$
Cosmological parameters		
H_0	Hubble constant	$70 \, km \, s^{-1} \, Mpc^{-1}$
Ω_M	matter density parameter	0.3
Ω_{Λ}	dark energy density parameter	0.7

Table 1: If not otherwise stated, physical constants as indicated here were used throughout this work. An extended list of quantities can be found in Allen and Cox (2000). The cosmological parameters applied for all calculations were recommended for the CALIFA collaboration by J. Walcher at the ‘‘Califa Busy Week 5’’ in April 2013.

Chapter 1

Introduction

For the purpose of studying molecular gas in nearby galaxies, a unique galaxy sample is used as a basis. CALIFA, the “Calar Alto Legacy Integral Field Area survey”, see also Sánchez et al. (2012), is obtaining integral-field spectroscopic data in the optical (from 370–700 nm) of a diameter selected ($45'' \leq D_{25} \leq 80''$) sample of 600 galaxies of all Hubble types, from elliptical to spiral galaxies, in the local universe ($0.005 \leq z \leq 0.03$). This ongoing survey has been granted 250 nights with the 3.5 m telescope at the Calar Alto observatory, using the PMAS/PPAK IFU (Roth et al., 2005; Kelz et al., 2006) with a hexagonal field-of-view (FOV) of $64'' \times 72''$. This large FOV covers the full optical extent of the selected galaxies down to a 3σ depth of $23 \text{ mag arcsec}^{-2}$, at a spatial resolution of about 2 arcsec.

The workhorse of CALIFA, Integral Field Spectroscopy (IFS), is able to tackle a large number of relevant issues on galaxy evolution, as shown in, e.g., Sánchez et al. (2012). However, some fundamental questions are essentially not reachable by IFS techniques, and must rely on, or be combined with, observations at other wavelengths. The CALIFA galaxies have a large multi-wavelength coverage from the UV to the infrared including legacy surveys such as GALEX, UKIDSS and WISE. However, a key piece for the complete understanding and interpretation of the nature and properties of the star formation in the investigated sample is missing: the cold molecular gas reservoirs, the fuel of star formation.

Hence, the present work foremost motivation is to fill this gap and build-up a basement for future molecular gas studies based on CALIFA galaxies. In order to achieve this aim, within this work some major steps were performed. First, an extensive archival search on CO detections and non-detections of all CALIFA galaxies was fulfilled. Previously published data from the centimeter to the optical spectral domain were compiled and calibrated to a homogeneous galaxy sample in order to investigate correlating parameters, with an emphasis on the cold and neutral interstellar medium. CO observed at $\approx 115 \text{ GHz}$ rest-frame frequency, corresponding to its J=1–0 rotational transition at $\approx 2.6 \text{ mm}$, is used

as an astrophysical tool for deriving general properties of galaxies and the ISM they are containing. Star formation laws (Kennicutt-Schmidt) and star formation efficiencies and gas depletion times were derived and analyzed. For the bulk of CALIFA galaxies, which were not observed in CO previously, CO luminosities could be estimated, which was an essential support for proposals submitted during my master thesis for the APEX, IRAM and PdBI facility.

Furthermore, a reasonable subsample of 65 CALIFA galaxies for future CO follow-up observations was defined obeying the criteria to be as homogeneous as possible in the parameters of stellar mass, star formation rate and morphology. For this kind of galaxy selection, an optimization algorithm was developed in order to assure the desired distribution.

Beside that global perspective, gas kinematics within NGC2623, a merging galaxy pair, were studied in detail on a sub-kiloparsec scale. To do so, the ionized gas component detected through $H\alpha$ within the CALIFA program is compared to the molecular gas traced by CO. To achieve the same resolution (subkpc) in both, the IFS data and CO maps, interferometric data gained with the Submillimeter Array was reduced and evaluated leading to a discussion on the origin of the gas and star formation timescales. This proto-study shows the capabilities of combining interferometric millimeter data and IFU data.

In addition, a MySQL database accessible through the Internet was created that summarizes all calculated and collected information on CALIFA galaxies. The database which supports several selecting and sorting features was provided to the whole CALIFA collaboration.

Chapter 2

Molecular Gas and Dust in the Interstellar Medium

In this introductory chapter, at first, a short outline of the observational history of molecules and dust in the interstellar medium (ISM) is given in section 2.1. Subsequently, the most important components of the ISM and its basic properties are rendered in a tabular form in 2.2. Since a substantial part of the present thesis is based on observational CO data, the physical concept behind CO line emission is treated in some detail in 2.3. I want to point out, that, for the sake of simplicity, in this section all considerations are based on a molecule model with two levels, upper and lower state, only! I aim to give an overview of the theoretical tools needed to understand diatomic energy levels and rotational transitions (2.3.1), the critical density (2.3.2) and calculations of the total column density within the LTE approximation (2.3.4). Since CO emission is generally optically thick, a few words on the topic of radiative trapping can be found in 2.3.3. The distribution of molecular gas within galaxies of different Hubble Type is the topic of this chapter's last section 2.4.

2.1 Historical Remarks

The existence of molecules in the interstellar medium (ISM) was first recognized by Swings and Rosenfeld (1937) through *absorption* bands originating from electronic transitions of various species (e.g. CH, CN). Later on, in the 1960's, also rotational transitions were observed at wavelengths in the millimeter and centimeter domain. Nevertheless, it was not before 1970, that Carbon monoxide (CO) was discovered for the very first time by Wilson et al. (1970).

In the same year, molecular hydrogen H_2 was observed by its Lyman resonance *absorption* lines in the ultraviolet (UV) by Carruthers (1970) for the first time, but it was not until the late 1990's, when more sensitive IR array detectors were available, that

molecular hydrogen was also detected in *emission* from forbidden rotational-vibrational transitions in the Near-Infrared (NIR).

Why is H_2 hardly seen in emission, though obviously it is the dominant, most abundant molecule in the ISM? This is, because its first rotational level, accessible only through a quadrupolar transition, is more than 500 K above the fundamental. Thus, H_2 due to its physical properties is not as easily excited as CO (see section 2.3).

It is a homo-nuclear and linear molecule, which is lacking of a permanent dipole moment. All lower energy levels are quadrupole transitions with very low probability and relatively high excitation energies. Hence, they are only excited at high temperatures or in strong UV radiation fields which are uncommon to the ISM. Thus, the most abundant molecule in the ISM, which is carrying most of the mass and playing a major role for physical processes like pressure- and thermal balance, is virtually invisible to direct observation. As a consequence, most of what we know about the ISM comes from observations of other molecules, so called "tracers".

Beside the gas, the ISM also consists of a macroscopic component – dust grains. In 1911, J. Hartmann, discovered Ca absorption lines in rest when observing δ Orionis, a double star system. The consequences of these observations were firstly underestimated and it was not before 1930, when Trümpler discovered that *interstellar* extinction increases with distance, which led to the only reasonable concept, that there must be matter along the line of sight. The ISM was discovered.

Interestingly, our knowledge of dust grains in the interstellar medium is still quite poor. Our understanding of the gaseous ISM is mainly due to the success of quantum physics during the last decades. But dust has to be treated by solid body physics. Since grain compositions and physical properties are mostly unknown, this is still left as a task for the future. Up to now nobody has yet been able to produce grains in the laboratory, much less reproduce the conditions they would experience in the ISM.

Dust, although its mass distribution to the ISM is only about one percent in the Milky Way, is intimately linked to the molecular phase of the ISM, because molecules are believed to grow on dust grain surfaces. A fact, which is confirmed by the empirical CO-IR relation which will be described in section 5.10.2. Further readings on this topic can be found in Draine (2003).

2.2 Components of the ISM

Medium	Temp [K]	Density [cm^{-3}]	Observable
cold molecular gas	10-20	$10^3 - 10^4$	low rotational transitions of CO (J=1-0 and J=2-1)
warm molecular gas	50-300	$\approx 10^4$	high rotational transitions of CO (above J=3-2)
cool neutral gas	50-100	1-100	hyperfine transition of H (21cm)
warm neutral gas	100-5000	0.1-1	hyperfine transition of H (21cm)
warm ionized gas	$10^3 - 10^4$	≈ 0.01	emission lines
hot gas	10^6	0.0001	X-ray emission

Table 2.1: Components of the ISM.

2.3 Physical and Chemical Properties of Carbon Monoxide

Following the classical theory of electrodynamics, an electron moving in its nuclear orbit, should emit radiation continuously. Thus, the electron would loose energy and fall into the nucleus within a very short time. No stable atoms would exist. This fundamental problem was already known in the 19th century and it was clear that other physical concepts were needed to understand atomic and subatomic scaled structures. But it was not until 1913, when Bohr postulated, that emission of radiation occurs only when an electron changes from a higher energy orbit E_2 to an orbit of lower energy E_1 . He found that the emitted photon energy $h\nu$, can be written as:

$$h\nu = E_2 - E_1 \quad (2.1)$$

This equation is known as the Bohr frequency condition. The reverse process, a transition from E_1 to E_2 , requires the absorption of a photon with energy $h\nu$. The wavelength of the emitted photon, λ , is related to the frequency ν by the simple expression:

$$\nu = \frac{c}{\lambda} \quad (2.2)$$

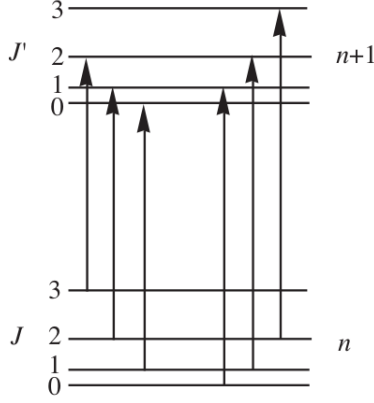


Figure 2.1: Energy-level diagram for ideal vibrator-rotator.

2.3.1 Diatomic Energy Levels and Transitions

A diatomic molecule model (e.g. CO) as described in Atkins and de Paula (2006) chapter 13 suggests that both, vibration along the bond between the atoms and rotation about that bond have to be considered. Excitation of any of the electrons to higher states are neglected for a first approximation. Then, we expect the possible energy levels to be the sum of a vibrational and a rotational part:

$$E = E_{rot} + E_{vib} \quad (2.3)$$

$$E_{rot} = \frac{\hbar^2}{2I} J(J+1) \quad (2.4)$$

$$E_{vib} = \hbar^2 \sqrt{\frac{k}{\mu}} \left(v + \frac{1}{2}\right) = hc\omega_e \left(v + \frac{1}{2}\right) \quad (2.5)$$

where I is the moment of inertia about an axis through the center of mass and perpendicular to the bond, and J is an integer quantum number. $I = \mu r_e^2$ with the reduced mass μ , r_e is the distance between the two atoms, k is the effective spring constant and v is the vibrational quantum number. On the right hand side, the equality is expressed in terms of the wavenumber ω_e .

The actual observed spectrum of a diatomic molecule like CO has to rely on certain selection rules, which are defined within the concept of quantum mechanics, see e.g. Atkins and de Paula (2006). Transitions between energy levels have to obey these rules. For vibrational states it is required that v changes by ± 1 , while for the rotational states J have to change by ± 1 , which can be seen in figure 2.1. Following formulae (2.4) and (2.5), estimations of the transition energies for CO can be derived. For the vibrational transitions, the quantities k and μ have to be found. In the given approximation, the

inter-atomic potential energy U can be expressed as:

$$U = k \frac{(r - r_e)^2}{2} \quad (2.6)$$

It is known that about 11 eV is needed to dissociate CO, see e.g. Visser et al. (2009), which is quite high, meaning that, once CO is created, it is hard to be destroyed! We assume that the dissociation occurs when the bond is stretched to twice its equilibrium length of about 0.1 nm, so that U is equal to the dissociation energy when $r = 2 r_e$. The quantity of k can now be derived and μ is known from the atomic masses. Hence, a vibrational level spacing of about 0.1 eV is found. Using the values of table 1, a wavelength of about $10 \mu\text{m}$ is found. Thus, vibrational transitions of CO are found in the far infrared region of the spectrum. Now, the rotational energy levels can be easily derived from r_e and the atomic masses, giving that $\Delta E = 0.7 \text{ meV}$ for the $J = 1 \rightarrow 0$ transition. Since this is much smaller than the vibrational energy, the rotational energy levels of CO are found in the sub-millimeter spectral domain indicating that the rotational transitions show up as a fine structure on the vibrational transitions.

The above considerations were based on a simple molecule model, a more detailed view on the topic can be found in Brown and Carrington (2003), where the energy levels of a diatomic molecule are derived:

$$E_{v,J} = \omega_e(\nu + \frac{1}{2})\omega_e x_e(\nu + \frac{1}{2}) + B_e J(J+1) D_e J^2(J+1)^2 \alpha_e(\nu + \frac{1}{2}) J(J+1) \quad (2.7)$$

The first two terms of equation (2.7) describe the vibrational energy, the next two the rotational energy, and the final term describes the vibration-rotation interaction. Thus, it can be seen that level spacings and the frequencies of transitions between rotational levels, depend on the values of the rotational constant, B_ν , and the rotational quantum number J as already outlined before.

Using equation (2.7), the transition frequencies for the molecule of interest, CO, can be calculated. For this purpose the values of B_e , α_e and D_e were assumed to be 57897.5 MHz, 524.0 MHz and 0.1834 MHz respectively. The results are given in table 2.2.

J	ν [MHz]	$\frac{E_u}{k}$ [K]
1 $\rightarrow$ 0	115.271	5.5
2 $\rightarrow$ 1	230.538	16.6
3 $\rightarrow$ 2	345.795	32.2

Table 2.2: CO rotational transition frequencies

2.3.2 Critical Density and Line Visibility

Knowing about the physical background of CO energy levels, this section is about the conditions needed for CO emission lines to occur. Basically the most important criteria is the density of the medium. The forthcoming equations and methods are mainly based on chapter 6 and 7 of the textbook of Draine (2011). Considering a simple system with only two levels, upper and lower state, which are separated by the energy E_{ul} with the statistical weights g_u (upper) and g_l (lower) and populations of n_u and n_l , that define the number of a given species in upper or lower state respectively, the levels are connected to each other by three radiative processes – namely: absorption, stimulated emission and spontaneous emission. The rates of these processes are given by:

$$\text{absorption rate} = B_{lu}I_\nu \quad (2.8)$$

$$\text{stimulated emission rate} = B_{ul}I_\nu \quad (2.9)$$

$$\text{spontaneous emission rate} = A_{ul} \quad (2.10)$$

where A and B are called the Einstein coefficients and I_ν is the specific Intensity. The following relationships hold between the given Einstein coefficients:

$$g_l B_{lu} = g_u B_{ul} \quad (2.11)$$

$$B_{ul} = A_{ul} \frac{c^2}{2h\nu^3} \quad (2.12)$$

Another important quantity is the excitation temperature, which can be understood in terms of the population density in two states:

$$\frac{n_u}{n_l} = \frac{g_u}{g_l} e^{\frac{-E_{ul}}{kT_{ex}}} \quad (2.13)$$

It is important to note, that T_{ex} is not equal to the kinetic temperature, although in some cases it will be a good approximation, which will be shown at the end of this section.

In addition to the discussed radiative processes, also collisions play an important role in the ISM. Both, collisional excitation and de-excitation is possible. It can be easily understood, that in the case of collisions, the kinetic temperature T_K must be the dominating quantity, since temperature is related to the movements of the particles within a medium. Similar to equation (2.13), the collisional rate coefficient C is defined:

$$C_{lu} = \frac{g_u}{g_l} e^{\frac{-E_{ul}}{kT_K}} \quad (2.14)$$

The actual rate of collisional excitation or de-excitation is:

$$\text{collisional excitation rate} = nC_{lu} \quad (2.15)$$

$$\text{collisional de - excitation rate} = nC_{ul} \quad (2.16)$$

Collisional processes are very important in the theory of the ISM, since they are able to excite atoms and molecules, which leads to detectable emissions and furthermore to cooling of the ISM, which plays a major role during the process of star formation and the matter circle of the ISM.

Putting all together, and assuming statistical equilibrium, the rates in and out of a energy level must be equal: $dn_u/dt = dn_l/dt = 0$ and the rate per unit volume in and out of a lower level state can be noted as:

$$n_l B_{lu} I_\nu + n_l C_{lu} n = n_u A_{ul} + n_u B_{ul} I_\nu + n_u C_{ul} n \quad (2.17)$$

Equation (2.17) can be solved for the ratio of interest:

$$\frac{n_u}{n_l} = \frac{B_{lu} I_\nu + C_{lu} n}{A_{ul} + B_{ul} I_\nu + C_{ul} n} \quad (2.18)$$

Using the definition of the collisional rate coefficient (2.14) and the relation between the Einstein coefficients (2.12), as well as the excitation temperature as indicated in (2.13), and furthermore representing the underlying radiation field (e.g. cosmic microwave background (CMB)) with a Planck function of temperature T_R , then equation (2.18) can be rewritten as:

$$e^{\frac{-h\nu}{kT_{ex}}} = \frac{A_{ul}[e^{\frac{h\nu}{kT_R}} - 1]^{-1} + C_{ul} n e^{\frac{-h\nu}{kT_K}}}{A_{ul}[1 - e^{\frac{-h\nu}{kT_R}}]^{-1} + C_{ul} n}, \quad (2.19)$$

and a critical density can be defined:

$$n_{crit} = \frac{A_{ul}}{C_{ul}} \quad (2.20)$$

Now, two distinct cases can be considered – $n \gg n_{crit}$ and $n \ll n_{crit}$ – which leads to the interesting circumstance, that in a medium of density n much below n_{crit} , no emission line will be visible, because the excitation temperature T_{ex} then will approach the (background) radiation temperature T_R . In the other case, when the density n of the medium is much higher than n_{crit} , an emission line will be visible and the excitation temperature T_{ex} will approach the kinetic temperature T_K . Under such conditions – when collision are dominant compared to radiation – the medium is said to be in “local thermal equilibrium” (LTE), due to high collision rates the particles can thermalize and will follow a Boltzmann distribution, which actually is given by equation (2.14), compare Krumholz

(2011).

Since, the value of n_{crit} differs from one species to another, observations of multiple molecules and transitions, can be used to derive the actual volume density of the emitting region. Furthermore, the temperature of the medium can be estimated.

As a precaution, I note, that the preceding considerations are strictly valid only for the optical thin case, because the CMB radiation field as solely initiator of stimulated emission and absorption processes was introduced, but CO is optical thick and self-absorption has to be taken into account too! The effect of optical thickness is that the critical density is reduced. This is, because trapping of photons within the cloud means that not every spontaneously-emitted photon escapes the cloud. This effect is the same like lowering the Einstein A coefficient (Krumholz, 2011).

2.3.3 Radiative Trapping, Optical Thick Case

There exist several methods to calculate the effects of radiative trapping, the most common is probably the “escape probability treatment” of Scoville and Solomon (1974). In this section, I will provide the basic idea, see the given literature for details.

Radiative trapping causes photons to scatter many times about the cloud, enhancing the resulting observed line flux due to stimulated emission. Each emission-line photon emitted by normal downward radiative transitions can effectively multiply itself by stimulated emission before escaping the cloud. The result is that, a larger excitation temperature is achieved at a lower density than in an optically thin region. Thus, the density at which the line appears to thermalize gets lower.

Since CO J=1–0 line is always extremely optically thick in molecular clouds, some kind of radiative trapping treatment must be performed. For most of the giant molecular clouds, the observed optical depths in the J=1–0 line are >10 , lowering the effective density at which $T_{ex} \approx T_K$ from 3000 cm^{-3} to as low as 300 cm^{-3} .

2.3.4 Total Column Density in LTE Approximation

Applying the theoretical aspects of the previous sections, one could compute column densities for molecules only in that particular rotational state. To convert this into the total column density, the fact that the CO line is only visible when the medium is in or near LTE conditions, can be exploited. The advantage then is, that the particle states follow the Boltzmann statistics, and the fraction of the population of a given rotational state J , is given by:

$$f_J = \frac{g_J e^{\frac{-E_J}{kT}}}{Q(T)}, \quad (2.21)$$

where $Q(T)$ is called the “partition function”, which is defined as the sum over all rotational states:

$$Q(T) = \sum_i g_i e^{\frac{E_i}{kT}}. \quad (2.22)$$

Another simplification can be introduced for linear molecules like CO or CS. For those, the statistical weights and energies of the J th rotational state can be calculated easily:

$$g_J = (2J + 1), \quad (2.23)$$

$$E_J = J(J + 1)hB(v). \quad (2.24)$$

$B(v)$ is a function of the moment of inertia I , which itself depends on the vibrational quantum number v :

$$B(v) = \frac{h}{8\pi^2 I(v)}. \quad (2.25)$$

The summation in equation (2.22) can be truncated at a high value of J , because transition probabilities increase with increasing J . Transitions at higher levels occur so fast, that they will be mostly depopulated and therefore won’t contribute much to the partition function (Mangum and Shirley, 2013). At low densities, the sum of $Q(T)$ can be approximated by the following integral:

$$Q(T) \approx \int (2J + 1) e^{\frac{-E_J}{kT}} dJ, \quad (2.26)$$

and when assuming LTE conditions, the partition function is approximately:

$$Q(T) \rightarrow \frac{kT}{hB(v)}. \quad (2.27)$$

For example, the LTE partition function for the CO $J=1-0$ transition is:

$$Q(T) \approx \frac{T}{2.76K} \quad (2.28)$$

Again, it is important to mention that LTE is not always a valid assumption! Explicit non-LTE calculations have to solve the equations of statistical equilibrium to evaluate the partition functions, which is much more complex than the procedure above. A more detailed insight into the topic can be found in Mangum and Shirley (2013).

2.4 Molecular Gas in Galaxies of Different Hubble Type

The predominant model of galaxy evolution, which is widely accepted, is the so called “bottom-up” hierarchical principle. Collapsing dark matter halos form small structures first, and only subsequent merging processes lead to high mass galaxy formation. Within this model, the early type galaxies (ETGs) are thought to build up the end of the time-line.

Since molecular gas content is intimately linked to the process of star formation, see e.g. Bigiel et al. (2008), Leroy et al. (2008) and Gao and Solomon (2004), which mostly occurs in late type spirals (Kennicutt, 1998; Bigiel et al., 2008; Leroy et al., 2008), it seems clear that in most of the early type galaxies molecular gas traced by CO is not observable.

However, some early types galaxies, do have detectable molecular gas content, which was first discovered by Wiklind and Rydbeck (1986). Since then, dozens of molecular gas studies were performed by various groups. The most comprehensive and largest of these studies so far, is based on the ATLAS^{3D} (Cappellari et al., 2011) sample of early type galaxies. They found that 22 percent of early type galaxies of their volume-limited galaxy sample have a detectable molecular gas reservoir (Davis et al., 2013a).

Based on the 41 galaxies ATLAS^{3D} sample, Davis et al. (2013b) surprisingly found, that the extent of the molecular gas in ETGs is comparable to spirals. As a comparison sample they used the BIMA-SONG (Helfer et al., 2003) 44 galaxies sample, which is also volume limited. Although on an absolute, linear scale, the molecular gas in spirals is more extended – when normalized to the galaxy scale length – this “relative CO-extent” between spirals and ellipticals is similar. See also figure 2.2 which was taken from Davis et al. (2013b).

2.5 Scale Length of Molecular Gas

The scale length is defined to be the radius r_e – also the “effective radius” – of a galaxy’s isophote at which the surface brightness $I(r)$, which is distributed following an exponential law, has declined to a value of $1/e$ of the central value I_0 . Based on the THINGS survey, Leroy et al. (2008) found that the CO distribution’s scale length $r_{e,CO}$ can be described by $r_{e,CO} = 0.2 r_{25}$, with r_{25} , the radius of the galaxy, where the surface brightness has reached a value of 25 mag/arcsec^2 in the B band. Hereafter, this quantity is simply referred to as the (optical) “blue radius”. Similarly, in a more recent publication of Lisenfeld et al. (2011), the mean CO scale length was found to be:

$$r_{e,CO} = 0.25r_{25}. \quad (2.29)$$

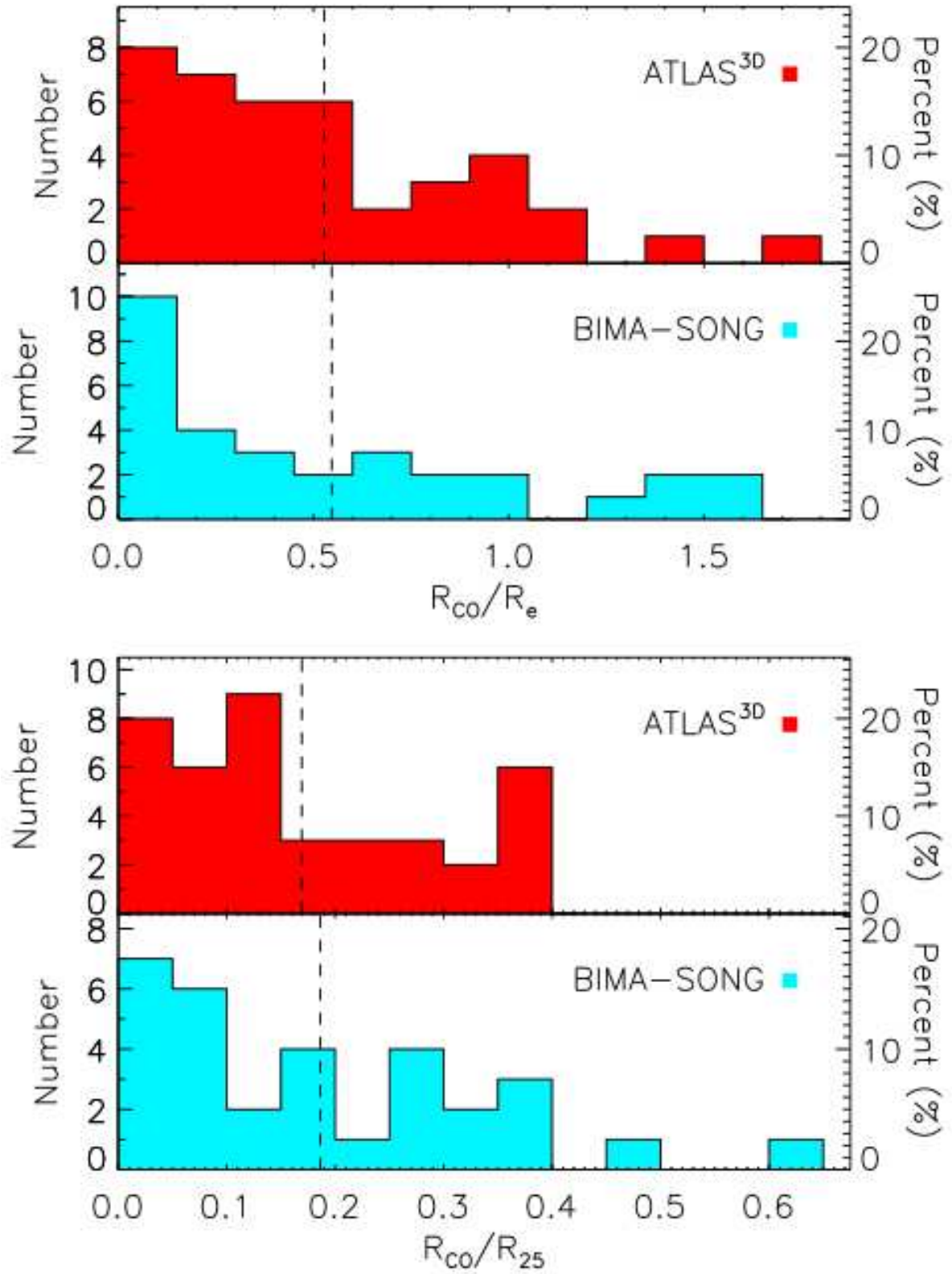


Figure 2.2: CO distribution in early type galaxies (ATLAS3D) and late type galaxies (BIMA-SONG). The figure is taken from Davis et al. (2013b).

The most comprehensive study on that topic was performed by Young et al. (1995). From a sample of more than 300 late type galaxies, they derived, that the diameter, within 70 percent of the total CO luminosity is found, $D_{70,CO}$, extends to half the size of the optical blue diameter, D_{25} . Summarizing, what is stated above, the following equations can be noted:

$$I(r) = I_0 e^{-\frac{r}{r_e}} \quad (2.30)$$

$$\frac{D_{70,CO}}{D_{25}} = 0.5 \quad (2.31)$$

To be able to compare these two different findings of (2.37) and (2.31), some calculations have to be performed.

$$0.5 = \int_0^{r_{e,CO}} I_0 e^{-\frac{r}{r_{e,CO}}} 2\pi dr \quad (2.32)$$

$$0.7 = \int_0^{r_{70,CO}} I_0 e^{-\frac{r}{r_{e,CO}}} 2\pi dr \quad (2.33)$$

$$0.5 = -I_0 2\pi \left[r_{e,CO} e^{-\frac{r}{r_{e,CO}}} \right]_0^{r_{e,CO}} = I_0 2\pi \left\{ [-r_{e,CO} e^{-1}] + r_{e,CO} \right\} \quad (2.34)$$

$$0.7 = -I_0 2\pi \left[r_{e,CO} e^{-\frac{r}{r_{e,CO}}} \right]_0^{r_{70,CO}} = I_0 2\pi \left\{ [-r_{e,CO} e^{-\frac{r_{70,CO}}{r_{e,CO}}}] + r_{e,CO} \right\} \quad (2.35)$$

Building the ratio of the last two equations, a simple relation between $r_{70,CO}$ and $r_{e,CO}$ can be found:

$$\frac{r_{70,CO}}{r_{e,CO}} = 2.16. \quad (2.36)$$

Using formula (2.31), this transforms into:

$$r_{e,CO} = 0.23 r_{25}, \quad (2.37)$$

which indeed is similar to the results in Leroy et al. (2008) or Lisenfeld et al. (2011). and also holds for the molecular gas in ETGs, compare Davis et al. (2013a).

Chapter 3

Observing CO at Millimeter Wavelengths

After the physical background given in chapter 2, observing strategies and methods used in sub-millimeter astronomy are briefly discussed. First, the concept of signal processing is explained in section 3.1. Then common flux units, various beam-efficiencies and brightness temperature scales found in section 3.2 are quoted and recommendations for the appropriate usage are given. A presentation of observatories available for the *submm* wavelength range follows in section 3.4. The selection is based on data used within this work. Then, typical observing modes in radio and *submm* astronomy are described in 3.5. Within my thesis, I also substantially contributed to CO observing proposals, therefore a discussion on the calculation of integration time is given in 3.6.

3.1 Heterodyne Receivers

It exists one *principal* difference between typical signal detection in the optical or near-infrared wavelength regime and radio receivers. In the optical, e.g. when using CCDs, single electrons corresponding to photons are collected and subsequently counted. Thus, the corpuscular nature of light is exploited. In contrary, radio and sub-millimeter detectors make use of the wave-nature of light. Similar to an ordinary radio device, astronomical signals within a certain frequency range, defined by the channel-number and channel-width, are processed. This is of course a highly sensitive and challenging task, because astronomical signals are weak and the noise produced through atmospheric turbulence, reflections and environment are relatively strong. Calibration is a serious and time-consuming procedure which typically lasts as long as the on-source observation. Moreover, the *submm* domain corresponds to frequencies of several hundreds of GHz, which makes it technically even more challenging than e.g. 21 cm observations, because electronic state-of-the-art devices cannot handle these kind of signals due to their high frequencies. For comparison

one can recall actual CPUs used in personal computing, which are limited to frequencies of approximately 3 GHz (per core) today. This limit results from two effects: transmission delays and heat build-up. The transistors on the chip behave like “On-Off” switches. In order to distinguish between these two states, electrons have to charge up or drain the wire that connects the transistors. The faster the state changes (the higher the frequency), the more power is needed, but power leads to heating and thus, cooling is needed. These considerations lead to a speed limit on the chip.

The solution to this problem is the use of “heterodyne” receivers. They consist of a “Local Oscillator” (LO), that mixes the high frequency (HF) signal of the astronomical source with a local and much lower frequency (LF). All further processing is then performed on LF basis. A detailed description on that topic is found in Wilson et al. (2009).

Another matter of fact to be considered is the spatial resolution available to single dish telescopes. The well known proportionality $\theta \propto \frac{\lambda}{D}$, limits the beamsizes θ due to diffraction to values of 10 to 60 arcsecs for single dish telescopes with diameters (D) of 50 to 10 m at a wavelength λ corresponding to the CO J=1–0 transition. An overview of some single-dish telescopes and their beamsizes is given in table 3.2.

On the other hand, with radio telescopes, one measures not only the source flux, but also a spectrum of the source is obtained. Thereby, the spectral range is given by the channel-width and the number of channels provided by the radio telescope’s backend. Interestingly, the effective spectral resolution is variable and can be enhanced by longer exposure times, which in fact leads to a better signal-to-noise (S/N) ratio within each channel. Thus, 3D kinematic information, similar to integral field spectroscopy in the optical, is easily available when observing in the radio or sub-millimeter domain.

3.2 Flux and Brightness Temperature Scales

The flux of an astronomical source attenuated through the distance d following the $1/d^2$ law, can be given in various units. Most common to optical astronomy is the scale of “magnitudes”. Its history goes back to a time, when the most important astronomical instrument was the human eye. Thus, magnitudes scale non-linearly with the brightness of a source, as does the human eye.

Although “magnitudes” are still widely used in optical astronomy (mostly broadband filter systems), with the extension of photon detectors to the X-ray, infrared and radio domain, more physically motivated brightness scales gained importance.

In radio and infrared astronomy for example, the unit of “Jansky” corresponding to $10^{-26} \text{ W Hz}^{-1} \text{ m}^{-2}$ is widely used. In fact it does not measure a flux, but rather the flux *density*, meaning that it is normalized to the frequency.

Another way of measuring a source's flux, probably the most widely used in radio astronomy, is to compute its corresponding black-body temperature. Although black-body radiation relies on thermal equilibrium, it is principally possible to convert a given flux density into a corresponding black-body temperature anyway. Exactly this is, what radio astronomers do. When using Planck's law, see equation (3.1), the resulting temperature is the so called *source brightness temperature* T_B .

Another simplification is often made and instead of Planck's law, its Rayleigh-Jeans (RJ) approximation is used for temperature derivations. This seems reasonable for sub-millimeter astronomy applications, since the RJ approximation is appropriate for low frequencies below $\approx 10^{12}$ GHz (see figure 3.2). The so derived temperature is referred to as the *radiation temperature* T_R .

It is important to keep in mind that brightness temperatures are only a kind of *brightness* measure and not necessarily a real physical temperature. Planck's law and its RJ approximation are shown in equation (3.1) and (3.2).

$$B_\nu(T) = \frac{2h\nu^3}{c^2} \frac{1}{e^{\frac{h\nu}{kT}} - 1} [W m^{-2} Hz^{-1}] \quad (3.1)$$

$$B_\nu(T) \approx \frac{2k}{\lambda^2} T [W m^{-2} Hz^{-1}] \quad (3.2)$$

Hence, the brightness of a source with an angular size expressed as solid angle Ω is given by the surface integral over either the brightness temperature T_B or the radiation temperature T_R . The latter is commonly used in radio astronomy. But what is effectively observed is neither T_B , nor T_R , because other effects have to be taken into account leading to other brightness scales. At first, the scale for the purely (instrumental) brightness of a source is indicated by T_A , the antenna temperature. This antenna temperature has to be corrected for atmospheric attenuation during the observing run by means of the calibration procedures. There are two common methods available: position and frequency switching. Both will be briefly explained in section 3.5. The resulting, atmospheric attenuation corrected brightness scale is then identified by T'_A . In the next step, T'_A has to be corrected for the so called *rearward spillover and scattering*. This accounts for instrumental effects, especially for the sensitivity of the detector not only to signals coming from the front side, but also to surrounding noise. The amount of this correction is quantified by η_{rss} , the efficiency of the antenna in forward direction in comparison to its rearward scattering and spillover. The resulting scale is identified by T_A^* , see figure 3.1 for better understanding. In analogy, also the sensitivity in forward direction is not uniform and signals from other sources and reflections from the ground can influence the measurement. The forward-efficiency η_{fss} (or F_{eff}) is a measure of the main beam lobe size and sensitivity compared to the side-lobes in forward direction. The so gained quantity, which is corrected for

atmospheric attenuation, radiative loss, rearward and forward scattering and spillover is then given in the T_R^* scale. This scale is often found in literature, but depending on the source's extent it may differ from the source's *real* radiation temperature or brightness temperature. Hence, another scale is commonly used, the so called *main beam brightness temperature* scale, T_{MB} . It takes into account the shape (most often described as a Gaussian) of the beam and its changing sensitivity described by its *power pattern*. For example, in a perfect world, when the source and the beam power pattern exactly match each other, the main beam brightness temperature scale gives exactly the real source brightness temperature. The efficiency that translates T_R^* to T_{MB} is η_{MB} (or also B_{eff}). The conversions from and to T_A^* , T_R^* and T_{MB} are given in equations (3.3) and (3.4). A combination of (3.3) and (3.4) leads furthermore to a relation between T_{MB} and T_A^* , which is shown in (3.5). Thereby the product of η_{fss} and η_{MB} is often referred to as the *beam efficiency* η_{beam} . One really has to take care about denotations and meanings of efficiencies indicated in the literature. Within this thesis, all mentioned scales and their meanings follow the suggestions of Kutner and Ulich (1981), who for the first time, tried to unify and define the denotations. Thus, one cannot generally recommend the use of a certain brightness temperature scale, but rather give an advise, for which objects, which scale might be closest to the source's real brightness temperature. Table 3.1 summarizes the available scales and gives some hints to their use in dependence of the source's angular size.

$$T_R^* = \frac{T_A^*}{\eta_{fss}} \quad (3.3)$$

$$T_{MB} = \frac{T_R^*}{\eta_{MB}} \quad (3.4)$$

$$T_{MB} = \frac{T_A^*}{\eta_{fss} \times \eta_{MB}} = \frac{T_A^*}{\eta_{beam}} \quad (3.5)$$

3.3 Solid Angle of a Radio Telescope Beam

The beam can be approximated as Gaussian. Thus, the following equation for the solid angle Ω of the beam, is valid:

$$\Omega = \frac{\pi \Theta_0^2}{4 \ln(2)} \quad (3.6)$$

The beam's half-power-beam-width (HPBW) is indicated by Θ_0 and must be given in *rad*. When incorporating all constants of the above equation into one single factor, and transforming *rad* to *arcsec*, one finds the solid angle from Θ_0 in *arcsec*:

$$\Omega = 1.13309 \times \Theta_0^2, \quad (3.7)$$

Source Size	Temperature Scale
$\Omega_S = 2\pi$	$T_R = T_A^*$
$\Omega_S = \Omega_{MB}$	$T_R = T_{MB}$
$2\pi < \Omega_S$	$T_R < T_A^*$
$\Omega_{MB} < \Omega_S < 2\pi$	$T_A^* < T_R < T_{MB}$
$\Omega_{MB} > \Omega_S$	$T_{MB} < T_R$

Table 3.1: Temperature Scales used in Radio Astronomy. T_R is the so called *radiation temperature* based on the RJ approximation which is not accessible to observations directly due to atmospheric and instrumental effects. Therefore, the T_A^* scale is commonly used which is corrected for atmospheric attenuation, radiative loss, rearward spillover and scattering. When additionally correcting for forward spillover and scattering, the scale is referred to as the T_R^* scale. In a last step, one can account for the shape of the main beam lobe when observing extended sources. Such a correction considering a Gaussian beam and source is referred to as the *main beam brightness temperature scale* T_{MB} .

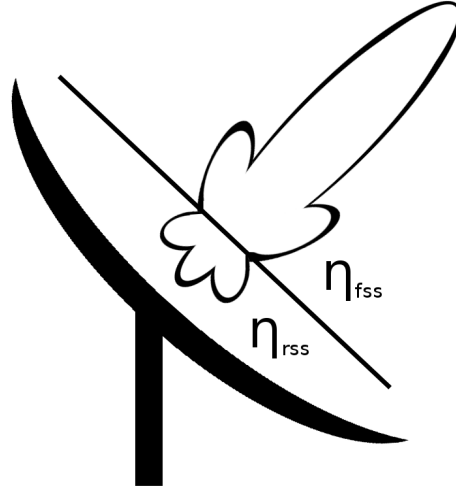


Figure 3.1: Antenna Efficiencies in rearward and forward direction indicated by η_{rss} and η_{fss} , respectively. The beam's sensitivity is displayed as *lobes*.

3.4 Facilities

The presented compiled catalog (see chapter 2) of CO observations relies on data gained at various sites. The following table summarizes facilities through which the presented data was obtained. The indicated beamsizes and main beam efficiencies at 115 GHz were taken from the references as noted. Since these properties are not fixed, but rather change throughout the years, the actual values might differ from the given ones.

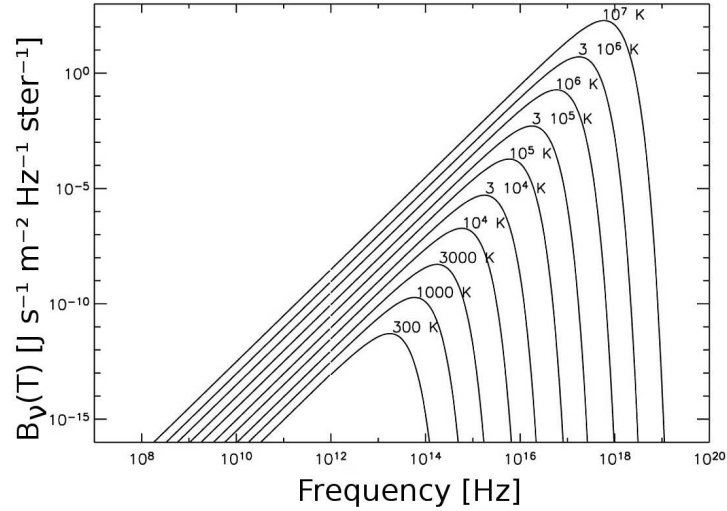


Figure 3.2: Planck's radiation law for black-body radiation of various temperatures. In the radio domain below 10^{12} the mostly linear Rayleigh-Jeans limit can be identified. Image Credit: Thompson et al. (2001).

Telescope & Diam. [m]	Location	Organization	Beamsize CO,1-0	Beam Efficiency η_{beam}
NRAO 12 m	Kitt Peak Arizona, US	National Radio Astronomy Observatory	55''	0.84*
FCRAO 14 m	New Salem Massachusetts, US	Univ. of Massachusetts & Amherst College & Hampshire College & Mount Holyoke College & Smith College	45''	0.73 (Young et al. 1995)
SEST 15 m	La Silla, Chile	ESO & Onsala Space Obs.	43''	0.72 (Johansson et al. 1998)
OSO 20 m	Onsala, Sweden	Onsala Space Observatory	33''	0.50 (Curran et al. 2000)
IRAM 30 m	Pico Veleta, Spanish Sierra Nevada	Institut de Radio Astronomie Millimétrique	24''	0.65 (IRAM Web 09/2013)
NRO 45 m	Nobeyama Minamimaki, Japan	National Astronomical Obs. of Japan	15''	0.38 (Komugi et al. 2008)

Table 3.2: Typical beamsize and beam efficiencies at 115 GHz of various single dish sub-millimeter telescopes. (*) At the NRAO 12m telescope the commonly used scale is T_R^* . Therefore, for NRAO the *main beam* efficiency is indicated, rather than the *beam* efficiency. Hence forward spillover is already taken into account.

3.5 Observing Modes

Similar to observations in the optical domain, calibrations are also needed when observing at radio wavelengths. In order to obtain scientifically useful data, various measurement schemes allow for the successful elimination or characterization of systematic effects, like the variable emission and absorption due to Earth's atmosphere. Basically, the system temperature¹ has to be measured in order to allow for calibration. Roughly speaking, two

¹receiver + atmosphere

procedures are available for that purpose: *position* and *frequency* switching.

Position switching is quite time consuming, because the telescope moves between an offset (OFF) position and the target (ON). Ideally, one specifies the OFF position to be at a fixed azimuth and the same elevation as the target to ensure that the ON and OFF positions are measured through the same airmass. At OFF position the atmosphere’s temperature T_{atm} is measured. On top of that, in order to correct for atmospheric attenuation, “tipping” – measuring T_{atm} at elevations ranging from the horizon up to the zenith – has to be performed regularly for the derivation of the atmosphere’s opacity τ . Moreover, the receiver noise T_{rx} is needed for further calibrations. Its average value is usually available from the telescope’s manual, but since T_{rx} is not constant, especially for mm/submm receivers, the best one can do is to measure it regularly by means of calibrators (hot/cold load). The overall system temperature is then the sum of T_{atm} and T_{rx} . The described procedure – the direct calibration of the atmosphere by tipping scans – is quite time consuming, but leads to best calibration results.

Another way, which is a combination of *position* and *beam* switching is referred to as the “chopper wheel method”. Thereby the process of measuring receiver and atmospheric temperature separately is simplified and the system temperature can be measured directly at one single OFF position. Details on that can be found in Mangum (2013). This method’s advantage is that the observing overhead can be reduced.

In the frequency switching observing mode, the local oscillator (LO) is shifted by several MHz at a rate of several Hz. The spectrum is recorded as a ratio of $(\text{SIGNAL} - \text{REF})/\text{REF}$. This leads to two advantages compared to the position switching mode. First, the on-source integration time is increased substantially and second, the problem of finding an emission-free OFF position when observing in a (spatially) complex emission region can be avoided.

If the frequency shift is small enough, the spectral line will appear in both, the signal and the reference spectra. Hence, when the resultant spectrum is formed, the line will appear twice, once in emission and once in absorption. Then the spectrum can be “folded” to obtain a $\sqrt{2}$ improvement in signal-to-noise. With this technique, which is called “in-band” or “overlapped” frequency switching, one is effectively observing on-source all the time.

However, the main caveat of frequency switching is, that the spectral baselines are generally not as good/flat as with beam switching. This is because the two frequency positions each have their own spectral bandpass shapes which do not cancel in the computation of the final spectrum.

Another method is the so called “On-the-Fly” (OTF) mapping. Thereby, total power data is acquired at a high rate (typically less than 0.1 seconds) while the telescope is moving/scanning continuously over the target. This is especially useful for the mapping

of extended objects.

3.6 Integration Time Calculations

During my master studies, I was given the possibility of working actively together with my supervisors on proposing CO observations at various facilities, namely IRAM, APEX (ESO, MPG and Swedish time) and PdBI, the “Plateau de Bure Interferometer”. A summary of the proposals is shown in table 3.3.

In order to make accurate estimates of the proposed observing time, the *expected* CO luminosities expressed as L'_{CO} were calculated for most of the CALIFA sources. The estimates rely thereby on the L'_{CO} vs. SFR relation as shown in figure 3.3, which was found by help of the homogenized archival CO data.

After extracting infrared fluxes based on WISE data and using data from the IRAS catalog², SFR calculations were made applicable for *all* CALIFA targets. Likewise, the CO luminosities were estimated through the correlation as described before for *all* CALIFA galaxies.

In order to translate the intrinsic value of L'_{CO} to an exposure time, some further constraints on the observing strategy were defined: For the sake of simplicity, the CO emission line was treated as it was of Gaussian shape. Its full-width-at-zero-intensity (FWZI) was estimated to be 300 km/s corresponding to the average value found from archival CO data for CALIFA galaxies.

For the following calculations, the channel width was fixed to 200 km/s. Hence, short integration times should be made possible. On top of that, for a clear detection, the integrated signal-to-noise ratio should be at least 3 within the 200 km/s channel. Summarizing what is stated above, the following can be noted:

$$dI_{CO} = T_{peak} \times e^{-\frac{dv^2}{2 \times \sigma^2}} \quad (3.8)$$

$$I_{CO} = \int_a^b dI_{CO} \quad (3.9)$$

Equation 3.8 indicates the CO line’s brightness temperature element dI_{CO} in dependence of the velocity dv . A relation between the Gaussian σ and the line’s FWHM is shown in equation (5.26). The total received flux I_{CO} (see equation 3.9) within a channel is then defined as the integral over dI_{CO} within the limits of a and b corresponding to -150 and +150 km/s for the prior constrained FWZI line-width. Furthermore, a 3 sigma detection is aspired within the limits of -100 km/s and +100 km/s for the given channel width. After defining these constraints, the computations were performed in four steps:

²Details on the used methods and formula can be found in the next chapter.

Facility	Period	Comment	Status
IRAM PdBI	WS2012/2013	We requested PdBI observations for four CALIFA galaxies drawn from the observed sample. We proposed PdBI CO(1-0) observations of the cold molecular gas reservoir, matching the spatial resolution of 2 arcsec of the optical IFU data.	REJECTED
*MPG APEX	2013A	We requested APEX SHeFI CO(2-1) observations of 8 CALIFA galaxies in order to confirm the presence of molecular gas and thus prepare PdBI and ALMA follow-up.	ACCEPTED & DATA OBTAINED.
IRAM 30m	SS2013	We requested EMIR CO(1-0) observations of 25 CALIFA galaxies in order to confirm the presence of molecular gas and thus prepare PdBI and ALMA follow-up on them.	ACCEPTED & DATA OBTAINED.
IRAM PdBI	SS2013	We requested PdBI observations for two CALIFA galaxies drawn from the observed sample. We proposed PdBI CO(1-0) observations of the cold molecular gas reservoir, matching the spatial resolution of 2 arcsec of the optical IFU data.	REJECTED
ESO APEX	P92	We requested APEX SHeFI CO(2-1) observations of 10 CALIFA galaxies in order to confirm the presence of molecular gas and thus prepare PdBI and ALMA follow-up.	ACCEPTED & DATA OBTAINED.
OSO APEX	P92	We requested APEX SHeFI CO(2-1) observations of 10 CALIFA galaxies in order to confirm the presence of molecular gas and thus prepare PdBI and ALMA follow-up.	ACCEPTED & DATA OBTAINED.

Table 3.3: Submitted proposals for CO follow-up observations of CALIFA galaxies. Helmut Dannerbauer is the PI of all proposals except for the MPG (Max Planck Gesellschaft) observing time, for which Glenn van de Ven is the PI.

1. Calculation of I_{CO} can be easily found from L'_{CO} by inversion of formula (5.33).
2. The peak brightness temperature in the main beam brightness temperature scale – on which the L'_{CO} vs. SFR relation relies – can be derived from the constrained FWZI line-width and the total integrated flux of the Gaussian line, because I_{CO} actually corresponds to the solution of the Gaussian CO line integral within the velocity range of $-150 \text{ km/s} +150 \text{ km/s}$. Luckily Gaussian integrals can be numerically solved by means of the Gaussian Errorfunction (*erf*). Hence, the peak brightness temperature in the main beam temperature scale can be derived from equation (3.10), when inserting $b = +150 \text{ km/s}$ and $a = -150 \text{ km/s}$.

$$I_{CO} = \sqrt{\frac{\pi}{2}} T_{peak} \sigma \left(\text{erf}\left(\frac{b}{\sqrt{2}\sigma}\right) - \text{erf}\left(\frac{a}{\sqrt{2}\sigma}\right) \right) \quad (3.10)$$

Note that, in the situation of a narrow line-width which is comparable to the desired channel-width, e.g. when resolving galaxies, there is no need for calculating the peak brightness temperature, no Gaussian Errorfunction has to be solved; instead the maximum allowed noise (RMS) can be directly inferred from the initially calculated I_{CO} (step 1) by simply dividing by the desired SNR, e.g. $\frac{I_{CO}}{3}$ for a 3σ detection. From that, one can directly make an exposure time estimate (step 4).

3. Once knowing the peak height, the Gaussian Integral can be solved for any other velocity range too. Hence, equation (3.10) directly leads to the source's flux found within a channel when inserting $b = +100 \text{ km/s}$ and $a = -100 \text{ km/s}$ for the desired channel-width of 200 km/s . The maximum allowed noise within the channel – defined by the root-mean-square (RMS) level – is then $1/3$ of the calculated flux in order to assure a 3 sigma detection.
4. Finally, the Exposure Time Calculator (ETC) of the desired telescope can be used for an integration time derivation through the found RMS values. For some ETCs it might be necessary to convert the found RMS value to another brightness temperature scale. For example, the ETC for the IRAM 30m telescope needs T_A^* as input scale. A conversion can be easily performed through equation (3.5).

A list of inferred RMS values assuming a Gaussian CO line and a beamsize of 24 arcsec is given for the interferometric CO subsample in the following table 3.4. Also CALIFA's observing status as of September 2013 is shown. Thereby, empty fields indicate that the galaxy was not observed so far. Moreover it is stated, if an object is part of one of the submitted proposals. Empty fields indicate that observations were not proposed, because single dish data is already available through the archive.

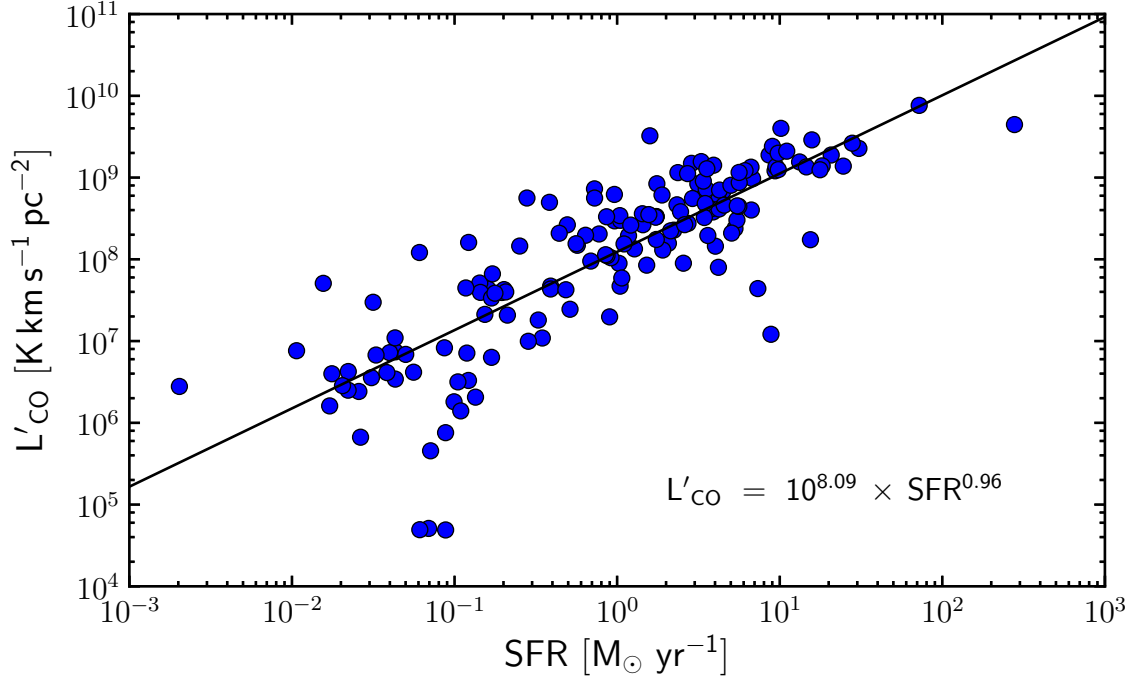


Figure 3.3: Fit to the L'_{CO} vs. SFR correlation. Both quantities were calculated as described in chapter 5. The best fit to the data is indicated and was used for L'_{CO} estimation based on the star formation rates.

ID	Name	Proposal	Observing Status	L'_{CO} [$K\ km\ s^{-1}\ pc^{-2}$]	I_{CO} [$K\ km\ s^{-1}$]	Peak [mK]	RMS [mK]
2	UGC00005		V500+V1200	1.21E+09	7.54	44.31	2.68
4	UGC00029	IRAM Mar 2013	V500+V1200	5.13E+08	2.22	13.04	0.79
9	NGC0023		V500+V1200	2.27E+09	35.71	209.86	12.68
14	UGC00312		V500+V1200	4.97E+08	8.60	50.57	3.05
17	UGC00335NED02	APEX Feb 2013	V500+V1200	3.80E+08	4.17	24.52	1.48
26	NGC0192		V500+V1200	1.89E+09	34.85	204.80	12.37
47	NGC0517	IRAM Mar 2013	V500+V1200	1.32E+07	0.25	1.44	0.09
100	NGC1056		V500+V1200	8.48E+07	11.41	67.03	4.05
113	UGC02367			1.10E+09	6.68	39.23	2.37
114	NGC1142			7.64E+09	34.09	200.37	12.10
119	NGC1167	IRAM Mar 2013	V500+V1200	1.72E+08	2.33	13.67	0.83
131	NGC1542		V500+V1200	2.95E+08	6.91	40.61	2.45
134	NGC1645	IRAM Mar 2013	V500+V1200	4.98E+07	0.69	4.04	0.24
141	IC2095	APEX Feb 2013	V500+V1200	2.31E+09	91.75	539.22	32.57
152	UGC03944		V500+V1200	7.27E+08	15.58	91.54	5.53
186	IC2247		V500+V1200	6.50E+08	11.38	66.88	4.04
201	NGC2592			3.98E+06	0.33	1.92	0.12
213	NGC2623	IRAM Mar 2013	V500+V1200	6.25E+09	67.04	394.00	23.80
232	NGC2730		V500	2.27E+08	5.02	29.49	1.78
306	UGC05358	APEX Feb 2013	V500+V1200	6.45E+07	2.47	14.54	0.88
310	SDSSJ100141.02+371447.4	IRAM Mar 2013	V500	3.53E+06	0.46	2.72	0.16
409	UGC06433			9.45E+07	6.89	40.47	2.45

ID	Name	Proposal	Observing Status	L'_{CO} [$K \text{ km s}^{-1} \text{ pc}^{-2}$]	I_{CO} [$K \text{ km s}^{-1}$]	Peak [mK]	RMS [mK]
417	NGC3712			1.32E+08	15.68	92.17	5.57
478	NGC3995			3.03E+08	8.90	52.30	3.16
487	UGC07017			4.60E+08	15.37	90.35	5.46
492	SDSSJ120353.51+252556.6			5.47E+07	1.69	9.95	0.60
520	NGC4211NED02	IRAM Mar 2013	V500	8.46E+08	6.25	36.76	2.22
537	NGC4306			1.31E+06	0.18	1.07	0.06
541	IC3305			1.17E+06	0.07	0.39	0.02
542	NGC4383			7.98E+07	8.96	52.68	3.18
554	IC3453			9.46E+06	0.47	2.77	0.17
566	NGC4598			3.93E+06	0.33	1.93	0.12
577	NGC4676A		V500+V1200	2.89E+09	21.63	127.14	7.68
588	NGC4816	IRAM Mar 2013	V500+V1200	2.79E+07	0.19	1.13	0.07
593	UGC08107	IRAM Mar 2013	V500+V1200	1.00E+09	4.84	28.47	1.72
634	NGC5218		V500+V1200	1.25E+09	48.39	284.41	17.18
655	UGC08726			8.61E+06	0.51	3.02	0.18
748	NGC5633		V500+V1200	3.82E+08	22.87	134.44	8.12
749	NGC5630	IRAM Mar 2013	V500+V1200	1.43E+08	6.55	38.50	2.33
767	NGC5731	IRAM Mar 2013	V500	4.65E+07	2.37	13.91	0.84
780	NGC5797	IRAM Mar 2013	V500+V1200	2.09E+07	0.43	2.52	0.15
784	NGC5829		V500	4.81E+08	4.92	28.93	1.75
794	NGC5928	IRAM Mar 2013 & APEX Mar 2013	V500	2.39E+07	0.39	2.31	0.14
795	NGC5930		V500	1.74E+08	8.19	48.13	2.91
801	NGC5953		V500	2.09E+08	17.30	101.66	6.14
802	ARP220		V500+V1200	4.45E+09	49.46	290.72	17.56
803	NGC5957		V500	1.21E+08	11.67	68.58	4.14
827	UGC10297	IRAM Mar 2013 & APEX Mar 2013	V500+V1200	2.29E+07	1.40	8.23	0.50
828	UGC10331	IRAM Mar 2013	V500+V1200	5.49E+08	8.67	50.94	3.08
843	UGC10650	IRAM Mar 2013	V500+V1200	5.47E+07	2.03	11.93	0.72
845	UGC10693	IRAM Mar 2013	V500+V1200	6.76E+07	0.32	1.88	0.11
846	UGC10695	IRAM Mar 2013	V500+V1200	4.97E+07	0.24	1.38	0.08
858	UGC10905	IRAM Mar 2013	V500+V1200	2.21E+08	1.17	6.85	0.41
870	NGC6945	IRAM Mar 2013	V500+V1200	1.16E+07	0.27	1.56	0.09
878	MCG-01-54-016	IRAM Mar 2013	V500+V1200	7.71E+06	0.29	1.70	0.10
882	NGC7236		V500+V1200	1.81E+07	0.10	0.57	0.03
885	UGC12054	IRAM Mar 2013 & APEX Mar 2013	V500+V1200	2.92E+06	0.22	1.27	0.08
895	UGC12308	IRAM Mar 2013 & APEX Mar 2013	V500+V1200	5.03E+06	0.32	1.87	0.11
904	NGC7591		V500+V1200	2.63E+09	35.18	206.76	12.49
913	NGC7625		V500+V1200	3.25E+08	39.69	233.28	14.09
914	NGC7631		V500	2.62E+08	6.07	35.66	2.15
917	NGC7683	IRAM Mar 2013 & APEX Mar 2013	V500	2.62E+07	0.62	3.64	0.22
927	NGC7738	IRAM Mar 2013 & APEX Mar 2013	V500+V1200	3.55E+09	25.06	147.29	8.90

ID	Name	Proposal	Observing Status	L'_{CO} [$K km s^{-1} pc^{-2}$]	I_{CO} [$K km s^{-1}$]	Peak [mK]	RMS [mK]
937	NGC7800	APEX Feb 2013	V500+V1200	6.87E+07	7.33	43.10	2.60
939	NGC4676B		V500+V1200	1.28E+09	9.94	58.44	3.53

Table: 3.4: CALIFA CO-interferometric subsample. Column specifications: CALIFA ID (1), other catalog ID (2), facility at which observations were proposed (3), CALIFA observing status (4), estimated L'_{CO} in [$K km s^{-1} pc^{-2}$] based on the L'_{CO} vs. SFR relation (5), derived velocity integrated flux I_{CO} in [$K km s^{-1}$] (6), peak brightness temperature in mK and T_{MB} scale (7), maximum allowed RMS within a 200 km/s channel assuming a beamsize of 24 arcsec and a Gaussian CO line-width of 300 km/s FWZI (8).

Chapter 4

CO Luminosities for CALIFA Galaxies

Legacy surveys, such as GALEX, SDSS and WISE, nowadays provide the community with an enormous amount of high quality data from the UV to the infrared. The resulting catalogs encompass several tens to hundreds of thousands of objects. Nevertheless, an important domain, the submm and radio, is missing. The reason? At long wavelengths, interferometers are needed in order to get spatially resolved data of extragalactic objects such as CALIFA galaxies, and interferometric observations are time and cost-intensive. Although surveys enfolding up to several hundred of objects like THINGS, BIMA-SONG and ATLAS^{3D}, were already carried out, a CO survey based on a *statistical* sample of nearby galaxies is still missing. Therefore, in the present work, a subsample of CALIFA (section 4.1) galaxies is defined in order to undertake such an interferometric survey in the future. Thereby, detailed studies of the cold, molecular gas on a statistical basis will be possible for the very first time. In order to define such a subsample, an extended search on available CO data in the literature (section 4.2) was performed, because a compulsive prerequisite for proposing observations at an interferometer, is the target's detection by means of a single dish telescope. This is, because detection can be a tricky task. For example, Davis et al. (2013b) found that only one out of four early type galaxies is detectable at all with typical CO line-sensitivities around 20mJy. Late types are generally more likely to detect, but depending on their stellar mass, it can be difficult anyhow (Helmut Dannerbauer, personal communication). Thus, not before a galaxy is detected by means of a single dish telescope, the derived flux in combination with a typical flux distribution is used in order to estimate the needed observing time.

Therefore, CO luminosities were calculated for all CALIFA galaxies with archival data available. The used method is described in section 4.3. The specifications which were used to find the subsample, and the algorithm developed to apply these constraints, are presented in the last section, 4.4, of this chapter.

4.1 Introducing CALIFA

CALIFA, the “Calar Alto Legacy Integral Field Area survey”, see also Sánchez et al. (2012), is obtaining integral-field spectroscopic (IFS) data in the optical ranging from 370 to 700 nm of a diameter selected sample of approximately 600 galaxies of all Hubble types (see Fig. 4.1(b)), from elliptical to spiral galaxies, in the local universe ($0.005 \leq z \leq 0.03$).

This ongoing survey has been granted 250 nights with the 3.5 m telescope at the Calar Alto observatory, using the PMAS/PPAK integral field unit (IFU) as described in Roth et al. (2005) and Kelz et al. (2006). The hexagonal field-of-view (FOV) of $64'' \times 72''$ covers the full optical extent of the selected galaxies down to a 3σ depth of 23 mag arcsec⁻², at a spatial resolution of about 2 arcsec.

Based on these constraints, a so called “mothersample” of 937 galaxies was defined. The mothersample was initially selected from the SDSS DR7 survey, but with additional restrictions for avoiding lines of sight to targets along the galactic plane, see figure 4.1(c). No explicit cut in apparent magnitude was involved, but the adopted criteria implicitly ensures that only relatively bright galaxies enter the sample. No CALIFA galaxy is fainter than $M_r = 16$. The distribution of the mothersample in the color magnitude diagram is given in figure 4.1(a). More details on the sample definition can be found in Sánchez et al. (2012).

From the mothersample, the galaxies are drawn as actual targets according to their *visibility*, in a random fashion, so that the final catalog of CALIFA galaxies will be a subset of approximately 2/3 of the galaxies of the mother sample. This will not influence the statistical nature of the resulting sample, but will simplify the process (schedule) of observations. Whenever a time slot at the 3.5 m telescope is available, it can likely be used for CALIFA, because the visibility of its targets is so diverse.

Up to now (Oct. 2013), 384 galaxies were already observed, more than half of the final sample.

4.2 Archival CO Data

In order to look for CO emission line data in the literature, NASA’s Extragalactic Database (NED¹), was used. Unfortunately, one cannot achieve such specific data as simply as e.g. SDSS photometry data, because NED’s search result page does not include information on any kind of molecular line data. Thus, for every single target, it would be necessary to check all publication’s abstracts and titles for keywords indicating that CO observational data is provided. Since for CALIFA’s mothersample of 937 galaxies, more

¹The NASA/IPAC Extragalactic Database (NED) is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

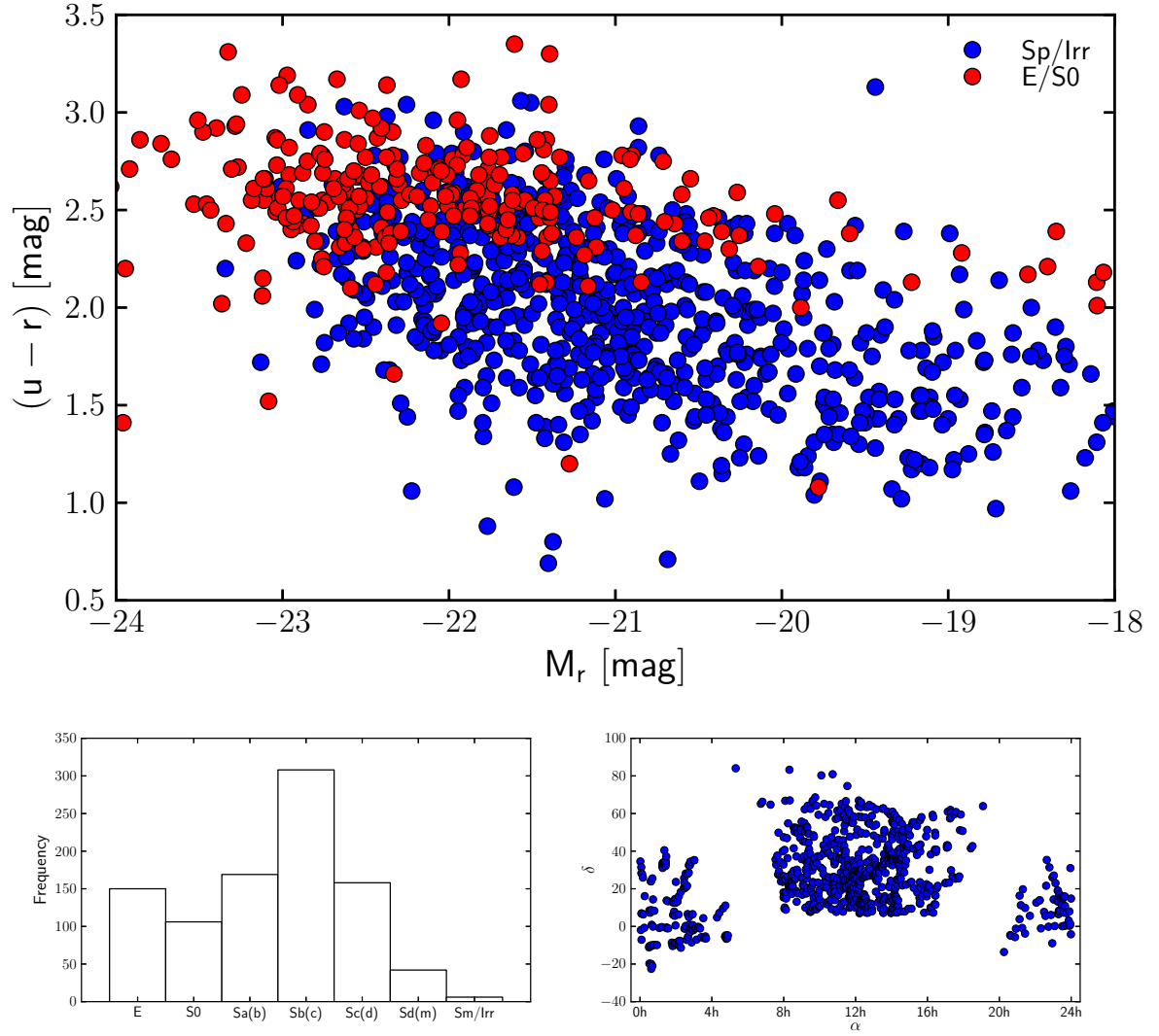


Figure 4.1: The color magnitude diagram (top) unambiguously reveals the red sequence of galaxies. The distribution of Hubble types in the CALIFA galaxies (bottom left) shows a widespread distribution. The mothersample is distributed over the whole hemisphere (bottom right). Regions without targets indicate the milky way plane, which is avoided due to dust extinction.

than 46350 publications exist, it was clear, that an automatisisation was needed to perform this task. Hence, I have developed a set of Linux scripts (see appendix). A description of their functionality follows in the next section.

4.2.1 Linux Scripts for NED Special Data Download

All shell scripts and needed input files can be found online at www.sonnensystem.at/master/scripts/NED/. The source codes use NED query result pages `part1.htm` and `part2.htm` as input (also downloadable). Since, the order and number of columns must be of a specific format, a preformatted NED formular `NED-Query.html` is also provided to create query result pages of the needed shape. Equipped with these tabular data, the functions of each shell script are:

1. `getNEDReferences.sh`: Script to download a html file for every single target containing a short version of titles, links to the abstracts and the bibliography codes of all references. This script will create a subfolder **REF** for data storage.
2. `getNEDPhotometry.sh`: Script to download a html file for every single target containing basic photometry from SDSS, 2MASS, IRAS and other surveys. This script will create a subfolder **PHOT** for data storage.
3. `getNEDAbstracts.sh`: Script to download a html file for every single title and abstract. Execution can take a long time depending on the number of references available. This script will create a subfolder **ABS** for data storage.
4. `tablebuild.sh`: This script will actually perform a query on the keywords given in the file `ref_keywords-CO`. In the case of CO, I have chosen the keywords: CO, carbonous oxide and carbon monoxid. Moreover, the script downloads SDSS post-stamp images for all targets, which will be stored in a subfolder **IMG**. After execution (which can last long), a html file is created summarizing all information and abstracts. The result of the CALIFA CO query, can be seen at: www.sonnensystem.at/master/scripts/NED/califa_tbl-CO.htm.

Based on the resulting html file, for every single target, the found publications were manually examined and all data of interest was collected for subsequent investigations.

4.2.2 Calibration to a Homogeneous Brightness Temperature Scale

Unfortunately, published CO data is not always given in the same brightness temperature scale (see section 3.2). Thus, for the purpose of comparing observations at different facilities, I have chosen to convert all data into the “main beam brightness temperature”

scale, T_{mb} . The reason for choosing T_{mb} is, that only this scale does take into account different beam efficiencies, antenna imperfections and feed coupling efficiencies (Wilson et al., 2009), which can vary strongly from one telescope to another (compare 3.4).

Due to CALIFA’s diameter selection covering the D_{25} diameter in most cases, all galaxies in question extensively do fill the typical single dish beam ranging from 24 arcsec for the IRAM 30m telescope to 55 arcsec for the NRAO 12m telescope in the CO J=1–0 transition, even when assuming an exponential CO distribution as described in section 2.4. Thus, beam dilution can be neglected in most cases and T_{mb} should approach the source brightness temperature.

Nevertheless, for molecular mass calculations, an aperture correction will be applied to the data, which is described in section 5.6.3.

4.3 Calculating CO Luminosities

4.3.1 CO Line Luminosity

The conversion from an observed brightness temperature given in Kelvin to a flux density given in Jansky is a strongly telescope- and frequency dependent task. For example, an observed *point* source’s flux of 1 Jansky, initiates a brightness temperature of approximately 33 mK at the NRAO 12m telescope, whereas at the IRAM 30m telescope the measured main beam brightness temperature would be around 200 mK!

The statement above silently was assuming a monochromatic, infinitesimal narrow line, which, of course, does not exist in reality. Several line broadening mechanisms (pressure, redshift, kinematics, etc.) must be taken into account. Thus, Gaussians integrals are widely used for line fitting leading to the so called “velocity integrated” brightness temperature and flux density measured in $K km s^{-1}$ and $Jy km s^{-1}$, respectively.

Therefore, different approaches as seen in equation (4.1) and (4.2) are available for computing molecular line luminosities.

$$L_{CO} = 1.04 \times 10^{-3} S_{CO} \Delta v \nu_{rest} (1+z)^{-1} D_L^2 \quad (4.1)$$

$$L'_{CO} = 23.5 \Omega_{s*b} I_{CO} (1+z)^{-3} D_L^2 \quad (4.2)$$

Both equations are taken from Solomon and Vanden Bout (2005). L_{CO} and L'_{CO} are measured in $L_{\odot}$ and $K km s^{-1} pc^2$, respectively, $S_{CO} \Delta v$ and I_{CO} in $Jy km s^{-1}$ and $K km s^{-1}$ respectively, ν , the frequency, in GHz and D_L , the luminosity distance in Mpc. Ω_{s*b} is the solid angle of the source convolved with the telescope beam in arcsec².

It is convenient to apply 4.1 on *point* sources, because then the observed brightness temperature can be converted to a flux density through a simple factor, which normally can be found in the radio telescope’s manual. But for extended sources, the conversion

is much more complicated and in that case, equation (4.2) seems to be more convenient. Then, Ω_{s*b} , which is the convolution of the source with the beam, has to be computed. See section 3.3 for a description of the solid angle of a beam and section 5.6.3 for a convolution of a Gaussian beam with an exponential source. However, it is convenient to assume both, source and beam Gaussian shaped in order to get a analytical convolution integral.

4.3.2 Table of CO Literature Data

The following table 4.1 lists all CO J=1–0 detections and non-detections of CALIFA galaxies found in the literature. In the case of non-detections, upper limits are given. Column descriptions are as follows:

Tabelle: 4.1: CO J=1–0 detections and upper limits for CALIFA galaxies. Column specifications: Sequence number (1), CALIFA ID (2), Other catalog ID (3), Morphology (4), I_{CO} homogenized to main beam brightness temperature scale in $K km s^{-1}$ (5), flux density S_{CO} in $Jy km s^{-1}$ assuming Gaussian beam (6), half-power beam-width in arcsec (7), telescope (8), short code of the publication (9), calculated CO luminosity L'_{CO} using equation (4.2) and the cosmology defined in table 1 (10).

(*) The original temperature scale of the published I_{CO} value is T_A^* , which is commonly used at the IRAM 30 m. The value was converted to T_{MB} by a multiplication with 1.628.
(**) The original temperature scale of the published I_{CO} value is T_R^* , which is commonly used at the NRAO 12 m. The value was converted to T_{MB} by a multiplication with 1.22 in all cases, but for BIMA-SONG, for which a factor of 1.16 was applied.

Nr.	ID	Name	Morph	I_{CO} $K km s^{-1}$	S_{CO} $Jy km s^{-1}$	θ_{beam} "	Tel	PUBL	L'_{CO} $K km s^{-1} pc^2$
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
1	2	UGC00005	Sbc	1.99±0.55	43.7±12.1	45	SEST	Sauty2003	1.210E+09
2	9	NGC0023	Sb	18±1.3	212.5±15.4	33	OSO	Elfhag1996	2.272E+09
3	11	UGC00139	Scd	<0.51	<11.2	45	SEST	Sauty2003	8.930E+07
4	26	NGC0192	Sab	9.48	208.1	45	SEST	Boselli1996	1.888E+09
5	30	NGC0237	Sc	3.53±0.56	77.5±12.3	45	SEST	Sauty2003	6.874E+08
6	68	NGC0741	E1	<0.39	<12.8	55	NRAO	Evans2005	2.042E+08
7	74	NGC0781	Sa	<0.77	<4.8	24	IRAM	AMIGA	2.983E+07
8	78	NGC0833	Sa	5.6±1.09*	35±6.8	24	IRAM	Leon1998	2.641E+08
9	100	NGC1056	Sa	11.2	69.9	24	IRAM	Albrecht2007	8.479E+07
10	114	NGC1142	Sd	8.88±0.4	195±8.8	45	SEST	Strong2004	7.635E+09
11	125	UGC02690	Scd	4.17±0.33*	26±2.1	24	IRAM	Leon1998	5.324E+08
12	131	NGC1542	Sab	6.64±0.46	41.5±2.9	24	IRAM	AMIGA	2.954E+08
13	138	NGC1665	S0	<0.51	<3.2	24	IRAM	ATLAS3D	1.210E+07
14	140	NGC1667	Sbc	15±1	177.1±11.8	33	OSO	Curran2000	1.888E+09
15	143	NGC1677	Scd	0.81±0.27	5.1±1.7	24	IRAM	ATLAS3D	1.977E+07
16	150	UGC03899	Sd	<0.9	<5.6	24	IRAM	AMIGA	4.335E+07
17	152	UGC03944	Sbc	4.25±0.24	93.3±5.3	45	FCRAO	AMIGA	7.275E+08
18	158	UGC04054	Scd	<1	<22	45	FCRAO	AMIGA	5.124E+07
19	162	NGC2481	S0	<0.03	<0.2	24	IRAM	ATLAS3D	4.546E+05
20	186	IC2247	Sab	2.07±0.17	67.9±5.6	55	NRAO	Lavezzi1998	6.502E+08
21	189	NGC2554	SOa	2.17±0.17	71.2±5.6	55	NRAO	Lavezzi1998	6.218E+08

Continued on next page

Table continued from previous page

Nr.	ID	Name	Morph	I_{CO} $K km s^{-1}$	S_{CO} $Jy km s^{-1}$	θ_{beam} "	Tel	PUBL	L'_{CO} $K km s^{-1} pc^2$
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
22	192	NGC2565	Sb	<0.48**	<15.7	55	NRAO	Boselli1997	1.045E+08
23	195	NGC2577	E7	<-0.11	<-0.7	24	IRAM	ATLAS3D	4.162E+06
24	198	UGC04386	Sbc	2.3±0.18	75.4±5.9	55	NRAO	Lavezzi1998	8.367E+08
25	201	NGC2592	E4	0.32±0.31	2±1.9	24	IRAM	ATLAS3D	3.983E+06
26	204	NGC2595	Sc	2.28±0.19	74.8±6.2	55	NRAO	Lavezzi1998	7.193E+08
27	221	UGC04551	S0	<-0.06	<-0.4	24	IRAM	ATLAS3D	2.785E+06
28	226	UGC04659	Sdm	<1.28	<28.1	45	FCRAO	AMIGA	4.693E+07
29	230	NGC2719	Sd	<0.34	<2.1	24	IRAM	Albrecht2004	1.090E+07
30	231	UGC04722	Sdm	1.19±0.25	26.1±5.5	45	FCRAO	AMIGA	3.930E+07
31	232	NGC2730	Scd	1.37±0.24	30.1±5.3	45	SEST	Albrecht2004	2.272E+08
32	238	NGC2764	Sab	16.2±0.58	101.2±3.6	24	IRAM	ATLAS3D	3.798E+08
33	243	NGC2778	E4	<0.18	<1.1	24	IRAM	ATLAS3D	2.418E+06
34	244	UGC04845	Scd	<0.79	<17.3	45	FCRAO	AMIGA	3.939E+07
35	258	NGC2832	E4	3.3	20.6	24	IRAM	Wiklind1995	4.979E+08
36	260	NGC2805	Sc	2.34±0.1	14.6±0.6	24	IRAM	Boeker2003	2.450E+07
37	272	NGC2880	E7	<-0.09	<-0.6	24	IRAM	ATLAS3D	2.507E+06
38	273	IC2487	Sc	3.94±0.41	86.5±9	45	FCRAO	AMIGA	8.406E+08
39	299	NGC3021	Sbc	5.1	112.0	45	SEST	Albrecht2007	1.342E+08
40	312	NGC3057	Sdm	<0.45	<2.8	24	IRAM	Albrecht2004	3.298E+06
41	316	IC0598	S0a	<-0.01	<-0.1	24	IRAM	ATLAS3D	7.391E+06
42	323	NGC3182	E7	3.01±0.35	18.8±2.2	24	IRAM	ATLAS3D	4.260E+07
43	328	NGC3230	S0a	<-0.37	<-2.3	24	IRAM	ATLAS3D	8.272E+06
44	346	UGC05820	Sbc	3.58±0.26	78.6±5.7	45	FCRAO	AMIGA	5.621E+08
45	355	NGC3395	Scd	1.45±0.21**	47.6±6.9	55	NRAO	Smith2001	5.911E+07
46	366	UGC06062	S0a	<-0.04	<-0.2	24	IRAM	ATLAS3D	6.870E+06
47	368	NGC3471	Sb	14.9±4.8	175.9±56.7	33	OSO	Elfhag1996	4.011E+08
48	374	UGC06176	Sa	3.92±0.38	24.5±2.4	24	IRAM	ATLAS3D	8.959E+07
49	382	NGC3561	E5	2.59±0.26**	85±8.5	55	NRAO	Smith2001	3.241E+09
50	389	NGC3610	E6	<-0.1	<-0.6	24	IRAM	ATLAS3D	3.167E+06
51	391	NGC3619	S0a	4.32±0.51	27±3.2	24	IRAM	ATLAS3D	3.363E+07
52	402	NGC3648	E7	<-0.14	<-0.9	24	IRAM	ATLAS3D	4.241E+06
53	406	NGC3656	Sa	23.4	146.1	24	IRAM	Wiklind1995	6.118E+08
54	410	NGC3674	S0	0.13±0.3	0.8±1.9	24	IRAM	ATLAS3D	1.610E+06
55	413	NGC3682	Sa	4.33±0.39	95.1±8.6	45	FCRAO	AMIGA	1.108E+08
56	418	NGC3752	Scd	1.15±0.26	25.3±5.7	45	FCRAO	AMIGA	4.702E+07
57	426	NGC3753	Sa	<2.82	<17.6	24	IRAM	Casoli1996	7.031E+08
58	430	NGC3800	Sbc	7.9	173.5	45	SEST	Albrecht2007	9.700E+08
59	431	NGC3798	Sab	1.54±0.3	50.5±9.8	55	NRAO	Casoli1996	3.336E+08
60	432	NGC3801	S0a	3.82±1.14	23.9±7.1	24	IRAM	Ocana-Flaquer2010	1.485E+08
61	438	UGC06653	Sab	1.59±0.3	52.2±9.8	55	NRAO	Casoli1996	2.751E+08
62	443	NGC3832	Sbc	2.95±0.39	96.8±12.8	55	NRAO	Casoli1996	2.407E+09
63	444	UGC06697	Scd	9.5±0.6	59.3±3.7	24	IRAM	Boselli1994	1.359E+09
64	447	NGC3862	E1	0.7±0.15	4.4±0.9	24	IRAM	Ocana-Flaquer2010	9.517E+07
65	451	NGC3884	S0a	1.09±0.22**	35.8±7.2	55	NRAO	Boselli1997	9.053E+08
66	452	NGC3883	Sbc	0.67±0.17**	22±5.6	55	NRAO	Boselli1997	5.617E+08
67	455	NGC3888	Sc	22.8	142.4	24	IRAM	Albrecht2007	4.135E+08
68	468	NGC3947	Sbc	2.06±0.3	67.6±9.8	55	NRAO	Casoli1996	1.340E+09
69	474	NGC3987	Sab	17.4	382.0	45	SEST	Albrecht2007	4.000E+09
70	475	NGC3991	Sm	0.82±0.25	26.9±8.2	55	NRAO	Casoli1996	1.448E+08
71	476	NGC3994	Sbc	21.2±6.3	49±14.6	14.6	NRO	Yao2003	2.381E+08
72	478	NGC3995	Sm	23.2±5.1	53.6±11.8	14.6	NRO	Yao2003	3.026E+08
73	485	NGC4017	Sc	2.06±0.29	67.6±9.5	55	NRAO	Casoli1996	4.124E+08
74	487	UGC07017	Sb	2.83±0.7	92.8±23	55	NRAO	Casoli1996	4.596E+08
75	494	NGC4078	S0	<-0.09	<-0.6	24	IRAM	ATLAS3D	7.215E+06
76	498	NGC4134	Sbc	1.35±0.29	44.3±9.5	55	NRAO	Casoli1996	3.329E+08
77	506	NGC4158	Sb	1.95±0.31	64±10.2	55	NRAO	Casoli1996	1.969E+08
78	508	NGC4162	Sbc	4.24±0.45	139.1±14.8	55	NRAO	Casoli1996	4.643E+08
79	509	NGC4168	E2	<0.22	<1.4	24	IRAM	ATLAS3D	3.569E+06
80	511	NGC4175	Sab	7.02±0.51	230.3±16.7	55	NRAO	Casoli1996	1.985E+09

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Nr.	ID	Name	Morph	I_{CO} $K km s^{-1}$	S_{CO} $Jy km s^{-1}$	θ_{beam} "	Tel	PUBL	L'_{CO} $K km s^{-1} pc^2$
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
81	512	IC0769	Sbc	<0.54**	<17.7	55	NRAO	Boselli2002	4.332E+07
82	516	NGC4191	S0	<0.49	<3.1	24	IRAM	ATLAS3D	1.094E+07
83	522	UGC07286	Sb	<1.21	<39.7	55	NRAO	Casoli1996	1.215E+09
84	525	NGC4233	E7	<0.11	<0.7	24	IRAM	ATLAS3D	1.808E+06
85	528	IC0776	Sdm	<0.45**	<14.8	55	NRAO	Boselli2002	4.463E+07
86	539	NGC4352	E7	<0.05	<0.3	24	IRAM	ATLAS3D	6.668E+05
87	542	NGC4383	Sbc	2.5	54.9	45	SEST	Albrecht2007	7.982E+07
88	543	NGC4405	Sab	3.08±0.49**	101±16.1	55	NRAO	Boselli2002	1.552E+08
89	545	NGC4450	Sa	4.84±0.53**	158.7±17.4	55	NRAO	BIMASONG	2.999E+08
90	548	NGC4470	Sc	2.1±0.28**	68.9±9.2	55	NRAO	Boselli2002	1.943E+08
91	549	NGC4475	Sbc	1.23±0.27**	40.3±8.9	55	NRAO	Boselli1997	1.150E+09
92	550	NGC4474	S0	<0.36	<2.2	24	IRAM	ATLAS3D	2.849E+06
93	551	NGC4476	E6	5.4	33.7	24	IRAM	Wiklind1995	6.634E+07
94	561	NGC4570	S0	<0.01	<0.1	24	IRAM	Combes2007	4.894E+04
95	562	IC3598	S0	<0.34**	<11.2	55	NRAO	Boselli1997	3.423E+08
96	563	NGC4578	E5	<0.38	<2.4	24	IRAM	ATLAS3D	6.322E+06
97	568	NGC4612	S0	<-0.44	<-2.7	24	IRAM	ATLAS3D	3.426E+06
98	572	IC3704	Sb	1.79±0.36	39.3±7.9	45	SEST	Strong2004	1.553E+09
99	576	UGC07941	Scd	<0.85	<18.7	45	FCRAO	AMIGA	5.082E+07
100	577	NGC4676A	Sdm	20.2	126.2	24	IRAM	Casoli1991	2.891E+09
101	581	UGC08004	Scd	<0.32**	<10.5	55	NRAO	Boselli1997	2.084E+08
102	582	NGC4746	Sb	4.6	101.0	45	SEST	Albrecht2007	1.571E+08
103	584	UGC08025	Sab	<0.39**	<12.8	55	NRAO	Boselli1997	2.648E+08
104	590	NGC4846	Sb	<2.09	<45.9	45	FCRAO	AMIGA	4.846E+08
105	594	NGC4892	S0a	<0.27**	<8.9	55	NRAO	Boselli1997	1.609E+08
106	598	IC4088	Sbc	0.65±0.24**	21.3±7.9	55	NRAO	Boselli1997	5.546E+08
107	603	NGC4961	Scd	<1.04	<34.1	55	NRAO	Casoli1996	1.138E+08
108	608	NGC5000	Sbc	1.52±0.12	49.9±3.9	55	NRAO	Casoli1996	8.050E+08
109	611	NGC5016	Sbc	3.17±0.3	104±9.8	55	NRAO	Casoli1996	3.610E+08
110	614	NGC5056	Sc	0.85±0.3	27.9±9.8	55	NRAO	Casoli1996	4.436E+08
111	617	NGC5081	Sb	2±0.33**	65.6±10.8	55	NRAO	Boselli1997	1.493E+09
112	620	NGC5127	E2	0.28±0.02	1.7±0.1	24	IRAM	Ocana-Flaquer2010	2.121E+07
113	631	NGC5198	E1	<0	<0	24	IRAM	Combes2007	5.107E+04
114	632	UGC08498	Sb	1.73±0.29**	56.7±9.5	55	NRAO	Boselli1997	1.568E+09
115	634	NGC5218	Sab	24.8±2.9	292.8±34.2	33	OSO	Elfhag1996	1.250E+09
116	654	NGC5308	S0	<0	<0	24	IRAM	Combes2007	4.929E+04
117	658	UGC08739	Sab	44.2±9	102.2±20.8	14.6	NRO	Yao2003	1.350E+09
118	669	NGC5347	Sb	1.3±0.5	15.4±5.9	33	OSO	Curran2000	4.386E+07
119	670	NGC5350	Sbc	11.43±0.68*	71.4±4.2	24	IRAM	Leon1998	1.955E+08
120	671	NGC5353	S0	1.36±0.58	8.5±3.6	24	IRAM	ATLAS3D	2.077E+07
121	673	NGC5379	Sab	3.91±0.35	24.4±2.2	24	IRAM	ATLAS3D	3.991E+07
122	680	NGC5394	Sbc	101.5±21.1	234.6±48.8	14.6	NRO	Yao2003	1.390E+09
123	688	NGC5439	Sb	3.42±0.32	21.4±2	24	IRAM	AMIGA	3.851E+07
124	692	NGC5433	Sc	20.3±0.54	126.8±3.4	24	IRAM	Albrecht2004	1.246E+09
125	699	NGC5434B	Sc	1.62±0.12	53.1±3.9	55	NRAO	Lavezzi1998	8.703E+08
126	703	NGC5473	S0	0.06±0.35	0.4±2.2	24	IRAM	ATLAS3D	7.578E+05
127	705	NGC5475	S0a	<0.44	<2.7	24	IRAM	ATLAS3D	4.117E+06
128	708	NGC5485	E5	<0.12	<0.7	24	IRAM	ATLAS3D	1.399E+06
129	710	NGC5490	E3	<1.92	<12	24	IRAM	Ocana-Flaquer2010	1.453E+08
130	729	NGC5557	E4	<-0.57	<-3.6	24	IRAM	ATLAS3D	9.942E+06
131	731	UGC09165	Sa	4.49±0.16	147.3±5.2	55	NRAO	Lavezzi1998	2.102E+09
132	732	NGC5559	Sb	3.15±0.16	103.3±5.2	55	NRAO	Lavezzi1998	1.416E+09
133	739	NGC5611	S0	<0.68	<4.2	24	IRAM	ATLAS3D	7.620E+06
134	742	NGC5610	Sb	3.19±0.15	104.6±4.9	55	NRAO	Lavezzi1998	1.380E+09
135	743	NGC5622	Sbc	0.91±0.28	20±6.1	45	FCRAO	AMIGA	1.542E+08
136	744	NGC5631	S0	0.17±0.36	1.1±2.2	24	IRAM	ATLAS3D	2.060E+06
137	748	NGC5633	Sbc	6.34±0.39	139.2±8.6	45	FCRAO	AMIGA	3.819E+08
138	756	NGC5665	Sc	78±16.6	180.3±38.4	14.6	NRO	Yao2003	4.509E+08
139	759	NGC5687	E4	0.45±0.32	2.8±2	24	IRAM	ATLAS3D	6.747E+06

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Nr.	ID	Name	Morph	I_{CO} $K km s^{-1}$	S_{CO} $Jy km s^{-1}$	θ_{beam} "	Tel	PUBL	L'_{CO} $K km s^{-1} pc^2$
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
140	777	NGC5772	Sab	0.83±0.33	18.2±7.2	45	SEST	Sauty2003	2.230E+08
141	784	NGC5829	Sc	4.64±0.73*	29±4.6	24	IRAM	Leon1998	4.812E+08
142	795	NGC5930	Sab	21.5±5.7	49.7±13.2	14.6	NRO	Yao2003	1.737E+08
143	801	NGC5953	Sa	45.7±9.8	105.6±22.7	14.6	NRO	Yao2003	2.094E+08
144	802	ARP220	Sd	126.3±26.2	291.9±60.6	14.6	NRO	Yao2003	4.448E+09
145	803	NGC5957	Sb	3.25±0.36	71.4±7.9	45	SEST	Strong2004	1.211E+08
146	844	NGC6278	S0a	<-0.23	<-1.4	24	IRAM	ATLAS3D	7.130E+06
147	856	IC1256	Sb	4.49±0.18	28±1.1	24	IRAM	AMIGA	3.274E+08
148	861	UGC10972	Sbc	1.36±0.49	29.9±10.8	45	FCRAO	AMIGA	3.317E+08
149	871	NGC6978	Sb	9.7±1.3*	60.6±8.1	24	IRAM	Leon1998	1.118E+09
150	874	NGC7025	S0a	<0.42	<13.8	55	NRAO	Sauty2003	1.748E+08
151	882	NGC7236	S0	0.09±0.02	0.6±0.1	24	IRAM	Ocana-Flaquer2010	1.808E+07
152	901	NGC7549	Sbc	16.2±0.85*	101.2±5.3	24	IRAM	Leon1998	1.155E+09
153	904	NGC7591	Sbc	6.36±0.26	208.6±8.5	55	NRAO	Lavezzi1998	2.632E+09
154	906	IC5309	Sc	1.19±0.16	39±5.2	55	NRAO	Lavezzi1998	3.524E+08
155	913	NGC7625	Sa	20.6±4.3	243.2±50.8	33	OSO	Elfhag1996	3.246E+08
156	914	NGC7631	Sb	1.11±0.14	36.4±4.6	55	NRAO	Lavezzi1998	2.621E+08
157	922	UGC12688	Scd	<0.86	<18.9	45	SEST	Sauty2003	2.652E+08
158	934	UGC12857	Sbc	<0.63	<13.8	45	SEST	Sauty2003	4.245E+07
159	939	NGC4676B	S0	1.77±0.28	58.1±9.2	55	NRAO	Casoli1996	1.282E+09
									Concluded

4.4 CALIFA Subsample for Interferometric CO Follow-Up Observations

4.4.1 Defining Constraints for the Subsample

In order to find a sample of CALIFA galaxies for future interferometric, CO follow-up observations, a reasonable selection criteria has to be applied. Without limitations to specific science cases, it seems reasonable to define the subsample such that all morphological types are covered homogeneously with the hugest possible variety of physical parameters available. Thus, for the resulting subsample, the stellar mass and star formation rate are selected to be as widespread as possible. In the end, the galaxy distribution along the three “parameter bins” (morphology, stellar mass and star formation) should be as homogeneous as possible. The morphology is separated into seven types/bins: E, S0, Sa, Sb, Sc, Sd, Irr. Likewise, for the sake of simplicity, also the other two parameters were divided in this manner. The galaxy number within each bin, the bin-height, should count ten galaxies for a theoretically perfect distribution. Hence, the resulting subsample would consist of exactly 70 galaxies, if every bin could be filled totally. In CALIFA’s case, this is not possible due to the limited number of only five irregular galaxies available in the full sample. Hence, the resulting subsample consists only of 65 galaxies as seen in figure 4.2.

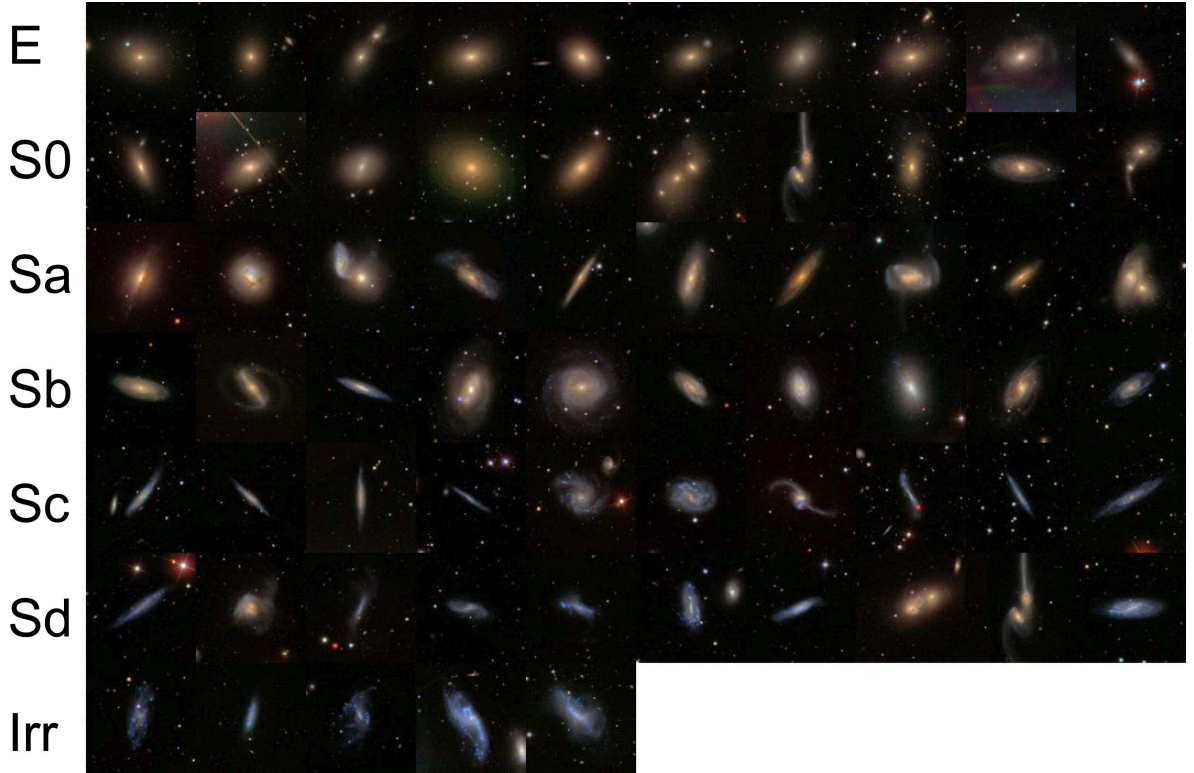


Figure 4.2: SDSS Cutouts of the Subsample

Homogeneity in all bins cannot be achieved perfectly, of course, because without previously limiting the range of the parameters, the extreme bins at the borders of a distribution – similarly to a Gaussian bell curve – are naturally less populated. This was also noticed when performing a subsample selection based on the MPA-JHU DR7 release with 13432 galaxies. A description on that is found in the appendix.

The resulting parameter distribution of the found subsample is given in figure 4.3. As explained before, only five irregular galaxies are available in CALIFA’s mothersample and the seventh bin cannot be fully populated, so that the subsample only counts 65 galaxies in total.

4.4.2 Algorithm for Subsample-Selection

Since the parameters morphology, stellar mass and star formation rate, are coupled to each other, a selection following the above stated criteria, is not a simple task. Therefore, an algorithm was developed based on the so called SIMPLEX method (Dvorak, 2012) to automatically select in an iterative way a subsample of galaxies that fulfills the criteria best. Figure 4.4 shows the flowchart of the developed algorithm. The script performing the selection can be found online at www.sonnensystem.at/master/scripts/subsample/samplebuilder_v3.pl. Whenever, more than one galaxy would comply with the criterion of the desired bin, a galaxy with the highest priority was selected. The priority system

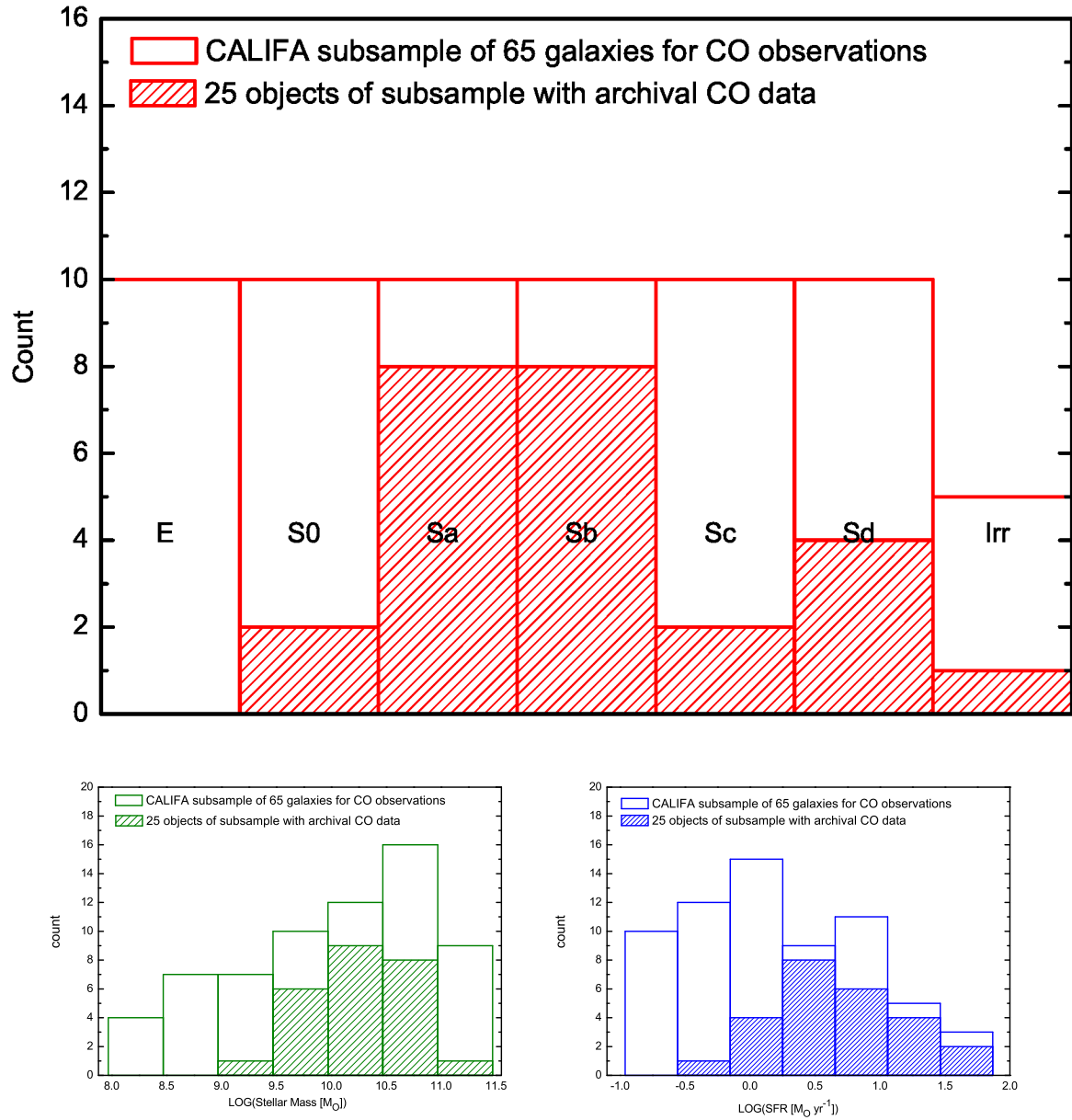


Figure 4.3: Homogeneity of the subsample for future interferometric CO observations. The best possible distribution of morphology (top), stellar mass (bottom left) and star formation rate (bottom right) is indicated.

included in the provided input file `Grandmother2.txt` prefers, at first, galaxies with CO observations already found in the literature and secondly it favors galaxies which were already observed within the CALIFA survey.

4.4.3 The CO Interferometric Subsample Table

Table 4.2: Subsample for Future Interferometric CO Observations. Column specifications: Sequence number (1), CALIFA ID (2), other catalog ID (2), Morphology code: E=0, S0=1, Sa=2, Sb=3, Sc=4, Sd=5, Irr=6 (4), SFR in $M_{\odot} \text{ yr}^{-1}$ (5), stellar mass in $M_{\odot}$ derived by S. Bekeraite through stellar population synthesis (6), CO J=1–0 luminosity (7), CALIFA survey observational status as of July 2013 (8), CALIFA survey date of observation (9)

Nr.	ID	Name	Morph	SFR $M_{\odot} \text{ yr}^{-1}$	M_{*} $M_{\odot}$	L'_{CO} $K \text{ km s}^{-1} \text{ pc}^2$	Status	Date
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
1	2	UGC00005	3	9.36	7.647E+10	1.088E+09	V500+V1200 Completed	2012-09-16
2	4	UGC00029	0	4.32	1.063E+11	–	V500+V1200 Completed	2011-10-25
3	9	NGC0023	3	30.68	8.887E+10	2.113E+09	V500+V1200 Completed	2012-10-17
4	14	UGC00312	5	4.18	3.360E+09	3.581E+08	V500+V1200 Completed	2011-07-30
5	17	UGC00335NED02	0	3.16	3.268E+10	–	V500+V1200 Completed	2012-09-15
6	26	NGC0192	2	8.60	5.921E+10	1.699E+09	V500+V1200 Completed	2012-10-15
7	47	NGC0517	1	0.10	4.059E+10	–	V500+V1200 Completed	2012-10-16
8	100	NGC1056	2	1.52	9.644E+09	8.076E+07	V500+V1200 Completed	2012-01-20
9	113	UGC02367	2	9.53	1.218E+11	–	–	–
10	114	NGC1142	5	72.07	9.479E+10	6.824E+09	–	–
11	119	NGC1167	1	1.39	1.346E+11	–	V500+V1200 Completed	2011-09-30
12	131	NGC1542	2	0.96	2.367E+10	2.739E+08	V500+V1200 Completed	2013-01-07
13	134	NGC1645	1	0.38	6.032E+10	–	V500+V1200 Completed	2013-02-05
14	141	IC2095	4	20.73	2.562E+08	–	V500+V1200 Completed	2013-01-07
15	152	UGC03944	3	0.73	7.160E+09	6.771E+08	V500+V1200 Completed	2012-01-21
16	186	IC2247	2	3.25	2.020E+10	5.944E+08	V500+V1200 Completed	2013-01-09
17	201	NGC2592	0	0.02	1.728E+10	–	–	–
18	213	NGC2623	4	58.41	2.537E+10	–	V500+V1200 Completed	2012-01-20
19	232	NGC2730	4	2.23	2.358E+09	2.114E+08	V500 Completed	2013-01-07
20	306	UGC05358	5	0.50	6.147E+08	–	V500+V1200 Completed	2011-04-04
21	310	SDSSJ100141.02+371447.4	6	0.02	4.958E+08	–	V500 Completed	2013-01-07
22	409	UGC06433	5	0.74	2.658E+08	–	–	–
23	417	NGC3712	5	1.05	9.397E+07	–	–	–
24	478	NGC3995	6	5.46	3.790E+09	2.725E+08	–	–
25	487	UGC07017	3	4.55	7.984E+09	4.408E+08	–	–
26	492	SDSSJ120353.51+252556.6	6	0.42	6.422E+08	–	–	–
27	520	NGC4211NED02	1	7.27	1.054E+10	–	V500 Completed	2013-01-07
28	537	NGC4306	0	0.01	3.124E+09	–	–	–
29	541	IC3305	0	0.01	1.781E+09	–	–	–
30	542	NGC4383	3	4.20	7.787E+09	–	–	–
31	554	IC3453	6	0.07	5.062E+08	–	–	–
32	566	NGC4598	1	0.03	7.959E+09	–	–	–
33	577	NGC4676A	5	15.76	3.282E+10	2.604E+09	V500+V1200 Completed	2011-06-29
34	588	NGC4816	0	0.21	1.020E+11	–	V500+V1200 Completed	2013-03-08
35	593	UGC08107	2	8.67	9.225E+10	–	V500+V1200 Completed	2013-06-12
36	634	NGC5218	2	9.80	2.944E+10	1.210E+09	V500+V1200 Completed	2013-03-15
37	655	UGC08726	5	0.06	2.394E+08	–	–	–
38	748	NGC5633	3	2.45	1.251E+10	3.655E+08	V500+V1200 Completed	2012-07-19

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Nr.	ID	Name	Morph	SFR $M_{\odot} \text{ yr}^{-1}$	M_{*} $M_{\odot}$	L'_{CO} $K \text{ km s}^{-1} \text{ pc}^2$	Status	Date
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
39	749	NGC5630	5	1.14	2.245E+09	–	V500+V1200 Completed	2013-03-18
40	767	NGC5731	5	0.35	1.395E+09	–	V500 Completed	2012-07-26
41	780	NGC5797	0	0.15	4.537E+10	–	V500+V1200 Completed	2013-03-20
42	784	NGC5829	4	3.48	1.249E+10	4.367E+08	V500 Completed	2012-02-26
43	794	NGC5928	0	0.18	6.406E+10	–	V500 Completed	2012-05-15
44	795	NGC5930	2	15.45	2.246E+10	1.637E+08	V500 Completed	2012-05-15
45	801	NGC5953	2	5.06	1.087E+10	1.969E+08	V500 Completed	2012-06-16
46	802	ARP220	5	277.89	5.399E+10	4.095E+09	V500+V1200 Completed	2011-07-02
47	803	NGC5957	3	0.06	8.213E+09	1.151E+08	V500 Completed	2012-04-25
48	827	UGC10297	4	0.17	1.799E+09	–	V500+V1200 Completed	2012-07-21
49	828	UGC10331	4	4.63	5.840E+09	–	V500+V1200 Completed	2011-07-30
50	843	UGC10650	4	0.42	1.857E+09	–	V500+V1200 Completed	2011-07-31
51	845	UGC10693	0	0.52	1.813E+11	–	V500+V1200 Completed	2010-07-18
52	846	UGC10695	0	0.38	1.108E+11	–	V500+V1200 Completed	2012-06-17
53	858	UGC10905	1	1.80	1.414E+11	–	V500+V1200 Completed	2011-08-31
54	870	NGC6945	1	0.08	5.231E+10	–	V500+V1200 Completed	2012-07-22
55	878	MCG-01-54-016	4	0.05	5.535E+08	–	V500+V1200 Completed	2011-07-30
56	882	NGC7236	1	0.33	6.110E+10	1.641E+07	V500+V1200 Completed	2011-08-29
57	885	UGC12054	4	0.02	9.617E+08	–	V500+V1200 Completed	2011-07-22
58	895	UGC12308	4	0.03	5.930E+08	–	V500+V1200 Completed	2012-08-21
59	904	NGC7591	3	27.94	5.861E+10	2.439E+09	V500+V1200 Completed	2011-09-27
60	913	NGC7625	2	3.44	1.095E+10	3.136E+08	V500+V1200 Completed	2012-10-13
61	914	NGC7631	3	1.21	3.239E+10	2.456E+08	V500 Completed	2012-09-13
62	917	NGC7683	1	0.19	5.670E+10	–	V500 Completed	2012-07-23
63	927	NGC7738	3	32.42	9.586E+10	–	V500+V1200 Completed	2012-12-11
64	937	NGC7800	6	0.53	7.145E+08	–	V500+V1200 Completed	2012-08-22
65	939	NGC4676B	1	3.56	5.019E+09	1.197E+09	V500+V1200 Completed	2011-06-29
								Concluded

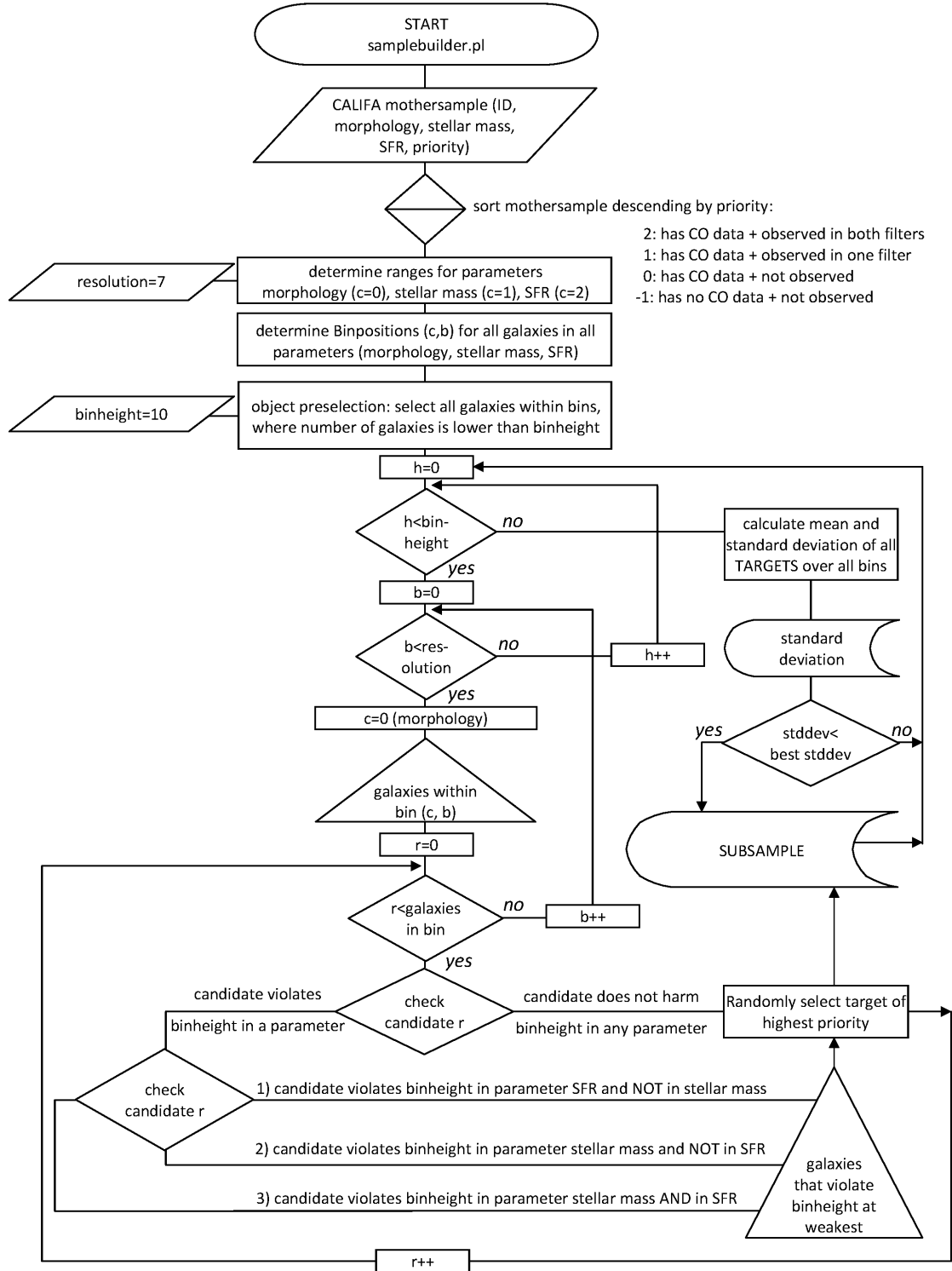


Figure 4.4: Flowchart of the Subsample Selection Algorithm

Chapter 5

Star Formation Rates and Gas Masses of CALIFA Galaxies

This chapter contains the scientific analysis of the archival single dish data as well as a detailed description of the methods used for deriving gas masses and star formation rates. In the first section, 5.1, three SFR indicators are introduced which build the basis for understanding the physical processes behind the SFR calculations of 5.3. Beside using cataloged IR data, SExtractor was used on the WISE Atlas Images in order to get accurate photometric quantities. A summary on that is found in 5.4. Subsequently, atomic and molecular gas mass calculations were performed for a substantial fraction of CALIFA galaxies. Sections 5.5.3 and 5.6.2 explain the most important issues on that topic, with a clear focus on the difficulties of deriving molecular gas masses. The metallicity-dependence of X_{CO} , the conversion factor, and the need of a sophisticated aperture correction are illuminated in sections 5.7 and 5.6.3, respectively. A tabular summary of the derived quantities is given in 5.8. The data analysis, with emphasis on the Kennicutt-Schmidt law, is presented in section 5.10. Gas density thresholds and star formation efficiencies get examined as well as the existence of correlations of the molecular gas masses with other parameters such as metallicity. Furthermore, an attempt on deriving ISM properties within a small subset of CALIFA galaxies, is presented in this chapter’s final section 5.11.

5.1 Tracers of Star Formation

5.1.1 Ultraviolet (UV)

From stellar evolution theory, it is known that UV-luminous stars, must be quite young, less than 10^9 years for early A stars. This is called the “mass-lifetime” relation. Thus, observations in the UV can reveal information about the *currently* ongoing star formation within a galaxy. Thereby UV flux is mainly produced by the stars that are *not* massive

or hot enough to ionize the surrounding ISM. This fraction of photons that are producing HII regions, indeed is missed by UV, but can be traced by recombination line emission of Balmer lines, e.g. $H\alpha$. See the next section for details on that.

A remarkable difference to optical measurements is that the luminosity in the UV domain is typically given in energy units rather than photon units. Furthermore, the photospheric light of a star is seen directly. However, one really has to take care of the effect of extinction. Radiative transfer calculations and resonant scattering has to be taken into account, because UV photons escape easier when the dust abundance is low, likewise large velocity gradients can help UV photons to escape. Thus, at these wavelengths, dust is a crucial factor which must be taken into account. The range in dust column density between no significant extinction and no significant transmission is very narrow! See Kennicutt (1998) and Hirashita et al. (2003) for further reading.

5.1.2 Recombination Lines ($H\alpha$)

Balmer line emission is one of the characteristics of a HII region. OB stars with lifetimes of only several million years (spectral types B0.5 and hotter) embedded in star forming clusters are hot enough to emit fluxes of strongly ionizing radiation, shortward of the Lyman limit. Thereby, hydrogen is ionized by absorption of Lyman continuum photons $\lambda < 912 \text{ \AA}$, corresponding to an energy of 13.6 eV. Balmer line radiation arises from the subsequent recombination of the electrons so released with another proton, and a cascade toward the ground state. Further explanations can be found in Kennicutt (1998) and Hirashita et al. (2003). Measurements of $H\alpha$ with a rest wavelength of 656.28 nm works out to be a very accurate tracer of star formation as long as internal extinction through dust is not too dominant.

5.1.3 Infrared

Far-IR (FIR) emission is ubiquitous in spiral and irregular galaxies, even when the optical data suggests only a very moderate dust content. Dust grains, as a by-product of star formation, get heated by the UV flux around young stars to temperatures above $\approx 30 \text{ K}$. Subsequently, the grains cool by approximately black-body emission, modified by a wavelength-dependent emissivity which is mainly caused due to the fact that the grains are typically smaller than the blackbody peak wavelength and therefore, cannot radiate such wavelengths as efficiently as perfect radiators (Draine, 2011).

In most cases, the peak emission is found around $70\text{--}140 \mu\text{m}$ which corresponds to a blackbody temperature of $40\text{--}20 \text{ K}$, respectively. But sometimes several discrete components are fit, including very cool dust measured in the sub-mm window. These components are sometimes attributed to different regimes of heating: environments of OB stars, re-

gions near cooler stars, and so-called infrared cirrus emission from a widely distributed grain population heated only by the average ambient stellar radiation field. Sometimes it is important to disentangle these components in order to get an accurate SFR estimation. For example, Melo et al. (2002) found five different dust temperatures within several morphological components (nucleus, disk, bar) of NGC253.

Beside that, It is important to note, that the interpretation of mid-IR ($10\ \mu\text{m}$) emission is very complex, because for such small grain sizes, *single* UV photons can heat those grains well above the *equilibrium* temperature of the radiation field. Then, the emitting radiation does not correspond to the temperature appropriate for the emitting region.

5.2 All-Sky Infrared Surveys

All-sky surveys in the infrared have not been possible for a long time due to technical difficulties. In fact, such a task can only be performed from Earth’s orbit with special detectors that must be cooled to temperatures right above the absolute zero point. The first survey in the infrared, called “The Infrared Astronomical Satellite” (IRAS) was launched in 1983 and it was not until 2006, when a successor was commenced, namely “AKARI”. AKARI, the Japanese word for light, operated until 2007 and took measurements of the whole sky at wavelengths similar to IRAS ($12\text{--}100\ \mu\text{m}$), but with a sensitivity never reached before.

After IRAS and AKARI, WISE, the “Wide Infrared Survey Explorer” was launched by end of 2009. Its major advantage in comparison to the preceding missions, is the much higher angular resolution which could be achieved, because for the first time also at higher wavelengths CCD detectors were used. On the other hand, thereby, the observing wavelength of WISE was limited to only 22 micrometers. WISE ended its operations in February, 2011.

A detailed summary (only in German) of all (not only survey mode) infrared satellites, can be found online in Leitenberger (2013).

5.2.1 The Infrared Astronomical Satellite (IRAS)

IRAS was a satellite project executed mainly by NASA, the Netherlands, and the United Kingdom. The aim of the mission was to obtain an all-sky survey over a wavelength range of 8 to 120 micrometers covered by four broadband photometric channels. IRAS detected about 350000 infrared sources and led to numerous discoveries including the revelation of our Milky Way’s core for the first time. The survey design was optimized for maximally reliable detection of *point* sources.

IRAS contained a 0.6 m Ritchey-Chretien telescope cooled by helium to a temperature of approximately 10 K. An array of 62 detectors was used to detect the infrared flux in

bands centered at 12, 25, 60, and 100 micrometers. The noise equivalent flux densities were, 0.1, 0.1, 0.1, and 0.3 Jansky in the four survey bands, respectively. The positions of galactic and extragalactic sources were determined to an accuracy of 0.5 arcmin. IRAS ceased operations on November 21, 1983. A further discussion on the IRAS mission can be found in Neugebauer et al. (1984b) and Neugebauer et al. (1984a).

5.2.2 Wide Infrared Survey Explorer (WISE)

WISE (Wright et al., 2010) is a satellite mission funded by NASA. It has observed the entire sky in four infrared bands: 3.4, 4.6, 12, and 22 μ m (W1 to W4, respectively). Raw and calibrated data as well as catalogs are publicly available through the NASA/IPAC Infrared Science Archive at: <http://irsa.ipac.caltech.edu/Missions/wise.html>. Each field of 47 arcmin was scanned at least eight times with single exposures of 8.8 s.

The gained individual frames were combined automatically by the pipeline for scientific use. The corresponding images, for which also cosmic rays and other transient features were removed, are called “WISE Atlas” images. The pixel scale is 1.375 arcsec per pixel in all bands, the angular resolution in the filters W1, W2, W3 and W4 is 6.1, 6.4, 6.5 and 12.0 arcsec, respectively. WISE achieved 5σ point source sensitivities better than 0.08, 0.11, 1 and 6 mJy. In comparison, IRAS reached only 100 mJy at its best!

5.3 Formula for SFR Calculations

5.3.1 SFR from CALIFA’s H α Flux

From the majority of CALIFA galaxies observed and reduced by CALIFA’s pipeline up to August 2013, star formation rates were derived by Sánchez et al. (2013) from H α fluxes applying the relation found by Kennicutt (1998):

$$SFR_{H\alpha} = 7.9 \times 10^{-42} L_{H\alpha}, \quad (5.1)$$

where the SFR is given in $M_{\odot} \text{ yr}^{-1}$ and $L_{H\alpha}$ in erg s^{-1} . The conversion factor between ionizing flux and the SFR was computed using an evolutionary synthesis model. Only stars with masses $> 10 M_{\odot}$ and lifetimes $< 20 \text{ Myr}$ contribute significantly to the integrated ionizing flux, so the emission lines provide a nearly instantaneous measure of the SFR, independent of the previous star formation history.

5.3.2 SFR from IRAS 4-Channel Data

In order to calculate the SFR from IRAS data, total IR luminosity L_{IR} has to be computed first. L_{IR} from IRAS 4-channel data is often also denoted as the luminosity in the

wavelength range of 8–1000 μm , which Sanders and Mirabel (1996) defined to be:

$$L_{IR} = L_{8-1000\mu\text{m}} = 5.6 \times 10^5 (13.48f_{12} + 5.16f_{25} + 2.58f_{60} + f_{100}) D_L^2. \quad (5.2)$$

The resulting L_{IR} is given in $L_\odot$, the fluxes at 12 (f_{12}), 25 (f_{25}), 60 (f_{60}) and 100 (f_{100}) μm are measured in Jansky and the luminosity distance D_L in Mpc.

In the next step, the SFR is calculated from L_{IR} , for which a calibration was found by Kennicutt (1998). It is important to note, that probably no single calibration applies to all galaxy types. However, the far infrared emission should provide an excellent measure of the SFR in dusty circumnuclear starbursts, as explained by Kennicutt (1998). After converting to typically used units, by the help of the parameters in table 1, the SFR can be computed to:

$$SFR_{8-1000\mu\text{m}} = 1.72755 \times 10^{-10} L_{8-1000\mu\text{m}}, \quad (5.3)$$

where the SFR is given in $M_\odot \text{ yr}^{-1}$ and $L_{8-1000\mu\text{m}}$ in $L_\odot$.

5.3.3 SFR from WISE 22 μm Data

SFRs and total infrared luminosities, L_{IR} , are determined from the WISE 22 μm photometry, using the relations presented in Rieke et al. (2009). Although they are calibrated for the Spitzer Space Telescope’s MIPS 24 μm band, they also apply to the WISE 22 μm band, because of the similarity of their bandpasses.

Rieke et al. (2009) constructed model spectral energy distribution (SED) templates from a sample of local LIRGs and ULIRGs and derived correlations between 24 μm flux, SFR, and L_{IR} . The flux-SFR relation given in their equation (14) can be used for both, MIPS 24 μm and WISE 22 μm data following Rieke et al. (2009). Furthermore, the similarity of the two bandpasses is confirmed by Goto et al. (2011), who quantified the correlation between L_{IR} and the inferred MIPS 24 μm and WISE 22 μm luminosities: MIPS and WISE luminosities are derived by applying a color correction to the 18 μm AKARI flux, and L_{IR} is derived from fitting the IR SED templates of Chary and Elbaz (2001) to all six AKARI bandpasses (9, 18, 65, 90, 140, and 160 μm) for approximately 600 galaxies at $z < 0.1$. The resulting correlations between the L_{IR} - L_{MIPS24} and L_{IR} - L_{WISE22} are nearly identical, with only a $\approx 4\%$ offset which is demonstrated by figure 5.1 taken from Goto et al. (2011). Therefore, within this thesis the SFR calibrations determined by Rieke et al. (2009) which were originally found for MIPS 24 μm data, were used for calculating L_{IR} and SFR based on WISE data.

It is worth to note, that for calculating SFRs as seen in equation (5.4), the IMF adopted by Rieke et al. (2009) is similar to the Kroupa (2002) and Chabrier (2003) IMFs, which have relatively fewer low-mass stars compared to a Salpeter IMF, and is more applicable for extragalactic star-forming regions (Rieke et al., 1993). Therefore a

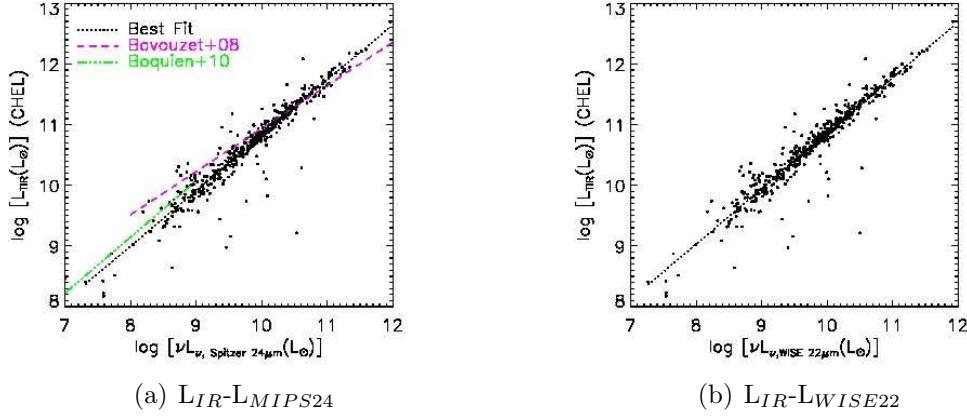


Figure 5.1: L_{IR} - L_{MIPS24} (a) and L_{IR} - L_{WISE22} (b) from Goto et al. (2011).

systematic difference to the calibrations found by Kennicutt (1998) would exist. Since, within this thesis, I combine SFRs computed by various methods, a further calibration which is described in Rieke et al. (2009) too, was applied, which is given in equation (5.5). Thus, all SFRs calculations are probably systematically overestimated.

$$\log_{10}(SFR_{Rieke}) = A(z) + B(z) (\log_{10}(4\pi D_L^2 f_{24,obs}) - 53) \quad (5.4)$$

$$\log_{10}(SFR_{Kennicutt}) = \frac{SFR_{Rieke}}{0.66} \quad (5.5)$$

The computed SFRs in equations (5.4) and (5.5) are given in $M_{\odot} \text{ yr}^{-1}$. The fit values $A(z)$ and $B(z)$ are taken from table 1 in Rieke et al. (2009) for a redshift $z = 0$. The luminosity distance D_L has to be inserted in cm and the flux at 24 or rather 22 μm in Jansky.

WISE fluxes, either derived from the Atlas images by SExtractor – see Bertin and Arnouts (1996) for details – or taken from the WISE data release catalogue, are normally given in Vega magnitudes. Therefore, before applying one of the formulas above, the WISE magnitudes have to be converted into a flux density. This task is performed as described in chapter 4.4 of the WISE mission’s explanatory supplement, which can be found online at http://wise2.ipac.caltech.edu/docs/release/allsky/expsup/sec4_4h.html. The conversion from a WISE W4 magnitude m_{22} into a flux density in Jansky, f_{22} , is given by:

$$f_{22} = 8.363 \times 10^{-m_{22}/2.5}. \quad (5.6)$$

For inferring infrared luminosities from WISE data, the L_{24} luminosity has to be calculated first by finding the inverse of equation (9) or (11) of Rieke et al. (2009), depending on the

resulting luminosity range. For $6 \times 10^8 \leq L_{24} \leq 1.3 \times 10^{10}$:

$$L_{24} = \frac{0.66 \times SFR_{Kennicutt} \times 10^9}{0.7788}, \quad (5.7)$$

and otherwise when $L_{24} > 1.3 \times 10^{10}$:

$$L_{24} = 9.58558 \times 10^8 \times SFR_{Kennicutt}^{\left(\frac{125}{131}\right)}. \quad (5.8)$$

Based on the value of L_{24} , for the infrared luminosity can be solved by applying equation (A6) of Rieke et al. (2009):

$$\log_{10} L_{IR} = 1.445 + 0.945 \times \log_{10} L_{24} \quad (5.9)$$

5.4 Performing a Growth Curve Analysis on WISE Atlas Images

Within the first, official WISE data release (DR1), for one single band (e.g. W4 for $22\mu\text{m}$), several magnitudes are available. For example, the quantity **w4mag** corresponds to the aperture-corrected intensity measured within an instrumental standard aperture. Unfortunately, the standard aperture used for **w4mag** is only 33 arcsec in diameter. Thus, even for a point source, more than 40 percent of the total flux are lost due to the complex shape of WISE’s PSF. Hence, for extended sources – as in the case of CALIFA galaxies – another magnitude indicated by **w4gmag** should be used, because **w4gmag** is based on an automatic elliptical aperture growth curve analysis. But again, due to the difficult shape of the PSF, still some flux is lost, see Cutri et al. (2012) for further details.

Therefore, I have decided to perform a growth curve analysis with SExtractor (Bertin and Arnouts, 1996) on all WISE Atlas images, that were available for the CALIFA galaxy sample. The following table 5.1 summarizes the most important SExtractor configuration parameters, which I found to work best on the WISE Atlas images. It is important to use the WISE uncertainty images which are also available for download through the NASA/IPAC Infrared Archive as weight images for source extraction. In order to check the photometric accuracy of the magnitudes derived with SExtractor, the intensity within a 33 arcsec aperture was measured and compared to the WISE DR1 value **w4mag**. As can be seen in figure 5.2(a), the zeropoint and aperture correction were applied correctly. Thus, SExtractor with the configuration of table 5.1 indeed can be used for further photometric analysis. In the end, SExtractor’s **MAG_BEST** values were used for all calculations. A comparison between **MAG_BEST** and **w4gmag** and the star formation rates computed relying on them, $\text{SFR}_{22\mu\text{m } SEX,BEST}$ and $\text{SFR}_{22\mu\text{m } DR,BEST}$ is given in figures 5.2(b) and 5.2(c).

DETECT.MINAREA	30	minimum number of pixels above threshold
DETECT.THRESH	5.0	
ANALYSIS.THRESH	4.0	
THRESH.TYPE	RELATIVE	
FILTER	Y	apply filter for detection (Y or N)?
FILTER.NAME	gauss_5.0_9x9_conv.txt	name of the file containing the filter
DEBLEND.NTHRESH	32	Number of deblending sub-thresholds
DEBLEND.MINCONT	0.0001	Minimum contrast parameter for deblending
CLEAN	Y	Clean spurious detections? (Y or N)?
CLEAN.PARAM	1.0	Cleaning efficiency
MASK.TYPE	CORRECT	type of detection MASKing
Photometry		
SATUR.LEVEL	350	level (in ADUs) at which arises saturation
MAG.ZEROPOINT	13	magnitude zero-point
MAG.GAMMA	4.0	gamma of emulsion (for photographic scans)
GAIN	1.0e+20	detector gain in e-/ADU
PIXEL.SCALE	0	size of pixel in arcsec (0=use FITS WCS info)
Star,Galaxy Separation		
SEEING.FWHM	8.3	stellar FWHM in arcsec
STARNNW.NAME	default.nnw.txt	Neural-Network.Weight table filename
Background		
BACK.SIZE	500	Background mesh: size or width,height
BACK.FILTERSIZE	7	Background filter: size or width,height
BACK.FILTTHRESH	0.0	Threshold for background-map filter
BACKPHOTO.TYPE	LOCAL	Either GLOBAL or LOCAL
BACKPHOTO.THICK	100	Thickness of the background LOCAL annulus
BACK.TYPE	AUTO	Subtract internal, automatically inter...
Check Image		
CHECKIMAGE.TYPE	-OBJECTS,BACKGROUND,SEGMENTATION,APERTURES	
Weighting		
WEIGHT.GAIN	N,N	
WEIGHT.TYPE	MAP-RMS,MAP-RMS	
WEIGHT.IMAGE	/PATH/TO/Uncertainty-map-image.fit	

Table 5.1: Important SExtractor configuration parameters for WISE W4 band Atlas images. Note, that the huge gain is artificial, intended to fool SExtractor. This has the effect of nulling out the (additional) internal Poisson noise estimated by SExtractor so all the contribution can come from the explicit MAP_RMS image specified by -WEIGHT_IMAGE. This trick is mentioned at http://wise2.ipac.caltech.edu/staff/fmasci/SEx_WPhot.html.

It can be seen, that on average, also the **w4gmag** found in the WISE DR1 underestimates the values found by SExtractor, which, according to Cutri et al. (2012), is expected.

5.4.1 Comparison and Analysis of SFR Indicators

After calculating the star formation rates and infrared luminosities by means of various indicators, a comparison between the resulting quantities was performed. As can be seen in figure 5.3, a 1:1 relation can be found between all computed values. In general, one can expect that for dusty galaxies like (U)LIRGs, the extinction through dust grains substantially lowers the observed $H\alpha$ flux, whereas in the infrared then the luminosity increases. This might be the case for data points above the blue, dashed line indicating a

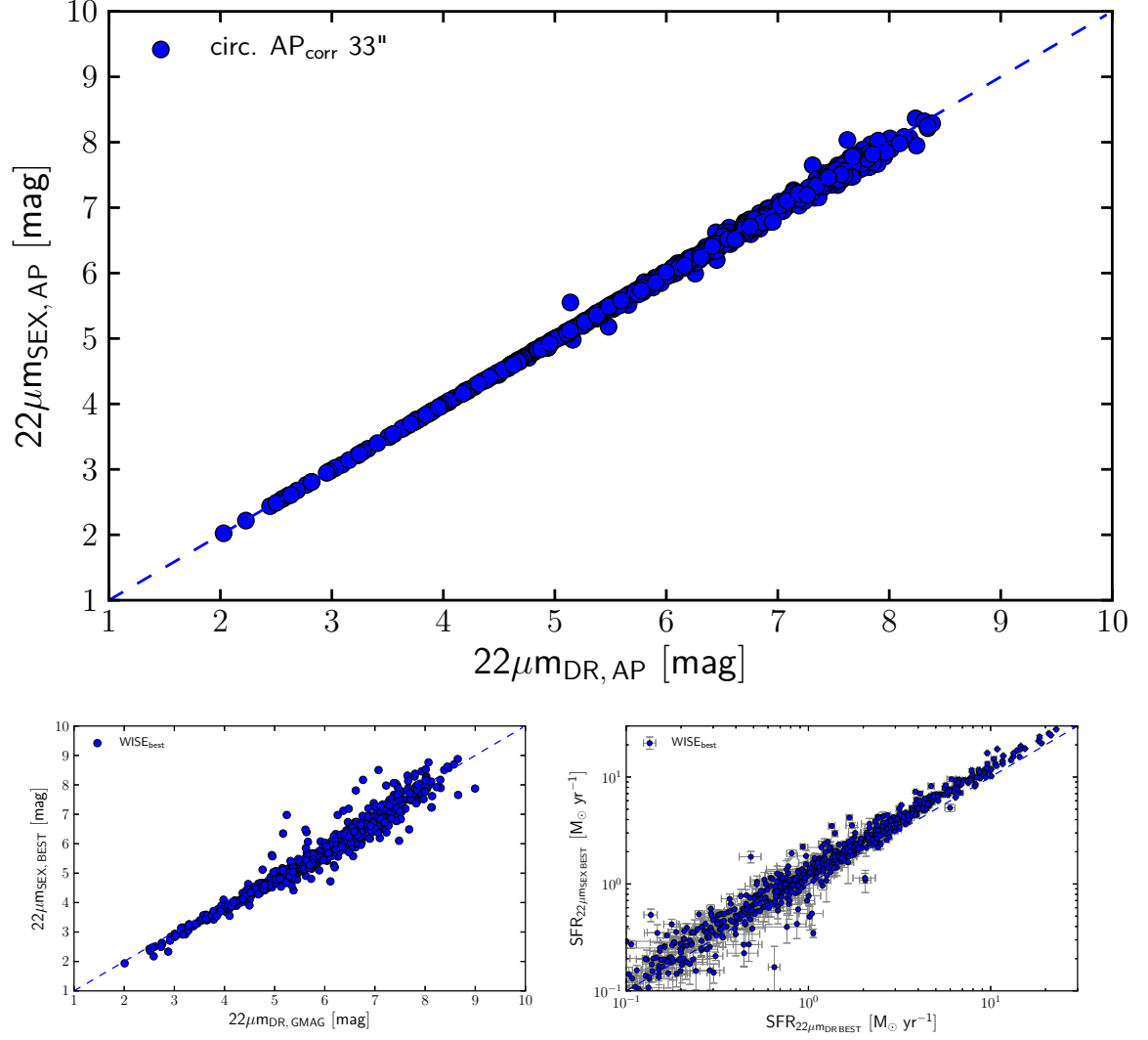


Figure 5.2: In the top panel it is shown that the photometric zeropoint as well as the aperture correction was set correctly when using SExtractor for photometric analysis. The panels in the bottom left and bottom right indicate that the “sextracted” magnitudes are, on average lower, hence the intensities higher, than that found in the WISE data release. According to Cutri et al. (2012) this result is expected, because even the **w4gmag** underestimates the true intensities due to the complex shape of the WISE PSF.

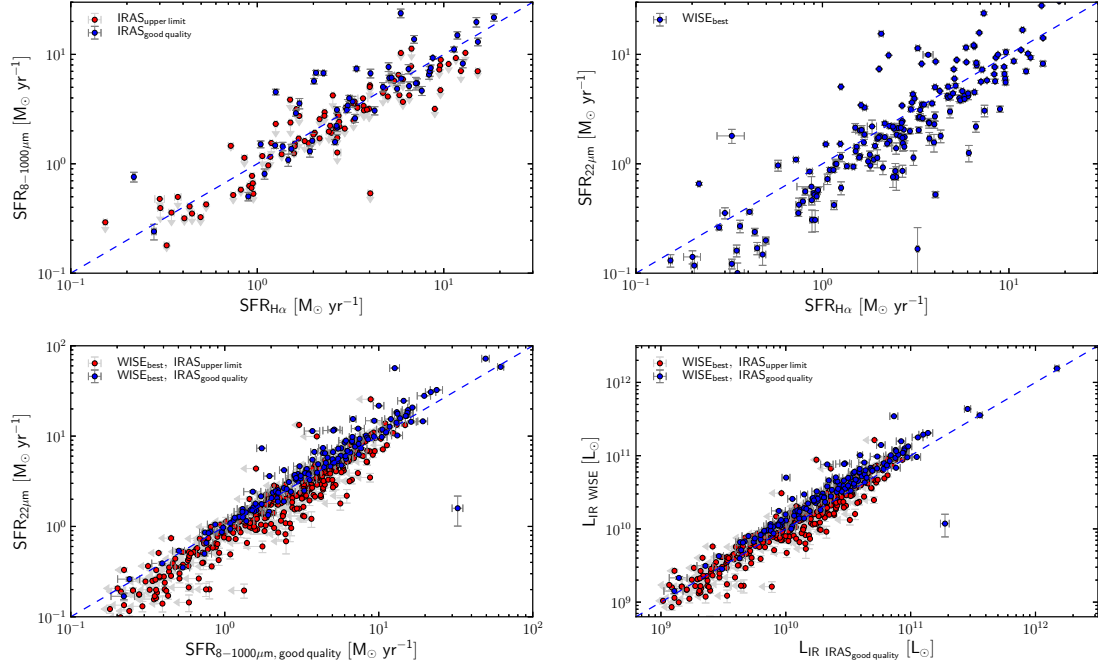


Figure 5.3: SFR inferred from $H\alpha$ versus SFR calculated from IRAS (top left) and WISE (top right) infrared data. In both cases, as expected, a 1:1 relation marked by the blue, dashed line, was found. The SFR and L_{IR} as computed from IRAS data following formula (5.3) and (5.2) versus the SFR and L_{IR} based on WISE data using equations (5.5) and (5.9) are shown in bottom left and right panel, respectively. Whenever in one of the four IRAS channels, an upper limit is indicated, the resulting SFR or L_{IR} is marked by a red-colored data point.

1:1 relation between the SFR inferred from $H\alpha$ and infrared data in figure 5.3(b). Thus, having SFRs computed from various indicators, can tell something about the intrinsic composition of a galaxy.

5.5 Atomic HI masses from Previous Studies

5.5.1 Digital Archive of HI 21 cm Line Spectra

Similar to the compilation and the subsequent homogenization of CO data, which was performed as part of this thesis, Springob et al. (2005) have compiled and homogenized a huge set of HI data from various sources in the archive. Their resulting catalog contains line fluxes and line widths of 9000 galaxies in the local universe. For the observed 21 cm flux, they have performed a correction for the source extent (double Gaussian with a central hole), the pointing error and self-absorption (which is a function of inclination). Furthermore, all published line widths were corrected for redshift stretching, instrumental effects and smoothing.

A cross match between the CALIFA mother sample and the Springob et al. (2005) data, reveals that for 374 out of 939 CALIFA galaxies, HI data is available. Although this is a big fraction already, more data is needed for performing various analysis. Therefore, also the homogenized HYPERLEDA data, see Paturel et al. (2003) for details, was used for atomic mass calculations.

5.5.2 HYPERLEDA

In order to compute atomic gas masses for a substantial fraction of CALIFA galaxies, homogenized HI data from HYPERLEDA¹ was also used. Paturel et al. (2003) compiled a catalog based on 611 references and observations made in Nancay for 16781 galaxies. All data was converted to a standard velocity and magnitude system, which is described in Mathewson and Ford (1996) and Theureau et al. (1998), respectively. The result is a catalog containing the logarithm of twice the maximum rotation velocity, a HI magnitude and the HI velocity expressed with the optical definition (i.e., using wavelengths instead frequencies). The typical uncertainties are: 0.04, 0.25 mag and 9 km s^{-1} , respectively.

For the data in the catalog, no correction for self-absorption is applied. Hence, that is left as task for this thesis (see next section) in order to get accurate values of the atomic masses for CALIFA galaxies which are comparable to the quantities found by Springob et al. (2005).

5.5.3 Calculating Atomic Gas Masses from HI Observations

Once the observed 21 cm fluxes, S_{21} , are corrected for source-extent, self-absorption and other (instrumental) effects, the atomic gas mass can be calculated following formula (5.10), which is taken from Roberts (1962).

$$M_{HI} = 2.36 \times 10^5 \times D_L^2 \times S_{21} \quad (5.10)$$

M_{HI} then is given in $M_\odot$, S_{21} , the velocity integrated source flux density, in Jy km s^{-1} and D_L , the luminosity distance, in Mpc. Thus, HI mass calculations is easily done for the Springob et al. (2005) data for which no preceding process is necessary.

Though, for the quantities taken from HYPERLEDA, a twofold procedure has to be deployed. First, the cataloged 21 cm *magnitudes*, m_{21} have to be transformed to a flux density S_{21} in Jy km s^{-1} following equation (5.11):

$$S_{21} = \frac{1}{0.2366} \times 10^{-\frac{m_{21} - 15.84}{2.5}} \quad (5.11)$$

¹<http://leda.univ-lyon1.fr>

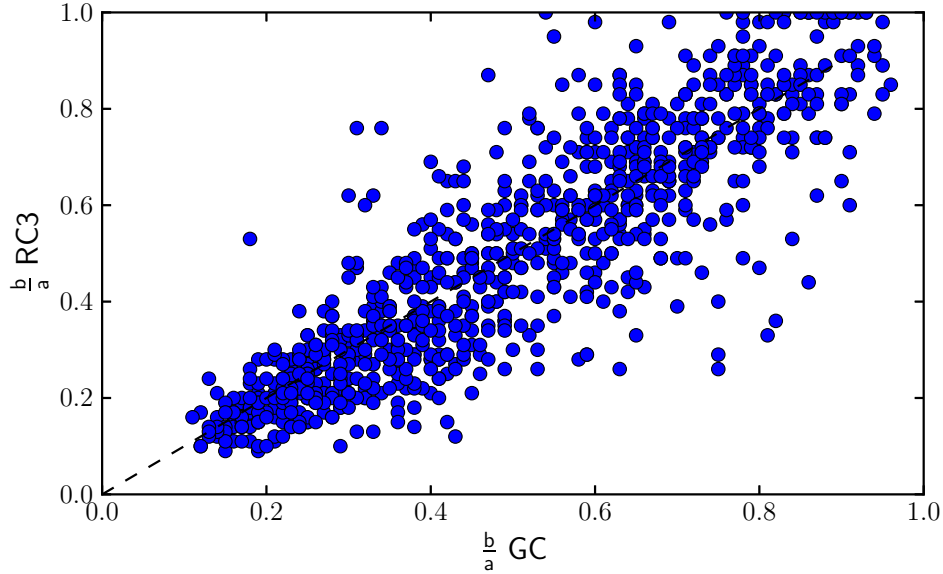


Figure 5.4: Comparison of major/minor axes ratios found in RC3 and derived through a isophotal analysis based on SDSS images.

In the second step, self-absorption within the galaxy, which is a function of inclination, is taken into account in the same way as described in Lang et al. (2003) on page 756. The inclination was calculated by a relation, which was even used by Hubble (1926) as seen in equation (5.12).

$$\cos^2(i) = \frac{\left(\frac{b}{a}\right)^2 - q^2}{1 - q^2} \quad (5.12)$$

The values for the major (a) and minor axes (b) as well as the blue diameters (D_{25}), were – in a first approach – downloaded automatically through a self-developed script (`getdiameter.sh`) from the Third Reference Catalog of Bright Galaxies (RC3) for all CALIFA galaxies. Finding an accurate parametrization for the major and minor axes is a complex problem, therefore the values in the RC3 suffer of large error bars and more accurate data would be of benefit. Luckily, Nadine Backsmann and Bernd Husemann have performed isophotal and growth curve analysis based on SDSS r band images for all CALIFA galaxies. Thus, they also derived the major and minor axes. A comparison between the RC3 values and the more reliable values derived by Nadine Backsmann and Bernd Husemann is shown in figure 5.4. Above $b/a > 0.5$ the scatter gets huge, hence in general the values for edge-on galaxies are more reliable than those for face-on galaxies. The parameter q in equation (5.12) is the minimum axial ratio, that is considered to be valid for edge-on galaxies with an inclination of 90 degree. The commonly accepted value for q is 0.2 and was also used within this thesis. If a galaxy’s disk appears more than five times longer than it is wide, the galaxy’s inclination is 90 degree (Tully and Fisher, 1977).

Now, after computing the inclination i , for spiral galaxies from types Sa to Sc, a factor

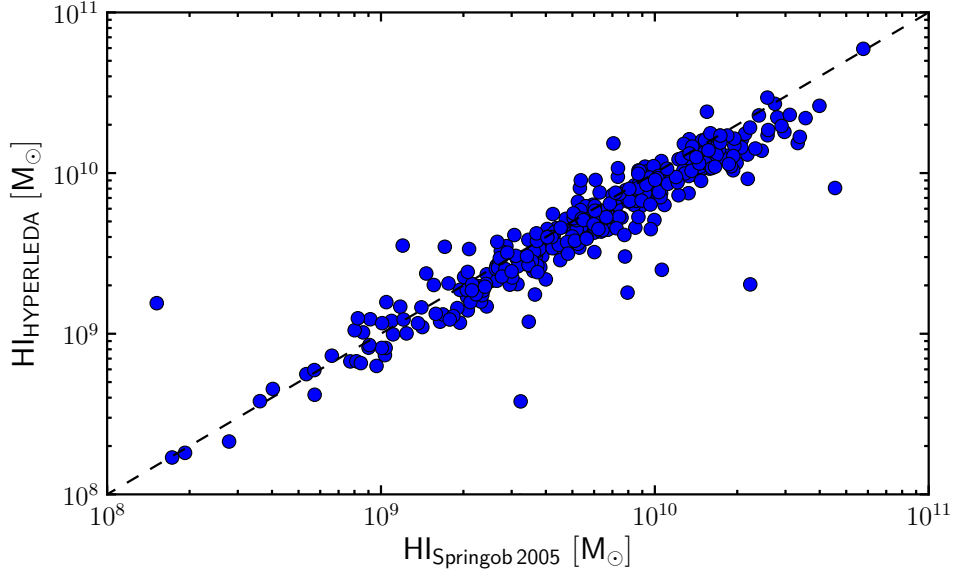


Figure 5.5: HI masses computed from data of Springob et al. (2005) versus HI masses based on Paturel et al. (2003), HYPERLEDA.

f can be found, that enhances the 21 cm flux, S_{21} , in order to account for self-absorption. The empirical formula found by Lang et al. (2003), distinguishes between early and late type spirals by introducing an exponent β , which is 0 for E and S0 galaxies and 0.04, 0.16 and 0.14 for Sa, Sb and Sc, respectively. The factor f and the corrected 21 cm flux, $S_{21,corr}$, then are given as seen in equations (5.13) and (5.14).

$$f = i^{-\beta} \quad (5.13)$$

$$S_{21,corr} = f \times S_{21} \quad (5.14)$$

As can be seen in figure 5.5, when applying a correction for self-absorption to the HYPERLEDA data, the atomic gas mass derived, are indeed of comparable quality to those quantities found in Springob et al. (2005).

5.6 Calculation of the Molecular Gas Mass

5.6.1 Difficulties of Deriving Molecular Gas Masses from CO Observations

Molecular gas is an important indicator for star formation and star formation *timescales*. Thus, accurate derivations of the molecular gas mass is a crucial topic for understanding internal processes and the evolution of galaxies. A caveat worth mentioning, is that when looking for published molecular gas masses in the literature, numerous authors quite often

only publish the so called “indicative mass” (Boselli et al., 1994; Lavezzi and Dickey, 1998; Böker et al., 2003; Albrecht et al., 2004). Thereby, they refer to the amount of molecular gas mass located only within the beam of the appropriate telescope. Though, probably a substantial fraction of flux is lost and the masses can only be taken as lower limits. Therefore, within this work, a sophisticated aperture correction (see 5.6.3) was applied in order to calculate the *total* molecular gas masses for the CALIFA galaxies. The method used is similar to the one presented by Lisenfeld et al. (2011) and Stark et al. (2013).

Another important issue when computing molecular masses in extragalactic sources, is the conversion factor, X_{CO} (also α_{CO}), which, in fact, corresponds to a mass-to-light ratio and transforms the measured CO flux into a H_2 mass under the assumption of a certain count ratio between the CO and H_2 column density which can be observationally derived when assuming that CO is mainly found in *virialized* molecular clouds (see section 5.7). But hereby, another large uncertainty comes into play, the value of X_{CO} is *not* constant throughout the whole galaxy disk and can vary up to a factor of five at least for different galaxies (see figure 5.14), depending on the ISM’s chemical composition. In most cases, the galactic standard conversion factor as found in Strong et al. (1988) is used in calculations. Its value is $X_{CO} = 2.3 \times 10^{20}$ and numerous publications, e.g. Casoli et al. (1991), Casoli et al. (1996), Boselli et al. (1996), Lavezzi et al. (1999) and Leon et al. (1998) make use of it.

The above mentioned value may be appropriate for “normal” spirals, where the molecular mass is believed to persist within dense molecular clouds only. Whereas within ULIRGs (Ultra Luminous Infrared Galaxies), for example, Solomon et al. (1997) and Downes and Solomon (1998) found that CO is distributed more diffuse leading to a much lower conversion factor. Hence, for (U)LIRGs a conversion of $X_{CO} = 0.8 \times 10^{20}$ is widely used nowadays, e.g. Strong et al. (2004) and Evans et al. (2005).

Summarizing what is stated above, probably the best one can do is to apply an aperture correction to all CO fluxes and use a metallicity-dependent X_{CO} value as it was done within this thesis, at least, for the 26 galaxies, where the metallicity (ratio of $[O/H]$) was available. A comparison of the molecular masses for CALIFA galaxies computed homogeneously within this work to the masses taken from other publications, shows quite a large scatter, as seen in figure 5.6. The scatter originates from the various strategies (e.g. extrapolation) and underlying assumptions (X_{CO}). It can be seen that, on average, molecular masses taken from the literature, are lower than those from the presented thesis. The reason is that, as explained before, most authors only publish indicative masses, whereas I have performed an extrapolation in order to make a reasonable estimation of the *total* molecular gas mass content. When investigating figure 5.6, some green points are found remarkable far from the other data. These masses were published in Yao et al. (2003), who used the NRO 45 m telescope with a beam size of only 15 arcsec and thus,

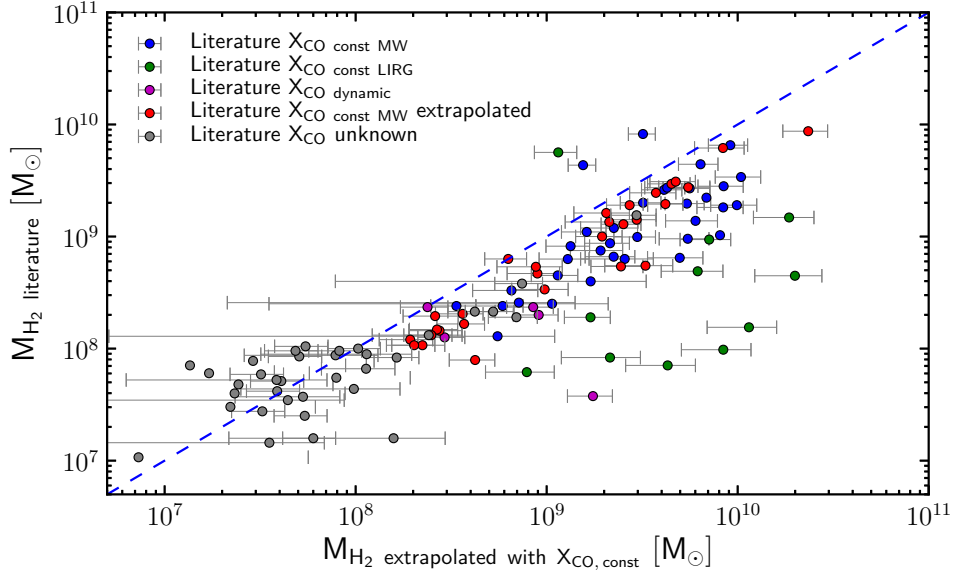


Figure 5.6: Extrapolated, molecular masses computed from 160 literature CO fluxes compared to published values. The scatter arises from different methods used (blue: constant Milky Way X_{CO} – green: constant LIRG X_{CO} ; pink: dynamic (e.g. metallicity-dependent) X_{CO} – red: constant Milky Way X_{CO} with extrapolation – gray: unknown method). Beside that, also the applied cosmological parameters and the decision whether including the mass of Helium or not, introduce scatter.

they only measured the very central part of the galaxies.

Unfortunately, another parameter can cause variations when calculating molecular masses, namely Helium. For example, when comparing extrapolated, total molecular masses from Lisenfeld et al. (2011) with the ones found in this thesis, it has to be considered that their values do *not* include the mass of Helium, which results to a 36 percent decrease.

However, I have decided to include Helium into the calculations following the suggestions found in the review of Bolatto et al. (2013) and in Solomon and Vanden Bout (2005). They state, that the mass of Helium – per definition – should be included in the conversion factor X_{CO} , so that the calculated molecular gas masses, in fact, indicate the total mass of the molecular clouds within a galaxy. But, unfortunately, it seems that no consensus exists on that topic.

Beside all those already mentioned caveats, pointing errors can lead to substantial flux loss, even when the pointing is checked regularly. Some uncertainty is left leading to non-systematic errors. Lastly, the shape of the beam is only known up to a certain degree. In most cases it can be approximated by a Gaussian. Note that, for example Casoli et al. (1996) calculate the gas masses assuming a homogeneous beam, which leads to a dramatically underestimation of the gas masses compared to a Gaussian beam (which is more appropriate). Likewise, the real flux distribution of an extended source is not

known, of course, and often assumed as exponential or Gaussian distribution, which in some cases, probably leads to spurious results.

Most of these issues can only be resolved by combining single dish data with highly resolved interferometric observations, which is specified as a long-term goal of the currently ongoing molecular gas study based on CALIFA.

On top of that, the underlying cosmological parameters play a role when computing luminosity distances, which leads to difficulties when comparing literature data from various publications. Within this thesis, the cosmological parameters as suggested by J. Walcher at the 5th CALIFA Busy Week are used for all calculations. Their quantities are found in table 1.

5.6.2 Formula for Molecular Gas Mass Calculations

The concept for molecular mass calculations is quite simple as can be seen in equation 5.15, but one has to be cautious, because the conversion factor X_{CO} relies on assumptions, that need not be valid for all galaxies. See section 5.7 for details. Moreover, when observing extended objects such as nearby galaxies, the measured brightness temperature should be extrapolated to a value corresponding to the total brightness temperature as described in the next section.

$$M(H_2) = I_{CO,extra} \times A \times X_{CO} \times 2 \times m_H \quad (5.15)$$

Once the conversion factor X given in $[(K \text{ km s}^{-1})^{-1} \text{ cm}^{-2}]$ is known and the source brightness temperature $I_{CO,extra}$ in $K \text{ km s}^{-1}$ is extrapolated, the product of these quantities with the galaxy surface area A in cm^2 and the mass of two hydrogen atoms in $M_\odot$ (see table 1) will lead to the total molecular mass $M(H_2)$ in $M_\odot$. It is important to note, that even in the case of a homogeneously beam-filling source, the area A is not simply a circular area of the telescope beam, because the Gaussian sensitivity of the beam has to be taken into account. That can be done by introducing the solid angle of the beam. Thus, for a Gaussian beam with the half power beam width Θ_{beam} in arcsec, the effective angular size is then given by $1.13 \times \Theta_{beam}^2$. See section 3.3 for a derivation.

When applying a standard conversion factor of $X = 2.3 \times 10^{20} (K \text{ km s}^{-1})^{-1} \text{ cm}^{-2}$ as found by Strong et al. (1988), which also includes the mass of Helium as suggested by Bolatto et al. (2013) and Solomon and Vanden Bout (2005), and rewriting the area A in terms of the luminosity distance D_L in Mpc and the beamsize Θ_{beam} in arcsec², and inserting the mass of two hydrogen atoms as found in table 1, one can find:

$$M(H_2) = C \times X \times I_{CO,extra} \times \Theta_{beam}^2 \times D_L^2 \quad (5.16)$$

The constant C can be divided into several parts according to the desired units. The

transformations are given below:

1. Beam (Θ_{beam}): $arcsec^2 \Rightarrow rad^2$

$$C_1 = 1.13 \times \left(\frac{\pi}{3600 \times 180} \right)^2 = 2.656 \times 10^{-11} \quad (5.17)$$

2. Distance (D_L): $Mpc^2 \Rightarrow cm^2$

$$C_2 = (10^6 \times 3.0857 \times 10^{16} \times 10^2)^2 = 9.5215 \times 10^{48} \quad (5.18)$$

3. Mass (m_{H_2}): $2 \times m_H \Rightarrow M_\odot$

$$C_3 = \left(\frac{2 \times 1.6735344 \times 10^{-27}}{1.9891 \times 10^{30}} \right) = 1.6827 \times 10^{-57} \quad (5.19)$$

The resulting constant C is then:

$$C = C_1 \times C_2 \times C_3 = 4.2554 \times 10^{-19} \quad (5.20)$$

When applying the standard milky way value of $X = 2.3 \times 10^{20} (K km s^{-1})^{-1} cm^{-2}$, one can find a resulting equation for the molecular gas mass (including Helium):

$$M(H_2) = 97.9 \times I_{CO,extra} \times \Theta_{beam}^2 \times D_L^2 \quad (5.21)$$

Note that equation 5.21 is widely used in the literature, e.g. Lavezzi et al. (1999) and Böker et al. (2003).

5.6.3 Aperture Correction

As already outlined, an aperture correction is needed when computing *total* molecular gas masses from single dish observations of nearby galaxies, because even when observing the CO J=1–0 transition with a relatively small telescope (e.g. NRAO 12 m) the half power beam width (HPBW) of 55 arcsec is not necessarily covering the total flux of a CALIFA galaxy with optical blue diameters D_{25} of more than 100 arcsec. When observing with e.g. the IRAM 30 m telescope, the amount of flux-loss is even higher, because of the much smaller HPBW of only 24 arcsec.

In order to extrapolate the measured flux to the total flux of a galaxy, one has to make assumptions about the source brightness distribution and the shape of the beam. In fact, the measured quantity is the result of a convolution of the source with the beam. As described in section 2.5, the CO distribution can be assumed to follow an exponential law in all Hubble types. And the beam can be approximated as a Gaussian. Hence, another

way of describing the applied method, which can be also found in Lisenfeld et al. (2011) or Stark et al. (2013), is to think of the beam as a weighting function which is applied to the exponential source distribution. For finding a value C_{AP} which transforms the observed quantity $I_{CO,obs}$ into the extrapolated total source brightness temperature $I_{CO,extra}$, the total molecular mass of a galaxy has to be defined first. Assuming an exponential CO source brightness distribution, the total CO flux of a circular ($\theta = 0 \dots 2\pi$) galaxy can be written in polar coordinates as:

$$I_{CO,extra} = \int_0^{2\pi} \int_0^\infty I(r) 2\pi r dr d\theta \quad (5.22)$$

Assuming $I_{CO}(r)$ exponentially distributed with a central peak I_0 and a scale length of $r_{e,CO}$, the above equation can be re-written as:

$$I_{CO,extra} = I_0 \int_0^{2\pi} \int_0^\infty e^{-\left(\frac{r}{r_{e,CO}}\right)} 2\pi r dr d\theta \quad (5.23)$$

This integral can be easily solved by partial integration and $I_{CO,extra}$ is found to be:

$$I_{CO,extra} = I_0 2\pi r_{e,CO}^2 \quad (5.24)$$

The shape of the main beam can be typically estimated as a Gaussian. In fact, it represents a weighting function, which attenuates the source flux. Its 2D Cartesian formula for a unity peak height is:

$$G(x, y) = e^{-\left(\frac{x^2}{\sigma_x^2} + \frac{y^2}{\sigma_y^2}\right)} \quad (5.25)$$

The standard deviation σ is related to the full width at half maximum or rather the half power beam width (Θ_{beam}) by:

$$\Theta_{beam} = 2\sqrt{2\ln(2)} \sigma \quad (5.26)$$

Since the measured flux is the result of a convolution of the source brightness distribution with a Gaussian, the observed flux within the beam can be expressed as:

$$\begin{aligned} I_{CO,obs} = I_{CO,extra} * G(x, y) = & 4 I_0 \int_0^\infty \int_0^\infty e^{-\left(\frac{\sqrt{x^2 + y^2}}{r_{e,CO}}\right)} \times \\ & \times e^{-4\ln(2)\left(\frac{x^2}{\Theta_{beam}^2} + \frac{(y \cos(i))^2}{\Theta_{beam}^2}\right)} dx dy \end{aligned} \quad (5.27)$$

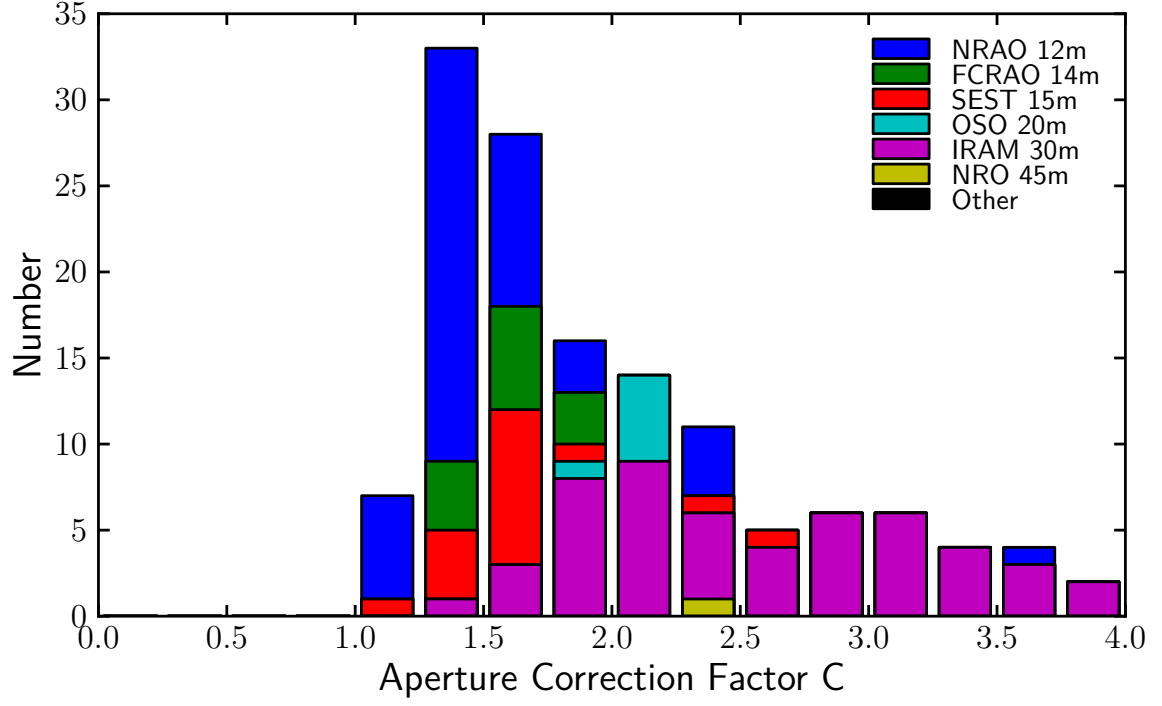
The inclination i of the galaxy is also accounted for in equation (5.27). It may be not

clear at first sight that the effect of i can be written within the Gaussian term, because in principle it should be taken into account in the source and not in the beam. This can be understood, when bringing to mind that the integration interval dy on the sky corresponds to a larger space interval on the source. This means that in the case of accounting for inclination in the source term of equation (5.27), also the integration interval had to be changed to $dy' = dy/\cos(i)$, where dy' is the interval on the source. If one takes into account this effect, the result is the same as in the given formula. A different way to see it is that the formula (5.27) can be derived by a variable substitution from y to $y' = y \cos(i)$.

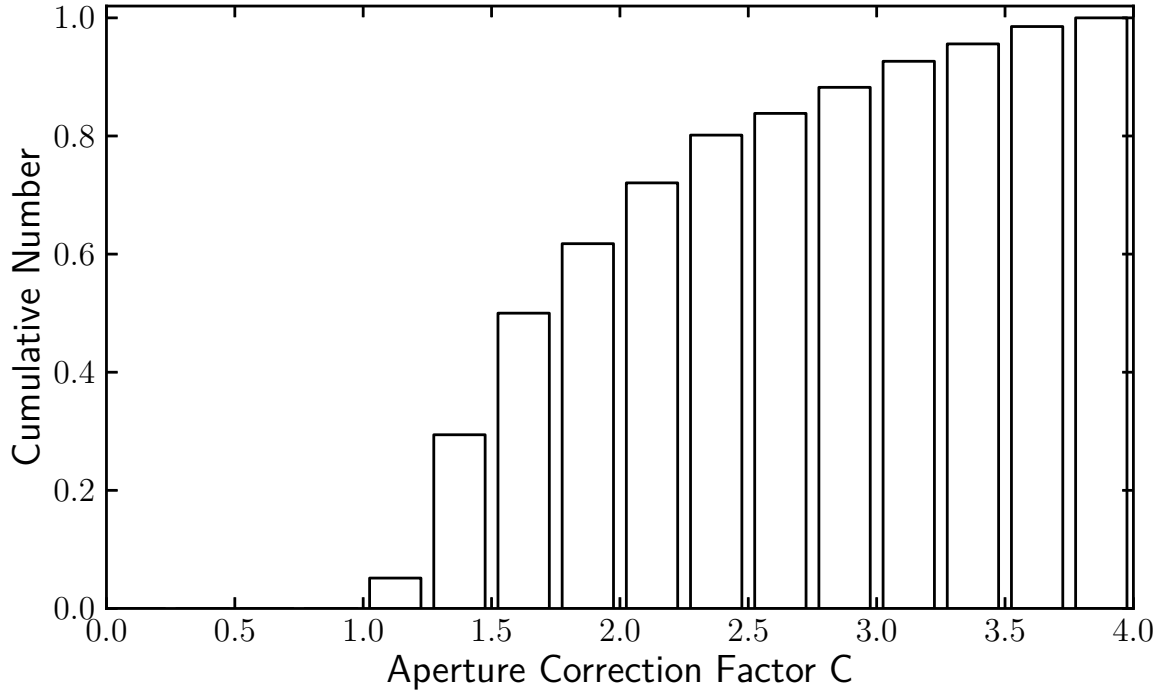
Unfortunately, the expression 5.27 cannot be solved analytically. Therefore a numerical integration was carried out for all galaxies with CO single dish data available in the literature. The aperture correction factor C_{AP} is defined to be:

$$C_{AP} = \frac{I_{CO,extra}}{I_{CO,obs}} \quad (5.28)$$

When calculating C_{AP} , luckily, the peak brightness temperature I_0 , cancels out and no unknown quantity is left. The scale length of the CO distribution, $r_{e,CO}$, can be estimated from the blue diameters of the galaxies as described in equation (2.37). A distribution of the computed values of C_{AP} is shown in figure 5.7. It can be clearly seen, that due to diffraction the smaller sized apertures (e.g. NRAO, FCRAO) cover much higher molecular mass fractions on average than the big dishes like IRAM or NRO, as expected. However, luckily for more than half of the galaxies, C_{AP} is lower than 1.75, as can be seen in the right panel (b) of figure 5.7, which indicates the cumulative frequency of the applied aperture correction factor. As a sanity test, for all CALIFA galaxies which are also part of the AMIGA (Lisenfeld et al., 2011) sample, the aperture correction factors were calculated following the above described procedure. In order to get comparable re-calculations of the published molecular masses, only for this purpose, AMIGA's luminosity distances, inclinations and CO scale lengths were used. Furthermore, AMIGA's published values were multiplied by a factor of 1.155 in order to account for the same conversion factor X_{CO} . The result is shown in figure 5.8. It can be seen, that the newly calculated values and AMIGA's published values are indeed comparable. However, a small scatter exists. After carefully checking all steps of the computing formalism, especially the numerical integration, and a discussion with U. Lisenfeld, it came out, that the performed procedure is correct and the offsets originate from a rounding error of the published data in Lisenfeld et al. (2011). A comparison of the extrapolated masses in log-space, shows their equality up to two digits as can be seen in table 5.2, which is expected when taking the rounding issue into account.



(a) Frequency of C_{AP}



(b) Cumulative Frequency of C_{AP}

Figure 5.7: Aperture correction factors C_{AP} applied to CO luminosities for calculating total molecular gas masses. In the left panel (a), the frequency of the calculated C_{AP} values is shown. The right panel (b) indicates the cumulative frequency of the computed aperture correction factors.

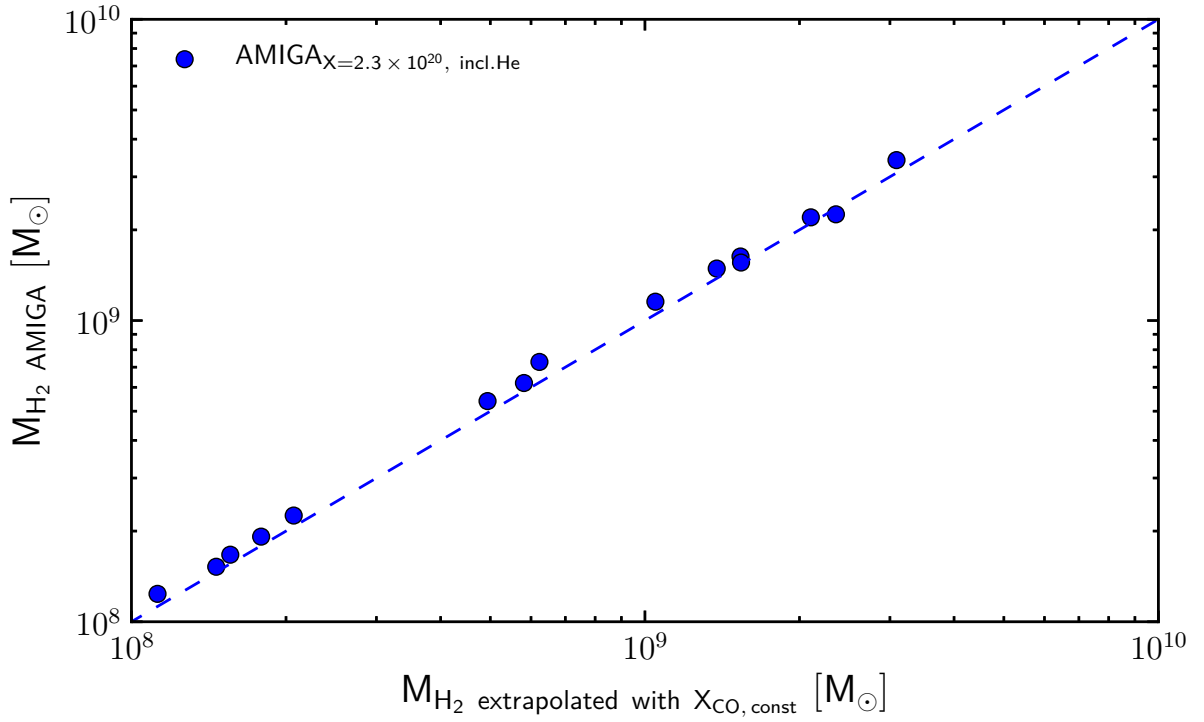


Figure 5.8: As a sanity test, a comparison of the newly calculated molecular masses following the described procedure with AMIGA’s published data was performed. The scatter originates from a rounding issue in the AMIGA data (see text for details).

ID	Name	$\frac{\log(M_{H_2+He,C})}{\log(M_{H_2+He,A})}$	ID	Name	$\frac{\log(M_{H_2+He,C})}{\log(M_{H_2+He,A})}$
131	NGC1542	0.9977	413	NGC3682	1.0006
150	UGC03899	0.9960	418	NGC3752	0.9969
152	UGC03944	0.9913	590	NGC4846	0.9973
158	UGC04054	0.9961	688	NGC5439	0.9945
244	UGC04845	0.9974	743	NGC5622	0.9961
273	IC2487	0.9979	748	NGC5633	0.9967
346	UGC05820	0.9954	856	IC1256	0.9961

Table 5.2: A comparison of the extrapolated masses following the described method with AMIGA’s published values shows a scatter (see figure 5.8) which originates from a rounding error in AMIGA’s published values. However, in log-space the molecular masses equal each other up to two digits as the ratio between the calculated values (C) and AMIGA’s published values (A) shows.

5.7 The Conversion Factor X_{CO}

One of the greatest challenges when calculating molecular gas masses, is the conversion factor X_{CO} . Within this section, theoretical aspects are given that explain why it is assumed that such a conversion factor should exist at all. Why is the CO J=1–0 luminosity related to the column density at all? This is the main question of interest and it cannot be answered in a short, but basically four assumptions have to be adopted in order to be able to derive the column density from CO observations. The problem is, that CO J=1–0 is optically thick and thus, in principal its luminosity is related to the *temperature* of the *surface* (at $\tau = 1$) and *not* to the column density. The most important reason, why column densities can be derived anyway, is that the *linewidth* which represents the velocity dispersion of a molecular cloud is related to its mass. Following Solomon et al. (1987), the virial mass of a giant molecular cloud (GMC) in $M_{\odot}$ is given by equation (5.29).

$$M_{\text{vir}} = \frac{3(5 - 2k)}{G(3 - k)} R \sigma^2 \quad (5.29)$$

R is the projected radius in pc, σ is the 1-dimensional velocity dispersion in km s^{-1} , G is the gravitational constant and k is the power law index of the spherical volume density distribution, which defines the density gradient within the cloud by: $\rho \propto r^{-k}$. In all further explanations, for the sake of simplicity, k is considered to be unity. As long as the molecular gas is dominating the mass enclosed by the sphere of radius R and the cloud is virialized, M_{vir} will be a good measure of the H_2 mass.

Now, another empirical relation comes into play, which gives rise to the “magic” behind the conversion factor – the linewidth-size correlation – as expressed in equation (5.30). Molecular clouds are observed to follow this relation and it is thought to apply under very general conditions (Bolatto et al., 2013).

$$\sigma = C \times R^{0.5} \quad (5.30)$$

Following Solomon et al. (1987) the constant C is approximately $0.7 \text{ km s}^{-1} \text{ pc}^{-0.5}$. This relation is also approximately followed by extragalactic GMCs. When combining equation (5.29) and (5.30), one finds that $M_{\text{vir}} \propto \sigma^4$, and, most important, that molecular clouds that fulfill both relations – virialized and following the linewidth-size relation – have a *characteristic* mean surface density Σ_{GMC} .

Since the CO luminosity of a cloud, is the product of its area and its integrated surface brightness, a relation between M_{vir} and L_{CO} can be obtained. Unfortunately, L_{CO} also depends on temperature. Thus, the additional assumption of constant temperature have to be introduced. Then, the following relation between molecular mass and CO luminosity

can be found:

$$\alpha_{CO} = \frac{M_{vir}}{L_{CO}} \approx 6.1 L_{CO}^{0.2} T_B^{-0.8} \Sigma_{GMC}^{0.6} \quad (5.31)$$

Summarizing what is stated above, the mass-to-light ratio as indicated by equation (5.31) relies on the following assumptions: 1) GMCs are virialized, 2) their masses are dominated by H_2 , 3) they follow the linewidth-size relation and 4) their temperature is approximately constant.

In some cases and environments all these conditions might be fulfilled, but certainly not within all galaxies. X_{CO} in general will be a function of the physical conditions in GMCs. For example, in starburst environments the situation is much more complex. There, the possibility of “overlapping” clouds cause spurious results and cloud-cloud collisions or other violent mechanisms will lead to GMCs far off from virialization. Further details on that topic can be found in Bolatto et al. (2013).

5.7.1 Transformation from X_{CO} to α_{CO} and Vice Versa

In the previous section, it was explained that α_{CO} principally corresponds to a mass-to-light ratio. But when calculating molecular gas masses as described in section 5.6.2, another conversion factor, namely X_{CO} given in $[(K km s^{-1})^{-1} cm^{-2}]$ has to be used. α_{CO} is defined to be:

$$\alpha_{CO} = \frac{M_{H_2}}{L'_{CO}}, \quad (5.32)$$

where M_{H_2} is given in $M_\odot$ and L'_{CO} is usually expressed in $K km s^{-1} pc^2$. Solomon and Vanden Bout (2005) define L'_{CO} as seen in equation (5.33):

$$L'_{CO} = 23.5 \times \Omega_{s*b} \times D_L^2 \times I_{CO} \quad (5.33)$$

Ω_{s*b} thereby is the solid angle of the source convolved with the beam given in $arcsec^2$. This property can be approximated by $1.13 \times \Theta_{beam}^2$ when assuming a Gaussian beam and source. See section 3.3 for a derivation. D_L^2 , the luminosity distance has to be inserted in Mpc and I_{CO} in $K km s^{-1}$.

By means of the molecular gas mass calculations from section 5.6.2, the definition of α_{CO} from equation (5.32) and the definition of the CO luminosity from equation (5.33), a conversion from X_{CO} to α_{CO} can be easily found. The result is shown in equation (5.34).

$$X_{CO} = \frac{\alpha \times 10^{20}}{1.60247} \quad (5.34)$$

Note that, X_{CO} per definition also includes a factor of 1.36 for accounting for the mass of Helium. Thus, the resulting mass corresponds to the total observed giant molecular clouds mass.

5.7.2 Constant Conversion for Normal Spirals and LIRGs

In normal star-forming galaxies a conversion factor similar to the one found in the milky way by Strong et al. (1988) seems to be appropriate, whereas in infrared-luminous galaxies, where the physical ISM structure is different and CO might be (partly) de-coupled from virialized molecular clouds, a different conversion factor should be more reasonable. For molecular gas mass calculations of CALIFA galaxies, based on a static conversion factor, the following values for normal and infrared-luminous galaxies are used:

$$* X_{CO} = 0.8 \times 10^{20} \text{ for } L_{IR} > 10^{11} L_{\odot} \text{ (Downes and Solomon, 1998)}$$

$$* X_{CO} = 2.3 \times 10^{20} \text{ for } L_{IR} \leq 10^{11} L_{\odot} \text{ (Strong et al., 1988)}$$

These values are widely used and accepted in the community. For example the given (U)LIRG value is also used in Strong et al. (2004) and Evans et al. (2005). The milky way value found by Strong et al. (1988) is frequently used, e.g. Böker et al. (2003), Lavezzi and Dickey (1998) and Leon et al. (1998).

5.7.3 Variable Conversion Factor Depending on [O/H]

So far, in section 5.7, it was explained, that four general assumptions are needed in order to derive column densities from CO luminosities. However, beside that, the conversion factor also depends on the spatial distribution and mass fraction of the molecular gas (relative to stars) in the cloud, and even on other parameters, such as turbulence in giant molecular clouds (Downes and Solomon, 1998). Since the penetration depth of UV radiation which is able to dissociate CO molecules, depends on the extinction through the cloud, and thus on its *metallicity*, the optical depth and the effective conversion factor in CO transitions are predicted to depend on metallicity (Genzel et al., 2012), especially in *low metallicity, diffuse gas* which was investigated by e.g. Pelupessy and Papadopoulos (2009), Shetty et al. (2011) and Glover and Mac Low (2011).

One possible approach to derive the value of α_{CO} observationally, takes advantage of the quite tight correlation between the gas-to-dust ratio and the metallicity of a galaxy. The typical scatter of this relation is only about 0.15 dex (Magdis et al., 2011). The physics of this relation can be understood when assuming that the abundances of all heavy elements were proportional to the oxygen abundance and that all heavy elements condensed to form dust in the same way as in the milky way. In that case, the dust-to-gas ratio should also scale proportionally to the oxygen abundance (Muñoz-Mateos et al., 2009).

If both, metallicity and the dust-mass are known, then the total gas ($HI + H_2$) mass can be derived. With knowledge of the atomic mass M_{HI} from HI observations, the pure molecular mass fraction can be easily calculated and subsequently, by means of the CO luminosity, L'_{CO} , the conversion factor α_{CO} can be extracted, since it is practically the

conversion factor from CO-light to H_2 -mass.

However, within this thesis, the conversion factor α_{CO} was not derived directly through this method, for the most part, because calculating the total (cold and warm) dust mass is not a simple task. Far-infrared (FIR) data, would be needed for SED fitting, which, so far, is available for almost none of the CALIFA galaxies. Far-infrared observations with SAFARI, an instrument on-board of SPICA would be of benefit for future prospects concerning the spatially-resolved derivation of α_{CO} in CALIFA galaxies. The dust-mass calculations performed in this thesis based on IRAS data unfortunately only covers the warm component due to the 12 to 100 μm wavelength range covered by IRAS which corresponds to a blackbody temperature above $\approx 30\text{ K}$. The performed calculations are described in Devereux and Young (1990) and shown in equations (5.35) and (5.36). The temperature and mass of the warm dust within CALIFA are shown in figures 5.9 and 5.10. It can be seen, that IRAS, indeed, did not pick up the coldest dust that contains most of the mass (Xu and Helou, 1996), because the mean temperature along the Hubble sequence lies above 30 K. Thus, the traced dust, is heated by UV flux associated with star formation as described in section 5.1.

The cold dust component, which for the first time was uncovered by the ISO satellite, shows typical temperatures of approximately 10–20 K. This cold dust component has a larger radial extent than the stars and may be partially associated with extended HI disks. Details on that can be found in Genzel and Cesarsky (2000). The temperature of the cold dust component is consistent with theoretical predictions from the balance of heating and cooling processes in the ISM for dust grains in the diffuse, stellar radiation field. Moreover, the gas-to-dust ratio inferred for this cold dust component is very close to the galactic value of approximately 100 in the milky way.

$$T_{warm\ dust} = \frac{95.94}{\log(7.78 \times \frac{f_{100}}{f_{60}})} \quad (5.35)$$

$$M_{warm\ dust} = 4.58 \times f_{100} \times D_L^2 \times e^{\frac{144}{T_{dust}} - 1} \quad (5.36)$$

The resulting T_{dust} and M_{dust} are given in K and $M_\odot$, respectively. The IRAS fluxes f_{60} and f_{100} must be given in Jy and the luminosity distance, D_L , in Mpc .

As can be seen in figure 5.11, the gas-to-warm-dust ratio found for the CALIFA sample, is around 1000 for the early type galaxies and reaches a value of approximately 3000 in late type galaxies. This finding is consistent with similar studies, e.g. Devereux and Young (1990). The reason for the slightly higher gas-to-dust ratios found within this thesis compared to the average values of Devereux and Young (1990) is due to the applied aperture correction for the CO data which leads to an enhanced molecular mass by a factor of 2–5. The increase along the Hubble sequence, can be explained by the increase of the atomic gas fraction solely, because when comparing the molecular gas to the warm

dust as seen in figure 5.12, one finds a nearly constant ratio of ≈ 1000 in all type of galaxies. This can be interpreted as an intrinsic connection between molecular gas from which star form and the dust heating mechanism introduced by the newly formed stars.

After this excursion, we can now come back to the conversion factor α_{CO} . As we have seen, unfortunately, without an estimate of the dust mass, we cannot make use of the gas-to-dust ratio vs. metallicity relation in order to derive the conversion factor directly. Therefore, the findings of Magdis et al. (2011) are used for deriving α_{CO} through an empirical relation. Fitting data of a local spiral galaxies sample taken from Leroy et al. (2011), a local ULIRGS sample taken from Solomon et al. (1997) and some data from Magdis et al. (2011), reveals the relation (5.37), from which α_{CO} can be estimated immediately based on the metallicity $[O/H]$.

$$\alpha_{CO} = 6.14974 \times 10^{15} \times e^{-4.02038 \times (12 + \log(\frac{O}{H}))} \quad (5.37)$$

The data and fit is shown in figure 5.13 and the derived α_{CO} values are given in table 5.3. The metallicity for CALIFA galaxies was taken from Sánchez et al. (2013). A comparison of the molecular masses derived by means of a static conversion factor and through the metallicity-dependent conversion factor is found in figure 5.14. As expected, the scatter is quite large, up to a factor of nearly four. However, it can be seen that in most cases, a standard conversion factor, leads to good estimates.

Thus, metallicity indeed is an important quantity when calculating molecular masses and should be taken into account whenever possible. Moreover, for deriving α_{CO} directly, also far-infrared data should be exploited in the future.

5.8 Table of Combined SFRs, Atomic and Molecular Masses

Following the formula of the preceding sections, infrared luminosities, star formation rates, atomic and molecular gas masses were calculated. In order to get as many quantities as possible for the following data analysis, the results from several computations were combined. I have performed a growth curve analysis with SExtractor (Bertin and Arnouts, 1996) as described in section 5.4 on all WISE Atlas images, that were available for the CALIFA galaxy sample. The star formation rate and infrared luminosity were then calculated following the equations (5.5) and (5.9), respectively. But whenever, SExtractor's `MAG_BEST` value did not converge for any reason, WISE catalogue's `w4gmag` value was taken as a basis for the computations. And in the case, that no WISE data was available at all for an object, the IRAS Faint Source Catalogue (FSC) was looked for available fluxes. In the last step, when no data was available even in the FSC, the IRAS point source

ID	Name	$12 + \log(\frac{O}{H})$	α_{CO}	ID	Name	$12 + \log(\frac{O}{H})$	α_{CO}
2	UGC00005	8.752	3.22	777	NGC5772	8.753	3.21
9	NGC0023	8.727	3.56	784	NGC5829	8.613	5.63
26	NGC0192	8.607	5.76	795	NGC5930	8.696	4.03
152	UGC03944	8.585	6.30	803	NGC5957	8.77	2.99
273	IC2487	8.604	5.83	856	IC1256	8.787	2.80
312	NGC3057	8.356	15.81	871	NGC6978	8.731	3.50
528	IC0776	8.355	15.88	901	NGC7549	8.773	2.96
548	NGC4470	8.589	6.20	904	NGC7591	8.735	3.45
603	NGC4961	8.581	6.40	906	IC5309	8.695	4.05
608	NGC5000	8.788	2.78	913	NGC7625	8.763	3.08
611	NGC5016	8.803	2.62	914	NGC7631	8.768	3.02
634	NGC5218	8.677	4.35	922	UGC12688	8.666	4.55
748	NGC5633	8.813	2.52	939	NGC4676B	8.638	5.09

Table 5.3: α_{CO} for CALIFA galaxies with [O/H] ratios available.

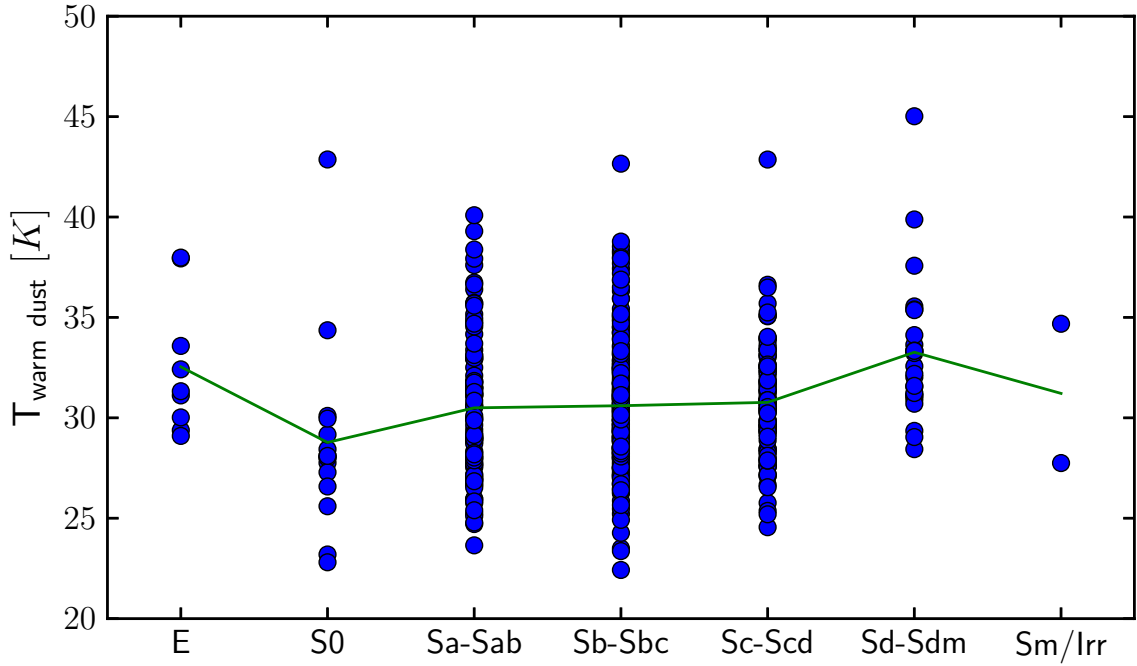


Figure 5.9: $T_{\text{warm dust}}$ along the Hubble sequence found for CALIFA galaxies.

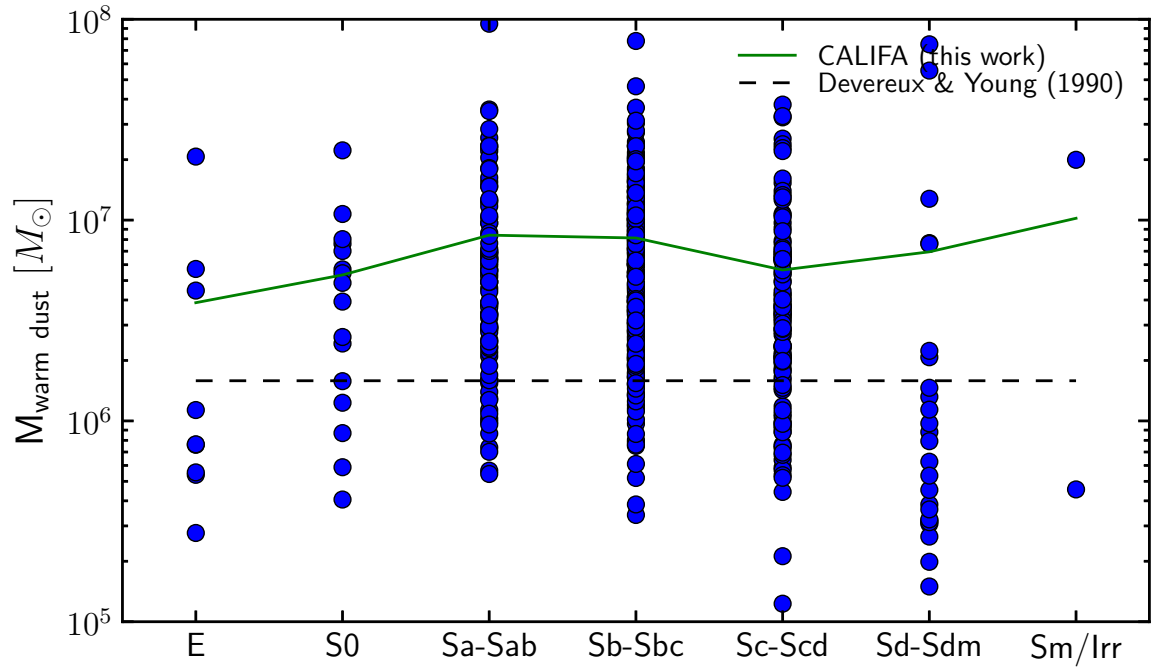


Figure 5.10: Warm dust along the Hubble sequence derived from IRAS data for the CALIFA sample.

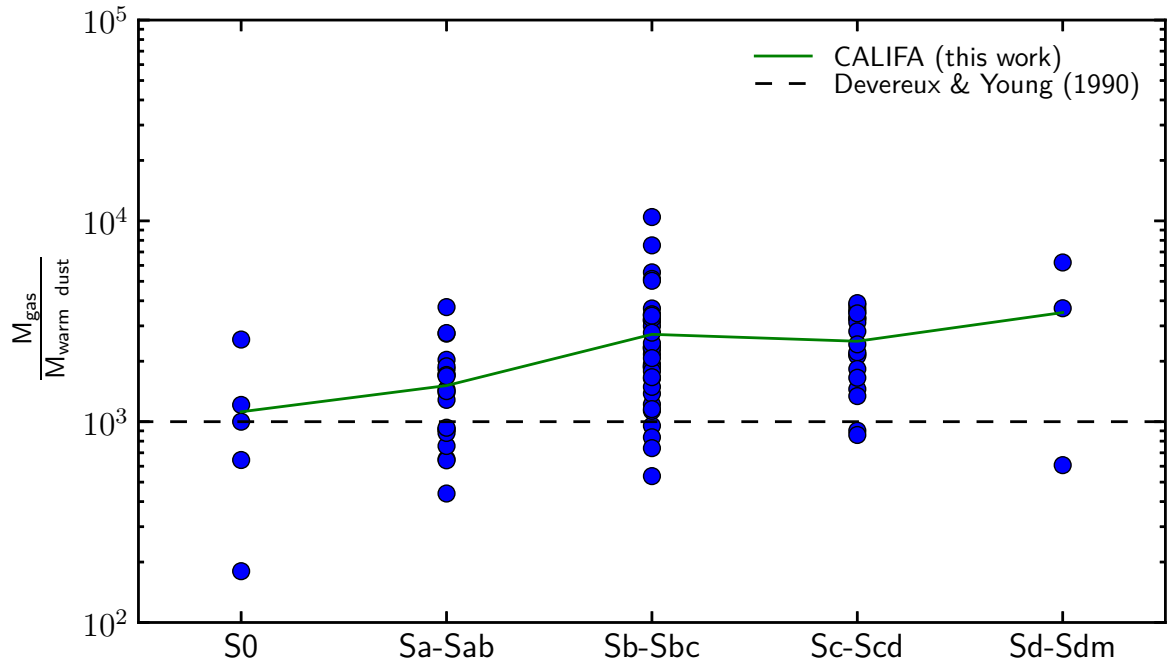


Figure 5.11: Gas-to-Warm-Dust ratio along the Hubble sequence found for CALIFA galaxies.

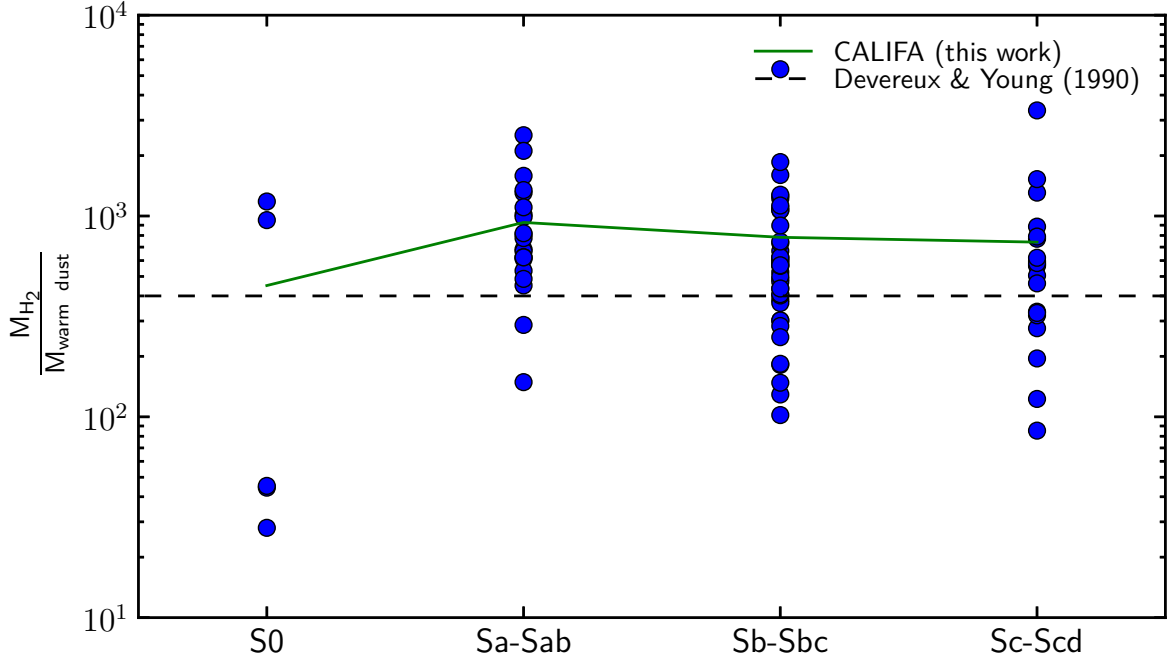


Figure 5.12: Molecular-Gas-to-Warm-Dust ratio along the Hubble sequence derived from IRAS data for the CALIFA sample.

catalogue (PSC) was looked for fluxes for further L_{IR} and SFR calculations following equations (5.2) and (5.3). In this way, for all galaxies of CALIFA’s mother sample, star formation rates could be computed. With the HI data, the procedure was similar. Data found in Springob et al. (2005) was preferred and whenever no data was found, atomic masses were calculated through HI magnitudes found in HYPERLEDA. Thus, for 599 out of 939 galaxies, nearly 2/3, of the mother sample, atomic gas masses could be calculated. As can be seen in table 4.1, only for 159 galaxies of the mother sample, CO data including upper limits was available in the literature. Therefore, future CO single dish observations would be of benefit in order to make statistically significant statements about the molecular gas content of CALIFA galaxies. The following table 5.4 is a compendium of the computed values for those galaxies with CO data available. See appendix A for all the data.

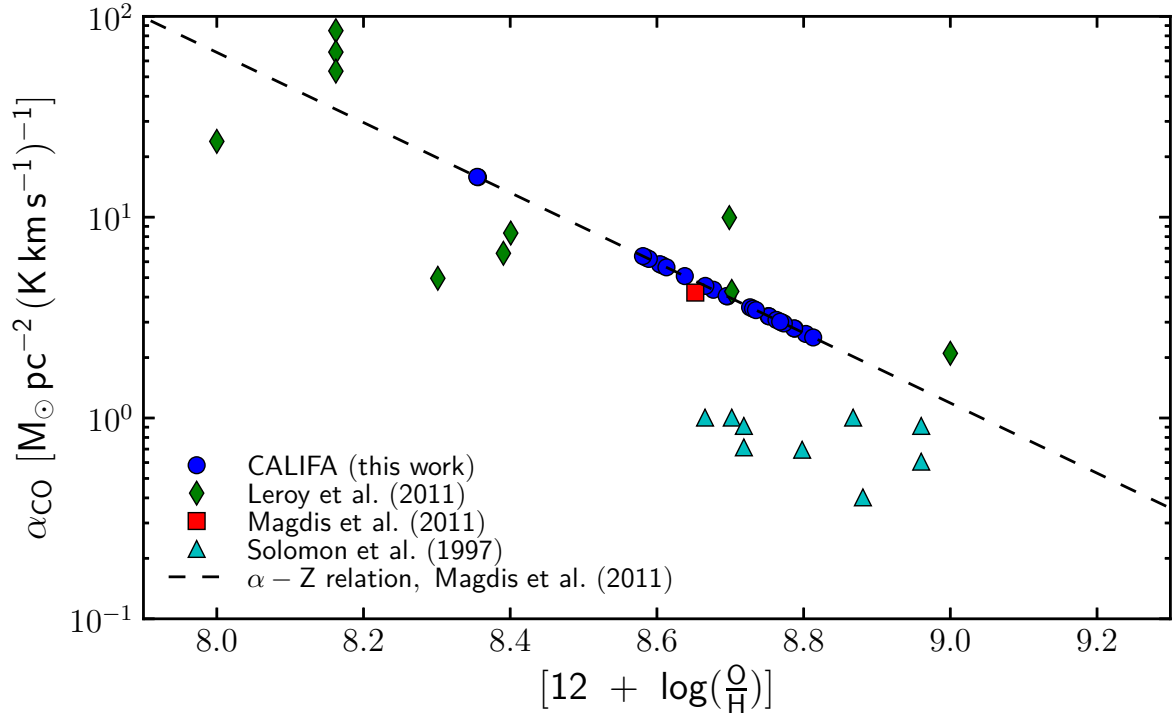


Figure 5.13: $\alpha_{CO} - Z$ relation from Magdis et al. (2011) used for estimating α_{CO} for the CALIFA galaxies with published $[\text{O}/\text{H}]$ ratios from Sánchez et al. (2013). The two extreme outliers (NGC3057 and IC0776) with much higher extrapolated values are found to be galaxies with very low-metallicities (8.356 and 8.355) which results to high α_{CO} values of 15.81 and 15.88 respectively.

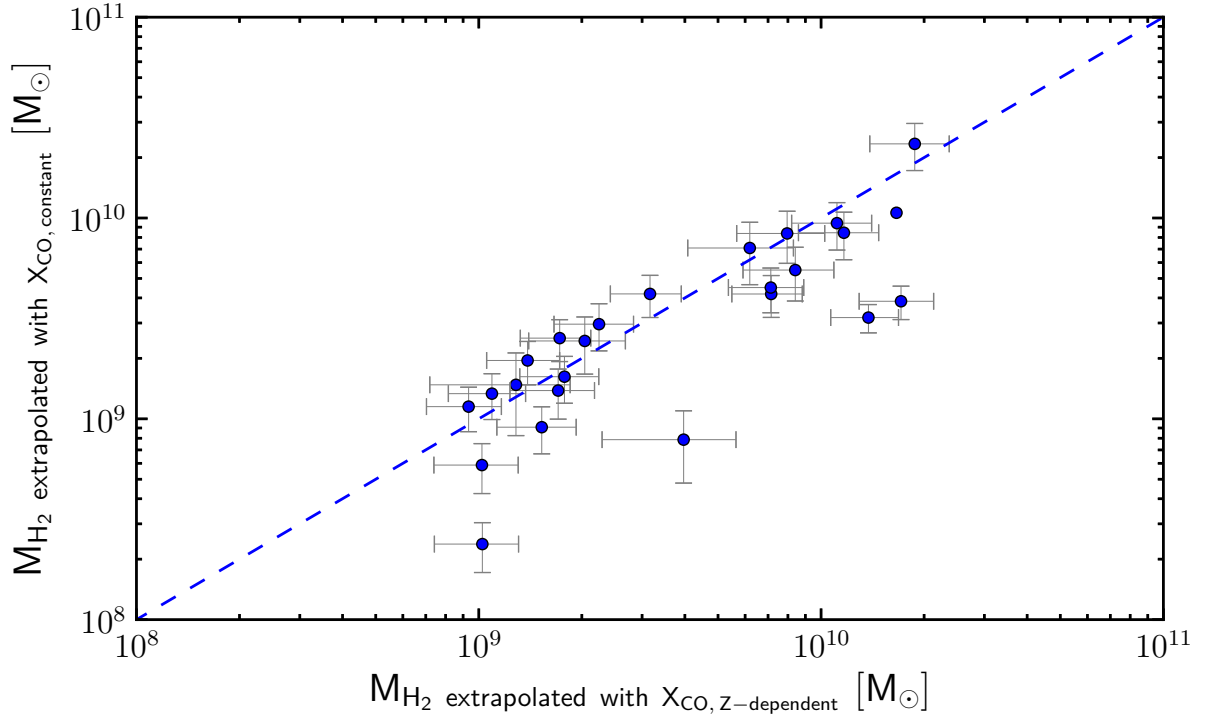


Figure 5.14: Molecular masses calculated with static and Z-dependent X_{CO} for the CALIFA galaxies with $[O/H]$ data available.

Table 5.4: Calculated L_{IR} , SFRs, atomic and molecular gas masses (see appendix for full dataset). Column specifications: CALIFA ID (1), other catalog ID (2), combined L_{IR} in $10^9 L_{\odot}$ (3), combined SFR in $M_{\odot} \text{ yr}^{-1}$ (4), combined M_{HI} in $10^9 M_{\odot}$ (5), C_{AP} used for molecular mass extrapolation (6), extrapolated M_{H_2} in $10^9 M_{\odot}$ with combined X_{CO} (7), ratio of M_{H_2} derived through Z-dependent and static X_{CO} (8)

ID	name	L_{IR} $10^9 L_{\odot}$	SFR $M_{\odot} \text{ yr}^{-1}$	M_{HI} $10^9 M_{\odot}$	C_{AP}	M_{H_2} $10^9 M_{\odot}$	$\frac{M_{H_2, Z-dep}}{M_{H_2, stat}}$
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
2	UGC00005	63.08 ± 2.41	9.4 ± 0.38	13.36 ± 1.62	1.6	$6.19 \pm 2.11^*$	0.9
9	NGC0023	193.74 ± 0.87	30.7 ± 0.15	9.53 ± 1.2	2.1	$17.12 \pm 4.2^*$	4.4
11	UGC00139	7.81 ± 0.73	1.0 ± 0.1	13.81 ± 2.27	1.7	$< 0.57 \pm 0.16$	–
26	NGC0192	58.23 ± 0.78	8.6 ± 0.12	1.44 ± 0.23	1.5	$16.61 \pm 16799.63^*$	1.6
30	NGC0237	31.51 ± 0.92	4.5 ± 0.14	10.3 ± 1.27	1.5	3.8 ± 1.05	–
68	NGC0741	5.99 ± 1.03	0.8 ± 0.14	–	2.3	$< 1.7 \pm 0.46$	–
74	NGC0781	0.29 ± 0.13	0.0 ± 0.02	–	2.0	$< 0.22 \pm 0.07$	–
78	NGC0833	3.91 ± 0.92	0.5 ± 0.12	–	2.1	2.05 ± 0.66	–
100	NGC1056	11.32 ± 0.13	1.5 ± 0.02	3.07 ± 0.41	3.7	1.16 ± 1015.74	–
114	NGC1142	434.19 ± 1.95	72.1 ± 0.34	–	1.3	7.66 ± 1.31	–
125	UGC02690	29.54 ± 1.66	4.2 ± 0.25	16.82 ± 2.2	1.9	3.73 ± 1.02	–
131	NGC1542	7.37 ± 0.54	1.0 ± 0.08	1.03 ± 0.16	1.8	1.95 ± 0.53	–
138	NGC1665	59.72 ± 1.07	8.8 ± 0.17	–	2.6	$< 0.11 \pm 0.08$	–
140	NGC1667	133.72 ± 1.2	20.7 ± 0.2	9.97 ± 1.08	2.1	3.17 ± 0.59	–
143	NGC1677	6.89 ± 0.26	0.9 ± 0.04	–	1.6	0.11 ± 0.05	–
150	UGC03899	1.35 ± 0.38	0.2 ± 0.05	3.94 ± 0.87	1.7	$< 0.27 \pm 0.09$	–

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Table continued from previous page

ID	name	L_{IR} $10^9 L_{\odot}$	SFR $M_{\odot} \text{ yr}^{-1}$	M_{HI} $10^9 M_{\odot}$	C_{AP}	M_{H_2} $10^9 M_{\odot}$	$\frac{M_{H_2, Z-dep}}{M_{H_2, stat}}$
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
152	UGC03944	5.63±0.58	0.7±0.08	6.73±0.88	1.6	7.15±1.66*	1.7
158	UGC04054	1.21±0.19	0.1±0.02	1.27±0.23	2.0	<0.37±0.1	—
162	NGC2481	0.63±0.15	0.1±0.02	0.39±0.15	1.9	<0.0±0.03	—
186	IC2247	23.22±0.83	3.3±0.12	4.37±0.76	1.3	3.2±0.77	—
189	NGC2554	7.35±0.61	1.0±0.08	1.47±0.36	2.4	5.42±1.26	—
192	NGC2565	7.02±0.61	0.9±0.08	10.61±1.35	1.4	<0.55±0.55	—
195	NGC2577	0.5±0.12	0.1±0.01	0.05±0.01	2.7	<0.04±0.01	—
198	UGC04386	22.44±1.16	3.1±0.17	4.05±0.59	1.3	4.12±0.98	—
201	NGC2592	0.17±0.06	0.0±0.01	—	3.0	0.04±0.04	—
204	NGC2595	25.1±1.35	3.5±0.2	18.98±3.11	2.3	6.1±1.42	—
221	UGC04551	0.02±0.02	0.0±0.0	0.11±0.04	3.8	<0.04±0.01	—
226	UGC04659	7.93±1.2	1.0±0.17	1.04±0.14	1.5	<0.27±0.08	—
230	NGC2719	2.8±0.24	0.3±0.03	9.88±3.82	1.7	<0.07±0.02	—
231	UGC04722	1.13±0.26	0.2±0.04	1.71±0.57	1.3	0.19±0.06	—
232	NGC2730	16.27±0.77	2.2±0.11	6.4±1.72	1.6	1.34±0.38	—
238	NGC2764	27.54±0.31	3.9±0.05	2.19±0.62	2.1	2.95±0.79	—
243	NGC2778	0.24±0.07	0.0±0.01	—	2.5	<0.02±0.04	—
244	UGC04845	1.22±0.21	0.1±0.03	3.21±0.53	1.4	<0.2±0.06	—
258	NGC2832	3.08±1.89	0.4±0.25	—	4.4	8.08±22898.02	—
260	NGC2805	4.06±0.52	0.5±0.07	11.43±2.43	19.4	1.75±0.46	—
272	NGC2880	0.21±0.05	0.0±0.01	—	3.5	<0.03±0.01	—
273	IC2487	12.97±0.93	1.8±0.13	9.89±2.1	1.5	7.13±1.77*	1.6
299	NGC3021	9.61±0.11	1.3±0.02	1.4±0.16	1.4	0.71±1379.17	—
312	NGC3057	1.04±0.1	0.1±0.01	0.99±0.16	3.5	<0.18±0.06*	4.3
316	IC0598	0.39±0.11	0.0±0.01	—	2.0	<0.05±0.02	—
323	NGC3182	1.68±0.13	0.2±0.02	0.37±0.03	3.3	0.52±0.15	—
328	NGC3230	0.76±0.21	0.1±0.03	—	3.4	<0.1±0.03	—
346	UGC05820	2.28±0.37	0.3±0.05	—	1.3	2.72±0.66	—
355	NGC3395	8.11±2.08	1.1±0.29	2.81±0.33	1.5	0.34±0.09	—
366	UGC06062	0.45±0.1	0.1±0.01	—	2.0	<0.05±0.02	—
368	NGC3471	45.9±0.21	6.7±0.03	0.91±0.1	2.0	2.99±1.19	—
374	UGC06176	18.5±0.33	2.6±0.05	—	2.3	0.74±0.21	—
382	NGC3561	11.81±4.04	1.6±0.58	—	1.1	12.99±3.22	—
389	NGC3610	0.91±0.1	0.1±0.01	—	4.6	<0.05±0.02	—
391	NGC3619	1.42±0.11	0.2±0.01	0.81±0.09	5.6	0.69±0.2	—
402	NGC3648	0.21±0.06	0.0±0.01	—	2.0	<0.03±0.01	—
406	NGC3656	13.89±0.28	1.9±0.04	2.12±0.33	3.0	6.86±2850.03	—
410	NGC3674	0.16±0.06	0.0±0.01	—	2.9	0.02±0.04	—
413	NGC3682	6.66±0.07	0.9±0.01	0.28±0.04	1.5	0.63±0.16	—
418	NGC3752	3.13±0.13	0.4±0.02	0.59±0.05	1.5	0.26±0.08	—
426	NGC3753	30.02±1.45	4.3±0.22	—	2.3	<5.96±1.79	—
430	NGC3800	46.69±0.52	6.8±0.08	2.72±0.47	1.6	5.87±7186.27	—
431	NGC3798	12.86±0.49	1.7±0.07	1.63±0.37	1.8	2.24±0.65	—
432	NGC3801	4.47±0.45	0.6±0.06	2.05±0.32	6.0	3.29±1.28	—
438	UGC06653	19.67±0.44	2.7±0.06	0.72±0.11	1.3	1.29±0.38	—
443	NGC3832	60.91±2.59	9.0±0.41	29.26±7.11	1.7	14.88±3.78	—
444	UGC06697	63.84±2.29	9.5±0.36	8.8±1.34	2.1	10.41±2.78	—
447	NGC3862	5.36±0.92	0.7±0.13	—	2.8	0.98±0.32	—
451	NGC3884	24.16±2.06	3.4±0.31	6.57±0.85	1.6	5.48±1.59	—
452	NGC3883	5.64±0.93	0.7±0.13	27.02±8.81	2.4	4.97±1.6	—
455	NGC3888	26.75±0.24	3.8±0.04	3.66±0.53	2.7	4.13±1768.88	—
468	NGC3947	45.72±1.74	6.7±0.27	11.8±2.4	1.3	6.24±1.66	—
474	NGC3987	68.23±1.07	10.2±0.17	8.34±1.16	1.6	24.25±13327.85	—
475	NGC3991	28.39±0.45	4.0±0.07	8.62±2.22	1.2	0.65±0.24	—
476	NGC3994	36.89±0.41	5.3±0.06	—	2.4	2.15±0.95	—
478	NGC3995	37.88±0.6	5.5±0.09	15.73±2.43	7.5	8.41±3.33	—
485	NGC4017	29.82±0.6	4.2±0.09	12.1±3.86	1.4	2.15±0.57	—
487	UGC07017	31.9±0.43	4.5±0.06	4.55±1.4	1.3	2.25±0.74	—
494	NGC4078	0.36±0.12	0.0±0.01	—	1.8	<0.05±0.02	—

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Table continued from previous page

ID	name	L_{IR} $10^9 L_{\odot}$	SFR $M_{\odot} \text{ yr}^{-1}$	M_{HI} $10^9 M_{\odot}$	C_{AP}	M_{H_2} $10^9 M_{\odot}$	$\frac{M_{H_2, Z-dep}}{M_{H_2, stat}}$
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
498	NGC4134	12.83±0.72	1.7±0.1	11.51±2.26	1.6	1.92±0.58	—
506	NGC4158	4.99±0.27	0.6±0.04	2.42±0.27	1.6	1.14±0.31	—
508	NGC4162	16.98±0.38	2.3±0.06	6.37±0.88	1.7	2.98±0.73	—
509	NGC4168	0.28±0.09	0.0±0.01	—	6.0	<0.08±0.11	—
511	NGC4175	65.75±0.59	9.8±0.09	3.59±0.82	1.3	9.84±2.33	—
512	IC0769	3.13±0.27	0.4±0.04	2.81±0.24	1.8	<0.29±0.08	—
516	NGC4191	0.39±0.12	0.0±0.01	—	1.9	<0.08±0.05	—
522	UGC07286	42.23±1.99	6.1±0.31	4.8±1.68	1.3	<5.61±1.54	—
525	NGC4233	0.86±0.14	0.1±0.02	—	4.4	<0.03±0.1	—
528	IC0776	1.01±0.2	0.1±0.03	3.72±0.47	1.4	<1.02±0.28*	4.3
539	NGC4352	0.25±0.1	0.0±0.01	—	3.0	<0.01±0.05	—
542	NGC4383	29.57±0.13	4.2±0.02	4.19±1.31	1.7	0.51±1986.56	—
543	NGC4405	4.4±0.13	0.6±0.02	0.17±0.02	1.5	0.85±0.23	—
545	NGC4450	7.97±0.29	1.0±0.04	0.83±0.31	3.5	3.9±0.95	—
548	NGC4470	8.88±0.24	1.2±0.03	2.01±0.22	1.3	1.53±0.4*	1.7
549	NGC4475	17.19±1.92	2.4±0.28	12.87±1.62	1.4	6.02±1.82	—
550	NGC4474	0.19±0.05	0.0±0.01	—	3.4	<0.04±0.03	—
551	NGC4476	1.44±0.12	0.2±0.01	—	2.8	0.67±1224.35	—
561	NGC4570	0.77±0.12	0.1±0.01	—	5.4	<0.0±0.0	—
562	IC3598	7.9±1.38	1.0±0.19	2.63±0.38	1.3	<1.7±1.62	—
563	NGC4578	1.42±0.34	0.2±0.04	—	6.8	<0.16±0.14	—
568	NGC4612	0.39±0.09	0.0±0.01	—	4.8	<0.06±0.02	—
572	IC3704	87.61±2.95	13.3±0.47	31.12±3.68	1.2	7.09±2.1	—
576	UGC07941	0.15±0.04	0.0±0.0	4.64±0.82	1.9	<0.36±0.1	—
577	NGC4676A	103.23±1.62	15.8±0.26	—	2.8	6.38±2956.07	—
581	UGC08004	3.51±0.91	0.4±0.12	11.09±1.55	1.4	<1.07±1.03	—
582	NGC4746	15.13±0.17	2.1±0.02	2.67±0.42	2.4	1.38±2954.35	—
584	UGC08025	10.76±1.2	1.4±0.17	14.64±2.75	1.4	<1.33±1.28	—
590	NGC4846	14.03±0.66	1.9±0.1	8.56±2.06	1.9	0.89±0.27	—
594	NGC4892	1.04±0.41	0.1±0.05	—	1.2	<0.72±0.69	—
598	IC4088	20.89±1.59	2.9±0.23	11.17±1.6	1.3	2.56±1.06	—
603	NGC4961	6.53±0.23	0.8±0.03	5.14±0.57	1.4	<1.02±0.28*	1.7
608	NGC5000	34.93±1.02	5.0±0.15	8.11±1.79	1.4	3.16±0.74*	0.8
611	NGC5016	10.69±0.34	1.4±0.05	3.56±0.41	1.5	1.39±0.33*	0.7
614	NGC5056	38.86±1.05	5.6±0.16	15.32±1.91	1.4	2.33±0.94	—
617	NGC5081	20.61±2.12	2.9±0.31	20.68±2.93	1.5	8.4±2.28	—
620	NGC5127	1.3±0.4	0.2±0.05	—	5.4	0.42±0.11	—
631	NGC5198	0.61±0.14	0.1±0.02	—	4.0	<0.0±0.0	—
632	UGC08498	23.49±1.95	3.3±0.29	36.12±11.74	1.7	9.9±2.68	—
634	NGC5218	65.87±0.15	9.8±0.02	1.71±0.2	2.0	11.13±2.92*	1.2
654	NGC5308	0.54±0.09	0.1±0.01	0.18±0.06	4.7	<0.0±0.0	—
658	UGC08739	95.95±1.08	14.6±0.17	13.05±1.6	4.0	19.94±7.66	—
669	NGC5347	50.1±0.22	7.3±0.03	3.52±1.14	1.9	0.31±0.14	—
670	NGC5350	25.66±0.29	3.6±0.04	6.57±0.29	6.6	4.74±1.27	—
671	NGC5353	1.75±0.15	0.2±0.02	3.26±1.02	3.2	0.24±0.12	—
673	NGC5379	1.72±0.08	0.2±0.01	1.21±0.1	2.9	0.42±0.12	—
680	NGC5394	118.55±1.06	18.2±0.17	11.66±0.92	5.6	6.18±2.2	—
688	NGC5439	1.49±0.08	0.2±0.01	—	1.8	0.25±0.07	—
692	NGC5433	115.17±0.52	17.7±0.08	6.85±1.47	2.0	2.02±0.42	—
699	NGC5434B	39.05±1.05	5.6±0.16	17.22±2.69	1.3	4.27±1.01	—
703	NGC5473	0.77±0.1	0.1±0.01	0.18±0.06	4.9	0.01±0.07	—
705	NGC5475	0.35±0.06	0.0±0.01	—	2.5	<0.04±0.03	—
708	NGC5485	0.94±0.11	0.1±0.01	0.9±0.32	4.5	<0.02±0.06	—
710	NGC5490	2.07±0.48	0.3±0.06	—	4.6	<2.45±0.74	—
729	NGC5557	2.32±0.29	0.3±0.04	—	4.5	<0.16±0.05	—
731	UGC09165	73.77±0.83	11.0±0.13	3.77±0.6	1.2	9.15±2.12	—
732	NGC5559	27.72±0.81	3.9±0.12	6.57±0.87	1.2	6.39±1.49	—
739	NGC5611	0.1±0.04	0.0±0.0	—	1.9	<0.05±0.03	—
742	NGC5610	157.18±0.71	24.6±0.12	4.69±0.68	1.4	1.55±0.25	—

Continued on next page

Table continued from previous page

ID	name	L_{IR} $10^9 L_{\odot}$	SFR $M_{\odot} \text{ yr}^{-1}$	M_{HI} $10^9 M_{\odot}$	C_{AP}	M_{H_2} $10^9 M_{\odot}$	$\frac{M_{H_2, Z-dep}}{M_{H_2, stat}}$
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
743	NGC5622	8.36±0.45	1.1±0.06	4.99±0.63	1.5	0.88±0.33	–
744	NGC5631	1.15±0.12	0.1±0.02	0.85±0.26	3.2	0.02±0.05	–
748	NGC5633	17.8±0.2	2.5±0.03	2.85±0.35	1.8	1.72±0.4*	0.7
756	NGC5665	38.05±0.17	5.5±0.03	1.84±0.24	6.9	11.46±4.54	–
759	NGC5687	0.3±0.08	0.0±0.01	–	3.9	0.1±0.07	–
777	NGC5772	15.6±0.7	2.1±0.1	6.77±0.55	1.8	1.28±0.56*	0.9
784	NGC5829	24.77±1.11	3.5±0.17	19.34±2.28	3.1	8.41±2.49*	1.5
795	NGC5930	101.3±0.23	15.5±0.04	1.06±0.33	5.7	3.97±1.67*	5.0
801	NGC5953	35.28±0.16	5.1±0.02	1.23±0.3	5.6	4.3±1.71	–
802	ARP220	1554.3±0.0	277.9±0.0	27.01±7.71	5.2	18.59±6.49	–
803	NGC5957	0.54±0.1	0.1±0.01	3.15±0.86	2.6	0.93±0.23*	0.8
844	NGC6278	1.02±0.2	0.1±0.02	0.47±0.16	3.1	<0.08±0.03	–
856	IC1256	12.76±0.63	1.7±0.09	11.16±1.25	2.5	2.25±0.59*	0.8
861	UGC10972	6.62±0.78	0.9±0.11	12.11±1.92	1.7	2.13±0.88	–
871	NGC6978	19.57±1.8	2.7±0.26	–	2.0	7.96±2.29*	1.0
874	NGC7025	12.87±1.15	1.7±0.17	3.0±0.4	1.6	<1.01±0.28	–
882	NGC7236	2.65±0.94	0.3±0.12	–	1.4	0.09±0.03	–
901	NGC7549	38.99±1.05	5.6±0.16	4.82±0.81	5.5	18.78±4.9*	0.8
904	NGC7591	177.29±1.19	27.9±0.2	23.99±3.04	1.5	13.75±3.08*	4.3
906	IC5309	11.65±0.7	1.6±0.1	2.07±0.26	1.2	1.78±0.46*	1.1
913	NGC7625	24.48±0.16	3.4±0.02	2.15±0.22	2.0	2.04±0.64*	0.8
914	NGC7631	9.14±0.68	1.2±0.1	2.89±0.37	1.4	1.09±0.28*	0.8
922	UGC12688	18.82±1.05	2.6±0.15	11.08±1.55	1.4	<1.71±0.47*	1.2
934	UGC12857	3.84±0.28	0.5±0.04	4.05±0.61	1.5	<0.23±0.06	–
939	NGC4676B	25.32±0.74	3.6±0.11	11.29±3.74	1.8	11.66±3.07*	1.4
							Concluded

5.9 The Kennicutt-Schmidt Law

The Kennicutt-Schmidt (KS) law was initially formulated by Schmidt (1959), who for the first time, assumed that star formation should be proportional to gas density. Since, SFR itself is proportional to the derivative of gas density with respect to time, by means of the above assumption, Schmidt (1959) was able to find a general correlation which is given by: $SFR \propto \rho_{gas}^n$. Subsequently, Kennicutt observationally confirmed the existence of such a relation and constrained the value of the exponent n . Expressed in terms of observable quantities (surface densities), the Kennicutt-Schmidt relation reads as shown in equation (5.38).

$$\Sigma_{SFR} = A \times \Sigma_{gas}^n \quad (5.38)$$

Kennicutt (1998) found an average exponent of $n = 1.4$ for normal *disks*. It is important to note that, Kennicutt has used the total gas density, the sum of atomic and molecular gas, whereas nowadays based on subkpc-resolved CO observations performed by Bigiel et al. (2008), it is known that the correlation is much tighter with the molecular gas component only. In that case, the relation is close to linearity with an exponent $n \approx 1$.

Furthermore, the correlation is even stronger when using dense-gas tracers like e.g. HCN, which was shown by Gao and Solomon (2004).

5.9.1 Understanding Kennicutt-Schmidt's Law Analytically

The empirical Kennicutt-Schmidt law seems to be universal, as it holds over a range of eight magnitudes in star formation – from normal galaxies to starburst galaxies. In order to explain its existence, especially Kennicutt's exponent in equation (5.38), one possible approach is to argue that stars form on a typical timescale equal to the free-fall time in the gas disk. Since the free-fall time τ_{ff} is related to the gas density through: $\tau_{ff} \propto \Sigma_{gas}^{-0.5}$ (Madore, 1977), and the star formation timescale is the inverse of the star formation *efficiency* which is given by: $SFE = \frac{1}{\tau_{ff}} = \frac{\Sigma_{SFR}}{\Sigma_{gas}}$, one finds that $\Sigma_{SFR} \propto \Sigma_{gas}^{0.5} \times \Sigma_{gas}$, which is approximately equation (5.38).

5.9.2 Kennicutt-Schmidt Law for CALIFA Galaxies

After calculating molecular masses and star formation rates, the Kennicutt-Schmidt relation can be established. For that purpose, as can be seen in formula (5.38), the star formation rate as well as the gas masses, have to be normalized to the “area” of the galaxy. This is not trivial, because how to tell where molecular gas or star formation extinguishes? Based on unresolved data, this question cannot be answered and this is another task for detailed interferometric studies. In order to get at least reasonable *averaged* surface densities, D_{25} the 25 mag arcsec⁻² isophotal (blue) diameter, can be used as a spatial limit to star formation and molecular gas content. Hence, the star formation rates and molecular masses were divided by the area which is given by $\pi D_{25}^2/4$, in order to find Σ_{SFR} and $\Sigma_{M_{H_2}}$. Unfortunately, D_{25} which was taken from the Third Reference Catalog (RC3), suffers from large uncertainties – on average around eight percent. Therefore the error bars in the diagram are increased. But at least, D_{25} from RC3 is available for almost all CALIFA galaxies.

In the case of the atomic gas, the situation is much different, because the HI disk is more extended than the optical one. Thus, another limit has to be defined. One possibility is to calculate the isophotal diameter at which the HI mass drops down to $1 M_{\odot} pc^{-2}$. This can be done by means of D_{25} , because a very tight correlation between D_{25} and the HI diameter, D_{HI} , exists. Broeils and Rhee (1997) published such a relation, which is shown in equation (5.39) and was used for further calculations.

$$\log(D_{HI}) = \log(D_{25}) + 0.23 \quad (5.39)$$

Finally, for 116 out of 160 galaxies with CO data, also HI masses could be calculated and the so gained Kennicutt-Schmidt relation for the CALIFA sample based on literature

data is presented in figure 5.15. It is expected that the slope in the KS law based on molecular surface gas density solely (fig. 5.15 top), is near unity (Bigiel et al., 2008), whereas in the “classical” KS relation (fig. 5.15 bottom) which is based on the total gas surface density, a slope between 1.29 and 2.47 (Kennicutt, 1998) – depending on the fitting method (conventional least square (LSQ) vs. bivariate regression) – would be reasonable.

It was found that the presented data’s linear regression (in log-space) fit slopes of 0.89 for the molecular gas and 1.22 for the total gas mass surface density, lie within the uncertainty limits of Bigiel’s subkpc study, who published slopes of 0.96 ± 0.07 and 1.85 ± 0.70 for the molecular- and total-gas surface densities, respectively.

Comparing the LSQ regression slope of 1.22 in the “classical” KS law as seen in the bottom panel of figure 5.15 with the Kennicutt (1998) conventional LSQ slope of 1.4, also shows that the derived result is reasonable and star formation laws indeed hold over a huge range of densities.

The result is also in good agreement with the one found by the AMIGA collaboration (Lisenfeld et al., 2011), which is not surprising due to the similarity of CALIFA’s and AMIGA’s redshift coverage and galaxy properties. The AMIGA sample consists of 173 galaxies, the presented CALIFA sample of 160 galaxies and both are dominated by galaxies of Hubble type Sb and Sc, mostly due to the higher detection rate for late type galaxies. AMIGA’s velocity range reaches from 1500 to 5000 km/s, whereas the presented sample ranges from 1500 to 8700 km/s. The reason for the offset to higher gas surface densities as can be seen in figure 5.15 is due to the inclusion of Helium into the total molecular mass for the CALIFA sample.

Furthermore, once the metallicity-dependent conversion factor is used instead of the constant one, the presented KS law is getting slightly tighter. This might indicate the importance of a more sophisticated X_{CO} derivation (e.g. through far-infrared data) for future purposes. Beside that, what is the physical origin of the large scatter? A dispersion of approximately 0.1 dex is real when investigating star formation laws by means of averaged quantities, which is not surprising when recalling that the local SFRs and gas densities span orders of magnitude within typical disks. Averaging over the entire galaxy (disk) will not necessarily preserve the form of the KS relation.

However, figure 5.16 (top) provides useful information on the average global star formation *efficiency* (SFE) in CALIFA galaxies. The dashed and dotted lines correspond to constant SFRs per unit gas mass (efficiency), in units of 1%, 10%, and 100% per 10^8 yr . The choice of 10^8 yr thereby is arbitrary, but it does correspond roughly to a typical orbital time in spiral galaxies (Kennicutt, 1998). Note that, various definitions for the SFE are commonly used, depending on considerations of total, molecular or atomic gas. Within this thesis in analogy to Leroy et al. (2008), without further notice, the SFE is calculated by means of the total gas mass. The SFE (in percent per 10^8 yr) for the presented sample

of CALIFA galaxies ranges from 0.03 to 61 % with a median (not average) value of 2.9 %. Alternatively, the efficiencies can also be expressed in terms of a gas consumption or gas depletion time, τ_{gas} . Thereby, τ_{gas} is the inverse of the recent star formation rate per unit gas mass. Hence, the dashed and dotted lines shown in figure 5.16 correspond to 10, 1, and 0.1 Gyr (bottom to top). For the CALIFA sample a median gas depletion time of 3.5 Gyr is found with a range of 321 to 0.2 Gyr.

It is important to note that these considerations do not incorporate the recycling of interstellar matter, which typically extends the actual consumption timescale by factors of 2–3 above the simple calculation (Kennicutt, 1998).

When studying figure 5.15, one can immediately conclude that the total gas does not scale *uniformly* with the star formation rate, whereas the SFR scales nearly linearly with H_2 , even where most gas is atomic.

Although only averaged (integrated) quantities are used in this analysis, for the *average* atomic gas density, a threshold similar to the one found by Bigiel et al. (2008) can be identified in figure 5.15 (middle). Thus, the threshold is ubiquitous and *independent* on the scale! The findings of Bigiel et al. (2008) who used high-resolution (≈ 1 kpc) HI data from the HI Nearby Galaxy Survey in seven spiral galaxies and 11 late-type galaxies, can be confirmed even on a much larger scale of up to several tens of kpc. Of course, the cut is not as sharp as seen in Bigiel’s resolved data. Nevertheless, it is also existent in the presented unresolved data and indicates that in the densest regions, above approximately $9 M_{\odot} pc^{-2}$ *on average* the ISM is dominated by molecular gas instead of atomic hydrogen. In other words, star formation is most effective above a certain density threshold and the threshold is a product of the changing molecular gas fraction. Hence, the second conclusion which can be drawn from the data is that the star formation threshold coincides with a atomic-to-molecular gas transition and is valid even for large scales.

Similar to Schrubba et al. (2011), a study of the recent star formation rate per unit total gas mass² was performed. In both figures, 5.16 and 5.17, the datapoints are plotted by color-weighting in dependence of the molecular gas fraction M_{H_2}/M_{HI} . Bright colors (white to yellow) and dark colors (brown to black) indicate a high and low molecular fraction, respectively. The dependence of the SFE on the molecular mass fraction, M_{H_2}/M_{HI} , is shown in the bottom panel of fig 5.16. It can be seen, that at a fixed ratio³ of SFR/H_2 , which is indicated by the three solid lines for different *molecular* gas depletion times, in galaxies with low molecular gas fractions, the SFE is most sensitive to the molecular-to-atomic gas mass ratio, hence environment, whereas in H_2 dominated galaxies with ratios $M_{H_2}/M_{HI} > 1$, the SFE approximates a value corresponding to the constant molecular depletion time.

What does this mean? First, star formation *within* giant molecular clouds (high

²SFE is equal to the inverse of the total gas depletion time

³this is reasonable as can be seen in figure 5.17

density) is mostly independent of environment, but the formation of H_2 from HI sensitively depends on local conditions (Leroy et al., 2008). Thus, another conclusion can be drawn. The SFE can be separated in two parts so that the SFE is a product of a *constant* molecular SFE_{H_2} and the molecular-to-atomic gas fraction which is a function of local conditions.

This means that the molecular gas depletion time (τ_{H_2}), accordingly the corresponding star formation efficiency is expected to be *constant*. Following this motivation, a molecular gas depletion time (accordingly SFE_{H_2}) analysis was performed which can be seen in figure 5.17. After allowing only for high quality datapoints, which have CO aperture correction factors $C_{AP} < 2$, one could reckon that the molecular gas depletion time, hence efficiency, indeed is *constant* over a huge range of parameters. The presented data suffers from large errors. Thus, more accurate derivations of the CO conversion factor by means of far-infrared, cold dust SED fits, could help to resolve this issue in the future.

For the presented sample, a mean *molecular* gas depletion time of 0.94 Gyr is found. After adopting the mean SFE⁴, published in Leroy et al. (2008) to $X_{CO} = 2.3 \times 10^{20}$ and a IMF-based star formation rate, the mean molecular gas depletion time of Leroy et al. (2008) is 1.4 Gyr. Hence, its value is increased by $\approx 67\%$ in comparison to the value found for the presented CALIFA sample. The reason is probably that Leroy et al. (2008) did not only use infrared data as a SFR tracer, but also included far-UV observations. Thus their SFR calculations differ from the one found in the present thesis systematically. And an enhanced SFR would lower the depletion time of Leroy et al. (2008).

Beside that, a constant molecular gas depletion time likely also implies or confirms that, although the local process of star formation may be ineffective, which is stated by Alves et al. (2007) in the context of a comparison between the Dense Core Mass Function (DCMF) and the Initial Mass Function (IMF), it is *uniformly* ineffective meaning that indeed a characteristic CMF similar to the IMF exists, which was found by Alves et al. (2007).

5.10 Relation of M_{H_2} to Other Parameters

In this section, some of the found correlations between molecular gas content and other parameters are presented. An overview of the tested correlations with the corresponding Spearman r-value is found in the following “correlation matrix” (see table 5.5). For a smaller sample of objects consisting of already observed and reduced CALIFA galaxies, correlations with CALIFA-based quantities, especially metallicity taken from Sánchez et al. (2013) were checked (see table 5.6). The distribution of Hubble types for both analysis samples is shown in figure 5.18. One can see that the sample is biased to late

⁴accordingly molecular gas depletion time

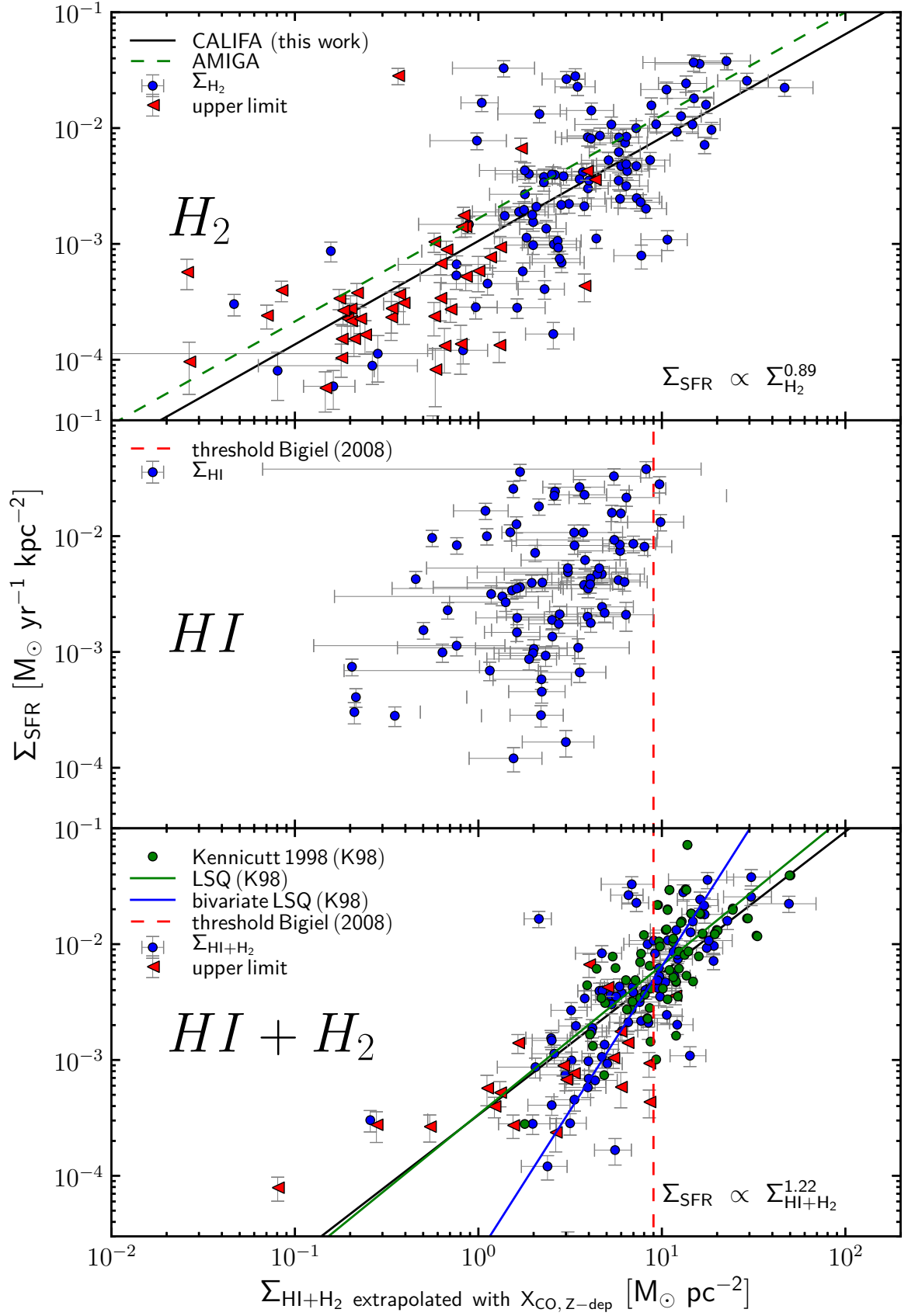


Figure 5.15: Kennicutt Schmidt law for CALIFA galaxies. Average surface densities of the molecular gas (top), the atomic gas (middle) and the total gas (bottom) versus the averaged star formation density for CALIFA galaxies.

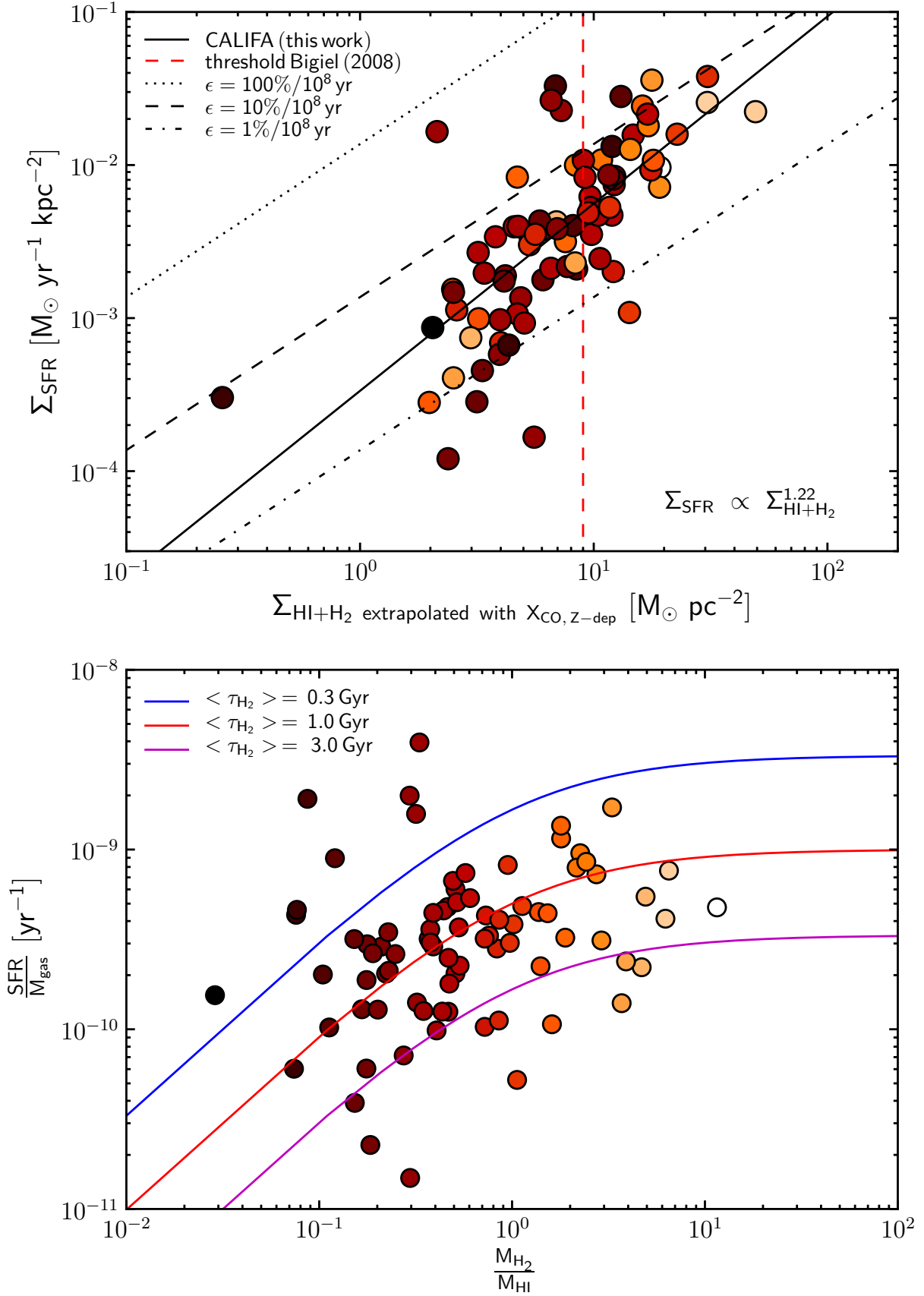


Figure 5.16: Star formation analysis of CALIFA galaxies. The “classical” KS law found for the CALIFA sample is shown in the top panel. SFE is indicated by the dotted/dashed lines corresponding to 1, 10 and 100 % gas consumption in 10^8 yr . The bottom panel shows the dependence of the recent SF on the molecular gas fraction. Curves show the recent SF for *constant* SFR/H_2 ratios. 84

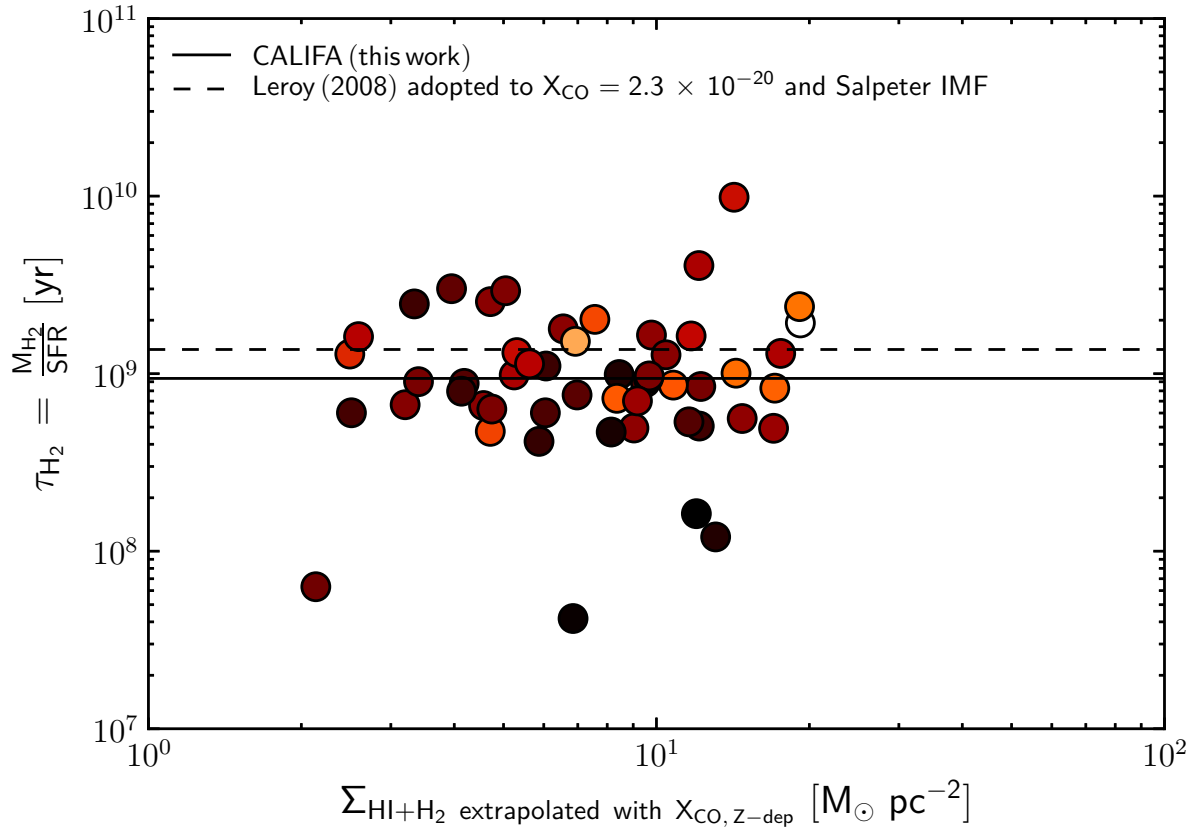
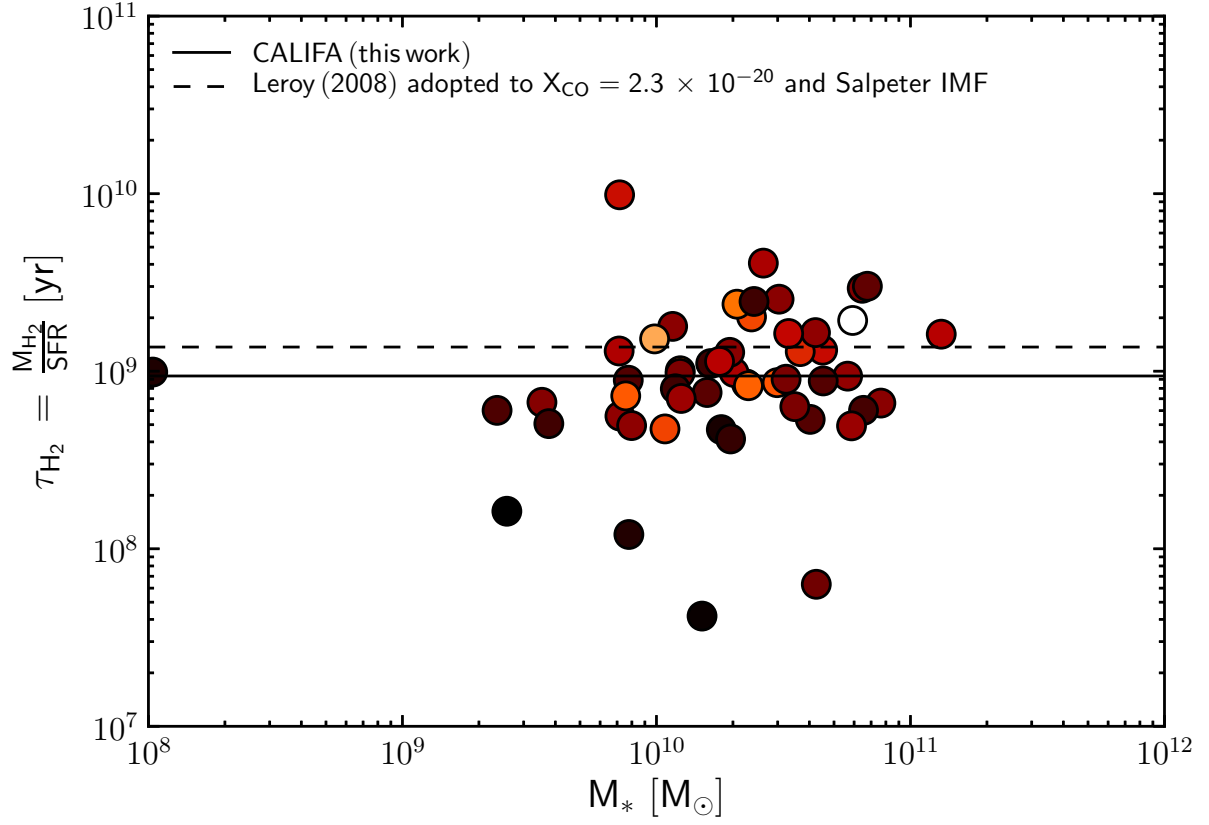


Figure 5.17: Star formation efficiency analysis of CALIFA galaxies.

type galaxies with a clear majority of Sb-types.

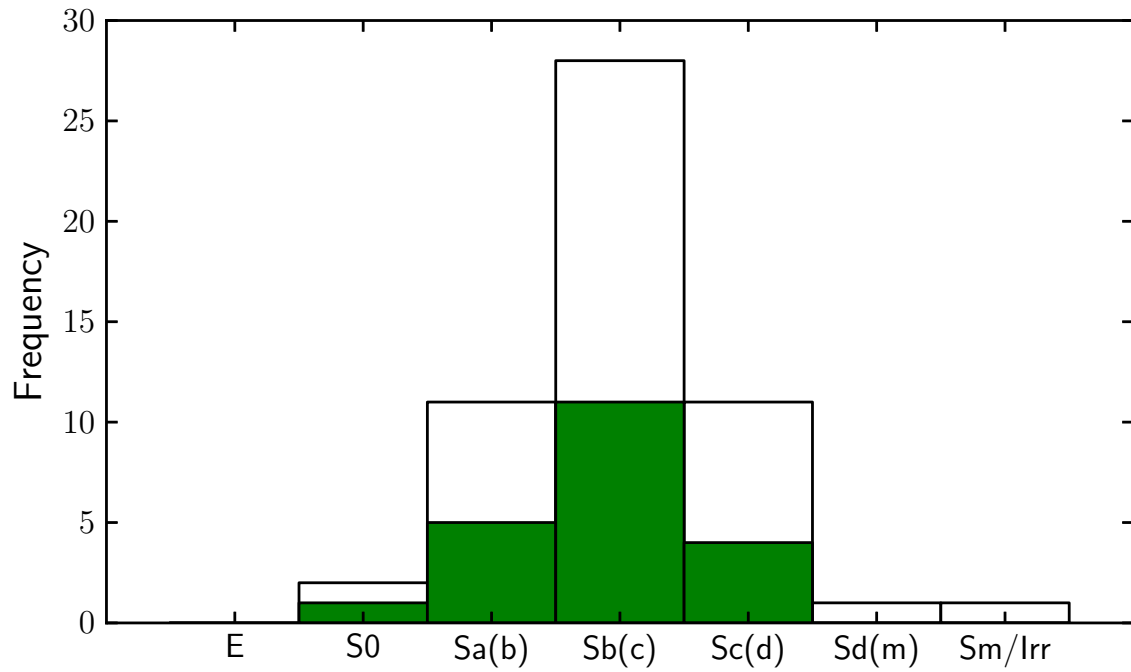


Figure 5.18: Hubble type distribution in the two available analysis samples. The fraction of galaxies with CALIFA data available is indicated by the green, filled area.

All CO data sample																
	M_*	M_{gas}	L_K	M_{H_2}	M_{HI}	$\frac{M_{\text{H}_2}}{M_{\text{HI}}}$	$\frac{M_{\text{H}_2}}{M_*}$	$\frac{M_{\text{H}_2}}{L_K}$	$\Sigma_{M_{\text{H}_2}}$	Σ_{SFR}	sSFR	SFR	SFE	$\frac{\text{SFR}}{M_{\text{H}_2}}$	D_{25}	D_e
M_*		0.5	0.9	0.57	0.39	0.18	-0.36	-0.11	-0.1	-0.23	-0.5	0.44	0.34	0.18	0.72	0.62
M_{gas}	0.5		0.71	0.84	0.89	-0.04	0.4	0.47	0.01	-0.18	0.07	0.62	0.4	0.23	0.81	0.8
L_K	0.9	0.71		0.76	0.55	0.22	-0.08	0.08	-0.03	-0.21	-0.27	0.61	0.41	0.2	0.86	0.78
M_{H_2}	0.57	0.84	0.76		0.56	0.46	0.46	0.66	0.35	-0.12	-0.02	0.6	0.28	0.04	0.72	0.69
M_{HI}	0.39	0.89	0.55	0.56		-0.4	0.22	0.21	-0.28	-0.26	0.06	0.48	0.46	0.36	0.76	0.76
$\frac{M_{\text{H}_2}}{M_{\text{HI}}}$	0.18	-0.04	0.22	0.46	-0.4		0.19	0.5	0.67	0.09	-0.19	0.07	-0.13	-0.31	0.0	-0.05
$\frac{M_{\text{H}_2}}{M_*}$	-0.36	0.4	-0.08	0.46	0.22	0.19		0.82	0.45	0.14	0.6	0.23	-0.11	-0.16	0.02	0.16
$\frac{M_{\text{H}_2}}{L_K}$	-0.11	0.47	0.08	0.66	0.21	0.5	0.82		0.63	0.13	0.3	0.28	-0.02	-0.21	0.12	0.2
$\Sigma_{M_{\text{H}_2}}$	-0.1	0.01	-0.03	0.35	-0.28	0.67	0.45	0.63		0.47	0.19	0.18	-0.1	-0.27	-0.3	-0.16
Σ_{SFR}	-0.23	-0.18	-0.21	-0.12	-0.26	0.09	0.14	0.13	0.47		0.66	0.49	-0.06	-0.07	-0.47	-0.4
sSFR	-0.5	0.07	-0.27	-0.02	0.06	-0.19	0.6	0.3	0.19	0.66		0.49	-0.08	0.0	-0.23	-0.13
SFR	0.44	0.62	0.61	0.6	0.48	0.07	0.23	0.28	0.18	0.49	0.49		0.34	0.21	0.48	0.49
SFE	0.34	0.4	0.41	0.28	0.46	-0.13	-0.11	-0.02	-0.1	-0.06	-0.08	0.34		0.88	0.4	0.42
$\frac{\text{SFR}}{M_{\text{H}_2}}$	0.18	0.23	0.2	0.04	0.36	-0.31	-0.16	-0.21	-0.27	-0.07	0.0	0.21	0.88		0.26	0.31
D_{25}	0.72	0.81	0.86	0.72	0.76	0.0	0.02	0.12	-0.3	-0.47	-0.23	0.48	0.4	0.26		0.88
D_e	0.62	0.8	0.78	0.69	0.76	-0.05	0.16	0.2	-0.16	-0.4	-0.13	0.49	0.42	0.31	0.88	

Table 5.5: Correlation matrix for the CO data sample with $C_{AP} < 2$ and excluding upper limits.

CO data sample with CALIFA analysis available														
	M_*	M_{gas}	M_{H_2}	M_{HI}	$\frac{M_{\text{H}_2}}{M_{\text{HI}}}$	$\frac{M_{\text{H}_2}}{M_*}$	Σ_{H_2}	Σ_{SFR}	sSFR	SFR	SFE	$\frac{\text{SFR}}{M_{\text{H}_2}}$	$12 + \log\left[\frac{\text{O}}{\text{H}}\right]$	$\Delta(\text{B} - \text{V})$
M_*		0.41	0.33	0.18	0.02	-0.34	-0.23	0.26	-0.04	0.63	0.07	0.49	0.17	-0.49
M_{gas}	0.41		0.85	0.68	0.26	0.53	-0.23	0.01	0.41	0.64	0.11	-0.05	-0.22	-0.41
M_{H_2}	0.33	0.85		0.28	0.69	0.71	0.07	0.26	0.6	0.72	0.12	-0.07	-0.39	-0.57
M_{HI}	0.18	0.68	0.28		-0.43	0.07	-0.4	-0.4	-0.01	0.15	0.06	-0.07	0.06	-0.08
$\frac{M_{\text{H}_2}}{M_{\text{HI}}}$	0.02	0.26	0.69	-0.43		0.67	0.41	0.48	0.61	0.48	0.12	-0.05	-0.5	-0.39
$\frac{M_{\text{H}_2}}{M_*}$	-0.34	0.53	0.71	0.07	0.67		0.25	0.05	0.54	0.21	0.05	-0.47	-0.6	-0.17
Σ_{H_2}	-0.23	-0.23	0.07	-0.4	0.41	0.25		0.34	0.11	-0.11	0.01	-0.13	-0.16	-0.33
Σ_{SFR}	0.26	0.01	0.26	-0.4	0.48	0.05	0.34		0.66	0.63	0.26	0.68	0.01	-0.34
sSFR	-0.04	0.41	0.6	-0.01	0.61	0.54	0.11	0.66		0.71	0.42	0.39	-0.21	-0.14
SFR	0.63	0.64	0.72	0.15	0.48	0.21	-0.11	0.63	0.71		0.38	0.54	-0.03	-0.41
SFE	0.07	0.11	0.12	0.06	0.12	0.05	0.01	0.26	0.42	0.38		0.38	0.18	0.01
$\frac{\text{SFR}}{M_{\text{H}_2}}$	0.49	-0.05	-0.07	-0.07	-0.05	-0.47	-0.13	0.68	0.39	0.54	0.38		0.32	-0.14
$12 + \log\left[\frac{\text{O}}{\text{H}}\right]$	0.17	-0.22	-0.39	0.06	-0.5	-0.6	-0.16	0.01	-0.21	-0.03	0.18	0.32		-0.03
$\Delta(\text{B} - \text{V})$	-0.49	-0.41	-0.57	-0.08	-0.39	-0.17	-0.33	-0.34	-0.14	-0.41	0.01	-0.14	-0.03	

Table 5.6: Correlation matrix for the CO data sample with CALIFA analysis available and excluding upper limits.

5.10.1 Optical Diameters and the K-band Luminosity

As can be seen in the correlation matrix and in figure 5.19 (top), a very strong correlation ($r=0.9$) exists between the luminosity in the K-band, L_K , and the total stellar mass. Thus, the K-band luminosity can be even used as a tracer for the stellar mass. The relation is due to the K-band's sensitivity to the *old* stellar component. Therefore the mass-to-light ratio varies only slightly with the age or star formation history of a galaxy. On the other side, that is why the K-band is less sensitive to the SFR ($r=0.61$).

Furthermore in figure 5.19 (middle) one can see that also a good correlation between the molecular gas mass and the K-band luminosity ($r=0.76$) exists. That may result from the dominant role played by the stellar disk in setting the midplane-pressure or, equivalently, the local density of the atomic gas (Leroy et al., 2005), from which subsequently H_2 is formed. On the other side, no good correlation exists between L_K and the atomic gas. This is, because the gas pressure gradient – accordingly the corresponding pressure force – and *not* the stellar content sets mostly the atomic gas extent.

The correlation of the molecular gas mass to the total stellar mass is only poor ($r=0.57$). This might be, because the recently formed, short-living, young, massive stars, do not play a major role in setting a stabilized long-lasting midplane-pressure, although due to other effects, e.g. feedback, they certainly influence the *local* process of H_2 formation.

The optical blue $25\text{ mag arcsec}^{-2}$ isophotal diameter, D_{25} , and the diameter D_e at which the luminosity in the SDSS r-band falls down to $1/e$ compared to the central peak brightness, show a tight correlation ($r=0.88$). This is not surprising as both trace the stellar disk extent. Hence, the correlation parameters between the various gas masses and either D_{25} or D_e are similar, although slightly tighter with D_{25} . Among the gas masses, the best correlation ($r=0.81$) to D_{25} is found with the total ($HI+H_2$) mass, in comparison to HI and H_2 with $r=0.76$ and $r=0.72$, respectively. See figure 5.20 top to bottom panel. The origin of the found relation is that the presented sample mostly consists of spirals of the same Hubble type. Thus, all galaxies have similar light profiles. The findings are in agreement with Lisenfeld et al. (2011).

5.10.2 Infrared Luminosity

Due to the direct relation of both, the molecular gas and the infrared luminosity to star formation, a relatively tight correlation between L_{IR} and L_{CO} is expected. Thereby, L_{CO} is the tracer for the molecular gas needed as fuel for star formation, and L_{IR} is the tracer of the recently formed stars due to heating of the dust as explained in section 5.1. In principal, this relation forms the basis of the Kennicutt-Schmidt star formation law, but without taking into account surface densities and CO-to- H_2 conversions. Hence, it is a tool

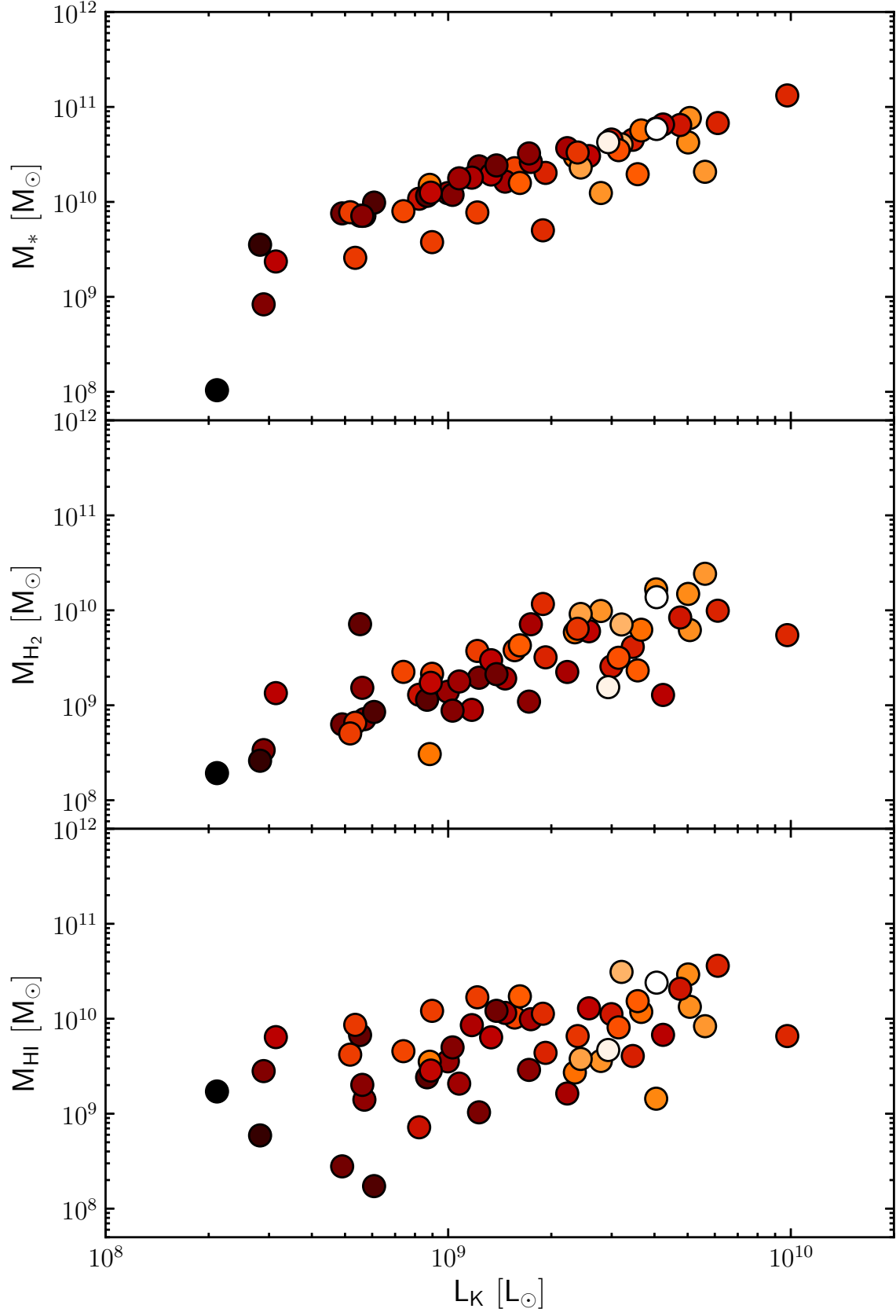


Figure 5.19: Correlation of L_K to M_* (top), M_{H_2} (middle) and M_{HI} (bottom).

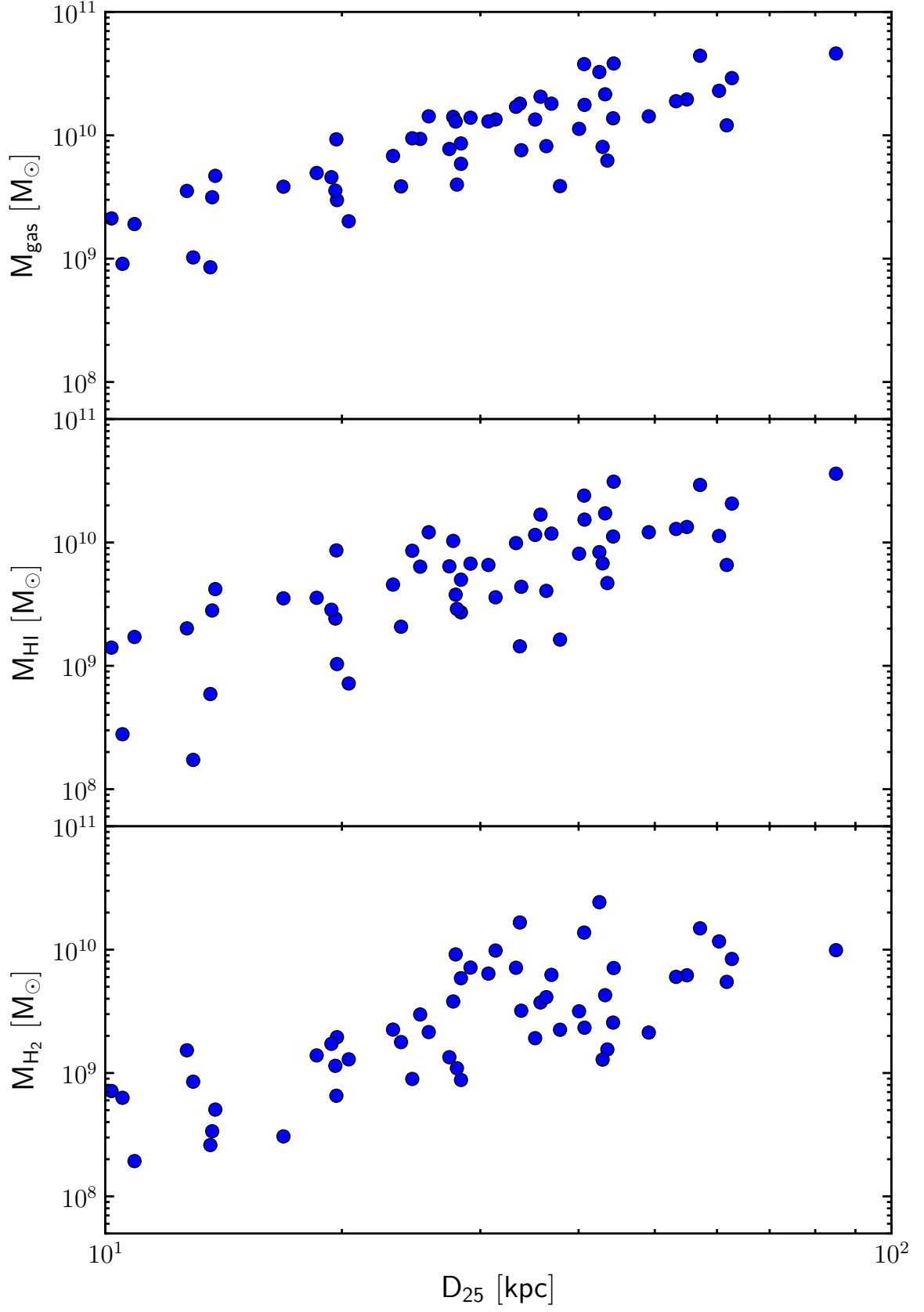


Figure 5.20: Blue isophotal diameter D_{25} vs. gas masses.

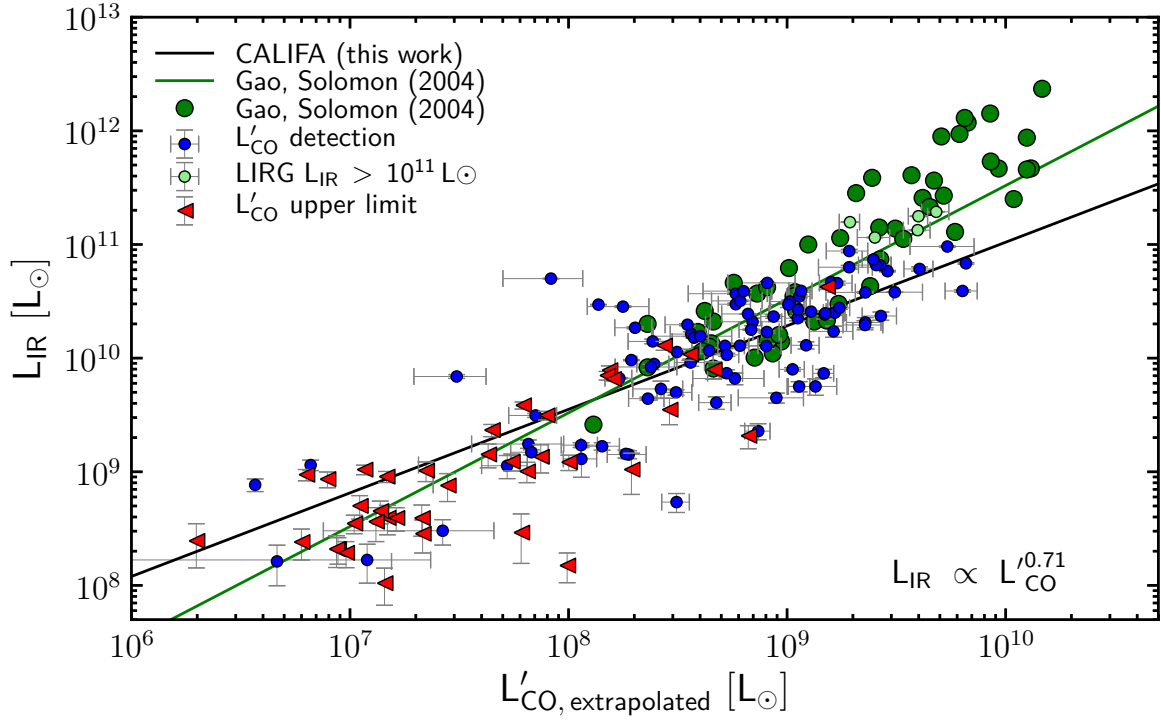


Figure 5.21: CO-IR relation for CALIFA galaxies

mostly used in high redshift studies (Greve et al. 2005, Iono et al. 2009, Genzel et al. 2010, Bothwell et al. 2013), when galaxies cannot be resolved and derivation of the conversion factor is dubious. Therefore, the underlying molecular transition's energy level (e.g. CO J=1-0) is important and one must care about the transition when comparing CO-IR relations. Gao and Solomon (2004) reported a unity slope for their unresolved galaxy sample and the CO J=1-0 transition. Consistent with that finding and the predicted scatter (Narayanan et al., 2008) of the relation, Iono et al. (2009), Genzel et al. (2010), Bothwell et al. 2013 and Daddi et al. (2010) found slopes of 1.10, 1.15, 1.20 and 1.31 for the relation using low-energy CO transitions. Narayanan et al. (2008) derived a physical model for the observed relation by combining 3D non-LTE radiative transfer calculations with hydrodynamic simulations of isolated disk galaxies and was able to confirm the observed quantities.

The relation found for the presented sample of CALIFA galaxies, is shown in figure 5.21. The slope of the presented sample of 0.71 is low compared to the model predictions, but lies within the expected scatter of ≈ 0.3 (Narayanan et al., 2008) for the CO J=1-0 transition. Also values and the unity slope fit from Gao and Solomon (2004) are indicated. As can be seen, the findings are in good agreement with the former study.

5.10.3 Metallicity

As noted by various authors (Bothwell et al., 2013), a fundamental relation between the molecular gas or star formation and stellar mass and metallicity (Z) should exist. Due to the currently limited size of the galaxy sample with metallicity measurements available, a deeper look into the topic cannot be performed. Nevertheless, the data was checked for some basic relations between the molecular mass and metallicity anyway. Table 5.6 already indicates that none of the given parameters correlates well with metallicity. The best correlations found are with the ratios of M_{H_2}/M_* and M_{H_2}/M_{HI} . In the top and middle panel of figure 5.22 the corresponding data is shown. The correlation parameters are $r=-0.6$ and $r=-0.5$. The datapoints are color-coded by means of the logarithmic star formation rate. Bright colors (white to yellow) and dark colors (brown to black) indicate a high and low SFR, respectively. In the bottom panel, which shows hardly any ($r=-0.39$) correlation between the molecular gas mass and the metallicity, at least the positive relation between the SFR and the molecular mass can be identified by the color gradient from low molecular mass to high molecular mass.

The origin of the tentative negative correlation between metallicity and M_{H_2}/M_* is basically the fundamental *mass-metallicity relation*. Since Z increases with the stellar mass, and on the other hand M_{H_2} does not show any dependence of the heavy metal content, the ratio of M_{H_2}/M_* is expected to decrease with Z , which is exactly what can be seen in the top panel of figure 5.22.

Table 5.6 shows a very weak and negative correlation of the molecular gas fraction with metallicity. When looking onto the data in the mid panel of figure 5.22, one can already suspect that this might be spurious due to “low-number-statistics”. A negative correlation seems not feasible in the context of *galaxy evolution*, because Z actually is an age indicator. Metal-poor galaxies typically have huge amounts of HI gas and lower molecular gas fractions. Later on, due to evolution, the atomic gas is consumed by the process of star formation, but the molecular gas fraction even increases. Thus, I expect the correlation parameter approaching zero, once having more data available.

5.11 ISM Pressure Analysis Based on Gas and Stellar Dynamics

Beside the CO luminosities, also CO line-widths were found in the archive. Although they depend on inclination and turbulences in the ISM (e.g. cloud-cloud collisions), at least in edge-on galaxies, the reported line-widths should be – to first order – a measure of the galaxy’s molecular gas rotation, if the ISM is not *dominated* by perturbation. A subsample of CALIFA galaxies was defined for such an analysis. Details on the target

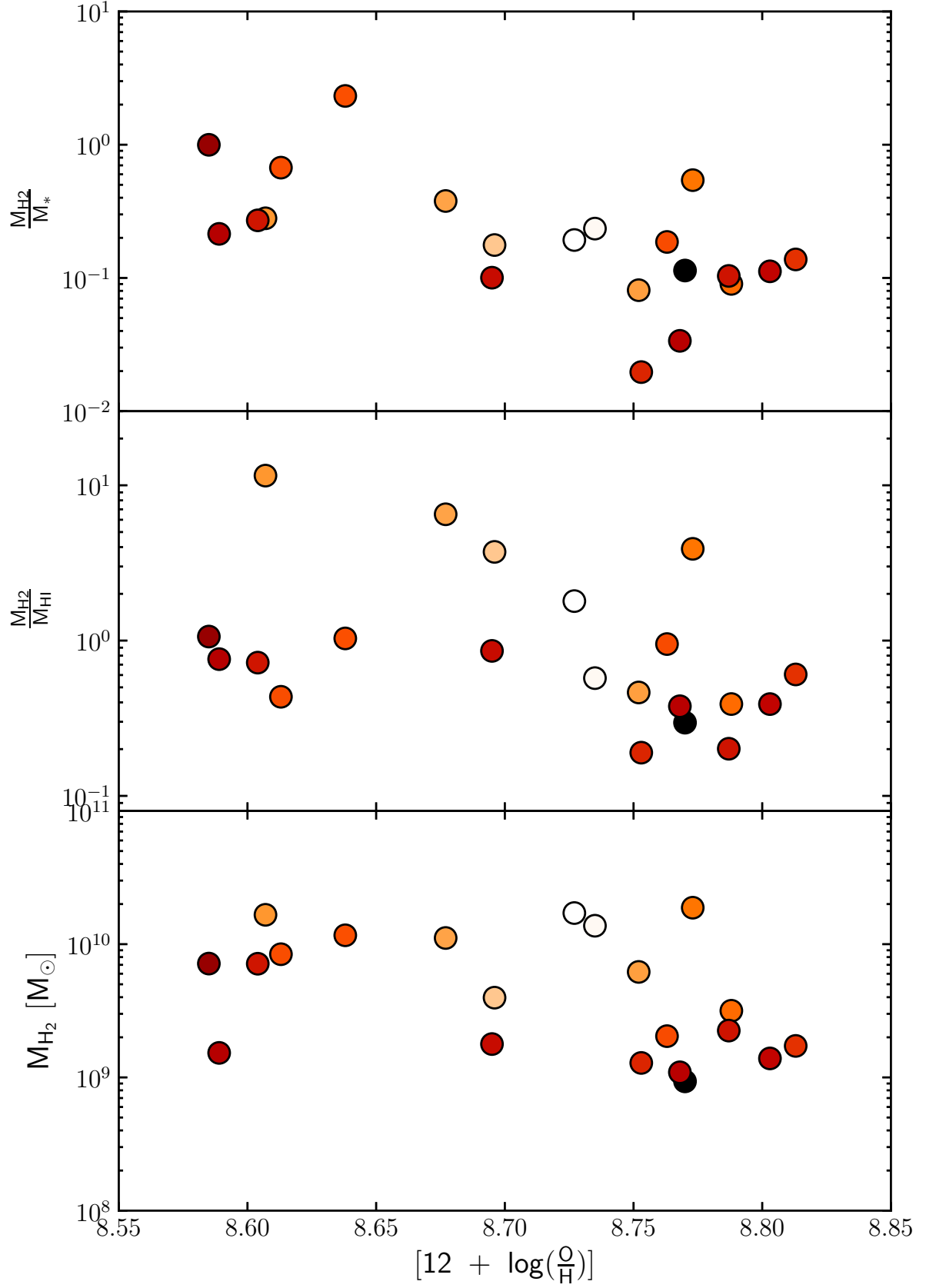


Figure 5.22: Correlations with metallicity for those CALIFA galaxies with $[\text{O}/\text{H}]$ ratios available from Sánchez et al. (2013).

selection are found in table 5.7.

For a set of a few CALIFA galaxies, for which rotation curve analysis were already performed by Mariya Lyubenova and Glenn van de Ven (see figure 5.23), the maximum circular rotation velocity of the stars and the CO line-widths at the zero level (FWZI) were compared in order to derive a first quantization of the pressure in the ISM. In fact, a correlation between such a pressure quantization and the star formation rate is expected, when assuming that star formation is more efficient in regions of higher density, accordingly pressure.

What is the physical principle of such a quantization of the ISM pressure? Basically it's due to the pressure gradient, accordingly the pressure force, that only acts onto the gas component and not onto the stars. Hence, the gas exhibits a higher equilibrium velocity than the stellar component.

The rotational, equilibrium velocity of the stars, can be easily found when equalizing the gravitational force F_G and the centrifugal force F_Z . Then the star's velocity at the galactical radius r is found to be:

$$v_{stars}^2 = \frac{G M(r)}{r} \quad (5.40)$$

On the contrary, the gas component within a galaxy also perceives a pressure force F_P , originating from the pressure gradient due to the density profile $\rho(r)$ within the disk. Thus the force equilibrium is given by: $F_G = F_Z + F_G$, which can be written as:

$$\frac{G M(r)}{r^2} = \frac{v_{gas}^2}{r} - \frac{1}{\rho} \nabla P \quad (5.41)$$

Note the minus sign, which is needed, because the pressure gradient ∇P is negative along the radius r with the origin in the galaxy's center. The pressure force itself acts against the gradient, outwards from the galactic center. After re-writing equation (5.41), one can find:

$$(v_{gas}^2 - v_{stars}^2) \frac{\rho}{r} = \nabla P \quad (5.42)$$

$$dP = (v_{gas}^2 - v_{stars}^2) \frac{\rho}{r} dr \quad (5.43)$$

$$\int_0^{P_e} dP = \int_0^{R_e} (v_{gas}^2 - v_{stars}^2) \rho \frac{1}{r} dr \quad (5.44)$$

For the sake of simplicity, now I am assuming a flat rotation curve (RC) and a homogeneous gas distribution with $\rho = 1$ to find:

$$P_e = (v_{gas}^2 - v_{stars}^2) \rho \ln(R_e) \quad (5.45)$$

$$P \propto (v_{gas}^2 - v_{stars}^2) \ln(R_e) \quad (5.46)$$

ID	Name	Σ_{SFR} [$10^{-3} M_{\odot} yr^{-1} pc^{-2}$]	RC	$\Delta V_{CO,1-0}$ [km/s] (FWZI)	note on spectrum
152	UGC03944	1.1	*	567	not published
186	IC2247	3.6	*	477	3 peaks
611	NGC5016				
742	NGC5610				
748	NGC5633	8.3	*	290	Horn profile+3rd bump
904	NGC7591	21.5	*	438	4 peaks
906	IC5309				
914	NGC7631				

Table 5.7: Definition of the kinematic analysis sample. An asterisk (*) in column (RC) marks the galaxies for which Mariya Lyubenova already derived rotation curves.

Thus, one can see that the difference in velocity between the stars and the gas, indeed should lead to a quantization of the ISM pressure. Furthermore a correlation to the star formation rate could be expected.

5.11.1 ISM Pressure Analysis for a Set of CALIFA Galaxies

In order to allow for an ISM pressure analysis as described before, some CALIFA galaxies were selected by means of the following constraints:

- Observed within CALIFA until July, 11th 2013
- Observed in CO with a S/N ratio better than 5
- Inclination $i < 0.6$
- The half-power beam-diameter of the CO observation is at least as big as the galaxy's half light diameter

The resulting set of CALIFA galaxies contains only eight galaxies, from which four were already analyzed by Mariya Lyubenova, who kindly provided the rotation curves shown in figure 5.23. The four galaxies used for further analysis are indicated by an asterisk (*) in the (RC) column of table 5.7. As can be already noticed from table 5.7 and figure 5.23, no relation between the star-gas velocity difference and the SFR – indicated as average surface density – can be found. In fact, the CO line-widths (FWZI) indicate

much higher gas velocities compared to the stellar rotation. Thus, I assume that the presented sample of only four galaxies, has a highly disturbed molecular gas component, which seems feasible considering the CO line shapes. As given in table 5.7, three of the CO spectra already show multiple kinematic components. Only in one case, NGC5633, the profile is similar to a “Horn” which is a good indication for more relaxed gas and a flat rotation curve. Interestingly, in that case, the derived gas velocity is much closer to the stellar one, which seems to be reasonable.

Thus, for future studies, a bigger sample of edge-on galaxies with “Horn” shaped CO profiles would be needed, in order to derive and quantify ISM pressure.

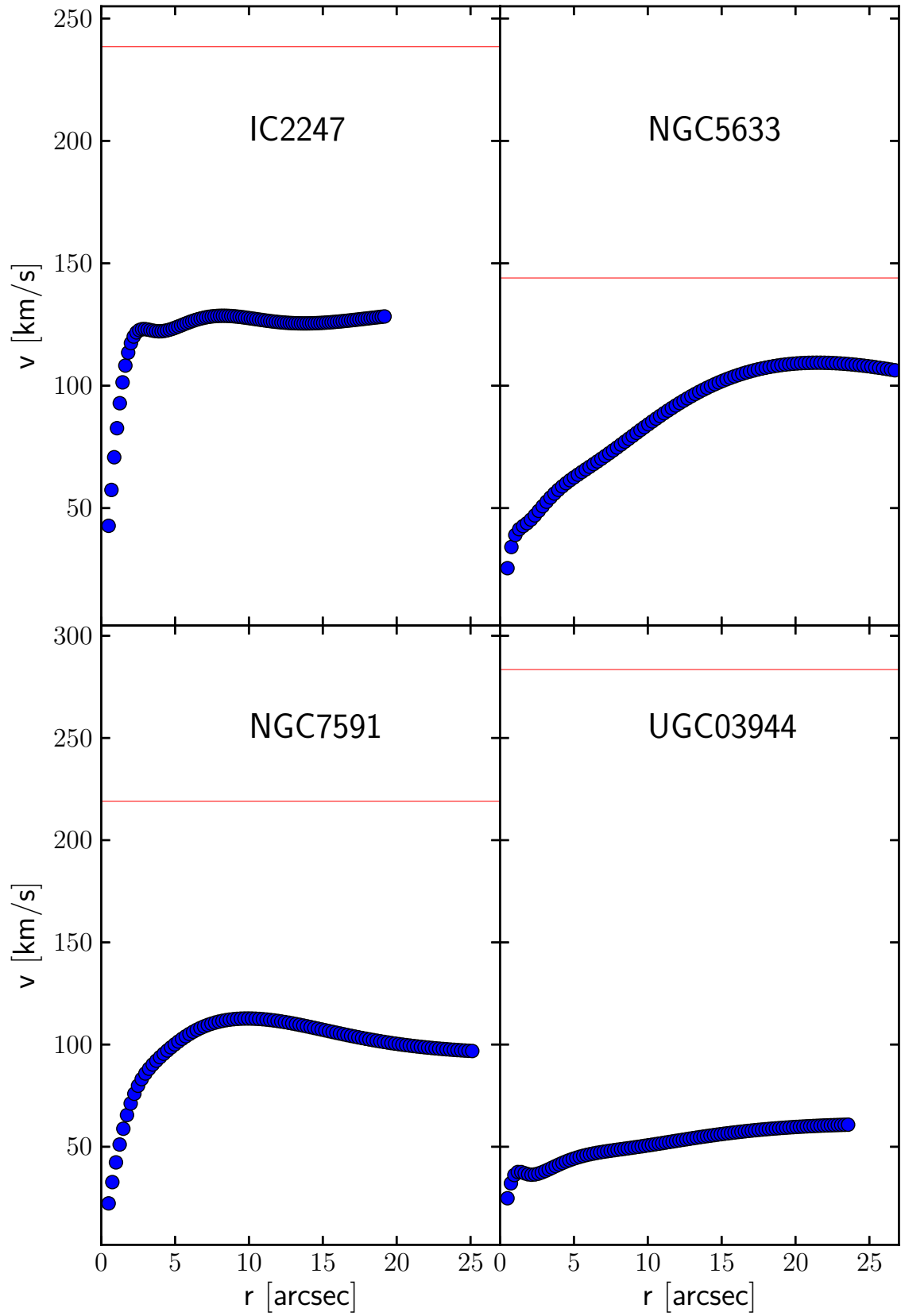


Figure 5.23: Rotation Curves of selected CALIFA galaxies. The red horizontal lines indicate the CO FWZI line-widths measured within a beam of 45–55 arcsec.

Chapter 6

Molecular and Ionized Gas in NGC2623

The number of interferometers capable of observing in the sub-millimeter domain is still limited. But the need for such facilities is high, because only with interferometers like ALMA, PdBI or the Submillimeter Array (SMA) resolutions in the one arcsecond range can be achieved. Thus, in order to compare cold, molecular gas data to the optical IFU data from CALIFA with a spacial resolution of two arcsec, interferometry becomes inevitable.

In principle, an interferometer measures the interference pattern produced by two or more apertures. Due to the *van Cittert Zernike* theorem, the measured interference pattern itself is related to the source brightness! It is said that the so called “visibility” $V(u,v)$ (also: uv-plane) is the 2D Fourier transform of the brightness on the sky (xy- or image-plane). Hence, in principle, the *inverse* Fourier transform has to be applied to the measured signal in order to get spacial information of the source’s brightness.

Unfortunately due to the limited (infinite) coverage of the uv-plane and the fact that the measured quantities are “dirty” due to beam effects, beside inversion, also cleaning has to be performed on the data. In the following, the used software, the data and the major calibration and imaging steps are described.

6.1 Interferometric Data Reduction with MIRIAD

MIRIAD (Multichannel Image Reconstruction, Image Analysis and Display) is mainly written in Fortran 77 and was originally developed by Bob Sault in 1987 on Sun workstations (SUN OS 3.2), but since then it has been ported to a large number of UNIX flavors (Teuben (2008)). It is a utility box including an environment for interferometric data reduction. The original release of MIRIAD is used for the reduction of BIMA and CARMA data, but there is also an own MIRIAD release for SMA available which was used within this

thesis. The software can be downloaded at <http://www.cfa.harvard.edu/sma/miriad/>.

There are two ways in handling MIRIAD. The first method makes use of the included MIRIAD shell which is started simply by typing "miriad" on any Linux terminal. When using the shell, one has to select the task to run, inspect and set its parameters, and run the task. The process is similar to IRAF.

The second method is to execute any MIRIAD task directly from any Linux shell. In that case, all MIRIAD programs need a supply of "keyword=value" pairs on the command line. The advantage is that shell scripts can be used in the future for an automatic analysis of similar data. This is what I have made use of. The whole data reduction script, can be found in the appendix. In the following, the main steps of interferometric data reduction, namely: bandpass correction, phase calibration, amplitude calibration, data inspection and bad data flagging, as well as the imaging process will be discussed.

6.1.1 SMA Data of NGC2623

For the target of interest, NGC2623, there is archival SMA (Submillimeter Array) data available, which was downloaded through the official SMA website at <http://www.cfa.harvard.edu/cgi-bin/sma/smaarch.pl>. The observations were led by Christine Wilson and executed in the years 2006 and 2007 for the CO J=2-1 and the CO J=3-2 transition respectively. Hence, the CO data is already published by Wilson et al. (2008), but this thesis' aim is to *compare* the molecular gas to the ionized gas component ($H\alpha$) which was derived from CALIFA data. To do so, the raw CO J=3-2 data was reduced again. Note that the CO J=3-2 images are of better quality and resolution compared to the CO J=2-1 transition due to better weather conditions during observations.

The resulting spatial resolution of approximately 1 arcsec is even better than CALIFA's resolution and corresponds to a linear size of ≈ 400 pc. Thus, the beam corresponds to the size of 2-3 giant molecular clouds. The SMA's primary beam at this frequency is $\approx 40 \times 40$ arcsec.

6.1.2 Calibration

The whole process of calibration and data reduction was executed as described in the "MIRIAD Users Guide for SMA" which was written by Zhao (2012). For the calibration, also a very helpful script which was kindly provided by Wei-Hao Wang was used as a starting point. The block diagram shown in figure 6.1-6.3 was taken from Zhao (2005) and gives an extended overview of all available tasks of the SMA MIRIAD package. Note that, depending on the needs and aims, not all of these tasks are essential. The initial bandpass and gain calibration were performed through the standard SMA calibration script for handling single 340GHz Rx DB data. The script can be downloaded from <http://>

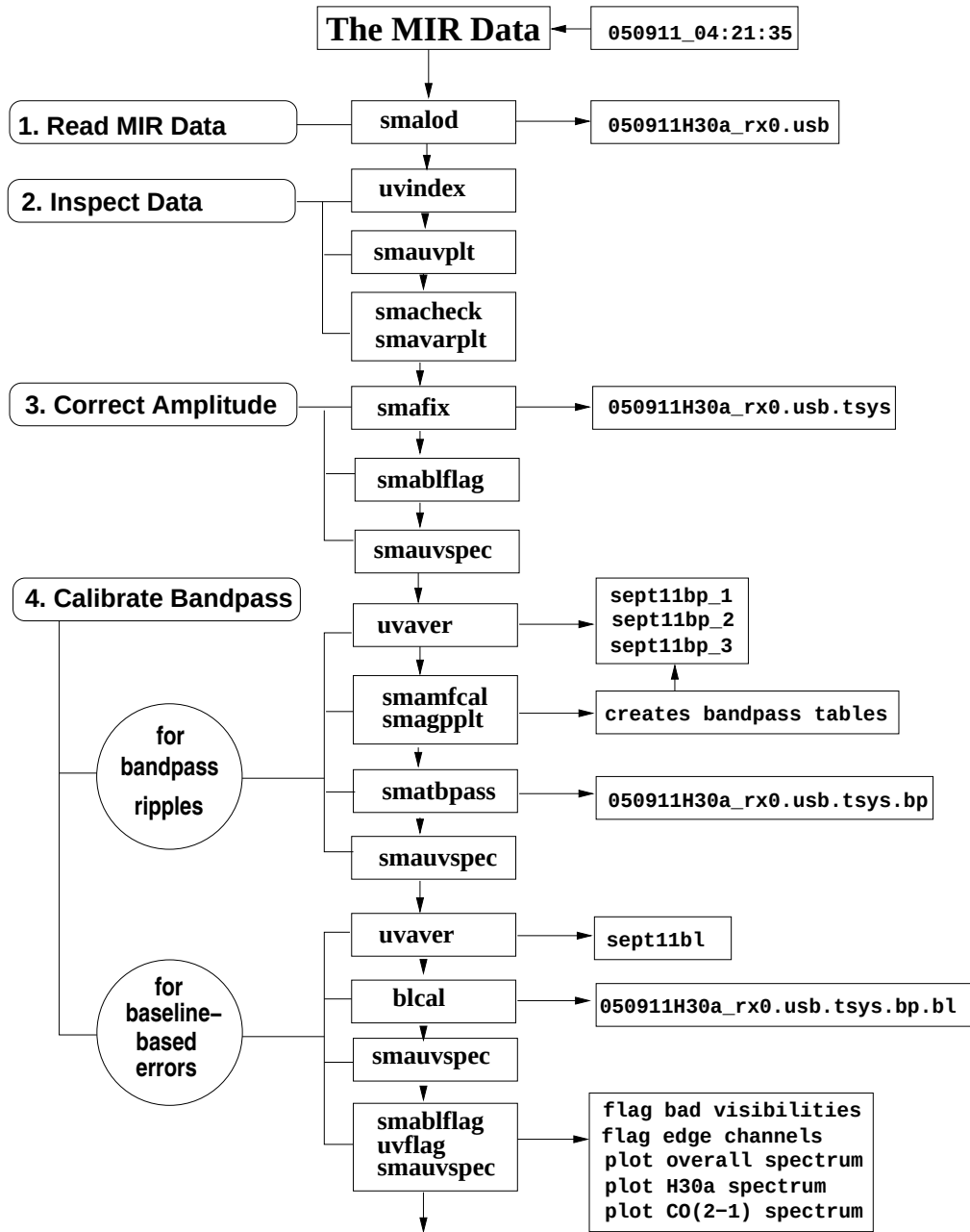


Figure 6.1: Overview of tasks available in the SMA MIRIAD package (Zhao, 2005)

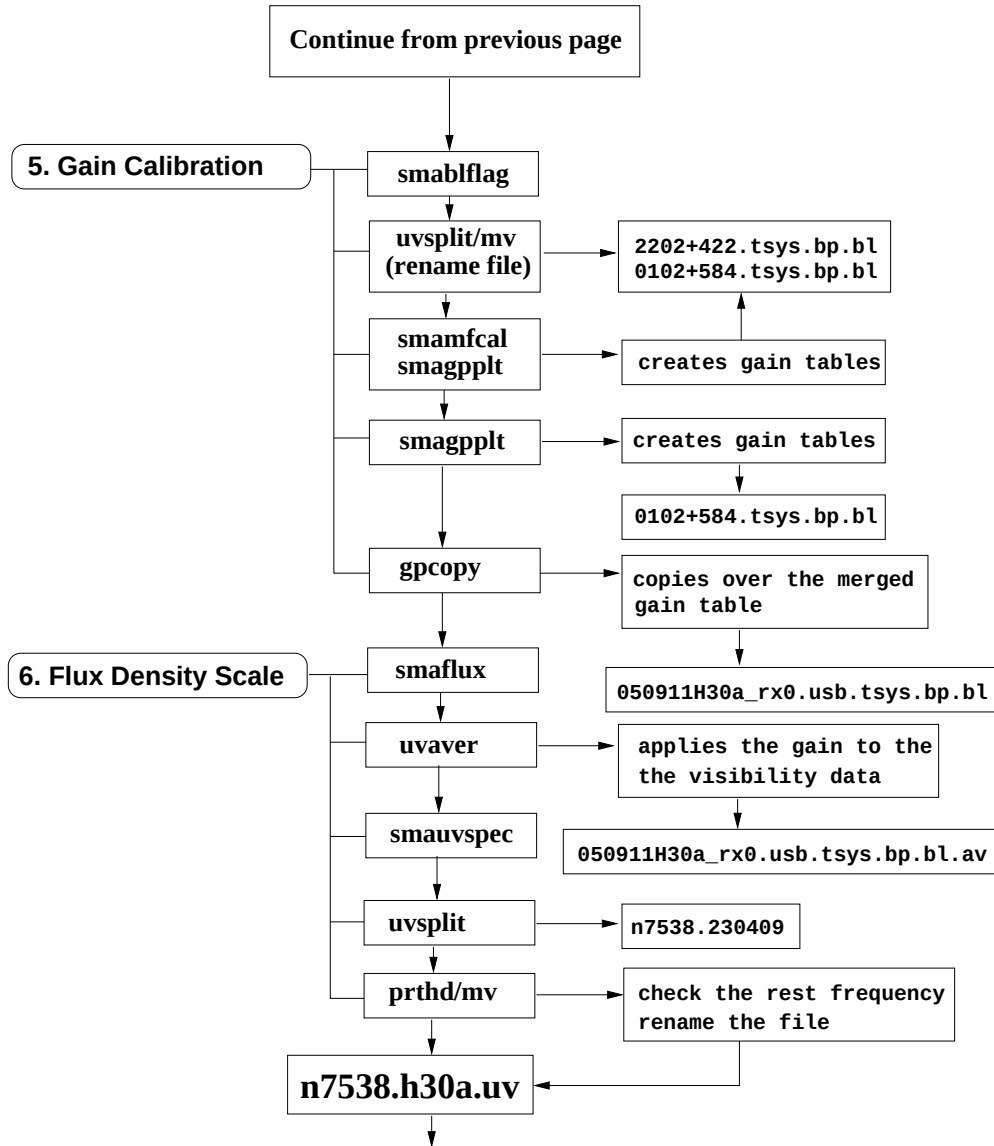


Figure 6.2: Overview of tasks available in the SMA MIRIAD package (Zhao, 2005)

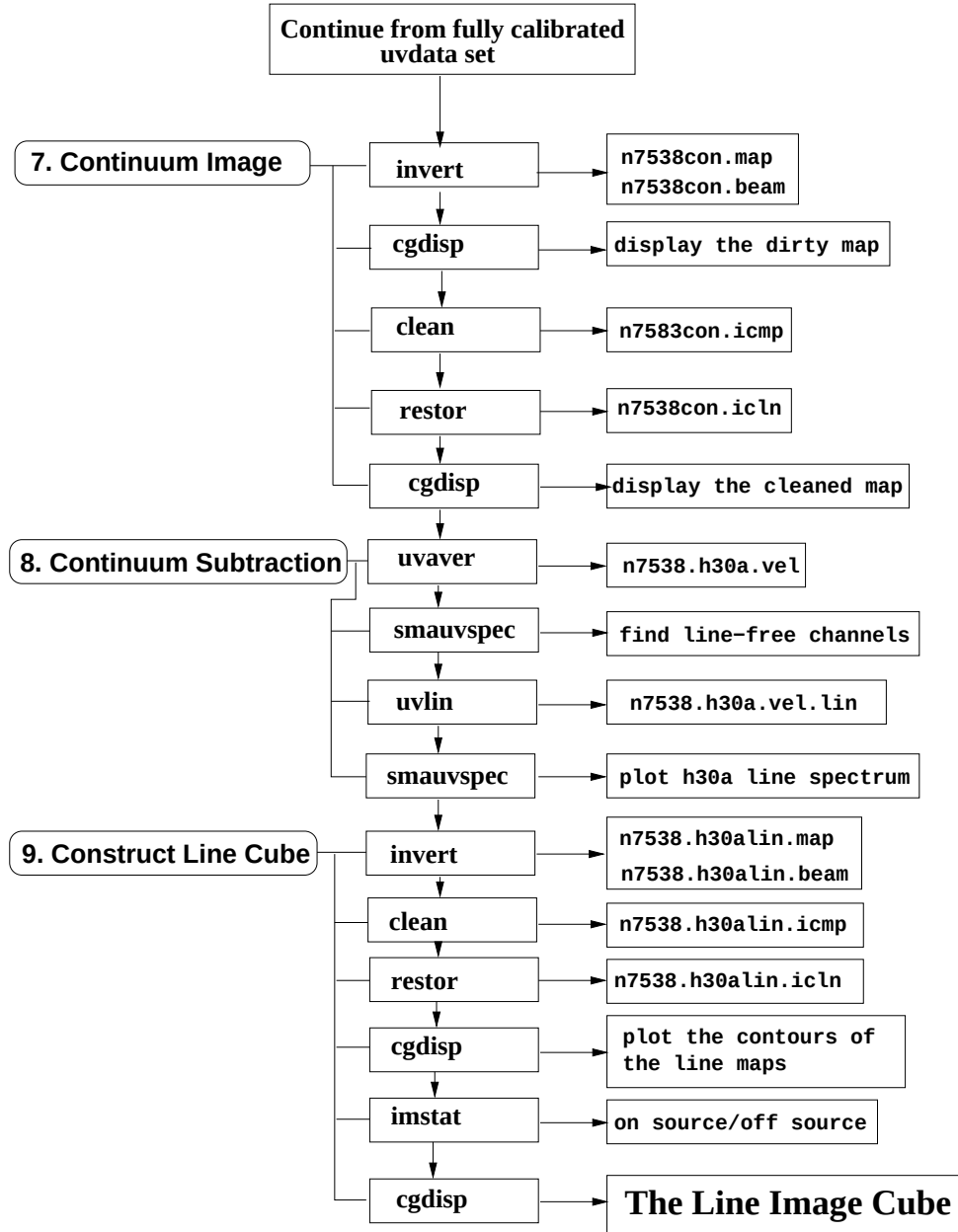


Figure 6.3: Overview of tasks available in the SMA MIRIAD package (Zhao, 2005)

www.cfa.harvard.edu/sma/miriad/spec/SMAscripts/. It includes the calibration of the bandpass, phase and the amplitude.

The bandpass calibration thereby compensates for the change of gain with frequency. A strong source, the quasar 3C273, with a flat spectrum is observed once during the track, which is sufficient, because bandpass calibration is generally stable across the track.

The subsequent phase calibration compensates for relative temporal variation of the phase of the correlated signal on different antennas (or baselines). This is done by means of a strong source with known shape which is observed every few minutes. If the gain calibrator is a point source, then the gain is derived assuming that the intrinsic phase 0.

The amplitude calibration corrects for atmospheric opacity and loss of signal within the interferometer (e.g., pointing errors). To do so, a source with known flux is observed. This can be a planet (e.g. Saturn) for which accurate models exists, or a radio source, which has been independently calibrated using, e.g., a planet. Typical accuracies are around 15 percent.

6.1.3 Data Reduction and Imaging

After performing the initial calibration, the data reduction and imaging was performed as suggested in the “MIRIAD Users Guide for SMA” (Zhao, 2012). The full script which was created by me can be found in the appendix.

Conversion from MIR to MIRIAD format

The task `smalod` converts the uv data file from the SMA archival format into MIRIAD format. The original single receiver (`rxif=1`) SMA data file will be loaded into MIRIAD in two separated files: `rx1.lsb` and `rx1.usb` for the lower and upper side bands, respectively. In calibration, the `lsb` and `usb` data sets are treated separately. Hence, if building a continuum map, both calibrated sidebands can subsequently used for imaging. But within this thesis, only the CO J=3–2 transition is studied which is included in the lower sideband of the available data. For example, the execution of:

```
smalod in=070116_06:01:13 out=ngc2623 sideband=2 rxif=1
```

will create the directory `ngc2623_lsb`, which is used for all further processing of the lower side band. Similarly, the first or upper sideband data could be converted into MIRIAD format.

Data Inspection and Flagging

Once having created the MIRIAD compatible directory, the task `uvflag` can be used to change flags corresponding to the visibility data. Using the keywords “select”, “line” and

“edge”, one can select a part of the uv-data that have been identified with problems. For all selected correlations, the flags are then set to the value specified with the keyword “flagval”. It is generally recommended to flag the edges of the channels which can be done by:

```
uvflag vis=n2623_1.uv edge=6 flagval=flag
```

In order to check for outliers and inspection of the data, the task `uvplt` is used. For example, the following command:

```
uvplt vis=n2623_1.uv device=/xs options=nobase
line=channel,1,100,1,1
```

will plot all baselines in one single diagram which is shown in figure 6.4 in order to check for outliers and bad data. The “line” parameter indicates that the amplitude should be plotted for each channel from 1 to 100 (600 channels are available in total) with a unity step-size and unity channel-width. When performing that on the NGC2623 lower side band data, it is found that values above an amplitude of 60 Jy/beam should be flagged, which can be done by:

```
uvflag vis=n2623_1.uv flagval=flag select="amp(60)"
```

The “Dirty” Beam and Image

The MIRIAD task `invert` forms images from visibilities by means of an *inverse* Fourier transform. The program creates a “dirty image” and a “dirty beam”. The resolution of the resulting frame is controlled by the option “cell=0.2” corresponding to 0.2 arcsec per pixel. Furthermore the signal-to-noise and sensitivity is controlled by binning the signal in frequency space, hence velocity space. With the following code the binning in the uv-plane is set to 40 km/s by the keyword “map=NGC2623co32.im40”. The same is valid for the resulting extracted beam:

```
invert vis=n2623_1.uv map=NGC2623co32.im40
beam=NGC2623co32.beam40 options=systemp robust=0.5
imsize=513,513 cell=0.2 line=velocity,31,-600,40,40
```

The so gained dirty beam and dirty image can be inspected as pixel map with overlaid contours with the MIRIAD task `cgdisp`:

```
cgdisp in=NGC2623co32.beam40,NGC2623co32.beam40
type=pixel,contour device=/xs slew=p,10 levs1=1,2,3,4,5,6,7,8,9
region="relpix,box(-20,-20,20,20)" labtyp=arcsec
```

The result is shown in figure 6.5 and 6.7 for the dirty beam and image respectively.

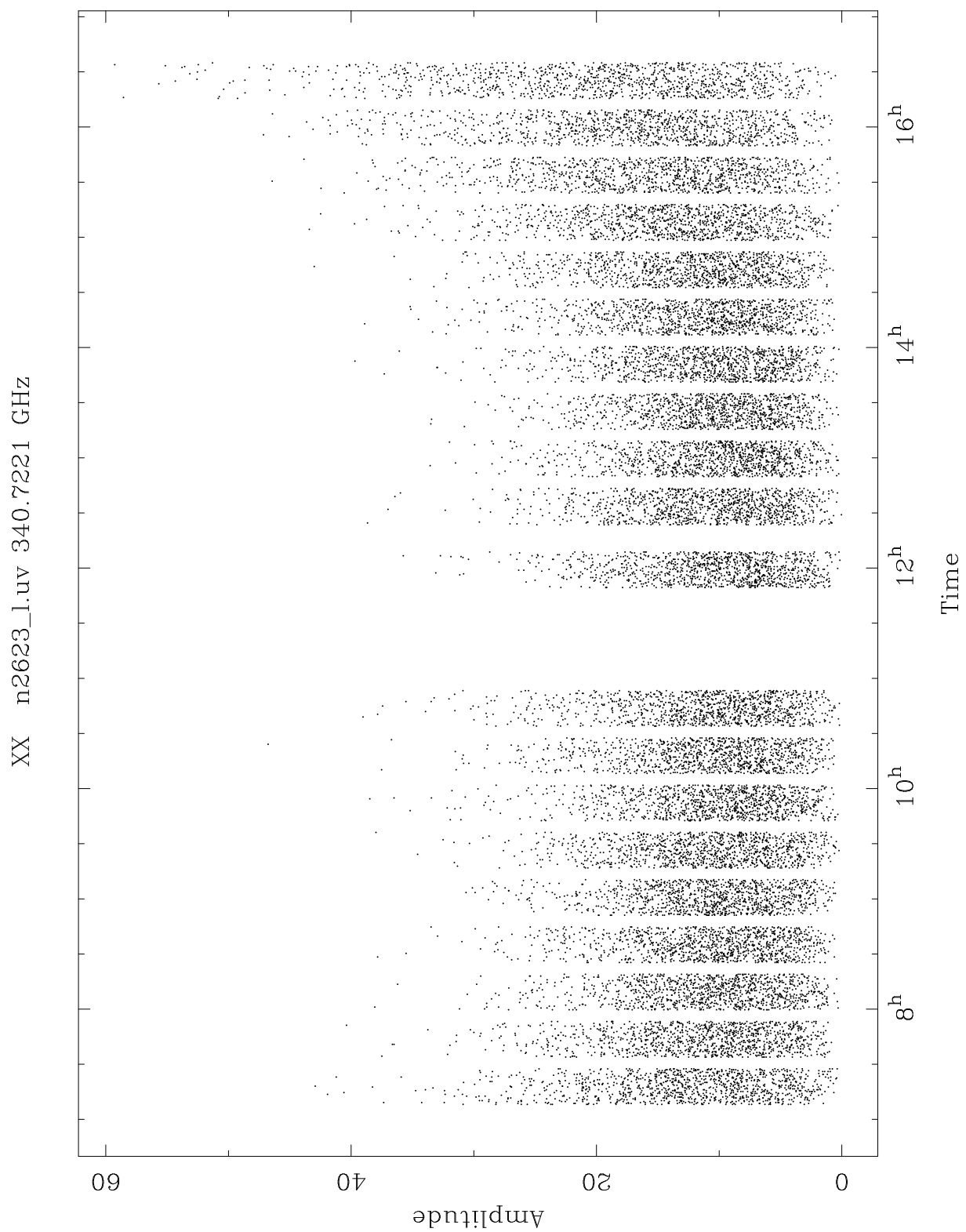


Figure 6.4: MIRIAD task `uvplt` for data inspection. All baselines in channels 1–100 out of 600 in total are shown. The values above an amplitude of 60 Jy/beam are flagged.

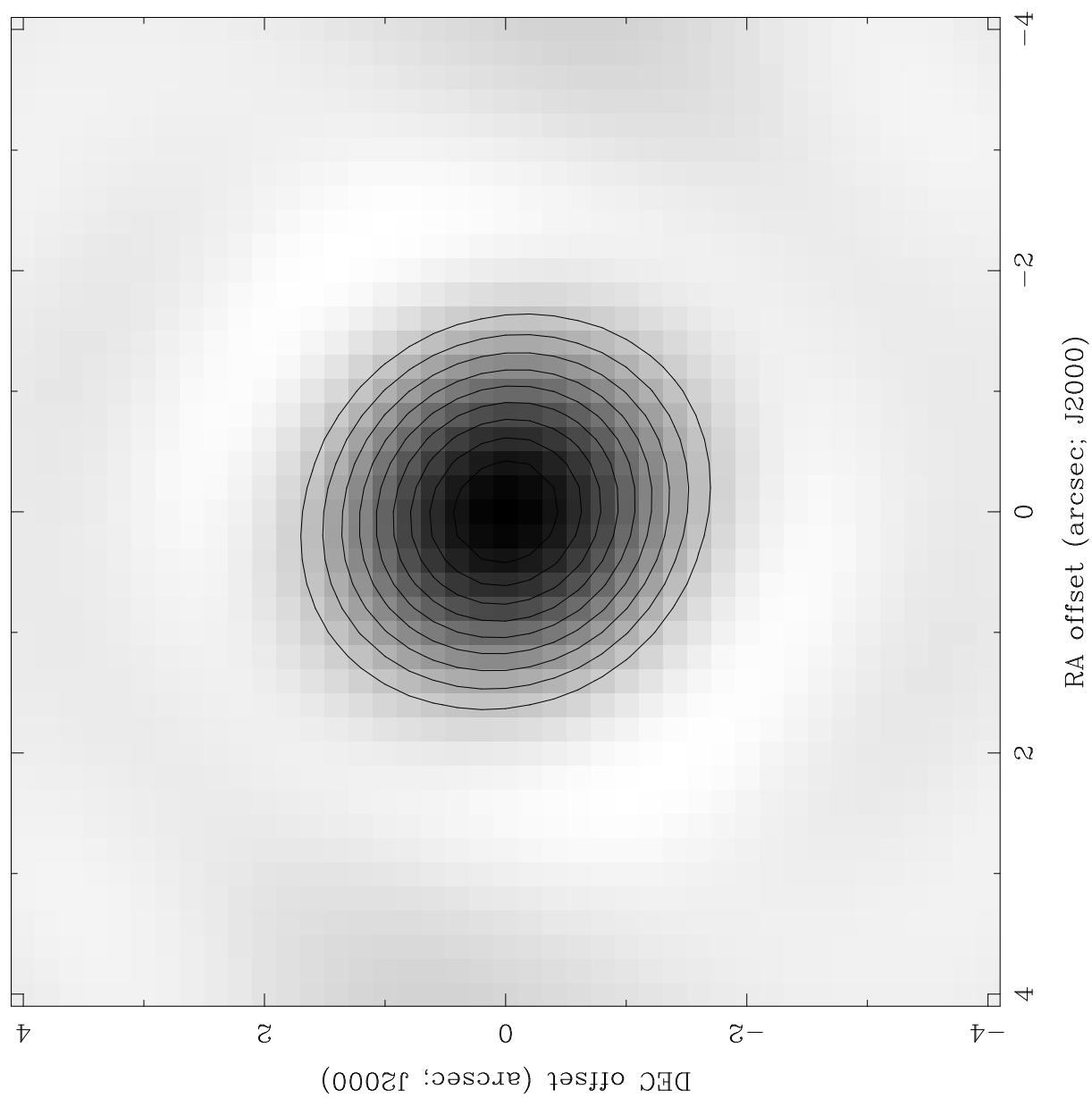


Figure 6.5: “Dirty Beam” extracted with the task `cgdisp`

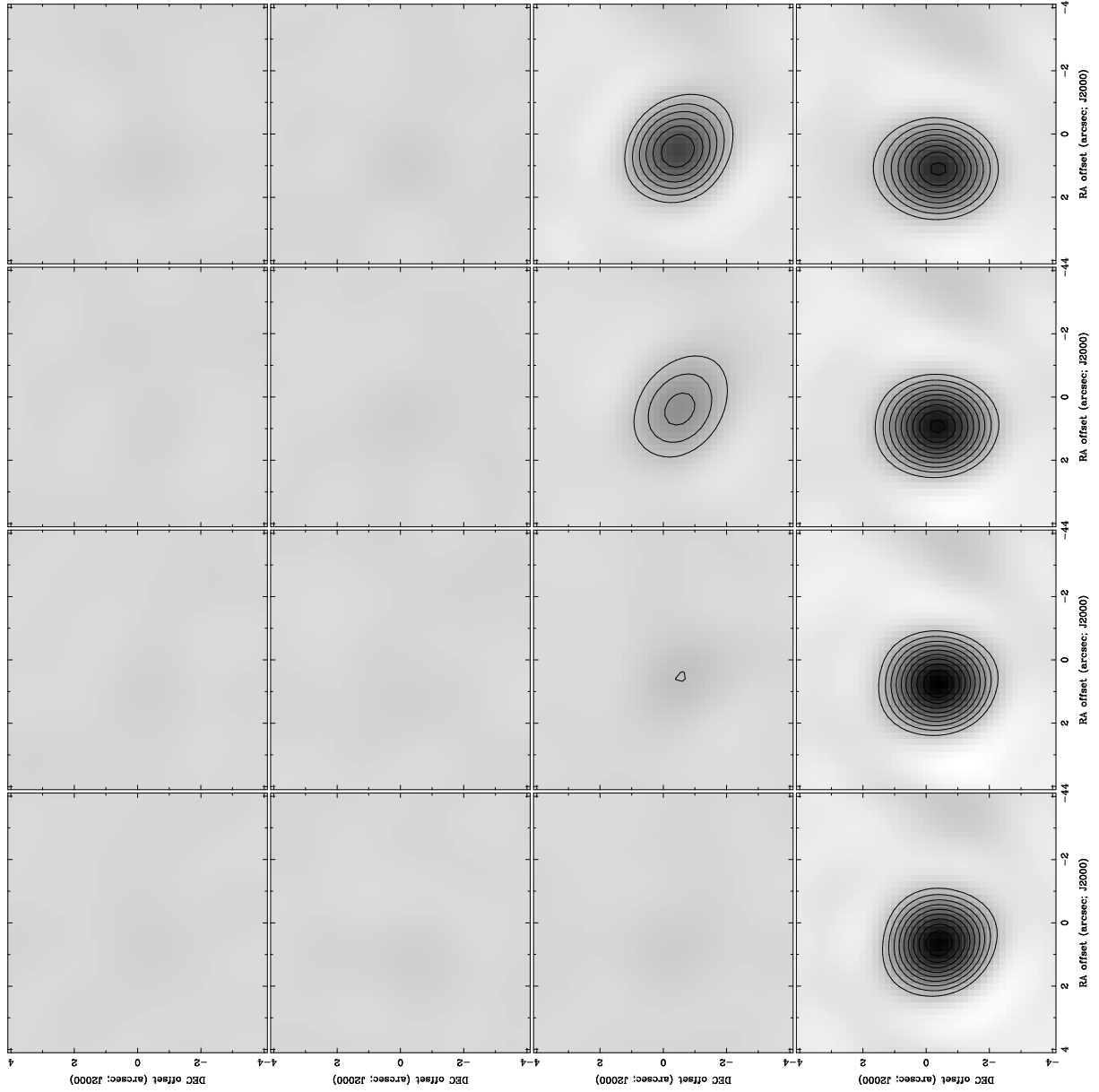


Figure 6.6: Central region of the “Dirty Image” extracted with the task `cgdisp`. Each panel corresponds to a 40 km/s binned slice. The relative velocity ranges from -600 to 0 km/s.

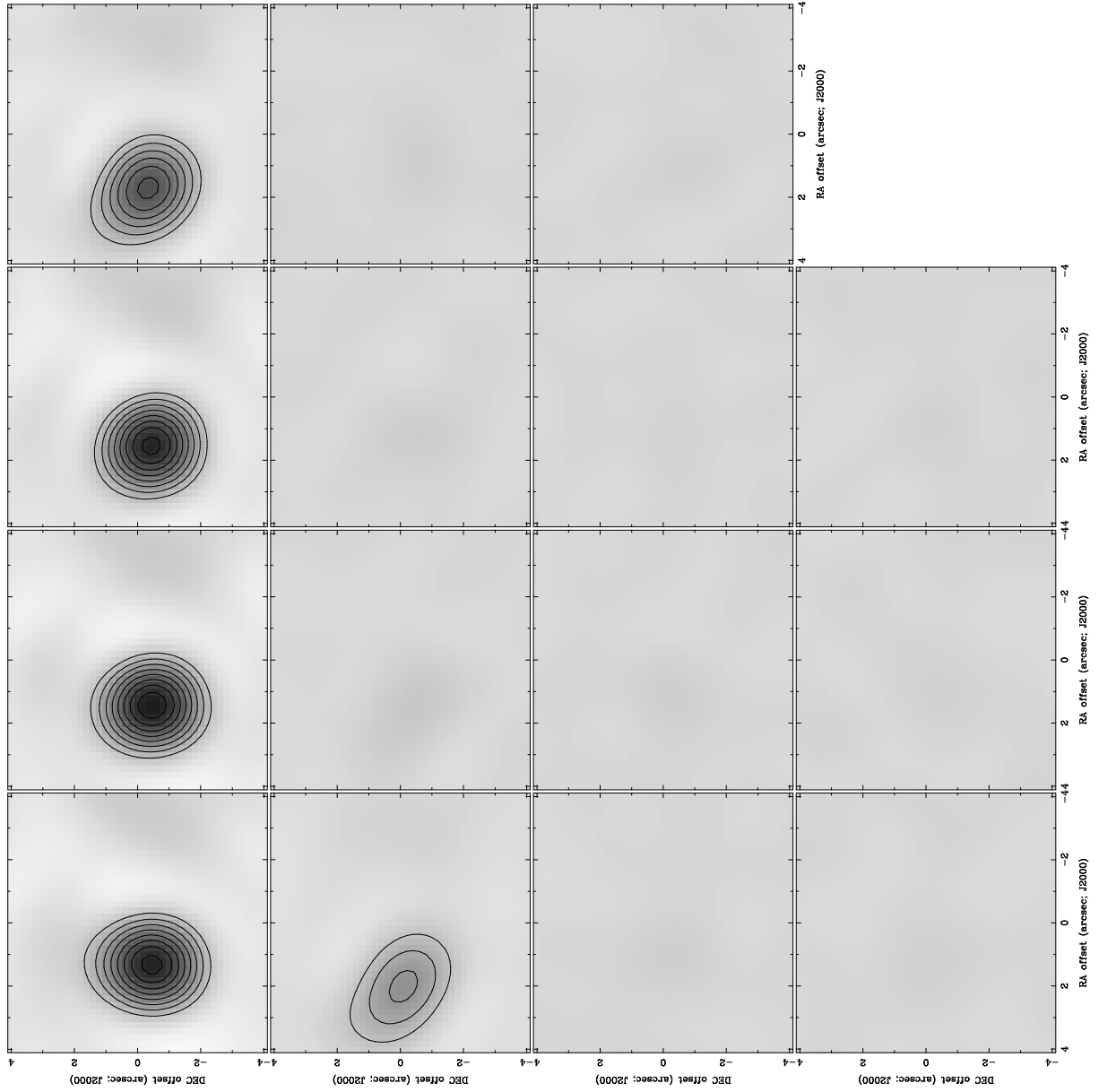


Figure 6.7: Central region of the “Dirty Image” extracted with the task `cgdisp`. Each panel corresponds to a 40 km/s binned slice. The relative velocity ranges from 40 to 600 km/s.

Cleaning

Since the produced dirty map is intrinsically the result of a convolution between the dirty beam and the true or “clean” map, the so called *Convolution theorem* can be used to disentangle these components and create a “clean” visibility. Thereby it has to be taken into account, that the measured visibility differs from the true visibility due to finite uv-coverage. The better the uv-coverage (sampling), the better will be the solution to the problem. Hence, after applying the MIRIAD task `clean`, the so gained sampled visibility has to be interpolated and extrapolated by means of a model. Thus, the output of `clean` is used for *restoring* the sampled data. The used MIRIAD task is `restor`. An example of usage is shown below:

```
clean map=NGC2623co32.im40 beam=NGC2623co32.beam40
out=NGC2623co32.clean40 region=quarter niters=2000 cutoff=0.018
```

```
restor map=NGC2623co32.im40 beam=NGC2623co32.beam40
model=NGC2623co32.clean40 out=NGC2623co32.map40
```

The cutoff is derived by inspection of the histogram which can be done with the task `hist`.

Creating Moment Maps

The process of creating smooth moment maps is quite complex and time-consuming. Several parameters (e.g. clipping, cutoff), have to be inspected and experimented with in order to get good results. The best method found can be reproduced by means of the shell script in the appendix. The first and easiest approach is to simply perform the MIRIAD task `moment`. The following code creates a moment 0 map (intensity) of the central region of the image with a clipping parameter corresponding to the 2σ RMS level:

```
moment in=NGC2623co32.map40 region="quarter(9,23)"
out=NGC2623co32.mom0_40 mom=-1 clip=0.018
```

The result is shown in figure 6.8.

6.1.4 Basic Properties of the Reduced Images

RA	DEC	z	D_L	V_{sys}	L'_{CO}	M_{H_2}
08:38:24.00	+25:45:16.31	0.01847300	80.241	5469 ¹	1.04 ± 0.06	1.66 ± 0.01

Table 6.1: Basic data for NGC2623 taken from Wilson et al. (2008). The luminosity distance D_L is given in Mpc, the systemic velocity V_{sys} in km/s , the CO luminosity L'_{CO} in $10^9 K km s^{-1} pc^{-2}$ and M_{H_2} in $10^9 M_\odot$.

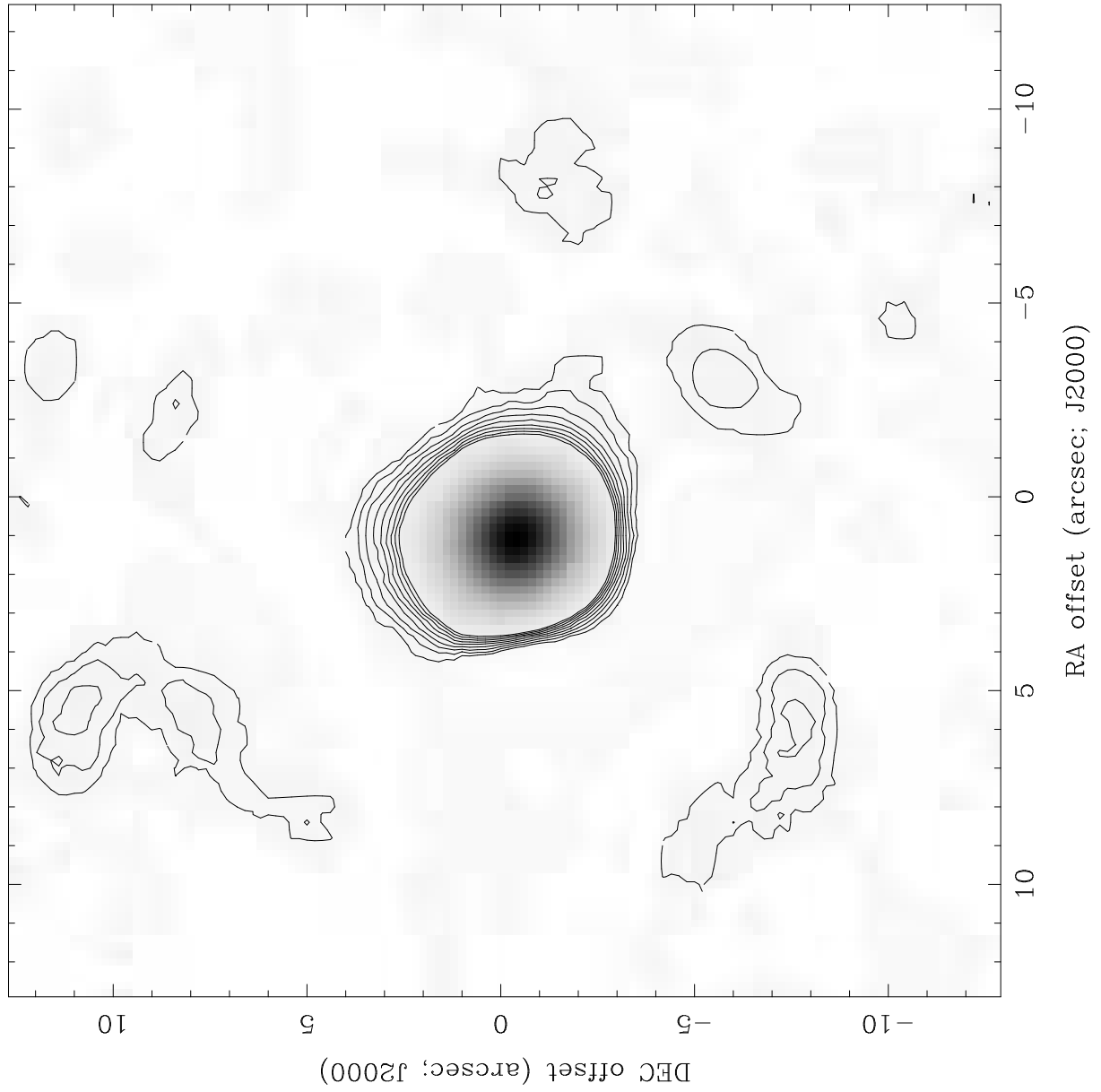


Figure 6.8: CO 3-2 Intensity map of the central region after execution of the MIRIAD task **moment**.

The derived moment maps of the SMA data are shown in figure 6.9. All derived maps were cleaned down to a 3σ level. The following CALIFA and SMA maps cover the central 20×20 arcsec of NGC2623 with a pixel-scale 1 arcsec corresponding to a linear scale of 400 pc. The CO sensitivity limit (3σ) is found to be 4 Jy/beam km/s which translates to a molecular mass (column density) limit of approximately $2 \times 10^6 M_\odot$ per pixel. The total molecular mass was found to be $1.58 \times 10^9 M_\odot$ in accordance to the findings of Wilson et al. (2008).

The molecular gas velocity and the velocity dispersion ranges from -180 to +160 km/s and 0 to 130 km/s.

The $\text{H}\alpha$ fluxes were corrected for extinction by means of the Whitford reddening curve parameterized by Miller and Mathews (1972) and using the $\text{H}\alpha$ fluxes provided by the CALIFA survey. A description of the applied method can be found in Saglia (1997).

6.2 Studies on NGC2623

NGC2623 is a well studied object which is classified as LIRG due to its infrared luminosity of $\approx 3.5 \times 10^{11} L_\odot$ (Joy & Harvey 1987). It is a late-stage major merger in prograde orbit (Toomre (1977)). Its stellar population is separated into two components: a young and an intermediate age population (Evans et al. 2009 and Joy & Harvey 1987). In the central region it exhibits a cone-shaped outflow due to a dusty starburst which was found by Lipari et al. (2003) and recently confirmed by Cortijo et al. (in prep.) who furthermore were able to trace the outflow farther. Cortijo et al. (in prep.) also performed a detailed stellar population synthesis and derived the star formation history (SFH) using HST multi-wavelength data, CALIFA datacubes and OSIRIS narrow-band images. The galaxy is “currently” evolving into an elliptical galaxy (Wright 1990, Scoville 2000 and Rothberg 2004) which can be seen in figure 6.10.

It was first classified as LINER (Low Ionization Nuclear Emission Line Region) by Heckman et al. (1983). Later, Condon et al. (1991) and Maiolino (2003) classified it as an obscured AGN using CHANDRA X-ray observations.

Recently Singh et al. (2013) were able to show that the phenomenon of LINERs is *not solely* connected to an AGN. They used CALIFA’s IFU data of 48 galaxies and found that the radial emission-line surface brightness profiles are inconsistent with ionization by a central point-source and hence cannot be due to an AGN alone. Furthermore, they assume that LINERs are connected to the very short, but very hot and energetic phase of post-AGB stars. Thus, the whole picture of AGNs have to be revised as LINERs were believed to form the largest AGN sub-population.

Beside that, NGC2623 is also a LIRG, for which the LINER phenomenon can be also explained by star forming activity (Lutz et al. 1999).

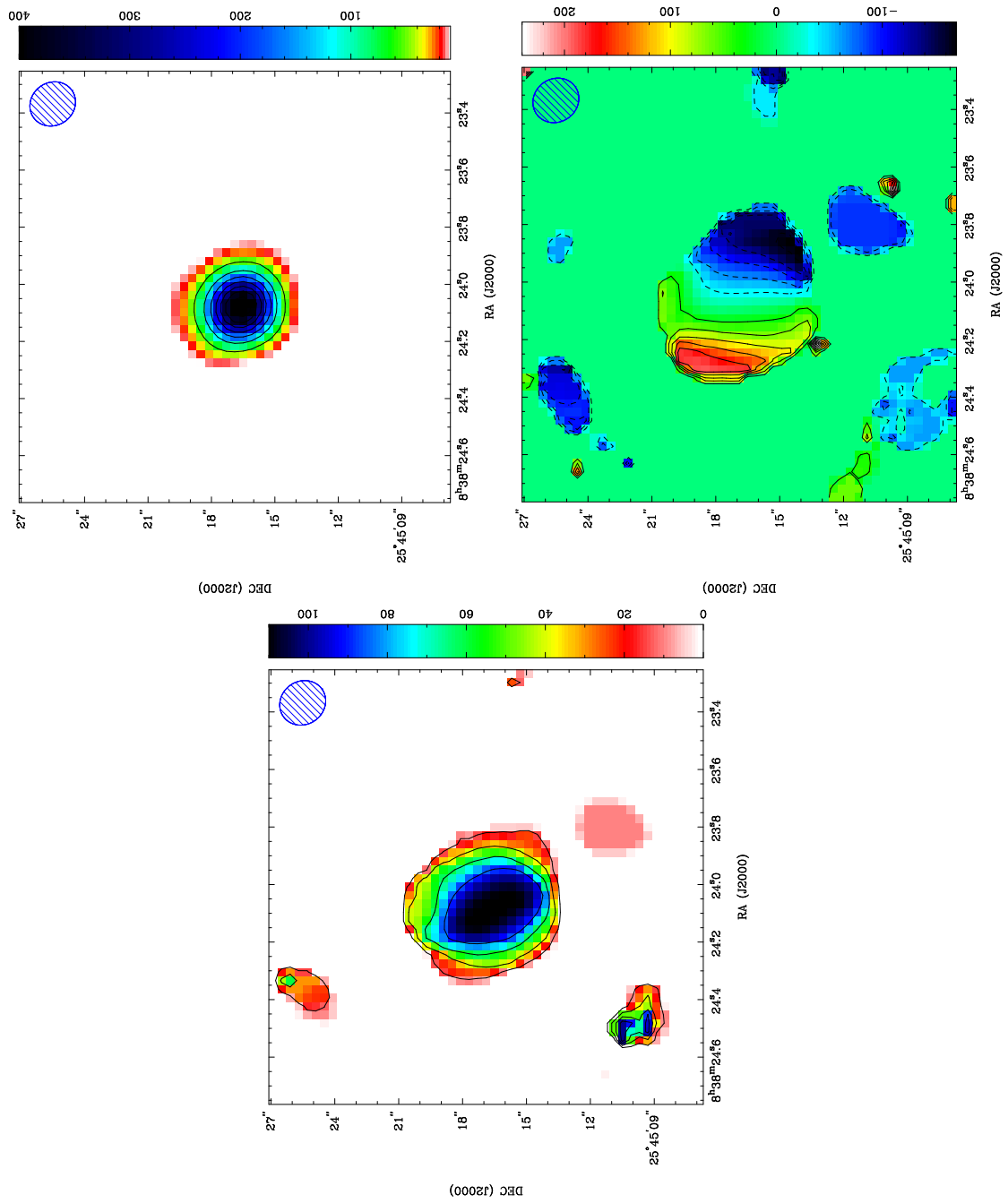


Figure 6.9: Moment maps of NGC2623 created with MIRIAD. The top left panel shows the intensity in Jy/beam km/s of the central 20 x 20 arcsec. The logarithmic contours are set to: 58, 116, 174, 232, 290, 348, 406 and 464 Jy/beam km/s. The top right panel gives the velocity in km/s of the central 20 x 20 arcsec with linear contours set to : -260, -227.5, -195, -162.5, -130, -97.5, -65, -32.5, 32.5, 65, 97.5, 130, 162.5, 195, 227.5 and 260 km/s. The bottom panel indicates the velocity dispersion in km/s of the central 20 x 20 arcsec with linear contours of 12.5, 37.5, 62.5, 87.5, 112.5, 137.5, 162.5, 187.5, 212.5 and 237.5 km/s.



Figure 6.10: NGC2623 as seen with Hubble², processing by Pugh (2012)

The LINERs far off the central region can be seen in figure 6.11. In the bottom right panel of figure 6.11 which is indicating the velocity dispersion of the ionized gas, the outflow can be clearly identified as the region of high velocity dispersion located slightly north to the galaxy's center.

6.3 Molecular and Ionized Gas Distribution

The molecular gas traced by CO is strongly concentrated to the central region of NGC2623, which is seen in figure 6.9 and consistent with the picture of a central starburst. Its size is around 3 kpc in diameter. The averaged radial distribution can be described by an exponential law with a relative error below 25 percent, which confirms the aperture correction method used within this thesis for total molecular mass calculations.

The intensity peaks in $H\alpha$ and CO (see figure 6.13) match each other within the uncertainty of approximately one arcsec.

Beside the central peak, a huge molecular clump with a dimension of ≈ 1 kpc can be identified south-west to the center in the CO map. Although the signal is relatively weak, with a level of 4 sigma, it is significant and not a remnant of the data reduction process (e.g. sidelobe). Furthermore its location matches up – although slightly offset – with a peak in $H\alpha$ (see figure 6.13). The $H\alpha$ peak is connected to a huge star forming cluster seen

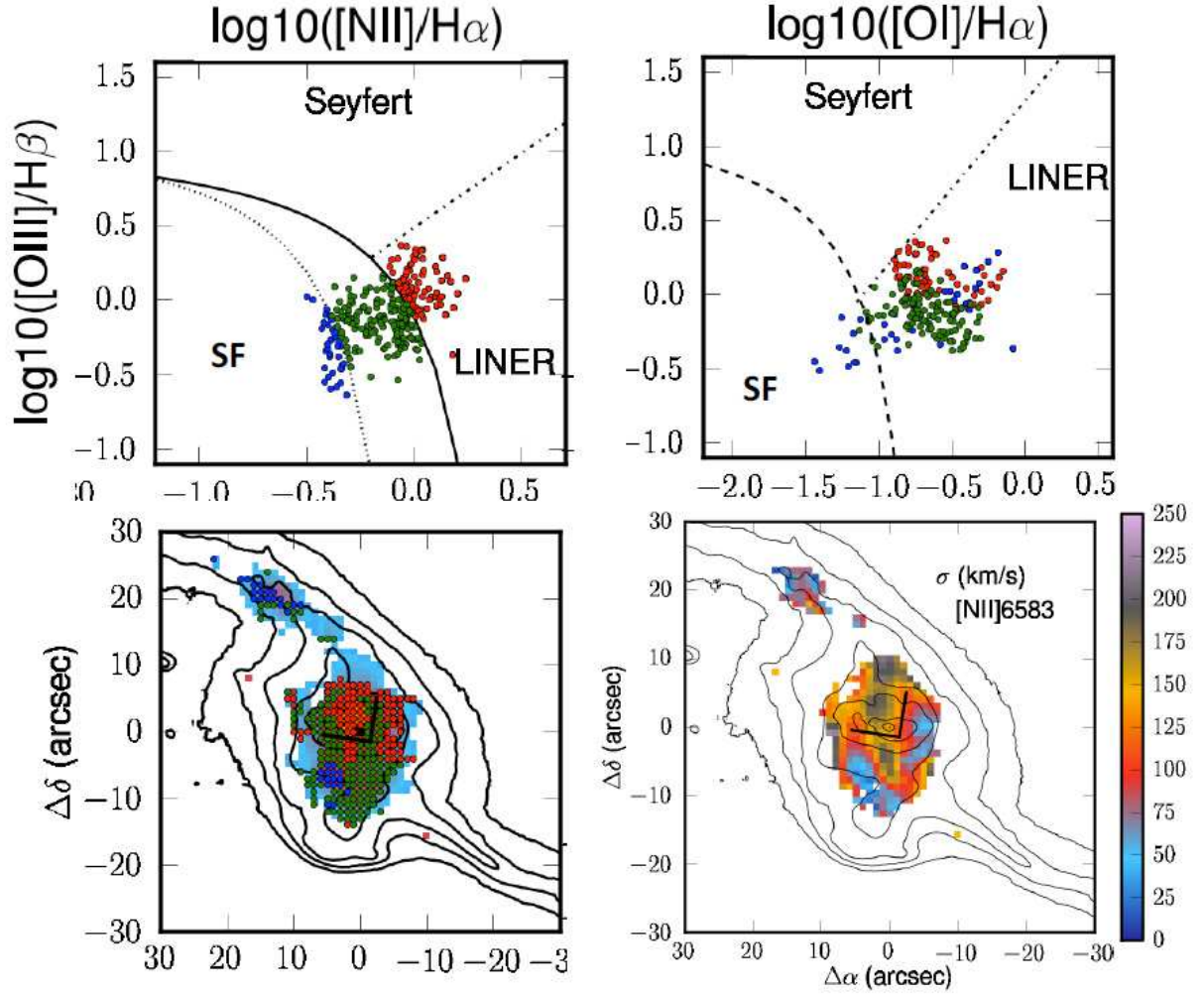


Figure 6.11: BPT diagrams of NGC2623 (top panels) extracted from Clara Cortijo and presented during the 5th CALIFA Busy week. The different classifications within the BPT diagram (SF, Seyfert and LINER) are color-coded. A comparison with the spatial location of the data-points (bottom left) identifies LINERs offset from the center confirming the findings of Singh et al. (2013). Furthermore, the cone-shaped central outflow connected to a large velocity dispersion (bottom right) can be seen.

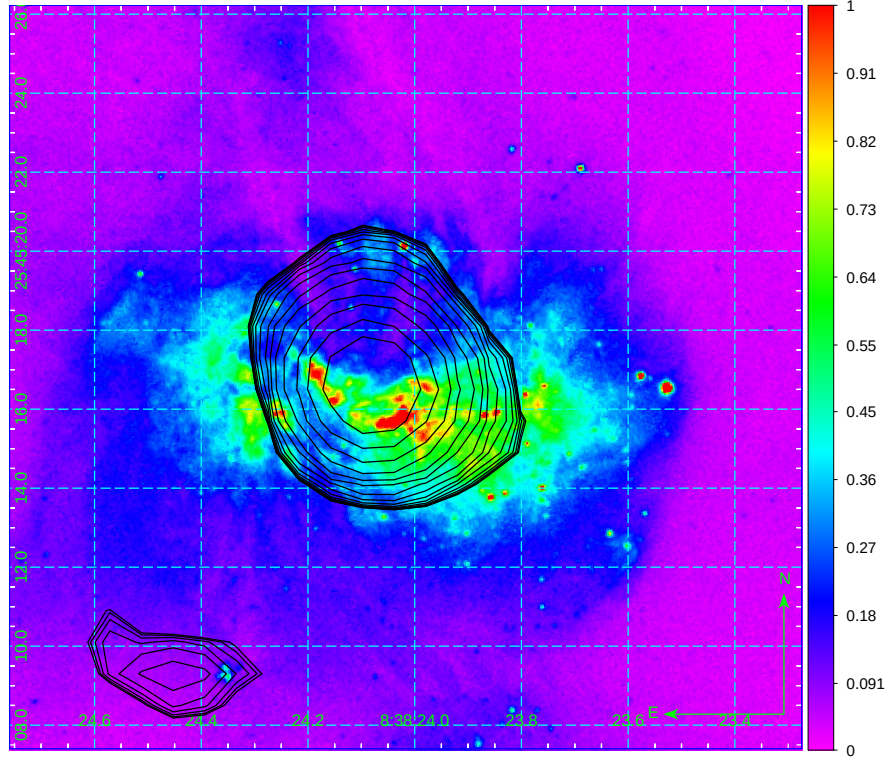


Figure 6.12: The HST ACS/WFC image in the blue filter (F435W) is shown as a pixelmap. The CO intensity is indicated by the contours. The level spacing is logarithmic and covers the range from 4 to 220 Jy/beam km/h.

in the blue F435W filter of Hubble’s ACS wide field camera³ (see figure 6.12). Thus, the offset is likely an extinction effect and $H\alpha$ can only penetrate around the newly formed stars where stellar winds dilute the ISM. Within the clump star formation is likely to occur invisible to the optical region.

6.4 Molecular and Ionized Gas Velocities

The molecular gas component shows a smooth rotation in the central region with perturbations at the western outskirts. The velocities are comparable to those derived from $H\alpha$. A rotating component (disk) can be likewise identified in $H\alpha$ and CO. However, in the outskirts, the overall velocity distribution does not show any systematic rotation which is a sign for the ongoing merging process.

A comparison between the molecular and ionized gas velocities is shown in figure 6.15. The colors are a representation of the given pixel’s radial distance to the $H\alpha$ peak. An outstanding (dark) clump can be identified in the diagram. After marking the pixel’s location in the velocity field of figure 6.16, it turns out that a closed region can be clearly

³The pipeline-reduced optical HST image was downloaded through <http://archive.stsci.edu/>.

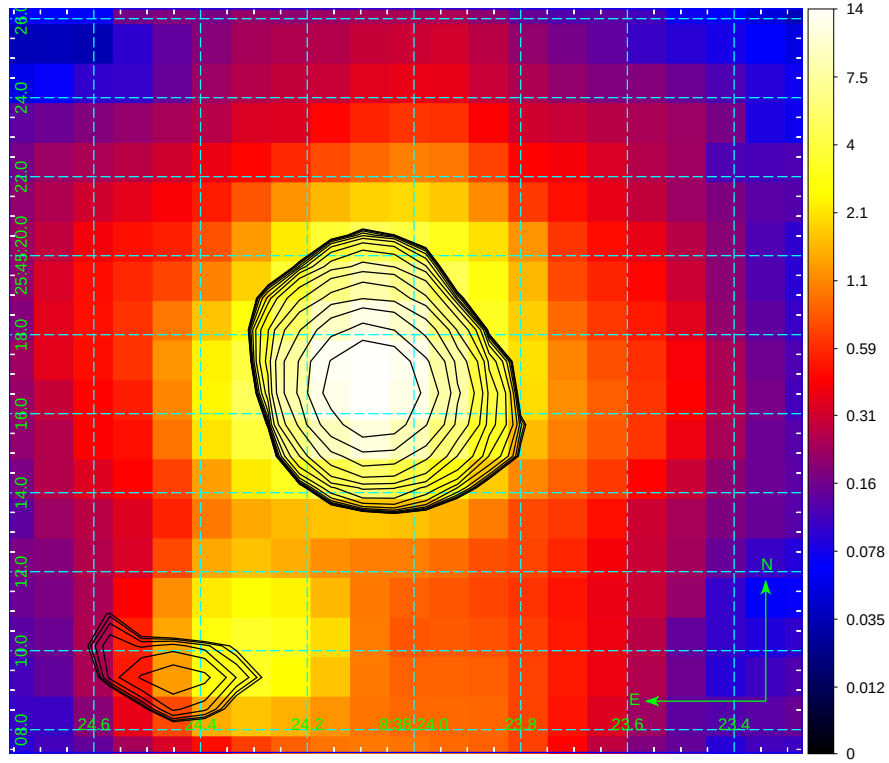


Figure 6.13: NGC2623 - Comparison H α intensity – CO intensity. H α is shown as a pixelmap. The colors are log-coded and the scale's unit is $10^{-16} \text{ erg/s/cm}^2$. The CO intensity is indicated by the contours. The level spacing is logarithmic and covers the range from 4 to 220 Jy/beam km/h.

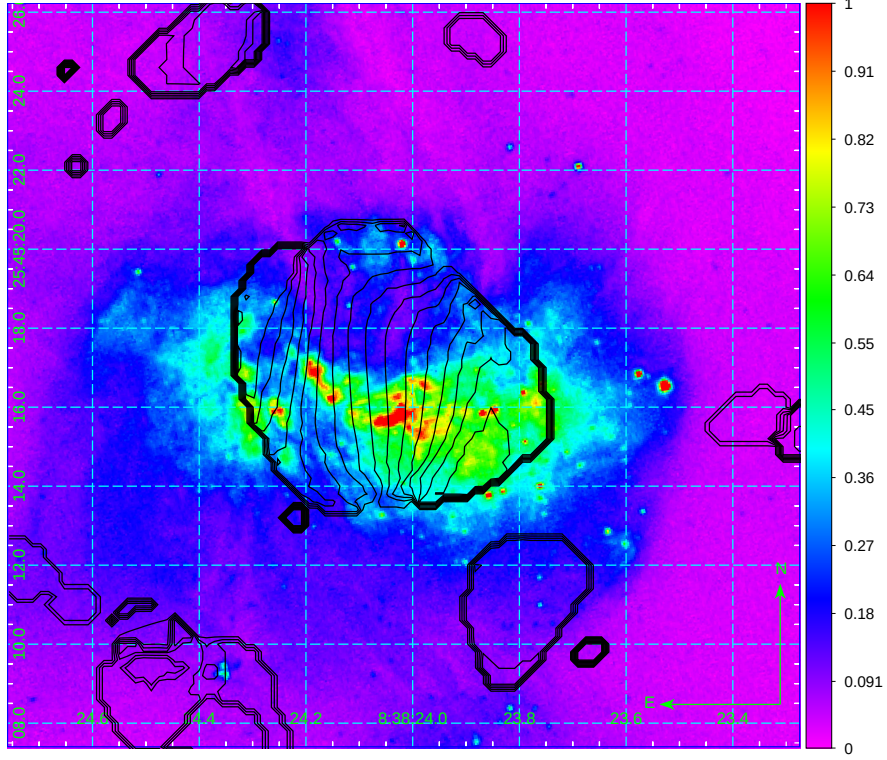


Figure 6.14: The HST ACS/WFC image in the blue filter (F435W) is shown as a pixelmap. The molecular gas velocity is indicated by the contours with level spacings of 40 km/h going from -160 km/h to 240 km/h.

associated with the molecular clump described previously.

Thus, the clump – which is marked with blue crosses in figure 6.16 – and the ionized gas fulfill different radial movements with velocities of -33 and +77 km/s, respectively.

This can be explained by cold neutral gas falling into the center, whereas the hot gas is moving outwards, as a result of the major merger event. The complex movements between ionized and the molecular gas furthermore disturb the ISM such that star formation is likely to be triggered which is confirmed by the presence of a young star cluster seen in figure 6.14. Such a scenario is, for example, described in Iono et al. (2004) and it also explains the highly concentrated molecular gas in the center which then indicates that the merger event is in a late stage already, where most of the cold gas is settled (in the center). However, the final merger stage is not reached yet, as there is still more than 10^9 solar masses of molecular gas available and star formation is actively going on in the central region, which can be seen from the $H\alpha$ maps and the associated velocity dispersion, which will be discussed in the next section.

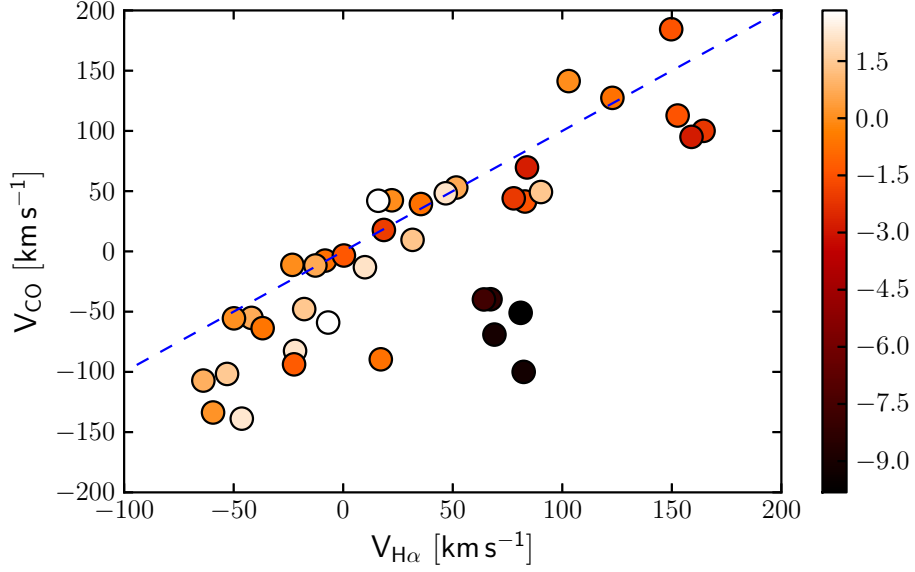


Figure 6.15: NGC2623 - Comparison of the velocity in $H\alpha$ and CO. The color-coding indicates the radial distance in pixels of individual data-points from the central $H\alpha$ intensity peak. A clump can be identified which corresponds to a closed region located 7–9 pixels – corresponding to 4–5 kpc – from the center. There, the molecular gas is approaching the line-of-sight and the ionized gas is departing.

6.5 Molecular Gas Velocity Dispersion

The cone shaped outflow found by Lipari et al. (2003) can be identified best in the $H\alpha$ velocity dispersion map in figure 6.19. It is connected to the regions of highest (molecular and ionized) gas velocity dispersion. Thus, it can be seen directly that star formation is tightly correlated to turbulences within the molecular ISM, which is quantitatively shown in figure 6.18.

The existence of such a relation can be understood on basis of Toomre’s criterion of stability of a differential rotating stellar disk. Combining that with the stellar-to-gas surface density relation of Rafikov (2001) and the Kennicutt-Schmidt law, the following proportionality is found:

$$\sigma = \Sigma_{SFR}^{0.7} \quad (6.1)$$

Thereby, the velocity dispersion is given in km/s and the star formation rate in $M_{\odot} yr^{-1}$. A derivation can be found in Swinbank et al. (2012).

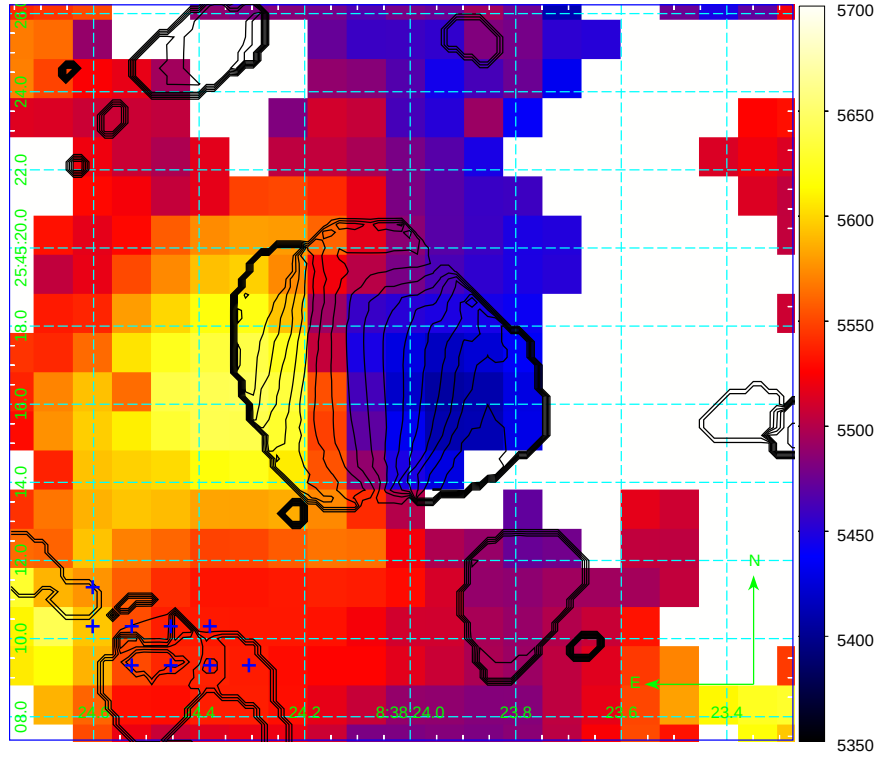


Figure 6.16: NGC2623 - Comparison of the velocity in $H\alpha$ and CO in the central region. The velocity $V_{H\alpha}$ is shown as a pixelmap with a linear coding in units of km/s . The molecular gas velocity is indicated by the contours. The unit is km/s with a linear scaling reaching from -160 to 240 km/h and a level spacing of 40 km/h. Blue crosses mark the (dark) outliers of figure 6.15 which are associated with a molecular clump.

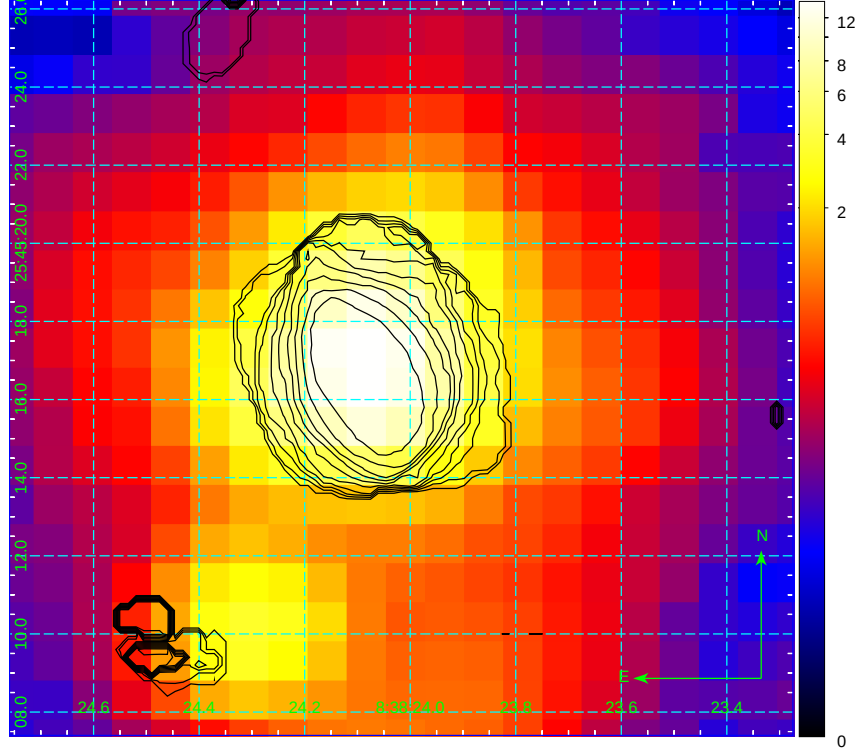


Figure 6.17: NGC2623 - Comparison of $H\alpha$ intensity to CO velocity dispersion. $H\alpha$ is shown as a pixelpmap. The colors are log-coded and the scale's unit is $10^{-16} \text{ erg/s/cm}^2$. The molecular gas velocity dispersion is indicated by the contours. The unit is km/s with linear scaling levels of: 0, 16, 32, 48, 64, 80, 96, 112 km/s .

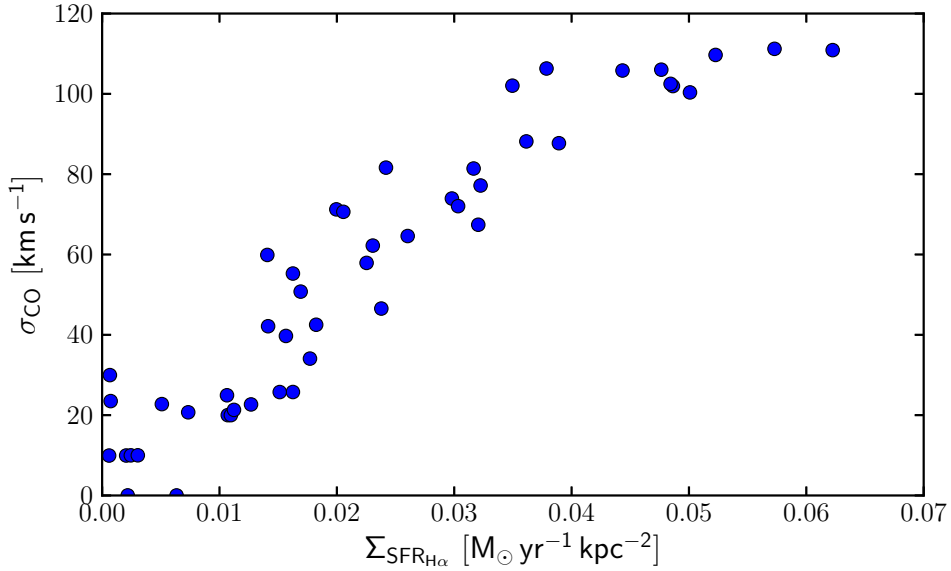


Figure 6.18: Relation between the SFR and the Molecular Gas Velocity Dispersion. The $H\alpha$ intensity, which transforms into a star formation rate through formula 5.1, is tightly correlated with the velocity dispersion in CO. Thus, molecular gas turbulences are essential for the process of star formation.

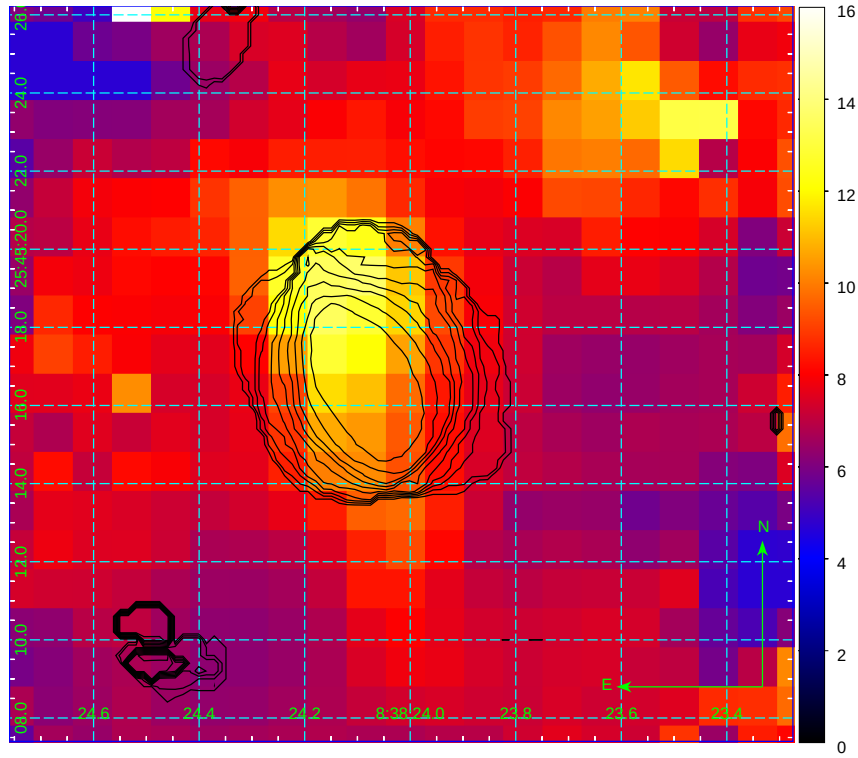


Figure 6.19: NGC2623 - Comparison H α -CO velocity dispersion. The H α velocity dispersion is shown as a pixelmap. The color scale's unit is $\text{\AA}$. The molecular gas velocity dispersion is indicated by the contours. The unit is km/s with linear scaling levels of: 0, 16, 32, 48, 64, 80, 96, 112 km/s .

Chapter 7

Conclusion

After performing a detailed literature study on CO data available through several archives, the following can be concluded:

- Comparing the results from Young et al. (1995)¹, Lisenfeld et al. (2011) and Leroy et al. (2008), the CO distribution of spiral galaxies is found to be well described by an exponential law with an “effective” radius of $r_{e,CO} = A \times r_{25}$ with r_{25} , the optical blue $25 \text{ mag arcsec}^{-2}$ isophotal radius with a value of A ranging from 0.20 to 0.25. The same relation also holds for early type galaxies as found by Davis et al. (2013b).
- The *main beam brightness temperature* scale is found to be the appropriate scale for homogenizing CO single-dish data of CALIFA galaxies, because it is a diameter-selected sample and typical single dish beams for the CO J=1–0 transition cover at least a substantial fraction of the total CO flux leading to a median value for the aperture correction factor of $C_{AP} = 1.9$. However, in some cases, with higher values of C_{AP} , the derived molecular masses are probably overestimated and the use of the T_A^* scale, which takes into account atmospheric attenuation, radiative loss and rearward spillover and scattering would be more appropriate.
- The importance of a metallicity-dependent X_{CO} derivation was demonstrated, as variations up to a factor of 4 can occur otherwise. It was shown that a compilation of molecular masses taken from the literature, is not suitable, due to the variety of the underlying parameters. Thus, the homogeneously derived total molecular masses of CALIFA galaxies will provide the community with a unique dataset which will be used for future scientific studies based on CALIFA galaxies.
- Several infrared satellite data were used in order to derive star formation rates for *all* CALIFA galaxies. Based on a relatively tight relation between the SFR and

¹Young et al. published radii within which 70 percent of the total CO luminosity is found. Thus, the comparison is not straightforward!

the CO luminosity, the latter could be *estimated* for *all* CALIFA galaxies. These results were used for integration time calculations (also described within this thesis) and proposing observations at several facilities such as IRAM, PdBI, APEX and OSO. The ultimate goal of the proposed observations is to build-up a well-studied reference sample of galaxies for which not only CALIFA’s optical IFU data, but also highly-resolved CO data is available. Within the presented thesis, such a sample was defined based on the physical properties of stellar mass, star formation rate and morphology. For the sample-selection, a program based on the SIMPLEX algorithm was developed leading to a final interferometric sample of 65 galaxies which is as homogeneous as possible in all of the mentioned coupled parameters. That sample will serve as a local representative sample for future studies of the cold, molecular ISM.

- Atomic gas masses were compiled from two different catalogs and homogenized. As a result, for approximately 2/3rd of the CALIFA galaxy sample, atomic gas masses were calculated in a uniform way. Subsequently, the Kennicutt-Schmidt relation was set-up based on single dish data. From that, three conclusions could be drawn. First, the SFR scales nearly linearly with H_2 , even where most gas is atomic. Second, the star formation threshold is independent on the scale and coincides with an atomic-to-molecular transition. And finally, to first order, the SFR/MH2 ratio is fixed in “normal” spiral galaxies. These findings are not totally new, but were not exhibited from *integrated*, hence *averaged* quantities before. Thus, to first order, even from integrated values, basic properties of the ISM can be derived which can be an asset for high-redshift investigations.
- In addition, a case study showing the capabilities of comparing CALIFA’s IFU data to highly resolved CO data, was also undertaken as part of this thesis. It was found that within NGC2623 – a late-stage merger evolving into an elliptical galaxy – beside the previously discovered (see Wilson et al. (2008)) rotating molecular gas disk in the central region, a huge clump with a dimension of ≈ 1 kpc is present. Its location is consistent with a counterpart in CALIFA’s $H\alpha$ map and optical HST data shows a huge star cluster associated with it. The finding can be explained by the late-stage merger model described in Iono et al. (2004), where molecular gas is falling into the center whereas hot gas is moving outwards. During that process, gas compressions lead to triggered star formation. The presented observations imply such a scenario.

Acknowledgements

First and foremost, I would like to thank my supervisor Helmut Dannerbauer for his valuable guidance and advice. Without his expertise in radio and especially sub-millimeter astronomy this thesis would not have been possible. I also want to acknowledge his efforts in establishing a new lecture at the Department of Astrophysics in Vienna including fundamental concepts of interferometry. Additionally, I owe special thanks to Bodo Ziegler, not only for several fruitful discussions, but also, because he inspired me to work within the CALIFA collaboration. He invited me to visit the 5th CALIFA Busy Week in Potsdam, where I had the chance to present my work. Beside that, Bodo's patience and his outstanding teaching skills made the fascinating field of extragalactic research accessible to me and many other students. I want to thank my family. Without their long lasting support, an academic career would not have been possible at all. When looking back, I also see many colleagues, which made life at the university fun for which I want to thank Andreas, Christoph, Conny, Patrick, Nadja, Thomas, Ulli, Paul and many other people I have forgotten to mention now. Lastly, I thank Veronica for the uncountable challenging discussions and so many wonderful and lovely moments, we were able to share in and around Vienna.

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Appendix A

Star Formation Rates and Gas masses in CALIFA Galaxies

Table A.1: Calculated L_{IR} , SFRs and gas masses (table 5.4 continued)

ID	name	L_{IR}	SFR	M_{HI}	C_{AP}	M_{H_2}	$\frac{M_{H_2, Z-dep}}{M_{H_2, stat}}$
		$10^9 L_{\odot}$	$M_{\odot} \text{ yr}^{-1}$	$10^9 M_{\odot}$		$10^9 M_{\odot}$	
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
1	IC5376	7.09±0.93	0.9±0.13	8.43±1.45	—	—	—
2	UGC00005	63.08±2.41	9.4±0.38	13.36±1.62	1.6	6.19±2.11*	0.9
3	NGC7819	30.36±0.95	4.3±0.14	14.86±1.75	—	—	—
4	UGC00029	30.36±0.95	4.3±0.14	—	—	—	—
5	IC1528	16.18±0.69	2.2±0.1	11.84±2.3	—	—	—
6	NGC7824	6.32±1.3	0.8±0.18	4.76±0.6	—	—	—
7	UGC00036	15.51±1.42	2.1±0.21	5.3±0.75	—	—	—
8	NGC0001	45.25±0.81	6.6±0.13	14.78±1.78	—	—	—
9	NGC0023	193.74±0.87	30.7±0.15	9.53±1.2	2.1	17.12±4.2*	4.4
10	NGC0036	29.25±1.97	4.2±0.3	20.81±2.97	—	—	—
11	UGC00139	7.81±0.73	1.0±0.1	13.81±2.27	1.7	<0.57±0.16	—
12	UGC00148	35.35±0.95	5.1±0.14	7.46±1.01	—	—	—
13	MCG-02-02-030	10.31±0.58	1.4±0.08	3.74±0.26	—	—	—
14	UGC00312	29.44±1.45	4.2±0.22	19.89±2.4	—	—	—
15	ESO539-G014	4.1±1.14	0.5±0.15	17.56±1.0	—	—	—
16	MCG-02-02-040	22.62±0.51	3.2±0.08	13.72±1.63	—	—	—
17	UGC00335NED02	22.62±0.51	3.2±0.08	—	—	—	—
18	NGC0155	1.59±0.84	0.2±0.11	—	—	—	—
19	ESO540-G003	4.04±0.47	0.5±0.06	13.16±0.96	—	—	—
20	NGC0160	7.96±0.79	1.0±0.11	7.18±1.11	—	—	—
21	NGC0165	35.78±1.6	5.1±0.24	7.94±2.76	—	—	—
22	NGC0169	30.89±1.04	4.4±0.16	9.69±1.72	—	—	—
23	NGC0171	8.24±1.82	1.1±0.26	3.55±0.94	—	—	—
24	NGC0177	3.0±0.45	0.4±0.06	5.21±0.41	—	—	—
25	NGC0180	35.87±2.73	5.1±0.42	21.78±3.19	—	—	—
26	NGC0192	58.23±0.78	8.6±0.12	1.44±0.23	1.5	16.61±16799.63*	1.6
27	NGC0216	2.06±0.11	0.3±0.01	2.03±0.67	—	—	—
28	NGC0214	52.17±0.82	7.7±0.13	13.28±1.68	—	—	—
29	NGC0217	8.61±0.87	1.1±0.12	4.22±0.33	—	—	—
30	NGC0237	31.51±0.92	4.5±0.14	10.3±1.27	1.5	3.8±1.05	—
31	NGC0234	73.25±1.15	11.0±0.18	7.56±0.84	—	—	—
32	MCG-02-03-015	11.71±1.26	1.6±0.18	7.77±0.62	—	—	—

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ID	name	L_{IR} $10^9 L_{\odot}$	SFR $M_{\odot} \text{ yr}^{-1}$	M_{HI} $10^9 M_{\odot}$	C_{AP}	M_{H_2} $10^9 M_{\odot}$	$\frac{M_{H_2, Z-dep}}{M_{H_2, stat}}$
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
33	NGC0257	68.17±1.68	10.2±0.27	18.42±2.3	—	—	—
34	NGC0309	97.21±2.62	14.8±0.42	39.91±1.59	—	—	—
35	NGC0364	1.39±0.47	0.2±0.06	—	—	—	—
36	NGC0429	0.96±0.4	0.1±0.05	—	—	—	—
37	IC1652	0.66±0.29	0.1±0.04	—	—	—	—
38	NGC0447	21.04±1.04	2.9±0.15	6.07±0.95	—	—	—
39	NGC0444	4.72±0.6	0.6±0.08	7.33±1.17	—	—	—
40	UGC00809	6.83±0.47	0.9±0.07	5.58±1.03	—	—	—
41	UGC00841	7.37±0.76	1.0±0.11	4.37±0.65	—	—	—
42	NGC0477	29.55±1.19	4.2±0.18	25.8±2.88	—	—	—
43	IC1683	57.47±0.65	8.5±0.1	1.05±0.16	—	—	—
44	NGC0499	2.12±0.44	0.3±0.06	—	—	—	—
45	NGC0496	31.62±1.13	4.5±0.17	12.21±1.47	—	—	—
46	NGC0504	0.29±0.16	0.0±0.02	—	—	—	—
47	NGC0517	0.83±0.25	0.1±0.03	—	—	—	—
48	NGC0523	47.4±0.47	6.9±0.07	19.32±3.41	—	—	—
49	UGC00987	14.67±0.66	2.0±0.1	7.35±1.12	—	—	—
50	NGC0528	5.33±1.38	0.7±0.19	—	—	—	—
51	NGC0529	3.36±0.64	0.4±0.08	—	—	—	—
52	NGC0551	20.86±0.89	2.9±0.13	4.24±0.74	—	—	—
53	UGC01057	16.72±1.27	2.3±0.19	12.81±1.72	—	—	—
54	NGC0570	5.78±0.99	0.7±0.14	—	—	—	—
55	UGC01062	0.81±0.36	0.1±0.04	—	—	—	—
56	2MASXJ01331766+1319567	0.56±0.14	0.1±0.02	2.18±0.31	—	—	—
57	UGC01123	1.56±0.46	0.2±0.06	5.67±0.79	—	—	—
58	IC0159	9.48±0.53	1.3±0.07	4.09±0.94	—	—	—
59	UGC01271	0.78±0.33	0.1±0.04	—	—	—	—
60	UGCA021	2.23±0.17	0.3±0.02	3.51±0.55	—	—	—
61	NGC0681	9.45±0.15	1.3±0.02	3.36±0.36	—	—	—
62	UGC01274	1.47±0.69	0.2±0.09	—	—	—	—
63	NGC0677	2.55±0.6	0.3±0.08	—	—	—	—
64	NGC0693	13.05±0.09	1.8±0.01	1.64±0.26	—	—	—
65	NGC0716	125.83±0.85	19.4±0.14	8.39±1.11	—	—	—
66	UGC01368	15.96±1.78	2.2±0.26	—	—	—	—
67	NGC0731	1.24±0.28	0.1±0.04	—	—	—	—
68	NGC0741	5.99±1.03	0.8±0.14	—	2.3	<1.7±0.46	—
69	NGC0755	3.37±0.14	0.4±0.02	4.08±0.29	—	—	—
70	IC1755	4.76±1.22	0.6±0.17	7.39±1.1	—	—	—
71	NGC0768	41.83±1.69	6.1±0.26	24.57±3.15	—	—	—
72	NGC0774	2.68±0.49	0.3±0.06	—	—	—	—
73	NGC0776	40.03±0.99	5.8±0.15	8.17±0.93	—	—	—
74	NGC0781	0.29±0.13	0.0±0.02	—	2.0	<0.22±0.07	—
75	NGC0787	8.09±0.83	1.1±0.12	—	—	—	—
76	NGC0810	6.47±1.43	0.8±0.2	—	—	—	—
77	NGC0825	1.59±0.31	0.2±0.04	3.99±0.58	—	—	—
78	NGC0833	3.91±0.92	0.5±0.12	—	2.1	2.05±0.66	—
79	IC0210	16.85±0.15	2.3±0.02	3.24±0.39	—	—	—
80	NGC0842	1.22±0.28	0.1±0.04	—	—	—	—
81	UGC01659	23.41±2.15	3.3±0.32	10.45±1.39	—	—	—
82	KUG0210-078	4.64±0.74	0.6±0.1	2.91±0.22	—	—	—
83	UGC01749	5.71±1.07	0.7±0.15	7.83±1.17	—	—	—
84	NGC0873	101.19±0.45	15.4±0.07	7.28±0.73	—	—	—
85	NGC0924	3.1±0.59	0.4±0.08	8.89±1.21	—	—	—
86	UGC01918	37.94±0.94	5.5±0.14	1.18±0.17	—	—	—
87	NGC0932	8.79±0.75	1.2±0.1	1.42±0.18	—	—	—
88	UGC01938	17.42±1.17	2.4±0.17	9.63±1.38	—	—	—
89	NGC0941	2.67±0.12	0.3±0.02	3.47±0.6	—	—	—
90	NGC0938	0.63±0.22	0.1±0.03	—	—	—	—
91	NGC0955	1.59±0.1	0.2±0.01	0.9±0.12	—	—	—

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Table continued from previous page

ID	name	L_{IR} $10^9 L_{\odot}$	SFR $M_{\odot} \text{ yr}^{-1}$	M_{HI} $10^9 M_{\odot}$	C_{AP}	M_{H_2} $10^9 M_{\odot}$	$\frac{M_{H_2, Z-dep}}{M_{H_2, stat}}$
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
92	NGC0962	0.88±0.49	0.1±0.06	—	—	—	—
93	UGC02018	0.66±0.38	0.1±0.05	—	—	—	—
94	NGC0976	64.68±0.87	9.6±0.14	11.28±1.23	—	—	—
95	NGC0991	1.96±0.23	0.3±0.04	1.67±0.21	—	—	—
96	UGC02099	2.52±1.07	0.3±0.14	8.4±1.09	—	—	—
97	UGC02134	24.69±1.11	3.5±0.16	10.5±1.31	—	—	—
98	NGC1026	0.96±0.31	0.1±0.04	—	—	—	—
99	NGC1041	1.21±0.6	0.1±0.08	—	—	—	—
100	NGC1056	11.32±0.13	1.5±0.02	3.07±0.41	3.7	1.16±1015.74	—
101	NGC1060	4.17±0.87	0.5±0.12	—	—	—	—
102	NGC1070	34.15±0.84	4.9±0.13	25.89±9.7	—	—	—
103	UGC02222	1.19±0.34	0.1±0.04	—	—	—	—
104	UGC02229	9.85±1.37	1.3±0.19	—	—	—	—
105	UGC02239	10.1±0.84	1.3±0.12	2.74±0.47	—	—	—
106	MCG-01-08-008	13.34±1.34	1.8±0.19	—	—	—	—
107	NGC1094	53.7±2.05	7.9±0.32	9.21±1.2	—	—	—
108	NGC1093	15.87±1.14	2.2±0.17	17.65±2.23	—	—	—
109	UGC02311	31.1±1.81	4.4±0.27	14.5±1.68	—	—	—
110	UGC02319	10.64±1.62	1.4±0.23	5.66±0.91	—	—	—
111	MCG-02-08-014	30.72±0.62	4.4±0.09	—	—	—	—
112	NGC1132	10.3±1.47	1.4±0.21	—	—	—	—
113	UGC02367	64.16±3.02	9.5±0.48	25.95±3.43	—	—	—
114	NGC1142	434.19±1.95	72.1±0.34	—	1.3	7.66±1.31	—
115	UGC02403	119.67±0.54	18.4±0.09	2.43±0.31	—	—	—
116	UGC02405	23.55±2.37	3.3±0.35	17.18±2.11	—	—	—
117	UGC02443	2.28±0.17	0.3±0.02	0.53±0.07	—	—	—
118	UGC02465	1.94±0.47	0.2±0.06	2.64±0.4	—	—	—
119	NGC1167	10.39±1.16	1.4±0.16	10.84±1.8	—	—	—
120	NGC1194	87.86±0.59	13.3±0.09	—	1.6	—	—
121	NGC1211	1.67±0.34	0.2±0.04	7.61±1.15	—	—	—
122	MCG-01-09-006	36.84±2.39	5.3±0.36	—	—	—	—
123	IC0307	27.57±2.53	3.9±0.38	8.12±0.64	—	—	—
124	UGC02628	14.25±1.63	1.9±0.23	13.55±1.67	—	—	—
125	UGC02690	29.54±1.66	4.2±0.25	16.82±2.2	1.9	3.73±1.02	—
126	NGC1324	48.65±1.75	7.1±0.27	29.73±3.46	—	—	—
127	NGC1349	16.02±2.15	2.2±0.31	5.41±1.3	—	—	—
128	NGC1361	1.26±0.34	0.1±0.04	—	—	—	—
129	MCG-01-10-015	6.05±0.73	0.8±0.1	—	—	—	—
130	MCG-01-10-019	9.21±1.09	1.2±0.15	9.04±0.69	—	—	—
131	NGC1542	7.37±0.54	1.0±0.08	1.03±0.16	1.8	1.95±0.53	—
132	UGC03038	25.88±3.07	3.6±0.46	5.33±0.82	—	—	—
133	UGC03107	53.92±2.66	7.9±0.41	12.76±1.7	—	—	—
134	NGC1645	3.06±0.68	0.4±0.09	5.58±0.46	—	—	—
135	UGC03151	9.71±0.89	1.3±0.13	1.66±0.6	—	—	—
136	NGC1656	0.3±0.23	0.0±0.03	—	—	—	—
137	NGC1659	59.72±1.07	8.8±0.17	5.79±0.68	—	—	—
138	NGC1665	59.72±1.07	8.8±0.17	—	2.6	<0.11±0.08	—
139	NGC1666	1.7±0.33	0.2±0.04	—	—	—	—
140	NGC1667	133.72±1.2	20.7±0.2	9.97±1.08	2.1	3.17±0.59	—
141	IC2095	133.72±1.2	20.7±0.2	1.23±0.07	—	—	—
142	IC2098	7.12±0.34	0.9±0.05	3.93±0.49	—	—	—
143	NGC1677	6.89±0.26	0.9±0.04	—	1.6	0.11±0.05	—
144	IC2101	47.08±0.85	6.9±0.13	7.45±0.53	—	—	—
145	ARP180	1.18±0.38	0.1±0.05	—	—	—	—
146	UGC03253	12.94±0.55	1.8±0.08	6.76±0.77	—	—	—
147	NGC2253	50.22±0.56	7.4±0.09	8.54±0.9	—	—	—
148	UGC03539	10.88±0.37	1.5±0.05	4.61±0.73	—	—	—
149	NGC2347	36.77±0.83	5.3±0.13	14.11±1.45	—	—	—
150	UGC03899	1.35±0.38	0.2±0.05	3.94±0.87	1.7	<0.27±0.09	—

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(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
151	NGC2410	78.6±1.06	11.8±0.17	17.9±5.73	—	—	—
152	UGC03944	5.63±0.58	0.7±0.08	6.73±0.88	1.6	7.15±1.66*	1.7
153	UGC03969	42.87±2.79	6.2±0.43	18.82±5.38	—	—	—
154	UGC03973	345.34±1.55	56.6±0.27	8.56±1.0	—	—	—
155	UGC03995	75.87±1.02	11.4±0.16	9.14±1.26	—	—	—
156	NGC2449	12.01±0.97	1.6±0.14	2.8±1.05	—	—	—
157	UGC04029	27.38±0.86	3.9±0.13	15.73±2.77	—	—	—
158	UGC04054	1.21±0.19	0.1±0.02	1.27±0.23	2.0	<0.37±0.1	—
159	IC0480	33.2±0.89	4.7±0.14	6.29±0.99	—	—	—
160	NGC2476	0.87±0.26	0.1±0.03	—	—	—	—
161	NGC2480	4.28±0.23	0.5±0.03	0.51±0.2	—	—	—
162	NGC2481	0.63±0.15	0.1±0.02	0.39±0.15	1.9	<0.0±0.03	—
163	NGC2486	3.58±0.7	0.4±0.09	3.66±0.46	—	—	—
164	NGC2487	8.18±2.83	1.1±0.4	8.25±2.64	—	—	—
165	UGC04132	93.01±1.46	14.1±0.23	15.2±2.28	—	—	—
166	UGC04140	2.94±0.68	0.4±0.09	5.37±0.79	—	—	—
167	UGC04145	139.66±0.94	21.7±0.15	2.53±0.95	—	—	—
168	UGC04136	8.18±1.31	1.1±0.18	—	—	—	—
169	IC0485	36.29±2.52	5.2±0.38	10.87±4.05	—	—	—
170	NGC2507	5.0±0.73	0.6±0.1	—	—	—	—
171	NGC2513	1.5±0.5	0.2±0.06	—	—	—	—
172	UGC04176	0.49±0.14	0.1±0.02	2.91±0.46	—	—	—
173	UGC04190	0.52±0.33	0.1±0.04	—	—	—	—
174	UGC04197	8.83±1.05	1.2±0.15	1.85±0.34	—	—	—
175	UGC04210	6.32±0.83	0.8±0.11	6.13±1.54	—	—	—
176	UGC04195	15.72±0.81	2.2±0.12	7.99±0.97	—	—	—
177	NGC2522	1.32±0.43	0.2±0.05	—	—	—	—
178	UGC04233	15.67±2.31	2.1±0.34	10.69±1.72	—	—	—
179	NGC2530	21.32±1.29	3.0±0.19	9.22±1.0	—	—	—
180	UGC04240	24.78±2.55	3.5±0.38	15.5±2.25	—	—	—
181	UGC04245	18.73±1.26	2.6±0.18	15.09±3.52	—	—	—
182	UGC04258	18.73±1.26	2.6±0.18	2.53±0.33	—	—	—
183	NGC2540	54.23±1.7	8.0±0.27	7.04±0.8	—	—	—
184	NGC2543	17.21±0.35	2.4±0.05	6.01±1.73	—	—	—
185	UGC04280	8.1±0.44	1.1±0.06	4.02±0.28	—	—	—
186	IC2247	23.22±0.83	3.3±0.12	4.37±0.76	1.3	3.2±0.77	—
187	UGC04308	19.21±0.82	2.7±0.12	12.21±1.52	—	—	—
188	NGC2553	0.25±0.2	0.0±0.02	—	—	—	—
189	NGC2554	7.35±0.61	1.0±0.08	1.47±0.36	2.4	5.42±1.26	—
190	UGC04262	17.95±1.01	2.5±0.15	21.36±2.67	—	—	—
191	NGC2558	8.62±1.27	1.1±0.18	15.83±1.99	—	—	—
192	NGC2565	7.02±0.61	0.9±0.08	10.61±1.35	1.4	<0.55±0.55	—
193	UGC04323	2.56±0.45	0.3±0.06	1.62±0.79	—	—	—
194	NGC2572	11.6±2.38	1.6±0.34	16.81±2.32	—	—	—
195	NGC2577	0.5±0.12	0.1±0.01	0.05±0.01	2.7	<0.04±0.01	—
196	UGC04375	4.15±0.31	0.5±0.04	3.24±0.47	—	—	—
197	IC2341	1.65±0.44	0.2±0.06	—	—	—	—
198	UGC04386	22.44±1.16	3.1±0.17	4.05±0.59	1.3	4.12±0.98	—
199	IC2361	2.29±0.17	0.3±0.02	0.26±0.05	—	—	—
200	UGC04405	8.45±1.32	1.1±0.19	10.54±1.44	—	—	—
201	NGC2592	0.17±0.06	0.0±0.01	—	3.0	0.04±0.04	—
202	UGC04416	61.8±1.66	9.2±0.26	22.31±3.24	—	—	—
203	NGC2596	34.13±1.76	4.9±0.27	13.85±1.69	—	—	—
204	NGC2595	25.1±1.35	3.5±0.2	18.98±3.11	2.3	6.1±1.42	—
205	UGC04425	28.55±1.28	4.0±0.19	6.08±1.44	—	—	—
206	NGC2598	15.13±0.85	2.1±0.12	0.42±0.16	—	—	—
207	UGC04464	5.66±0.97	0.7±0.13	6.01±0.93	—	—	—
208	UGC04461	24.75±0.89	3.5±0.13	10.1±0.69	—	—	—
209	NGC2604	5.23±0.23	0.7±0.03	3.36±1.36	—	—	—

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(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
210	UGC04468	1.11±0.58	0.1±0.07	—	—	—	—
211	UGC04505	2.61±0.32	0.3±0.04	—	—	—	—
212	NGC2620	14.34±2.47	2.0±0.36	23.41±8.55	—	—	—
213	NGC2623	355.96±1.6	58.4±0.28	2.84±1.05	—	—	—
214	UGC04515	7.96±1.0	1.0±0.14	5.53±0.81	—	—	—
215	UGC04532	0.54±0.25	0.1±0.03	7.32±1.42	—	—	—
216	NGC2638	3.39±0.41	0.4±0.05	—	—	—	—
217	UGC04548	18.54±1.99	2.6±0.29	12.49±3.73	—	—	—
218	UGC04550	3.56±0.21	0.4±0.03	6.43±2.26	—	—	—
219	NGC2639	18.08±0.45	2.5±0.07	—	—	—	—
220	UGC04546	1.3±0.43	0.2±0.05	—	—	—	—
221	UGC04551	0.02±0.02	0.0±0.0	0.11±0.04	3.8	<0.04±0.01	—
222	UGC04559	1.55±0.15	0.2±0.02	3.36±0.6	—	—	—
223	IC2393	1.9±0.64	0.2±0.08	—	—	—	—
224	UGC04587	0.56±0.2	0.1±0.02	—	—	—	—
225	IC2407	7.93±1.2	1.0±0.17	4.73±0.76	—	—	—
226	UGC04659	7.93±1.2	1.0±0.17	1.04±0.14	1.5	<0.27±0.08	—
227	NGC2692	0.3±0.19	0.0±0.02	4.0±0.6	—	—	—
228	NGC2693	5.18±0.81	0.7±0.11	—	—	—	—
229	NGC2710	3.75±0.25	0.5±0.03	3.41±0.27	—	—	—
230	NGC2719	2.8±0.24	0.3±0.03	9.88±3.82	1.7	<0.07±0.02	—
231	UGC04722	1.13±0.26	0.2±0.04	1.71±0.57	1.3	0.19±0.06	—
232	NGC2730	16.27±0.77	2.2±0.11	6.4±1.72	1.6	1.34±0.38	—
233	NGC2735	4.56±0.51	0.6±0.07	3.33±0.5	—	—	—
234	NGC2738	27.66±0.43	3.9±0.07	4.07±0.67	—	—	—
235	2MASXJ09043394+4517323	0.05±0.04	0.0±0.0	—	—	—	—
236	UGC04773	7.53±0.49	1.0±0.07	3.0±0.94	—	—	—
237	IC2434	91.24±2.46	13.8±0.39	—	—	—	—
238	NGC2764	27.54±0.31	3.9±0.05	2.19±0.62	2.1	2.95±0.79	—
239	UGC04800	0.99±0.2	0.1±0.03	2.43±0.3	—	—	—
240	NGC2742A	94.82±2.13	14.4±0.34	—	—	—	—
241	NGC2769	4.33±0.73	0.5±0.1	2.74±0.77	—	—	—
242	NGC2776	26.93±0.42	3.8±0.06	13.29±1.28	—	—	—
243	NGC2778	0.24±0.07	0.0±0.01	—	2.5	<0.02±0.04	—
244	UGC04845	1.22±0.21	0.1±0.03	3.21±0.53	1.4	<0.2±0.06	—
245	UGC04851	1.68±0.76	0.2±0.1	—	—	—	—
246	NGC2783	1.65±0.86	0.2±0.11	—	3.3	—	—
247	UGC04869	31.1±1.81	4.4±0.27	—	—	—	—
248	NGC2794	18.66±2.75	2.6±0.4	—	—	—	—
249	NGC2795	2.32±1.6	0.3±0.21	—	—	—	—
250	NGC2796	7.88±1.58	1.0±0.22	—	—	—	—
251	IC2450	4.02±0.11	0.5±0.01	—	—	—	—
252	UGC04906	3.96±0.21	0.5±0.03	1.56±0.2	—	—	—
253	NGC2800	1.66±0.79	0.2±0.1	—	—	—	—
254	UGC04926	24.73±1.83	3.5±0.27	14.88±2.27	—	—	—
255	CGCG151-054	24.73±1.83	3.5±0.27	—	—	—	—
256	UGC04938	15.96±2.57	2.2±0.37	4.45±0.77	—	—	—
257	NGC2826	3.97±0.98	0.5±0.13	—	—	—	—
258	NGC2832	3.08±1.89	0.4±0.25	—	4.4	8.08±22898.02	—
259	IC2461	7.62±0.22	1.0±0.03	3.88±0.72	—	—	—
260	NGC2805	4.06±0.52	0.5±0.07	11.43±2.43	19.4	1.75±0.46	—
261	UGC04958	40.46±2.09	5.8±0.32	—	—	—	—
262	UGC04970	0.52±0.14	0.1±0.02	1.09±0.17	—	—	—
263	UGC04982	4.6±0.29	0.6±0.04	1.02±0.2	—	—	—
264	NGC2854	15.31±0.24	2.1±0.03	3.6±0.44	—	—	—
265	NGC2860	44.57±0.7	6.5±0.11	—	—	—	—
266	NGC2872	2.02±0.37	0.2±0.05	—	—	—	—
267	NGC2874	27.12±2.35	4.7±0.41	3.51±0.52	—	—	—
268	UGC05020	27.12±2.35	4.7±0.41	0.77±0.13	—	—	—

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(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
269	NGC2882	5.94±0.24	0.8±0.03	1.13±0.27	—	—	—
270	2MASXJ09283754+3832213	1.95±0.39	0.2±0.05	—	—	—	—
271	NGC2894	3.51±0.24	0.4±0.03	3.68±0.41	—	—	—
272	NGC2880	0.21±0.05	0.0±0.01	—	3.5	<0.03±0.01	—
273	IC2487	12.97±0.93	1.8±0.13	9.89±2.1	1.5	7.13±1.77*	1.6
274	IC0540	1.11±0.14	0.1±0.02	—	—	—	—
275	NGC2906	7.2±0.24	0.9±0.03	0.91±0.11	—	—	—
276	NGC2919	6.42±0.29	0.8±0.04	2.06±0.28	—	—	—
277	NGC2916	22.57±0.96	3.2±0.14	6.82±2.42	—	—	—
278	UGC05108	76.85±2.41	11.5±0.38	—	—	—	—
279	NGC2918	4.22±0.81	0.5±0.11	—	—	—	—
280	UGC05111	41.8±1.69	6.1±0.26	—	—	—	—
281	UGC05113	1.16±0.6	0.1±0.08	—	—	—	—
282	NGC2927	20.91±2.48	2.9±0.37	21.93±7.87	—	—	—
283	NGC2929	88.01±2.76	13.3±0.44	25.51±5.32	—	—	—
284	NGC2939	23.29±0.52	3.3±0.08	12.71±1.86	—	—	—
285	NGC2943	1.17±1.04	0.1±0.13	—	—	—	—
286	NGC2942	14.2±1.02	1.9±0.15	14.86±1.83	—	—	—
287	UGC05145	72.36±2.27	10.8±0.36	—	—	—	—
288	NGC2954	0.9±0.25	0.1±0.03	—	—	—	—
289	UGC05164	25.12±1.69	3.5±0.25	—	—	—	—
290	UGC05157	23.68±0.85	3.3±0.13	8.69±1.14	—	—	—
291	NGC2955	84.33±2.08	12.7±0.33	28.0±3.3	—	—	—
292	NGC2968	0.15±0.05	0.0±0.01	0.33±0.08	—	—	—
293	NGC2965	5.08±1.18	0.7±0.16	—	—	—	—
294	NGC2959	14.16±0.89	1.9±0.13	1.68±0.26	—	—	—
295	UGC05215	19.91±1.43	2.8±0.21	15.17±1.91	—	—	—
296	IC0565	16.28±1.42	2.2±0.21	20.88±3.52	—	—	—
297	UGC05244	1.61±0.29	0.2±0.04	2.7±0.49	—	—	—
298	UGC05267	20.41±1.42	2.8±0.21	1.51±0.27	—	—	—
299	NGC3021	9.61±0.11	1.3±0.02	1.4±0.16	1.4	0.71±1379.17	—
300	UGC05315	0.98±0.33	0.1±0.04	—	—	—	—
301	UGC05320	7.11±0.78	0.9±0.11	7.41±1.03	—	—	—
302	NGC3053	15.79±0.6	2.2±0.09	3.13±0.42	—	—	—
303	NGC3043	12.07±0.24	1.6±0.03	1.94±0.33	—	—	—
304	NGC3060	15.94±0.57	2.2±0.08	5.27±1.07	—	—	—
305	NGC3070	15.94±0.57	2.2±0.08	—	—	—	—
306	UGC05358	2.88±0.63	0.5±0.11	2.1±0.81	—	—	—
307	UGC05359	21.56±2.56	3.0±0.38	23.77±3.0	—	—	—
308	NGC3075	16.42±0.66	2.3±0.1	10.73±3.65	—	—	—
309	UGC05396	6.59±1.07	0.9±0.15	8.72±1.24	—	—	—
310	SDSSJ100141.02+371447.4	0.23±0.06	0.0±0.01	—	—	—	—
311	NGC3106	11.48±1.67	1.5±0.24	9.68±2.67	—	—	—
312	NGC3057	1.04±0.1	0.1±0.01	0.99±0.16	3.5	<0.18±0.06*	4.3
313	UGC05481	31.11±1.81	4.4±0.27	12.03±3.68	—	—	—
314	UGC05498NED01	15.31±1.71	2.1±0.25	—	—	—	—
315	UGC05499	16.95±1.1	2.3±0.16	13.7±1.44	—	—	—
316	IC0598	0.39±0.11	0.0±0.01	—	2.0	<0.05±0.02	—
317	NGC3153	5.08±0.4	0.7±0.05	8.49±1.15	—	—	—
318	NGC3158	10.0±1.4	1.3±0.2	—	—	—	—
319	NGC3160	33.74±1.29	4.8±0.19	—	—	—	—
320	UGC05520	4.61±0.37	0.6±0.05	9.86±1.01	—	—	—
321	UGC05529	7.33±1.23	1.0±0.17	9.99±2.59	—	—	—
322	NGC3179	0.58±0.42	0.1±0.05	—	—	—	—
323	NGC3182	1.68±0.13	0.2±0.02	0.37±0.03	3.3	0.52±0.15	—
324	NGC3209	3.29±0.79	0.4±0.1	—	—	—	—
325	UGC05597	8.61±1.15	1.1±0.16	9.36±3.39	—	—	—
326	UGC05598	15.06±1.32	2.1±0.19	8.88±1.74	—	—	—
327	UGC05604	5.96±0.87	0.8±0.12	7.06±0.83	—	—	—

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ID	name	L_{IR} $10^9 L_{\odot}$	SFR $M_{\odot} \text{ yr}^{-1}$	M_{HI} $10^9 M_{\odot}$	C_{AP}	M_{H_2} $10^9 M_{\odot}$	$\frac{M_{H_2, Z-dep}}{M_{H_2, stat}}$
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
328	NGC3230	0.76±0.21	0.1±0.03	—	3.4	<0.1±0.03	—
329	UGC05642	2.17±0.21	0.3±0.03	1.76±0.3	—	—	—
330	NGC3237	9.16±1.7	1.2±0.24	—	—	—	—
331	UGC05657	32.39±1.82	4.6±0.27	—	—	—	—
332	NGC3251	21.12±1.14	2.9±0.17	6.92±0.69	—	—	—
333	UGC05680	4.76±1.21	0.6±0.16	—	—	—	—
334	UGC05695	1.64±0.34	0.2±0.04	2.59±0.87	—	—	—
335	UGC05693	39.71±2.23	5.7±0.34	—	—	—	—
336	UGC05713	76.74±1.72	11.5±0.27	7.71±0.76	—	—	—
337	UGC05727	2.17±0.26	0.3±0.03	—	—	—	—
338	UGC05760	10.48±0.49	1.4±0.07	2.06±0.17	—	—	—
339	NGC3300	1.5±0.23	0.2±0.03	—	—	—	—
340	NGC3303	4.84±1.07	0.6±0.15	5.12±0.42	—	—	—
341	UGC05771	5.86±1.34	0.8±0.18	—	—	—	—
342	NGC3304	15.06±1.65	2.1±0.24	—	—	—	—
343	NGC3320	11.61±0.26	1.6±0.04	4.23±0.46	—	—	—
344	NGC3332	2.37±0.69	0.3±0.09	—	—	—	—
345	NGC3334	12.23±1.56	1.6±0.22	—	—	—	—
346	UGC05820	2.28±0.37	0.3±0.05	—	1.3	2.72±0.66	—
347	NGC3352	1.87±0.68	0.2±0.09	—	—	—	—
348	UGC05855	43.17±1.65	6.3±0.25	8.19±1.12	—	—	—
349	UGC05859	2.21±0.77	0.3±0.1	—	—	—	—
350	NGC3363	36.27±1.22	5.2±0.19	8.83±3.3	—	—	—
351	UGC05894	29.06±1.56	4.1±0.23	17.09±5.8	—	—	—
352	IC0642	3.35±1.03	0.4±0.14	—	—	—	—
353	NGC3381	4.25±0.13	0.5±0.02	2.08±0.27	—	—	—
354	UGC05924	8.11±2.08	1.1±0.29	11.2±3.38	—	—	—
355	NGC3395	8.11±2.08	1.1±0.29	2.81±0.33	1.5	0.34±0.09	—
356	UGC05957	13.32±0.93	1.8±0.13	3.47±0.21	—	—	—
357	NGC3419A	4.87±0.37	0.6±0.05	5.24±0.95	—	—	—
358	NGC3426	7.23±1.26	0.9±0.18	—	—	—	—
359	NGC3415	10.85±0.41	1.5±0.06	1.01±0.14	—	—	—
360	NGC3406NED01	10.85±0.41	1.5±0.06	—	—	—	—
361	UGC05990	0.56±0.06	0.1±0.01	0.67±0.22	—	—	—
362	NGC3440	1.47±0.12	0.2±0.01	3.82±0.49	—	—	—
363	NGC3462	1.72±0.97	0.2±0.13	—	—	—	—
364	UGC06036	5.86±1.08	0.8±0.15	—	—	—	—
365	NGC3468	2.88±0.8	0.4±0.11	—	—	—	—
366	UGC06062	0.45±0.1	0.1±0.01	—	2.0	<0.05±0.02	—
367	UGC06063	15.89±1.64	2.2±0.24	7.99±1.13	—	—	—
368	NGC3471	45.9±0.21	6.7±0.03	0.91±0.1	2.0	2.99±1.19	—
369	NGC3488	6.28±0.42	0.8±0.06	3.82±0.44	—	—	—
370	UGC06104	0.47±0.13	0.1±0.02	3.45±0.46	—	—	—
371	UGC06106	29.17±1.57	4.1±0.24	6.02±0.88	—	—	—
372	UGC06136	54.42±1.95	8.0±0.3	13.96±1.01	—	—	—
373	UGC06148	23.21±1.56	3.2±0.23	—	—	—	—
374	UGC06176	18.5±0.33	2.6±0.05	—	2.3	0.74±0.21	—
375	NGC3540	18.5±0.33	2.6±0.05	—	—	—	—
376	UGC06199	13.89±0.75	1.9±0.11	9.34±1.17	—	—	—
377	UGC06207	73.69±2.81	11.0±0.45	—	—	—	—
378	NGC3547	4.14±0.13	0.5±0.02	1.36±0.18	—	—	—
379	NGC3543	0.85±0.08	0.1±0.01	—	—	—	—
380	UGC06219	36.45±1.72	5.2±0.26	—	—	—	—
381	IC0674	6.06±1.28	0.8±0.18	11.09±0.9	—	—	—
382	NGC3561	11.81±4.04	1.6±0.58	—	1.1	12.99±3.22	—
383	UGC06256	1.22±0.24	0.1±0.03	—	—	—	—
384	IC0677	10.24±0.46	1.4±0.06	3.7±0.46	—	—	—
385	UGC06273	7.81±1.34	1.0±0.19	—	—	—	—
386	UGC06312	8.62±1.23	1.1±0.17	—	—	—	—

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(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
387	NGC3615	3.18±0.87	0.4±0.12	—	—	—	—
388	NGC3614	6.74±0.35	0.9±0.05	9.23±0.47	—	—	—
389	NGC3610	0.91±0.1	0.1±0.01	—	4.6	<0.05±0.02	—
390	UGC06332	8.75±1.47	1.2±0.21	—	—	—	—
391	NGC3619	1.42±0.11	0.2±0.01	0.81±0.09	5.6	0.69±0.2	—
392	UGC06336	1.19±0.71	0.1±0.09	—	—	—	—
393	NGC3625	1.63±0.12	0.2±0.01	2.65±0.34	—	—	—
394	NGC3629	1.7±0.11	0.2±0.01	3.15±0.38	—	—	—
395	UGC06355	1.7±0.11	0.2±0.01	2.32±0.4	—	—	—
396	CGCG126-035	2.04±0.94	0.2±0.12	—	—	—	—
397	UGC06380	17.38±1.44	2.4±0.21	—	—	—	—
398	UGC06383	0.42±0.15	0.0±0.02	2.14±0.3	—	—	—
399	NGC3649	21.67±0.78	3.0±0.11	4.11±1.16	—	—	—
400	NGC3642	2.84±0.11	0.4±0.01	10.49±1.17	—	—	—
401	IC2763	0.44±0.07	0.0±0.01	0.33±0.07	—	—	—
402	NGC3648	0.21±0.06	0.0±0.01	—	2.0	<0.03±0.01	—
403	NGC3650	3.2±0.56	0.4±0.07	—	—	—	—
404	NGC3652	8.87±0.18	1.2±0.03	2.87±0.35	—	—	—
405	UGC06397	22.65±1.22	3.2±0.18	2.82±0.66	—	—	—
406	NGC3656	13.89±0.28	1.9±0.04	2.12±0.33	3.0	6.86±2850.03	—
407	UGC06414	10.24±1.99	1.4±0.28	9.86±1.91	—	—	—
408	NGC3668	18.29±0.45	2.5±0.07	2.1±0.28	—	—	—
409	UGC06433	5.75±0.18	0.7±0.02	1.21±0.1	—	—	—
410	NGC3674	0.16±0.06	0.0±0.01	—	2.9	0.02±0.04	—
411	UGC06455	0.1±0.03	0.0±0.0	—	—	—	—
412	NGC3683	38.52±0.09	5.6±0.01	1.2±0.15	—	—	—
413	NGC3682	6.66±0.07	0.9±0.01	0.28±0.04	1.5	0.63±0.16	—
414	NGC3687	4.4±0.31	0.6±0.04	2.63±0.45	—	—	—
415	NGC3697	21.64±1.89	3.0±0.28	24.71±3.56	—	—	—
416	NGC3683A	7.99±0.29	1.1±0.04	5.37±0.56	—	—	—
417	NGC3712	7.99±0.29	1.1±0.04	1.02±0.08	—	—	—
418	NGC3752	3.13±0.13	0.4±0.02	0.59±0.05	1.5	0.26±0.08	—
419	UGC06526	2.57±0.14	0.3±0.02	0.51±0.13	—	—	—
420	NGC3728	6.8±1.29	0.9±0.18	8.17±0.63	—	—	—
421	NGC3725	17.61±0.43	2.4±0.06	2.34±0.29	—	—	—
422	UGC06545	12.45±0.28	1.7±0.04	0.41±0.09	—	—	—
423	UGC06588	2.51±0.55	0.3±0.07	3.2±0.46	—	—	—
424	NGC3762	1.38±0.23	0.2±0.03	—	—	—	—
425	NGC3772	1.38±0.23	0.2±0.03	—	—	—	—
426	NGC3753	30.02±1.45	4.3±0.22	—	2.3	<5.96±1.79	—
427	UGC06617	1.54±0.49	0.2±0.06	—	—	—	—
428	NGC3780	17.22±0.32	2.4±0.05	5.37±0.55	—	—	—
429	NGC3786	17.22±0.32	2.4±0.05	5.04±0.66	—	—	—
430	NGC3800	46.69±0.52	6.8±0.08	2.72±0.47	1.6	5.87±7186.27	—
431	NGC3798	12.86±0.49	1.7±0.07	1.63±0.37	1.8	2.24±0.65	—
432	NGC3801	4.47±0.45	0.6±0.06	2.05±0.32	6.0	3.29±1.28	—
433	NGC3805	8.12±1.14	1.1±0.16	—	—	—	—
434	NGC3812	1.64±0.33	0.2±0.04	—	—	—	—
435	NGC3809	1.6±0.24	0.2±0.03	3.75±1.17	—	—	—
436	NGC3811	23.78±0.48	3.3±0.07	7.88±0.46	—	—	—
437	NGC3815	11.03±0.57	1.5±0.08	6.06±2.03	—	—	—
438	UGC06653	19.67±0.44	2.7±0.06	0.72±0.11	1.3	1.29±0.38	—
439	NGC3816	0.12±0.12	0.0±0.01	—	—	—	—
440	NGC3825	10.91±1.75	1.5±0.25	2.79±0.77	—	—	—
441	UGC06677	5.73±1.52	0.7±0.21	—	—	—	—
442	IC2951	1.88±0.85	0.2±0.11	—	—	—	—
443	NGC3832	60.91±2.59	9.0±0.41	29.26±7.11	1.7	14.88±3.78	—
444	UGC06697	63.84±2.29	9.5±0.36	8.8±1.34	2.1	10.41±2.78	—
445	NGC3842	2.78±1.0	0.3±0.13	—	2.5	—	—

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(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
446	NGC3853	0.88±0.26	0.1±0.03	—	—	—	—
447	NGC3862	5.36±0.92	0.7±0.13	—	2.8	0.98±0.32	—
448	NGC3867	0.88±0.65	0.1±0.08	—	—	—	—
449	NGC3869	1.67±0.26	0.2±0.03	—	—	—	—
450	NGC3872	1.1±0.27	0.1±0.03	—	—	—	—
451	NGC3884	24.16±2.06	3.4±0.31	6.57±0.85	1.6	5.48±1.59	—
452	NGC3883	5.64±0.93	0.7±0.13	27.02±8.81	2.4	4.97±1.6	—
453	NGC3886	0.46±0.36	0.1±0.04	—	—	—	—
454	UGC06758	5.09±0.42	0.7±0.06	2.93±0.23	—	—	—
455	NGC3888	26.75±0.24	3.8±0.04	3.66±0.53	2.7	4.13±1768.88	—
456	NGC3891	58.88±1.85	8.7±0.29	29.02±3.71	—	—	—
457	UGC06774	1.28±0.16	0.2±0.02	1.94±0.31	—	—	—
458	NGC3897	35.2±1.82	5.0±0.28	58.99±19.19	—	—	—
459	UGC06791	0.63±0.13	0.1±0.02	0.86±0.2	—	—	—
460	UGC06794	3.89±0.41	0.5±0.05	3.04±0.59	—	—	—
461	NGC3910	2.83±1.0	0.4±0.13	—	—	—	—
462	NGC3899	9.63±0.13	1.3±0.02	0.98±0.22	—	—	—
463	NGC3916	25.64±1.15	3.6±0.17	—	—	—	—
464	NGC3921	37.4±1.09	5.4±0.17	9.12±3.21	—	—	—
465	UGC06845	27.38±1.47	3.9±0.22	4.85±0.75	—	—	—
466	NGC3937	3.57±0.94	0.4±0.13	—	—	—	—
467	NGC3944	0.11±0.09	0.0±0.01	—	—	—	—
468	NGC3947	45.72±1.74	6.7±0.27	11.8±2.4	1.3	6.24±1.66	—
469	IC2973	4.17±0.38	0.5±0.05	3.79±0.44	—	—	—
470	NGC3958	1.34±0.28	0.2±0.04	2.26±0.29	—	—	—
471	UGC06891	19.3±1.51	2.7±0.22	14.67±2.1	—	—	—
472	NGC3968	62.67±2.81	9.3±0.44	45.5±6.91	—	—	—
473	UGC06905	9.95±1.31	1.3±0.19	8.18±2.34	—	—	—
474	NGC3987	68.23±1.07	10.2±0.17	8.34±1.16	1.6	24.25±13327.85	—
475	NGC3991	28.39±0.45	4.0±0.07	8.62±2.22	1.2	0.65±0.24	—
476	NGC3994	36.89±0.41	5.3±0.06	—	2.4	2.15±0.95	—
477	NGC3993	10.39±0.86	1.4±0.12	5.6±1.02	—	—	—
478	NGC3995	37.88±0.6	5.5±0.09	15.73±2.43	7.5	8.41±3.33	—
479	NGC4003	15.63±1.36	2.1±0.2	—	—	—	—
480	NGC4002	3.35±0.59	0.4±0.08	—	—	—	—
481	NGC4008	0.97±0.34	0.1±0.04	—	—	—	—
482	NGC4012	5.12±0.61	0.7±0.08	6.62±0.98	—	—	—
483	NGC4018	38.78±0.78	5.6±0.12	8.67±1.85	—	—	—
484	NGC4015NED01	3.5±0.29	0.4±0.04	—	—	—	—
485	NGC4017	29.82±0.6	4.2±0.09	12.1±3.86	1.4	2.15±0.57	—
486	UGC07012	3.7±0.33	0.5±0.04	5.96±0.76	—	—	—
487	UGC07017	31.9±0.43	4.5±0.06	4.55±1.4	1.3	2.25±0.74	—
488	UGC07016	72.79±2.12	10.9±0.34	—	—	—	—
489	NGC4047	41.41±0.46	6.0±0.07	3.62±0.45	—	—	—
490	UGC07031	3.19±0.49	0.4±0.07	4.06±0.65	—	—	—
491	UGC07041	0.41±0.11	0.0±0.01	3.64±0.64	—	—	—
492	SDSSJ120353.51+252556.6	3.36±0.36	0.4±0.05	—	—	—	—
493	NGC4070	5.06±1.32	0.6±0.18	—	—	—	—
494	NGC4078	0.36±0.12	0.0±0.01	—	1.8	<0.05±0.02	—
495	UGC07082	13.46±1.66	1.8±0.24	—	—	—	—
496	UGC07100	10.34±0.74	1.4±0.11	7.78±1.24	—	—	—
497	NGC4131	0.22±0.14	0.0±0.02	0.95±0.37	—	—	—
498	NGC4134	12.83±0.72	1.7±0.1	11.51±2.26	1.6	1.92±0.58	—
499	UGC07141	8.97±1.26	1.2±0.18	27.89±8.71	—	—	—
500	UGC07145	9.45±1.52	1.3±0.21	—	—	—	—
501	NGC4148	14.05±1.35	1.9±0.2	—	—	—	—
502	NGC4149	10.05±0.29	1.3±0.04	—	—	—	—
503	NGC4155	1.09±0.65	0.1±0.08	—	—	—	—
504	UGC07180	11.75±1.24	1.6±0.18	—	—	—	—

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(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
505	UGC07179	17.59±0.2	2.4±0.03	—	—	—	—
506	NGC4158	4.99±0.27	0.6±0.04	2.42±0.27	1.6	1.14±0.31	—
507	IC0768	2.42±0.5	0.3±0.06	6.3±0.75	—	—	—
508	NGC4162	16.98±0.38	2.3±0.06	6.37±0.88	1.7	2.98±0.73	—
509	NGC4168	0.28±0.09	0.0±0.01	—	6.0	<0.08±0.11	—
510	NGC4169	3.65±0.51	0.5±0.07	3.01±0.86	—	—	—
511	NGC4175	65.75±0.59	9.8±0.09	3.59±0.82	1.3	9.84±2.33	—
512	IC0769	3.13±0.27	0.4±0.04	2.81±0.24	1.8	<0.29±0.08	—
513	NGC4180	15.02±0.2	2.0±0.03	0.76±0.22	—	—	—
514	IC3046	13.0±1.92	1.8±0.28	27.44±3.8	—	—	—
515	NGC4185	13.17±0.83	1.8±0.12	9.71±3.58	—	—	—
516	NGC4191	0.39±0.12	0.0±0.01	—	1.9	<0.08±0.05	—
517	NGC4200	0.26±0.09	0.0±0.01	—	—	—	—
518	NGC4210	6.74±0.3	0.9±0.04	1.48±0.12	—	—	—
519	UGC07270	48.84±1.64	7.1±0.25	11.69±2.27	—	—	—
520	NGC4211NED02	49.71±1.67	7.3±0.26	—	—	—	—
521	NGC4213	0.54±0.46	0.1±0.06	—	—	—	—
522	UGC07286	42.23±1.99	6.1±0.31	4.8±1.68	1.3	<5.61±1.54	—
523	NGC4227	2.84±0.83	0.4±0.11	—	—	—	—
524	NGC4238	4.1±0.27	0.5±0.04	3.16±0.41	—	—	—
525	NGC4233	0.86±0.14	0.1±0.02	—	4.4	<0.03±0.1	—
526	2MASXJ12170922+1227142	0.95±0.18	0.1±0.02	—	—	—	—
527	NGC4256	5.43±0.28	0.7±0.04	1.79±0.11	—	—	—
528	IC0776	1.01±0.2	0.1±0.03	3.72±0.47	1.4	<1.02±0.28*	4.3
529	UGC07358	8.57±0.54	1.1±0.08	4.28±0.6	—	—	—
530	UGC07367	1.3±0.26	0.2±0.03	—	—	—	—
531	NGC4272	0.23±0.22	0.0±0.03	—	—	—	—
532	NGC4284	7.56±0.63	1.0±0.09	10.34±1.17	—	—	—
533	NGC4290	44.47±0.3	6.5±0.05	3.59±0.27	—	—	—
534	UGC07416	43.26±1.94	6.3±0.3	15.41±2.32	—	—	—
535	IC3203	6.85±1.36	0.9±0.19	11.41±1.72	—	—	—
536	NGC4305	6.85±1.36	0.9±0.19	—	—	—	—
537	NGC4306	0.09±0.04	0.0±0.0	—	—	—	—
538	NGC4351	3.17±0.25	0.4±0.03	1.11±0.13	—	—	—
539	NGC4352	0.25±0.1	0.0±0.01	—	3.0	<0.01±0.05	—
540	IC3300	15.62±1.43	2.1±0.21	5.67±1.73	—	—	—
541	IC3305	0.08±0.04	0.0±0.0	—	—	—	—
542	NGC4383	29.57±0.13	4.2±0.02	4.19±1.31	1.7	0.51±1986.56	—
543	NGC4405	4.4±0.13	0.6±0.02	0.17±0.02	1.5	0.85±0.23	—
544	IC3376	23.86±1.66	3.3±0.25	7.04±2.68	—	—	—
545	NGC4450	7.97±0.29	1.0±0.04	0.83±0.31	3.5	3.9±0.95	—
546	IC3392	4.13±0.13	0.5±0.02	0.19±0.03	—	—	—
547	IC0796	1.63±0.08	0.2±0.01	0.04±0.01	—	—	—
548	NGC4470	8.88±0.24	1.2±0.03	2.01±0.22	1.3	1.53±0.4*	1.7
549	NGC4475	17.19±1.92	2.4±0.28	12.87±1.62	1.4	6.02±1.82	—
550	NGC4474	0.19±0.05	0.0±0.01	—	3.4	<0.04±0.03	—
551	NGC4476	1.44±0.12	0.2±0.01	—	2.8	0.67±1224.35	—
552	NGC4500	50.47±0.34	7.4±0.05	4.23±0.5	—	—	—
553	NGC4495	62.1±0.84	9.2±0.13	16.47±3.88	—	—	—
554	IC3453	0.6±0.16	0.1±0.02	0.67±0.17	—	—	—
555	IC0797	2.91±0.19	0.4±0.02	0.84±0.13	—	—	—
556	IC0800	3.03±0.22	0.4±0.03	0.36±0.04	—	—	—
557	NGC4545	9.41±0.3	1.2±0.04	5.17±0.3	—	—	—
558	UGC07740	20.83±2.24	2.9±0.33	—	—	—	—
559	NGC4555	3.75±0.96	0.5±0.13	—	—	—	—
560	NGC4556	1.41±0.68	0.2±0.09	—	—	—	—
561	NGC4570	0.77±0.12	0.1±0.01	—	5.4	<0.0±0.0	—
562	IC3598	7.9±1.38	1.0±0.19	2.63±0.38	1.3	<1.7±1.62	—
563	NGC4578	1.42±0.34	0.2±0.04	—	6.8	<0.16±0.14	—

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(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
564	UGC07799	46.53±1.88	6.8±0.29	—	—	—	—
565	NGC4584	0.83±0.09	0.1±0.01	—	—	—	—
566	NGC4598	0.25±0.12	0.0±0.01	—	—	—	—
567	UGC07848	1.08±0.19	0.1±0.02	2.36±0.27	—	—	—
568	NGC4612	0.39±0.09	0.0±0.01	—	4.8	<0.06±0.02	—
569	NGC4644	9.77±0.77	1.3±0.11	5.84±0.94	—	—	—
570	NGC4644B	8.45±0.62	1.1±0.09	—	—	—	—
571	NGC4641	1.32±0.13	0.2±0.02	0.16±0.06	—	—	—
572	IC3704	87.61±2.95	13.3±0.47	31.12±3.68	1.2	7.09±2.1	—
573	UGC07904	4.71±0.64	0.6±0.09	—	—	—	—
574	UGC07922	13.88±0.59	1.9±0.09	13.31±1.94	—	—	—
575	NGC4675	47.03±0.63	6.9±0.1	5.08±0.74	—	—	—
576	UGC07941	0.15±0.04	0.0±0.0	4.64±0.82	1.9	<0.36±0.1	—
577	NGC4676A	103.23±1.62	15.8±0.26	—	2.8	6.38±2956.07	—
578	NGC4686	15.99±0.79	2.2±0.11	—	—	—	—
579	UGC07959	0.35±0.32	0.0±0.04	—	—	—	—
580	NGC4711	13.59±0.64	1.8±0.09	5.3±1.66	—	—	—
581	UGC08004	3.51±0.91	0.4±0.12	11.09±1.55	1.4	<1.07±1.03	—
582	NGC4746	15.13±0.17	2.1±0.02	2.67±0.42	2.4	1.38±2954.35	—
583	NGC4779	20.39±0.37	2.8±0.05	3.7±0.65	—	—	—
584	UGC08025	10.76±1.2	1.4±0.17	14.64±2.75	1.4	<1.33±1.28	—
585	UGC08040	12.41±0.17	1.7±0.02	3.03±0.45	—	—	—
586	NGC4795	0.71±0.19	0.1±0.02	0.84±0.11	—	—	—
587	IC0836	18.81±0.21	2.6±0.03	—	—	—	—
588	NGC4816	1.73±0.72	0.2±0.09	—	—	—	—
589	NGC4841A	3.88±1.18	0.5±0.16	—	—	—	—
590	NGC4846	14.03±0.66	1.9±0.1	8.56±2.06	1.9	0.89±0.27	—
591	NGC4859	3.39±1.12	0.4±0.15	—	—	—	—
592	NGC4874	2.33±1.49	0.3±0.2	—	—	—	—
593	UGC08107	58.69±2.24	8.7±0.35	—	—	—	—
594	NGC4892	1.04±0.41	0.1±0.05	—	1.2	<0.72±0.69	—
595	NGC4895	5.46±1.42	0.7±0.19	—	—	—	—
596	UGC08119	12.9±1.99	1.7±0.29	—	—	—	—
597	IC0843	5.92±1.25	0.8±0.17	—	—	—	—
598	IC4088	20.89±1.59	2.9±0.23	11.17±1.6	1.3	2.56±1.06	—
599	NGC4931	1.14±0.38	0.1±0.05	—	—	—	—
600	NGC4944	1.85±0.66	0.2±0.09	—	—	—	—
601	NGC4952	2.83±0.66	0.4±0.09	—	—	—	—
602	NGC4956	2.81±0.51	0.3±0.07	—	—	—	—
603	NGC4961	6.53±0.23	0.8±0.03	5.14±0.57	1.4	<1.02±0.28*	1.7
604	NGC4978	1.44±0.56	0.2±0.07	—	—	—	—
605	IC4202	22.79±1.89	3.2±0.28	10.57±1.88	—	—	—
606	UGC08231	1.62±0.17	0.2±0.02	—	—	—	—
607	UGC08234	6.39±1.31	0.8±0.18	—	—	—	—
608	NGC5000	34.93±1.02	5.0±0.15	8.11±1.79	1.4	3.16±0.74*	0.8
609	UGC08250	8.75±0.8	1.2±0.11	5.95±0.98	—	—	—
610	UGC08267	36.04±1.54	5.2±0.23	—	—	—	—
611	NGC5016	10.69±0.34	1.4±0.05	3.56±0.41	1.5	1.39±0.33*	0.7
612	NGC5029	3.12±1.15	0.4±0.15	—	—	—	—
613	UGC08322	9.75±1.59	1.3±0.22	2.06±0.41	—	—	—
614	NGC5056	38.86±1.05	5.6±0.16	15.32±1.91	1.4	2.33±0.94	—
615	IC4215	7.78±0.51	1.0±0.07	0.4±0.07	—	—	—
616	NGC5057	0.48±0.25	0.1±0.03	—	—	—	—
617	NGC5081	20.61±2.12	2.9±0.31	20.68±2.93	1.5	8.4±2.28	—
618	IC0881	1.93±0.61	0.2±0.08	—	—	—	—
619	IC4225	3.71±0.64	0.5±0.09	—	—	—	—
620	NGC5127	1.3±0.4	0.2±0.05	—	5.4	0.42±0.11	—
621	NGC5125	47.35±2.02	6.9±0.31	11.03±1.76	—	—	—
622	NGC5129	4.42±1.03	0.6±0.14	—	—	—	—

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623	UGC08451	8.0±1.04	1.1±0.14	8.34±1.01	—	—	—
624	NGC5157	3.38±0.86	0.4±0.11	4.53±1.23	—	—	—
625	UGC08457	30.84±1.18	4.4±0.18	7.01±1.15	—	—	—
626	NGC5169	2.32±0.19	0.3±0.02	3.69±0.55	—	—	—
627	NGC5166	18.64±0.79	2.6±0.12	2.46±0.75	—	—	—
628	2MASXJ13283353+4655382	0.63±0.15	0.1±0.02	2.05±0.29	—	—	—
629	NGC5165	5.95±1.14	0.8±0.16	—	—	—	—
630	NGC5205	2.14±0.1	0.3±0.01	2.95±0.31	—	—	—
631	NGC5198	0.61±0.14	0.1±0.02	—	4.0	<0.0±0.0	—
632	UGC08498	23.49±1.95	3.3±0.29	36.12±11.74	1.7	9.9±2.68	—
633	NGC5216	0.68±0.13	0.1±0.02	1.9±0.24	—	—	—
634	NGC5218	65.87±0.15	9.8±0.02	1.71±0.2	2.0	11.13±2.92*	1.2
635	NGC5207	29.84±2.21	4.2±0.33	23.29±3.01	—	—	—
636	NGC5208	16.19±1.34	2.2±0.2	—	—	—	—
637	NGC5210	16.39±1.54	2.2±0.22	2.29±0.76	—	—	—
638	UGC08539	29.22±2.03	4.1±0.31	17.37±6.09	—	—	—
639	NGC5223	2.8±0.88	0.3±0.12	—	—	—	—
640	IC0900	64.01±2.3	9.5±0.36	19.51±2.17	—	—	—
641	NGC5222NED01	4.87±0.69	0.6±0.09	8.17±0.89	—	—	—
642	UGC08564	3.02±0.69	0.4±0.09	—	—	—	—
643	NGC5233	6.59±1.38	0.9±0.19	—	—	—	—
644	NGC5240	2.05±0.19	0.2±0.02	1.24±0.16	—	—	—
645	IC0902	2.84±0.09	0.4±0.01	0.8±0.11	—	—	—
646	NGC5250	0.75±0.29	0.1±0.04	—	—	—	—
647	UGC08600	1.58±0.69	0.2±0.09	—	—	—	—
648	NGC5249	10.53±1.72	1.4±0.24	—	—	—	—
649	UGC08633	16.07±1.94	2.2±0.28	10.29±1.81	—	—	—
650	NGC5263	78.72±0.88	11.8±0.14	10.33±3.35	—	—	—
651	NGC5267	13.92±1.15	1.9±0.17	1.38±0.25	—	—	—
652	UGC08662	0.2±0.06	0.0±0.01	0.57±0.1	—	—	—
653	NGC5289	2.93±0.19	0.4±0.03	2.45±0.3	—	—	—
654	NGC5308	0.54±0.09	0.1±0.01	0.18±0.06	4.7	<0.0±0.0	—
655	UGC08726	0.54±0.09	0.1±0.01	2.15±0.31	—	—	—
656	NGC5305	6.93±1.1	0.9±0.15	4.61±0.34	—	—	—
657	UGC08733	1.36±0.16	0.2±0.02	5.24±0.25	—	—	—
658	UGC08739	95.95±1.08	14.6±0.17	13.05±1.6	4.0	19.94±7.66	—
659	NGC5320	9.95±0.33	1.3±0.05	8.09±0.89	—	—	—
660	NGC5318NED01	4.4±0.5	0.6±0.07	—	—	—	—
661	IC4336	5.68±0.22	0.7±0.03	—	—	—	—
662	NGC5326	1.99±0.21	0.2±0.03	0.63±0.05	—	—	—
663	IC0944	39.38±1.68	5.7±0.26	7.24±0.98	—	—	—
664	UGC08778	2.21±0.27	0.3±0.04	1.42±0.2	—	—	—
665	UGC08781	11.65±2.0	1.6±0.29	4.44±0.96	—	—	—
666	UGC08794	46.85±2.42	6.8±0.37	13.62±2.11	—	—	—
667	NGC5349	39.22±0.97	5.7±0.15	—	—	—	—
668	UGC08806	11.2±0.4	1.5±0.06	8.54±1.04	—	—	—
669	NGC5347	50.1±0.22	7.3±0.03	3.52±1.14	1.9	0.31±0.14	—
670	NGC5350	25.66±0.29	3.6±0.04	6.57±0.29	6.6	4.74±1.27	—
671	NGC5353	1.75±0.15	0.2±0.02	3.26±1.02	3.2	0.24±0.12	—
672	NGC5376	6.59±0.16	0.9±0.02	0.54±0.04	—	—	—
673	NGC5379	1.72±0.08	0.2±0.01	1.21±0.1	2.9	0.42±0.12	—
674	IC0959	8.32±1.32	1.1±0.18	9.9±1.27	—	—	—
675	UGC08858	31.31±0.98	4.5±0.15	—	—	—	—
676	NGC5378	1.25±0.24	0.1±0.03	2.53±1.04	—	—	—
677	UGC08873	13.25±1.95	1.8±0.28	15.25±2.35	—	—	—
678	UGC08881	28.78±1.42	4.1±0.21	—	—	—	—
679	NGC5402	9.45±0.25	1.3±0.04	1.99±0.29	—	—	—
680	NGC5394	118.55±1.06	18.2±0.17	11.66±0.92	5.6	6.18±2.2	—
681	UGC08896	9.27±0.54	1.2±0.08	7.72±2.34	—	—	—

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(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
682	UGC08902	77.69±1.74	11.7±0.28	—	—	—	—
683	NGC5401	77.69±1.74	11.7±0.28	—	—	—	—
684	NGC5406	30.88±1.32	4.4±0.2	20.8±4.32	—	—	—
685	NGC5425	2.11±0.16	0.3±0.02	2.23±0.3	—	—	—
686	NGC5421NED02	2.11±0.16	0.3±0.02	—	—	—	—
687	NGC5409	13.25±1.54	1.8±0.22	12.7±3.74	—	—	—
688	NGC5439	1.49±0.08	0.2±0.01	—	1.8	0.25±0.07	—
689	NGC5411	1.86±0.42	0.2±0.05	—	—	—	—
690	NGC5443	2.67±0.13	0.3±0.02	0.82±0.08	—	—	—
691	NGC5417	7.24±0.83	0.9±0.11	1.01±0.14	—	—	—
692	NGC5433	115.17±0.52	17.7±0.08	6.85±1.47	2.0	2.02±0.42	—
693	UGC08955	2.19±0.39	0.3±0.05	3.39±0.68	—	—	—
694	UGC08960	19.82±1.07	2.7±0.16	—	—	—	—
695	NGC5423	0.39±0.28	0.0±0.03	—	—	—	—
696	NGC5448	7.42±0.2	1.0±0.03	5.18±0.27	—	—	—
697	UGC08988	0.2±0.04	0.0±0.01	0.66±0.17	—	—	—
698	NGC5444	1.24±0.31	0.1±0.04	—	—	—	—
699	NGC5434B	39.05±1.05	5.6±0.16	17.22±2.69	1.3	4.27±1.01	—
700	NGC5445	0.81±0.25	0.1±0.03	—	—	—	—
701	NGC5436	2.39±0.67	0.3±0.09	—	—	—	—
702	UGC08984	0.2±0.14	0.0±0.02	—	—	—	—
703	NGC5473	0.77±0.1	0.1±0.01	0.18±0.06	4.9	0.01±0.07	—
704	NGC5454	1.37±0.68	0.2±0.09	—	—	—	—
705	NGC5475	0.35±0.06	0.0±0.01	—	2.5	<0.04±0.03	—
706	UGC09014	9.57±0.43	1.3±0.06	1.03±0.13	—	—	—
707	NGC5480	15.76±0.14	2.2±0.02	1.59±0.18	—	—	—
708	NGC5485	0.94±0.11	0.1±0.01	0.9±0.32	4.5	<0.02±0.06	—
709	NGC5482	2.22±0.63	0.3±0.08	—	—	—	—
710	NGC5490	2.07±0.48	0.3±0.06	—	4.6	<2.45±0.74	—
711	UGC09071	0.68±0.11	0.1±0.01	0.82±0.11	—	—	—
712	NGC5492	5.04±0.17	0.6±0.02	3.83±0.8	—	—	—
713	UGC09080	1.19±0.21	0.1±0.03	—	—	—	—
714	UGC09067	41.58±1.77	6.0±0.27	9.6±1.23	—	—	—
715	NGC5520	8.26±0.13	1.1±0.02	1.35±0.1	—	—	—
716	NGC5513	1.88±0.47	0.2±0.06	—	—	—	—
717	UGC09110	15.15±0.68	2.1±0.1	8.31±2.82	—	—	—
718	UGC09113	8.67±0.29	1.1±0.04	7.99±2.1	—	—	—
719	NGC5519	38.19±1.63	5.5±0.25	14.75±2.46	—	—	—
720	NGC5522	35.46±0.64	5.1±0.1	9.15±2.89	—	—	—
721	UGC09117	10.56±0.71	1.4±0.1	16.16±2.01	—	—	—
722	UGC09121	6.62±0.71	0.9±0.1	8.7±1.13	—	—	—
723	NGC5525	6.06±0.68	0.8±0.09	—	—	—	—
724	NGC5533	25.79±0.64	3.6±0.09	19.53±1.53	—	—	—
725	IC0995	2.46±0.26	0.3±0.03	2.82±0.52	—	—	—
726	NGC5532	9.05±1.27	1.2±0.18	—	—	—	—
727	NGC5546	1.92±1.07	0.2±0.14	—	—	—	—
728	IC0994	4.02±0.92	0.5±0.12	—	—	—	—
729	NGC5557	2.32±0.29	0.3±0.04	—	4.5	<0.16±0.05	—
730	NGC5549	4.28±0.94	0.5±0.13	—	—	—	—
731	UGC09165	73.77±0.83	11.0±0.13	3.77±0.6	1.2	9.15±2.12	—
732	NGC5559	27.72±0.81	3.9±0.12	6.57±0.87	1.2	6.39±1.49	—
733	UGC09182	17.97±0.77	2.5±0.11	17.28±2.98	—	—	—
734	NGC5580	0.33±0.12	0.0±0.01	—	—	—	—
735	UGC09199	20.84±1.49	2.9±0.22	8.7±1.43	—	—	—
736	NGC5587	2.02±0.16	0.2±0.02	3.06±1.13	—	—	—
737	NGC5602	0.16±0.05	0.0±0.01	—	—	—	—
738	NGC5598	1.37±0.26	0.2±0.03	—	—	—	—
739	NGC5611	0.1±0.04	0.0±0.0	—	1.9	<0.05±0.03	—
740	NGC5614	23.32±0.63	3.3±0.09	3.02±0.45	—	—	—

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ID	name	L_{IR} $10^9 L_{\odot}$	SFR $M_{\odot} \text{ yr}^{-1}$	M_{HI} $10^9 M_{\odot}$	C_{AP}	M_{H_2} $10^9 M_{\odot}$	$\frac{M_{H_2, Z-dep}}{M_{H_2, stat}}$
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
741	NGC5616	117.87±2.64	18.1±0.43	35.52±6.13	—	—	—
742	NGC5610	157.18±0.71	24.6±0.12	4.69±0.68	1.4	1.55±0.25	—
743	NGC5622	8.36±0.45	1.1±0.06	4.99±0.63	1.5	0.88±0.33	—
744	NGC5631	1.15±0.12	0.1±0.02	0.85±0.26	3.2	0.02±0.05	—
745	UGC09253	5.85±0.43	0.8±0.06	4.31±0.66	—	—	—
746	NGC5623	1.05±0.22	0.1±0.03	—	—	—	—
747	UGC09262	108.97±1.96	16.7±0.32	—	—	—	—
748	NGC5633	17.8±0.2	2.5±0.03	2.85±0.35	1.8	1.72±0.4*	0.7
749	NGC5630	8.61±0.21	1.1±0.03	3.4±0.47	—	—	—
750	NGC5635	9.88±0.6	1.3±0.08	11.17±3.37	—	—	—
751	UGC09291	4.12±0.31	0.5±0.04	3.71±0.23	—	—	—
752	NGC5642	0.63±0.2	0.1±0.02	—	—	—	—
753	NGC5656	27.88±0.31	3.9±0.05	3.43±0.35	—	—	—
754	NGC5657	26.36±0.41	3.7±0.06	5.77±1.29	—	—	—
755	NGC5659	10.98±0.57	1.5±0.08	3.7±0.54	—	—	—
756	NGC5665	38.05±0.17	5.5±0.03	1.84±0.24	6.9	11.46±4.54	—
757	NGC5675	11.88±0.45	1.6±0.06	—	—	—	—
758	NGC5682	1.97±0.15	0.2±0.02	1.21±0.18	—	—	—
759	NGC5687	0.3±0.08	0.0±0.01	—	3.9	0.1±0.07	—
760	NGC5689	1.66±0.13	0.2±0.02	0.57±0.1	—	—	—
761	NGC5684	1.29±0.26	0.2±0.03	—	—	—	—
762	UGC09401	14.04±0.94	1.9±0.14	4.46±0.63	—	—	—
763	NGC5714	6.5±0.19	0.8±0.03	5.6±0.61	—	—	—
764	NGC5720	15.96±1.68	2.2±0.24	33.26±4.01	—	—	—
765	UGC09448	0.99±0.11	0.1±0.01	1.84±0.12	—	—	—
766	NGC5730	5.76±0.22	0.7±0.03	6.12±0.77	—	—	—
767	NGC5731	2.86±0.19	0.4±0.02	3.06±0.82	—	—	—
768	NGC5732	7.27±0.34	1.0±0.05	—	—	—	—
769	UGC09476	10.87±0.37	1.5±0.05	4.51±0.48	—	—	—
770	NGC5739	7.01±0.69	0.9±0.1	—	—	—	—
771	NGC5735	12.55±0.48	1.7±0.07	9.34±3.51	—	—	—
772	UGC09492	1.25±0.7	0.1±0.09	—	—	—	—
773	UGC09518	1.78±0.62	0.2±0.08	—	—	—	—
774	UGC09537	38.92±1.44	5.6±0.22	57.71±9.58	—	—	—
775	UGC09542	14.59±0.75	2.0±0.11	10.31±1.43	—	—	—
776	UGC09539	1.33±0.35	0.2±0.04	—	—	—	—
777	NGC5772	15.6±0.7	2.1±0.1	6.77±0.55	1.8	1.28±0.56*	0.9
778	NGC5784	19.13±0.69	2.6±0.1	—	—	—	—
779	UGC09598	8.28±0.74	1.1±0.1	5.17±0.76	—	—	—
780	NGC5797	1.3±0.18	0.2±0.02	—	—	—	—
781	IC1079	1.05±0.76	0.1±0.1	—	—	—	—
782	UGC09629	4.94±1.02	0.6±0.14	—	—	—	—
783	UGC09665	11.24±0.2	1.5±0.03	6.03±0.83	—	—	—
784	NGC5829	24.77±1.11	3.5±0.17	19.34±2.28	3.1	8.41±2.49*	1.5
785	UGC09711	44.98±1.72	6.5±0.26	—	—	—	—
786	IC4534	44.98±1.72	6.5±0.26	—	—	—	—
787	NGC5876	2.86±0.31	0.4±0.04	1.71±0.14	—	—	—
788	UGC09759	8.28±0.3	1.1±0.04	6.65±0.91	—	—	—
789	NGC5888	29.06±1.95	4.1±0.29	—	—	—	—
790	UGC09777	16.99±0.57	2.3±0.08	9.32±1.09	—	—	—
791	NGC5908	55.7±0.38	8.2±0.06	21.84±1.19	—	—	—
792	UGC09842	109.2±1.96	16.7±0.32	—	—	—	—
793	UGC09849	0.87±0.19	0.1±0.02	4.78±0.62	—	—	—
794	NGC5928	1.49±0.3	0.2±0.04	—	—	—	—
795	NGC5930	101.3±0.23	15.5±0.04	1.06±0.33	5.7	3.97±1.67*	5.0
796	NGC5934	32.35±0.58	4.6±0.09	—	—	—	—
797	UGC09873	11.39±0.54	1.5±0.08	7.44±1.1	—	—	—
798	UGC09892	8.0±0.66	1.1±0.09	—	—	—	—
799	NGC5951	2.93±0.11	0.4±0.01	2.74±0.26	—	—	—

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ID	name	L_{IR} $10^9 L_{\odot}$	SFR $M_{\odot} \text{ yr}^{-1}$	M_{HI} $10^9 M_{\odot}$	C_{AP}	M_{H_2} $10^9 M_{\odot}$	$\frac{M_{H_2, Z-dep}}{M_{H_2, stat}}$
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
800	UGC09901	0.91±0.21	0.1±0.03	3.11±0.51	—	—	—
801	NGC5953	35.28±0.16	5.1±0.02	1.23±0.3	5.6	4.3±1.71	—
802	ARP220	1554.3±0.0	277.9±0.0	27.01±7.71	5.2	18.59±6.49	—
803	NGC5957	0.54±0.1	0.1±0.01	3.15±0.86	2.6	0.93±0.23*	0.8
804	NGC5971	1.2±0.16	0.1±0.02	—	—	—	—
805	UGC09919	4.4±0.27	0.6±0.04	2.72±0.5	—	—	—
806	NGC5966	1.56±0.32	0.2±0.04	—	—	—	—
807	IC4566	15.97±0.68	2.2±0.1	2.52±0.2	—	—	—
808	UGC09937	1.63±0.27	0.2±0.03	—	—	—	—
809	NGC5987	3.6±0.27	0.5±0.04	6.85±0.49	—	—	—
810	NGC5980	63.0±0.57	9.3±0.09	6.46±2.09	—	—	—
811	UGC10043	5.12±0.14	0.7±0.02	5.11±0.93	—	—	—
812	UGC10042	10.58±0.69	1.4±0.1	5.06±0.82	—	—	—
813	NGC6004	22.24±0.65	3.1±0.1	2.4±0.29	—	—	—
814	UGC10097	3.51±0.48	0.4±0.06	—	—	—	—
815	NGC6020	0.87±0.24	0.1±0.03	—	—	—	—
816	NGC6021	1.62±0.44	0.2±0.06	—	—	—	—
817	IC1151	4.53±0.21	0.6±0.03	3.46±0.53	—	—	—
818	UGC10123	24.23±0.27	3.4±0.04	3.95±0.85	—	—	—
819	NGC6027	12.56±1.49	1.7±0.21	—	—	—	—
820	NGC6032	14.77±0.7	2.0±0.1	7.14±1.4	—	—	—
821	NGC6060	49.65±1.0	7.3±0.16	25.75±3.25	—	—	—
822	UGC10205	19.38±1.35	2.7±0.2	9.66±1.16	—	—	—
823	NGC6063	3.99±0.38	0.5±0.05	3.41±0.43	—	—	—
824	IC1199	17.23±0.89	2.4±0.13	—	—	—	—
825	UGC10257	5.67±0.32	0.7±0.04	5.35±0.8	—	—	—
826	NGC6081	7.38±0.79	1.0±0.11	—	—	—	—
827	UGC10297	1.42±0.17	0.2±0.02	1.78±0.49	—	—	—
828	UGC10331	32.47±0.36	4.6±0.06	5.42±0.37	—	—	—
829	NGC6125	2.05±0.3	0.2±0.04	—	—	—	—
830	UGC10337	21.92±2.5	3.1±0.37	12.55±1.7	—	—	—
831	NGC6132	14.9±0.93	2.0±0.14	10.23±1.36	—	—	—
832	NGC6146	7.3±1.59	1.0±0.22	—	—	—	—
833	NGC6154	1.4±0.74	0.2±0.09	8.94±1.01	—	—	—
834	UGC10380	20.68±2.27	2.9±0.33	18.39±3.17	—	—	—
835	NGC6150	1.85±1.02	0.2±0.13	—	—	—	—
836	NGC6155	13.2±0.15	1.8±0.02	1.13±0.09	—	—	—
837	UGC10384	49.94±1.01	7.3±0.16	8.07±1.26	—	—	—
838	UGC10388	0.29±0.21	0.0±0.02	2.76±0.43	—	—	—
839	NGC6166NED01	6.68±1.44	0.9±0.2	—	—	—	—
840	NGC6173	2.74±0.95	0.3±0.13	—	—	—	—
841	NGC6168	8.35±0.74	1.4±0.13	2.66±0.38	—	—	—
842	NGC6186	25.79±0.35	3.6±0.05	0.96±0.11	—	—	—
843	UGC10650	3.36±0.29	0.4±0.04	1.88±0.24	—	—	—
844	NGC6278	1.02±0.2	0.1±0.02	0.47±0.16	3.1	<0.08±0.03	—
845	UGC10693	4.13±1.01	0.5±0.14	—	—	—	—
846	UGC10695	3.05±0.91	0.4±0.12	—	—	—	—
847	UGC10710	28.14±1.83	4.0±0.27	15.96±2.68	—	—	—
848	NGC6310	3.66±0.14	0.5±0.02	2.26±0.14	—	—	—
849	NGC6301	55.88±2.76	8.2±0.43	33.84±4.02	—	—	—
850	NGC6314	23.39±1.42	3.3±0.21	4.2±0.52	—	—	—
851	NGC6338	4.54±1.15	0.6±0.16	—	—	—	—
852	UGC10796	1.66±0.12	0.2±0.01	1.77±0.13	—	—	—
853	NGC6361	66.84±0.3	10.0±0.05	14.52±0.97	—	—	—
854	UGC10811	13.26±1.66	1.8±0.24	—	—	—	—
855	UGC10799	10.28±1.61	1.4±0.23	7.95±2.81	—	—	—
856	IC1256	12.76±0.63	1.7±0.09	11.16±1.25	2.5	2.25±0.59*	0.8
857	NGC6394	80.48±1.63	12.1±0.26	—	—	—	—
858	UGC10905	13.27±1.84	1.8±0.26	—	—	—	—

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(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
859	NGC6411	1.05±0.22	0.1±0.03	—	—	—	—
860	NGC6427	0.43±0.17	0.0±0.02	—	—	—	—
861	UGC10972	6.62±0.78	0.9±0.11	12.11±1.92	1.7	2.13±0.88	—
862	NGC6478	64.23±3.46	11.1±0.6	17.34±2.21	—	—	—
863	NGC6497	4.13±0.25	0.5±0.03	—	—	—	—
864	NGC6515	1.04±0.38	0.1±0.05	—	—	—	—
865	UGC11228	3.66±0.7	0.5±0.09	—	—	—	—
866	UGC11262	2.5±0.54	0.3±0.07	10.02±1.25	—	—	—
867	NGC6762	0.52±0.1	0.1±0.01	—	—	—	—
868	MCG-02-51-004	29.67±1.66	4.2±0.25	5.3±1.03	—	—	—
869	NGC6941	30.21±2.71	4.3±0.41	15.58±1.23	—	—	—
870	NGC6945	0.73±0.25	0.1±0.03	—	—	—	—
871	NGC6978	19.57±1.8	2.7±0.26	—	2.0	7.96±2.29*	1.0
872	UGC11649	3.37±0.48	0.4±0.06	6.05±0.69	—	—	—
873	UGC11680NED01	152.11±4.44	23.8±0.73	11.19±1.61	—	—	—
874	NGC7025	12.87±1.15	1.7±0.17	3.0±0.4	1.6	<1.01±0.28	—
875	UGC11694	5.63±0.86	0.7±0.12	2.89±0.39	—	—	—
876	NGC7047	22.62±1.37	3.2±0.2	3.65±0.5	—	—	—
877	UGC11717	66.64±1.5	9.9±0.24	—	—	—	—
878	MCG-01-54-016	0.49±0.11	0.1±0.01	—	—	—	—
879	UGC11740	12.6±1.61	1.7±0.23	11.84±1.57	—	—	—
880	UGC11792	10.71±0.79	1.4±0.11	5.05±0.9	—	—	—
881	NGC7194	2.65±0.94	0.3±0.12	—	—	—	—
882	NGC7236	2.65±0.94	0.3±0.12	—	1.4	0.09±0.03	—
883	UGC11958	2.65±0.94	0.3±0.12	—	—	—	—
884	UGC11982	1.47±0.44	0.2±0.06	7.19±1.22	—	—	—
885	UGC12054	0.19±0.1	0.0±0.01	1.67±0.28	—	—	—
886	NGC7311	26.92±1.33	3.8±0.2	4.53±0.55	—	—	—
887	NGC7321	45.49±2.04	6.6±0.31	17.94±2.2	—	—	—
888	UGC12127	45.49±2.04	6.6±0.31	—	—	—	—
889	NGC7364	52.44±1.18	7.7±0.18	11.95±1.4	—	—	—
890	UGC12185	8.57±1.51	1.1±0.21	7.33±0.95	—	—	—
891	UGC12224	7.61±0.73	1.0±0.1	7.74±0.95	—	—	—
892	VV488NED02	19.73±2.03	2.7±0.3	17.35±2.33	—	—	—
893	NGC7436B	3.18±0.88	0.4±0.12	—	—	—	—
894	UGC12274	4.68±1.31	0.6±0.18	1.75±0.26	—	—	—
895	UGC12308	0.32±0.07	0.0±0.01	5.41±0.9	—	—	—
896	NGC7466	56.74±2.04	8.4±0.32	15.7±2.29	—	—	—
897	UGC12348	162.99±2.56	25.6±0.43	6.55±0.96	—	—	—
898	NGC7489	47.99±2.04	7.0±0.32	31.11±4.06	—	—	—
899	NGC7536	30.92±0.97	4.4±0.15	13.39±1.89	—	—	—
900	NGC7550	3.07±0.67	0.4±0.09	—	—	—	—
901	NGC7549	38.99±1.05	5.6±0.16	4.82±0.81	5.5	18.78±4.9*	0.8
902	NGC7563	1.76±0.34	0.2±0.04	1.62±0.13	—	—	—
903	NGC7562	1.55±0.35	0.2±0.04	2.62±0.77	—	—	—
904	NGC7591	177.29±1.19	27.9±0.2	23.99±3.04	1.5	13.75±3.08*	4.3
905	UGC12494	2.49±0.51	0.3±0.07	5.65±0.72	—	—	—
906	IC5309	11.65±0.7	1.6±0.1	2.07±0.26	1.2	1.78±0.46*	1.1
907	NGC7608	7.6±0.56	1.0±0.08	1.46±0.21	—	—	—
908	NGC7611	0.93±0.27	0.1±0.03	—	—	—	—
909	UGC12519	17.15±1.65	2.4±0.24	5.49±0.76	—	—	—
910	UGC12518	2.25±0.34	0.3±0.04	0.15±0.03	—	—	—
911	NGC7619	1.86±0.45	0.2±0.06	—	—	—	—
912	NGC7623	0.74±0.24	0.1±0.03	—	—	—	—
913	NGC7625	24.48±0.16	3.4±0.02	2.15±0.22	2.0	2.04±0.64*	0.8
914	NGC7631	9.14±0.68	1.2±0.1	2.89±0.37	1.4	1.09±0.28*	0.8
915	NGC7653	27.65±0.99	3.9±0.15	6.01±0.67	—	—	—
916	NGC7671	0.72±0.3	0.1±0.04	—	—	—	—
917	NGC7683	1.63±0.43	0.2±0.05	—	—	—	—

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ID	name	L_{IR} $10^9 L_{\odot}$	SFR $M_{\odot} \text{ yr}^{-1}$	M_{HI} $10^9 M_{\odot}$	C_{AP}	M_{H_2} $10^9 M_{\odot}$	$\frac{M_{H_2, Z-dep}}{M_{H_2, stat}}$
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
918	UGC12633	60.08±0.81	8.9±0.13	5.98±0.64	—	—	—
919	NGC7684	1.62±0.46	0.2±0.06	2.19±0.36	—	—	—
920	NGC7691	12.85±0.89	1.7±0.13	8.71±1.15	—	—	—
921	UGC12653	3.42±0.67	0.4±0.09	5.64±0.79	—	—	—
922	UGC12688	18.82±1.05	2.6±0.15	11.08±1.55	1.4	<1.71±0.47*	1.2
923	NGC7711	1.01±0.46	0.1±0.06	—	—	—	—
924	NGC7716	4.57±0.38	0.6±0.05	6.44±0.83	—	—	—
925	NGC7722	13.64±0.7	1.9±0.1	3.73±0.49	—	—	—
926	UGC12723	14.92±1.37	2.0±0.2	2.85±0.47	—	—	—
927	NGC7738	204.07±2.29	32.4±0.39	6.22±1.12	—	—	—
928	UGC12767	24.58±1.76	3.5±0.26	9.63±1.17	—	—	—
929	UGC12810	70.25±3.31	10.5±0.52	22.27±2.85	—	—	—
930	UGC12816	4.22±0.3	0.5±0.04	16.6±2.08	—	—	—
931	NGC7782	38.44±1.9	5.5±0.29	18.64±2.3	—	—	—
932	NGC7783NED01	2.63±1.15	0.3±0.15	—	—	—	—
933	NGC7787	27.21±1.59	3.8±0.24	6.1±1.08	—	—	—
934	UGC12857	3.84±0.28	0.5±0.04	4.05±0.61	1.5	<0.23±0.06	—
935	UGC12864	9.78±0.64	1.3±0.09	14.17±1.74	—	—	—
936	MCG-01-01-012	8.59±1.19	1.1±0.17	6.46±1.04	—	—	—
937	NGC7800	3.08±0.55	0.5±0.09	3.89±0.93	—	—	—
938	NGC5947	25.32±0.74	3.6±0.11	—	—	—	—
939	NGC4676B	25.32±0.74	3.6±0.11	11.29±3.74	1.8	11.66±3.07*	1.4
Concluded							

Appendix B

C/C++, PHP and Shell Script Development

B.1 Overview of developed Programs and Scripts

Script Name	Description	Lines
<code>getcalifadata.sh</code>	Basic CALIFA data (id, name, coordinates, redshift, ...) download from www.caha.es . Output is stored in ASCII file.	16
<code>getNEDReferences.sh</code>	Download of tables of references available through NED for CALIFA galaxies. The output is stored in HTML files in a subfolder.	37
<code>getNEDPhotometry.sh</code>	Download of photometric data available in NED (SDSS, IRAS, 2MASS, ...). The output is stored in HTML files in a subfolder.	37
<code>getNEDAbstracts.sh</code>	Abstract retrieval from NED for all objects. Execution takes a long time due to huge amount of abstracts. The output is stored in HTML files in a subfolder.	18
<code>tablebuild.sh</code>	All information downloaded so far is used to create a single HTML file summarizing all information and keyword search for reference selection.	557
<code>checkstat.sh</code>	Checks the current observing status of CALIFA galaxies.	58
<code>buildobssample.sh</code>	Builds a HTML table only for the observed galaxy sample.	163
<code>paperloader.sh</code>	Retrieve abstracts of interest from NED.	103
<code>altnames_califa.sh</code>	Check for alternative names for all CALIFA galaxies. Output is stored in an ASCII file.	155
<code>getdiameter.sh</code>	Retrieve all blue D_{25} diameters from RC3.	10
Total code lines w/o white-space and comment lines:		1154

Table B.1: Scripts developed for archival data inspection.

Script Name	Description	Lines
<code>index_v4.php</code>	Data access and data filtering at http://galaxy.univie.ac.at/califa/db/ .	1277
<code>style.css</code>	CSS Style sheet for data access website.	165
<code>javascript.js</code>	Javascript routines for data access website.	37
Total code lines w/o white-space and comment lines:		1479

Table B.2: Scripts developed for data access and data inspection.

Script Name	Description	Lines
<code>cosmic.cc</code>	Main program for transforming redshifts into distances.	253
<code>cosmo.cc</code>	Definitions of function used in <code>cosmic.cc</code> .	220
Total code lines w/o white-space and comment lines:		473

Table B.3: C Program for Luminosity Distance Calculations.

Script Name	Description	Lines
<code>samplebuilder_v3.pl</code>	Reads 3 parameters from ASCII file (morphology, mass, SFR) and selects a homogeneous sample from it.	685
<code>alternativ_targets.pl</code>	Looks for alternative targets – targets with same properties – within a given sample.	269
<code>shortenaltlist.sh</code>	Shortens long lists of alternative targets found by <code>alternativ_targets.pl</code> .	37
Total code lines w/o white-space and comment lines:		991

Table B.4: PERL Subsample Builder

Script Name	Description	Lines
<code>WCShalpha.sh</code>	Copies WCS information from one FITS file to another (needed for CALIFA’s H α maps).	22
<code>nametrafo.sh</code>	Unifies several naming variations in order to get matchable names for all CALIFA targets.	33
Total code lines w/o white-space and comment lines:		55

Table B.5: Other Scripts

Script Name	Description	Lines
<code>reduction_12co32.csh</code>	Data reduction script used for archival SMA data of NGC2623.	80
<code>imaging_12co32.csh</code>	Imaging and moment map creation script.	376
Total code lines w/o white-space and comment lines:		456

Table B.6: MIRIAD Data Reduction and Imaging Scripts

B.2 Testing the Subsample Selection with a Huge SDSS Sample

In order to check the functionality of the developed “Subsample Builder”, a larger galaxy sample was needed for which morphologies, stellar masses and star formation rates are available. Such a sample was created from data derived by the “MPA-JHU” group ¹ in combination with the Bayesian automated classification of Huertas-Company et al. (2011). After cross-matching both datasets, the 20.000 nearest galaxies were selected and used as input for the “Subsample Builder”.

The result shows that in comparison to the CALIFA based subsample, all morphology bins were totally filled, which is not surprising considering the huge number of galaxies available. However, even when using such a large sample size, homogeneity cannot be reached perfectly in all parameters, because whenever selecting galaxies without considering parameter constraints *a priori*, a growing galaxy number will also lead to a growing number of “exotic” objects, which then increase the parameter space, e.g. the stellar mass range, such that these extreme bins cannot be populated homogeneously.

¹MPA-JHU is collaboration of researchers from the MPA (Max-Planck-Institut für Astrophysik) and the JHU (Johns Hopkins University)

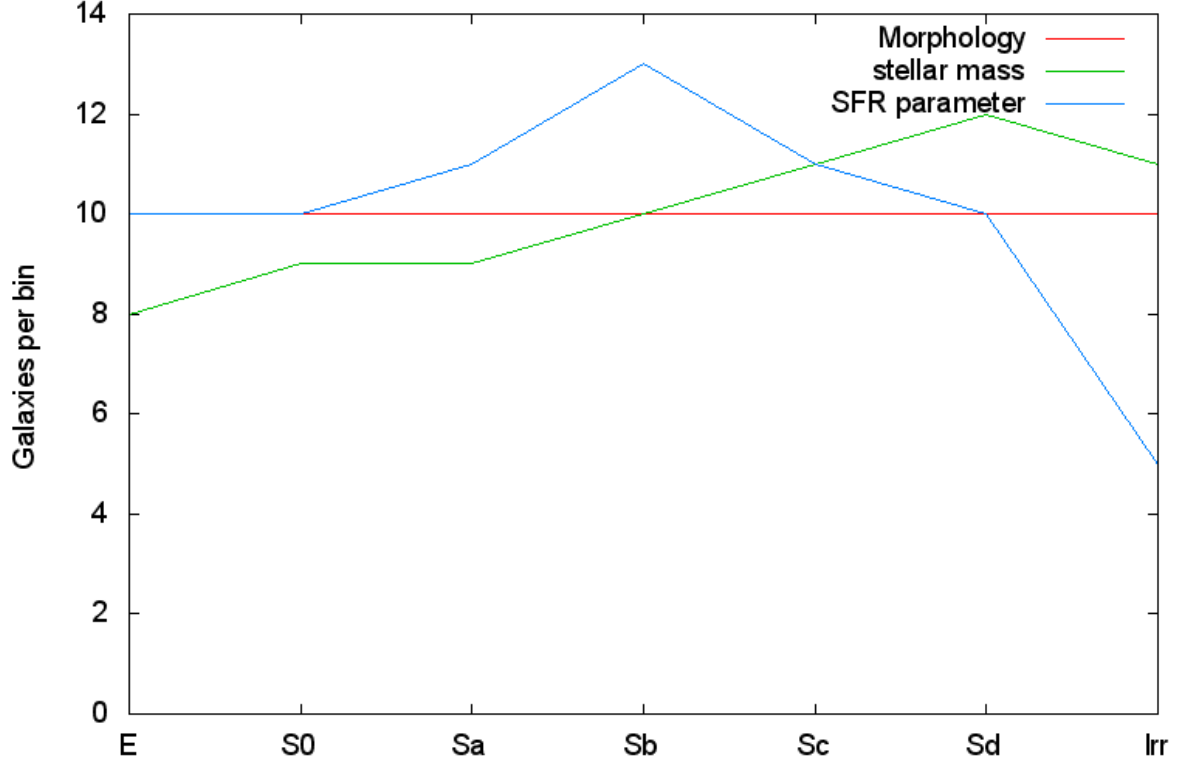


Figure B.1: The result of a SDSS-based subsample selection, shows that even in the case of a huge sample of 20.000 galaxies, homogeneity in all parameters cannot be achieved perfectly (see text for details).

The resulting subsample’s homogeneity is shown in figure B.1. It can be seen that the morphology bins are all equally filled (red line), whereas the bins of the SFR parameter (blue) and the stellar mass parameter (green) – as explained before – show inequally distributed bin-heights.

This result also explains the fact, that the CALIFA sample can only be statistically representative over a *limited* range of luminosities ($-18.6 > M_r > -23.1$) or stellar masses ($9.4 < \log(M^*/M_\odot) < 11.4$). However, these ranges are wide and the selection function is almost independent of intrinsic galaxy properties. Thus, a volume-correction can be applied to the CALIFA sample.

B.3 MIRIAD Data Reduction Script

B.3.1 Part 1, Analysis

```
# SMA extended configuration data reduction script
# by Johannes Puschig, 2013
```

```
#####
```

```

# FLAGGING
#####
# Edges
uvflag vis=n2623_1.uv edge=6 flagval=flag options=noapply
uvflag vis=n2623_1.uv edge=6 flagval=flag

# Check for unreasonable amplitudes
uvplt vis=n2623_1.uv device=/xs options=nobase line=channel,1,100,1,1
uvplt vis=n2623_1.uv device=/xs options=nobase line=channel,1,200,1,1
uvplt vis=n2623_1.uv device=/xs options=nobase line=channel,1,300,1,1
uvplt vis=n2623_1.uv device=/xs options=nobase line=channel,1,400,1,1
uvplt vis=n2623_1.uv device=/xs options=nobase line=channel,1,500,1,1
uvplt vis=n2623_1.uv device=/xs options=nobase line=channel,1,600,1,1

# FLAG
uvflag vis=n2623_1.uv flagval=flag options=noapply select="amp(60)"
uvflag vis=n2623_1.uv flagval=flag select="amp(60)"

#####
# INVERT
#####
# create 40 km/s slices
invert vis=n2623_1.uv map=NGC2623co32.im40 beam=NGC2623co32.beam40
options=systemp robust=0.5 imsize=513,513 cell=0.2 line=velocity,31,-600,40,40
# Theoretical rms noise: 1.633E-02

# create 10 km/s slices
invert vis=n2623_1.uv map=NGC2623co32.im10 beam=NGC2623co32.beam10
options=systemp robust=0.5 imsize=513,513 cell=0.2 line=velocity,121,-600,10,10
# Theoretical rms noise: 3.266E-02

# create 20 km/s slices
invert vis=n2623_1.uv map=NGC2623co32.im20 beam=NGC2623co32.beam20
options=systemp robust=0.5 imsize=513,513 cell=0.2 line=velocity,61,-600,20,20
# Theoretical rms noise: 2.310E-02

#####
# INSPECT DIRTY IMAGE
#####
# SHOW and CHECK the BEAM
cgdisp in=NGC2623co32.beam40,NGC2623co32.beam40 type=pixel,contour device=/xs
region=quarter slew=p,10 levs1=1,2,3,4,5,6,7,8,9
cgdisp in=Arp193co32.beam40,Arp193co32.beam40 type=pixel,contour device=/xs
region=quarter slew=p,10 levs1=1,2,3,4,5,6,7,8,9,-1,-2,-3,-4,-5,-6,-7,-8,-9
cgdisp in=NGC2623co32.beam40,NGC2623co32.beam40 type=pixel,contour device=/xs
slew=p,10 levs1=1,2,3,4,5,6,7,8,9 region="relpix,box(-20,-20,20,20)"
cgdisp in=NGC2623co32.beam40,NGC2623co32.beam40 type=pixel,contour device=/xs
slew=p,10 levs1=1,2,3,4,5,6,7,8,9 region="relpix,box(-20,-20,20,20)"
labtyp=arcsec

# CHECK the RMS

```

```

# 10 km/s channels
histo in=NGC2623co32.im10 region="quarter(1,18)"
histo in=NGC2623co32.im10 region="quarter(104,121)"
# Rms 1.66336E-02 Rms 1.77743E-02

# 20 km/s channels
histo in=NGC2623co32.im20 region="quarter(1,9)"
histo in=NGC2623co32.im20 region="quarter(53,61)"
# Rms 1.20756E-02 Rms 1.27820E-02

# 40 km/s channels
histo in=NGC2623co32.im40 region="quarter(1,5)"
histo in=NGC2623co32.im40 region="quarter(27,31)"
# Rms 8.68721E-03 Rms 9.21316E-03

#####
# CLEANING
#####
# Clean down to 2 sigma for each velocity binning
clean map=NGC2623co32.im10 beam=NGC2623co32.beam10 out=NGC2623co32.clean10
region=quarter niters=2000 cutoff=0.034
restor map=NGC2623co32.im10 beam=NGC2623co32.beam10 model=NGC2623co32.clean10
out=NGC2623co32.map10

clean map=NGC2623co32.im20 beam=NGC2623co32.beam20 out=NGC2623co32.clean20
region=quarter niters=2000 cutoff=0.025
restor map=NGC2623co32.im20 beam=NGC2623co32.beam20 model=NGC2623co32.clean20
out=NGC2623co32.map20

clean map=NGC2623co32.im40 beam=NGC2623co32.beam40 out=NGC2623co32.clean40
region=quarter niters=2000 cutoff=0.018
restor map=NGC2623co32.im40 beam=NGC2623co32.beam40 model=NGC2623co32.clean40
out=NGC2623co32.map40

# RESULT of restor:
# Gaussian beam fwhm: 2.225 x 2.022 arcsec
# Position angle: 35.8 degrees

#####
# MOMENT MAPS
#####
# Clip to 2 sigma for each velocity binning
moment in=NGC2623co32.map10 region="quarter(31,91)" out=NGC2623co32.mom0_10
mom=-1 clip=0.034
moment in=NGC2623co32.map20 region="quarter(16,46)" out=NGC2623co32.mom0_20
mom=-1 clip=0.025
moment in=NGC2623co32.map40 region="quarter(9,23)" out=NGC2623co32.mom0_40
mom=-1 clip=0.018

# Contour levels correspond to 2 sigma in the moment maps
# 0.034 / sqrt(60) = 0.004; this is roughly 2 sigma in all the moment maps

```

```

# use this for fixed contouring
cgdisp in=NGC2623co32.mom0_10,NGC2623co32.mom0_10 type=pixel,contour
device=1/xs levs1=1,2,3,4,5,6,7,8,9 slew=a,0.004
cgdisp in=NGC2623co32.mom0_10,NGC2623co32.mom0_10 type=pixel,contour
device=1/xs levs1=1,2,3,4,5,6,7,8,9 labtyp=arcsec region=quarter slew=a,0.004
cgdisp in=NGC2623co32.mom0_20,NGC2623co32.mom0_20 type=pixel,contour
device=1/xs levs1=1,2,3,4,5,6,7,8,9 labtyp=arcsec region=quarter slew=a,0.004
cgdisp in=NGC2623co32.mom0_40,NGC2623co32.mom0_40 type=pixel,contour
device=1/xs levs1=1,2,3,4,5,6,7,8,9 labtyp=arcsec region=quarter slew=a,0.004

histo in=NGC2623co32.mom0_10
#Maximum value 7.497535E-01 at (124,127,1)
histo in=NGC2623co32.mom0_20
#Maximum value 7.430678E-01 at (124,127,1)
histo in=NGC2623co32.mom0_40
# maximum value fluctuates through the maps until at 40 km/s it is
#Maximum value 7.661203E-01 at (124,127,1)

#####
# INSPECT SPECTRA
#####
# Correct pixel coordinates
inspect in=NGC2623co32.map10 device=/xs region="box(252,255,252,255)"
# range -260 to 260
inspect in=NGC2623co32.map20 device=/xs region="box(252,255,252,255)"
# range -260 to 260
inspect in=NGC2623co32.map40 device=/xs region="box(252,255,252,255)"
# range -260 to 260

#####
# ENHANCE MOMENT MAPS
#####
#
moment in=NGC2623co32.map10 out=NGC2623co32.mom0_10t mom=-1
region="kms,quarter(-260,260)" clip=0.034
moment in=NGC2623co32.map20 out=NGC2623co32.mom0_20t mom=-1
region="kms,quarter(-260,260)" clip=0.025
moment in=NGC2623co32.map40 out=NGC2623co32.mom0_40t mom=-1
region="kms,quarter(-260,260)" clip=0.018

# 0.034 / sqrt(52) = 0.005; this is approx. 2 sigma in all the moment maps
# best for fixed contours
cgdisp in=NGC2623co32.mom0_10t,NGC2623co32.mom0_10t type=pixel,contour
device=1/xs levs1=1,2,3,4,5,6,7,8,9 labtyp=arcsec region=quarter slew=a,0.005
cgdisp in=NGC2623co32.mom0_20t,NGC2623co32.mom0_20t type=pixel,contour
device=1/xs levs1=1,2,3,4,5,6,7,8,9 labtyp=arcsec region=quarter slew=a,0.005
cgdisp in=NGC2623co32.mom0_40t,NGC2623co32.mom0_40t type=pixel,contour
device=1/xs levs1=1,2,3,4,5,6,7,8,9 labtyp=arcsec region=quarter slew=a,0.005

histo in=NGC2623co32.mom0_10t
histo in=NGC2623co32.mom0_20t

```

```

histo in=NGC2623co32.mom0_40t
# maximum value *decreases* through the maps until at 40 km/s it is
#Maximum value 8.161935E-01 at (124,127,1)

# Moment 0 maps with 1 sigma cutoff
moment in=NGC2623co32.map10 out=NGC2623co32.mom0_10t1 mom=-1
region="kms,quarter(-260,260)" clip=0.017
moment in=NGC2623co32.map20 out=NGC2623co32.mom0_20t1 mom=-1
region="kms,quarter(-260,260)" clip=0.012
moment in=NGC2623co32.map40 out=NGC2623co32.mom0_40t1 mom=-1
region="kms,quarter(-260,260)" clip=0.009

histo in=NGC2623co32.mom0_10t1
histo in=NGC2623co32.mom0_20t1
histo in=NGC2623co32.mom0_40t1
# maximum value *decreases* through the maps until at 40 km/s it is
#Maximum value 8.161935E-01 at (124,127,1)

cgdisp in=NGC2623co32.mom0_10t1,NGC2623co32.mom0_10t1 type=pixel,contour
device=2/xs levs1=1,2,3,4,5,6,7,8,9 labtyp=arcsec region=quarter slev=a,0.005
cgdisp in=NGC2623co32.mom0_20t1,NGC2623co32.mom0_20t1 type=pixel,contour
device=2/xs levs1=1,2,3,4,5,6,7,8,9 labtyp=arcsec region=quarter slev=a,0.005
cgdisp in=NGC2623co32.mom0_40t1,NGC2623co32.mom0_40t1 type=pixel,contour
device=2/xs levs1=1,2,3,4,5,6,7,8,9 labtyp=arcsec region=quarter slev=a,0.005

#####
# CORRECT FOR PRIMARY BEAM
#####
#
mossen in=NGC2623co32.map40 gain=NGC2623.map.gain
imbin in=NGC2623.map.gain region="quarter(1,1)" bin=1,1,1,1,1,1
out=NGC2623.mom0.gain
maths exp="NGC2623co32.mom0_40t1/NGC2623.mom0.gain" mask=NGC2623.mom0.gain.gt.0.5
out=NGC2623co32.mom0_40t1g
cgdisp in=NGC2623co32.mom0_40t1g,NGC2623co32.mom0_40t1g type=pixel,contour
device=1/xs levs1=1,2,3,4,5,6,7,8,9 labtyp=arcsec region=quarter slev=a,0.005

maths exp="NGC2623co32.mom0_40/NGC2623.mom0.gain" mask=NGC2623.mom0.gain.gt.0.5
out=NGC2623co32.mom0_40g
cgdisp in=NGC2623co32.mom0_40g,NGC2623co32.mom0_40g type=pixel,contour
device=2/xs levs1=1,2,3,4,5,6,7,8,9 labtyp=arcsec region=quarter slev=a,0.005
# BEST IMAGE --> USED FOR FURTHER ANALYSIS

maths exp="NGC2623co32.mom0_40t/NGC2623.mom0.gain" mask=NGC2623.mom0.gain.gt.0.5
out=NGC2623co32.mom0_40tg
cgdisp in=NGC2623co32.mom0_40tg,NGC2623co32.mom0_40tg type=pixel,contour
device=3/xs levs1=1,2,3,4,5,6,7,8,9 labtyp=arcsec region=quarter slev=a,0.005

maths exp="NGC2623co32.map40/NGC2623.map.gain" mask=NGC2623.map.gain.gt.0.5
out=NGC2623co32.map40g

```

```
#####
# FLUX ANALYSIS
#####

inspect in=NGC2623co32.map40g device=/xs region="box(252,255,252,255)"
cgdisp in=NGC2623co32.mom0_40g,NGC2623co32.mom0_40g type=pixel,contour
device=2/xs levs1=1,2,3,4,5,6,7,8,9 region=quarter slev=a,0.005
cgdisp in=NGC2623co32.mom0_40g,NGC2623co32.mom0_40g type=pixel,contour
device=2/xs levs1=1,2,3,4,5,6,7,8,9 region="relpix,box(-21,-18,17,20)"
slev=a,0.005

imlist in=NGC2623co32.map40g options=stat region="relpix,kms,box(-21,-18,17,20)(-260,260)"
log=NGC2623co32.flux.txt
# DATA of analysis stored in file: NGC2623co32.flux.txt
# SUM is 15.8975 and average is 1.13553
# FLUX is 15.8975 Jy * 40 km/s = 635.9 Jy km/s
# K/Jy = 2.3606
# --> 1501.3416 K km/s

#####
# IMAGING MOMENT MAPS
#####
#
cgdisp in=NGC2623co32.mom0_40g,NGC2623co32.mom0_40g type=pixel,contour
device=2/xs levs1=1,2,3,4,5,6,7,8,9 region="relpix,box(-17,-17,17,17)"
labtyp=arcsec slev=p,50
cgdisp in=NGC2623co32.beam40,NGC2623co32.beam40 type=pixel,contour device=1/xs
slev=p,50 levs1=1,2,3,4,5,6,7,8,9 region="relpix,box(-17,-17,17,17)"
labtyp=arcsec

# moment maps
./imaging.csh file=NGC2623co32.map20 rms=0.012 vmin=-260 vmax=260 start=clip
xyreg="arcsec,box(-5,-5,5,5)"
./imaging.csh file=NGC2623co32.map40 rms=0.009 vmin=-260 vmax=260 start=clip
xyreg="arcsec,box(-5,-5,5,5)"

#####
# INTEGRATED LINE WIDTH
#####
#
inspect in=NGC2623co32.map40 device=/xs region="box(255,257,255,257)"
# -260 to 260 km/s FWZI --> total FWZI = 520 km/s
```

B.3.2 Part 2, Imaging of Moment Maps

```
#!/bin/csh -xf
# imaging.csh - for moment maps
# based on BIMA SONG file moment.csh
# modified by Johannes Puschnig, 2013
```

```

# Usage:  imaging.csh file=[_name_] rms=#
# start=[straight/clip/]
# interact=[y/n] [vmin=] [vmax=] [xyreg=]
# EXAMPLE:
# ./imaging.csh file=NGC2623co32.map40 rms=0.013 vmin=-260 vmax=260 start=clip
xyreg="arcsec,box(-5,-5,5,5)"
#
#-----
echo " started program"
### REQUIRED PARAMETERS:
set file= # root of filename (omit .map40, .map20)
set rms= # rms noise per channel

### OPTIONAL PARAMETERS:
set interact=y
set mosaic=n
set fwhm=1 # resolution of smoothed cube for masking
set vest= # Name of input velocity image, which overrides
# default VEL for gaufit when unblanked
set fluxclip=3 # min allowed flux (Jy/bm km/s) for gaufits
set velclip=30 # max allowed velocity error (km/s) for gaufits
set log=imaging.log
# velocity range of emission (defaults to all):
set vmin=
set vmax=
set delv=
# spatial extent of emission (defaults to all):
set xyreg=
#-----
# Override above parameters if given on command line
foreach a ( $* )
set check='echo $a | awk -F= 'print NF''
if ( "$check" == 2 ) set $a
end

# Check parameters
if ($file == "") then
echo "### FATAL ERROR: file= must be specified"
exit 0
endif
if ($rms == "") echo "### Warning:  rms= not specified"
#-----
# convert ($vmin,$vmax) to pixel range
set delv='gethd in=$file/cdelt3'
set vi='gethd in=$file/crval3'
set nmaps='gethd in=$file/naxis3'
if ($vmin == "" && $vmax == "") then
set vmin=$vi
set vmax='calc -i "$vi+($nmaps-1)*$delv'
echo "Setting vmin=$vmin and vmax=$vmax"
endif

```

```

set vminpix='calc -i "1+$vmin-($vi)/$delv"'
set vmaxpix='calc -i "1+$vmax-($vi)/$delv"'
set vrange="image($vminpix,$vmaxpix)"
# Generate normalized sensitivity cube (used in all methods):
if ($mosaic == "y") && !(-e $file.sen) then
rm -rf $file.tmp
moscen in=$file sen=$file.tmp
set minval='histo in=$file.tmp region='image(1)'|grep Min|awk 'print $3''
echo "Normalizing rms by $minval"
maths exp="$file.tmp/$minval" out=$file.sen
rm -rf $file.tmp
endif
if ($interact == "n") then
set device=/xs
else
set device=/xw
endif
if !(-e $log) then
echo "===== imaging.csh =====" gt $log
endif

if ($?start) goto $start

goto continue
continue:
#-----
# Method 0. Straight moment map with no clipping. Useful for comparison.
#-----
straight:
rm -rf $file.dmom0
moment in=$file out=$file.dmom0 mom=0 region=$vrange
cgdisp in=$file.dmom0 device=$device nxy=1 options=full,beaml

range=0,0,lin,3 labtyp=arcsec region=$xyreg
echo "" | tee -a $log
echo "Making moment-0 map for $file with no clipping" | tee -a $log
set sum='histo in=$file.dmom0 | grep Flux | awk 'print $6''
echo -n "### Total flux, no clipping (Jy km/s):" | tee -a $log
calc -f f7.1 $sum | tee -a $log
goto end
#-----
# Method 1. Reduce noise by clipping.
# This is the quickest method but can screen out low-level emission.
# The clipping level rises as the sensitivity declines at edge of map.
#-----
clip:
### SET CLIPPING LEVELS:
set clip2='calc -f f7.5 "$rms*2"'
set clip3='calc -f f7.5 "$rms*3"'
set clip4='calc -f f7.5 "$rms*4"'

```

```

# MOMENT 0:
echo "" | tee -a $log
echo "Making moment maps for $file using clipping" | tee -a $log
echo "Clipping at $clip2 for Moment 0" | tee -a $log
if ($mosaic == "y") then
rm -rf $file.senmsk0
maths exp=$file mask="abs($file/$file.sen).gt.$clip2"

out=$file.senmsk0
rm -rf $file.mom0
moment in=$file.senmsk0 out=$file.mom0 region=$vrange
else
rm -rf $file.mom0
moment in=$file out=$file.mom0 region=$vrange clip=$clip2
endif
mv $file.mom0/mask $file.mom0/mask1
cgdisp in=$file.mom0 device=$device nxy=1 options=full,beamb1

range=0,0,lin,3 labtyp=arcsec region=$xyreg
rm -rf $file.senmsk0
# Flux calculation
set sum='histo in=$file.mom0 region=$xyreg | grep Flux | awk 'print $6''
echo -n "### Total flux, clip method (Jy km/s):" | tee -a $log
calc -f f7.1 $sum | tee -a $log
# MOMENT 1:
# doing clips at 2 sigma, 3sigma, 4 sigma
echo "Clipping at $clip2, $clip3, $clip4 for Moment 1 (3 files)" | tee -a $log
if ($mosaic == "y") then
rm -rf $file.senmsk2
rm -rf $file.senmsk3
rm -rf $file.senmsk4
maths exp=$file mask="$file/$file.sen.gt.$clip2"

out=$file.senmsk2
maths exp=$file mask="$file/$file.sen.gt.$clip3"

out=$file.senmsk3
maths exp=$file mask="$file/$file.sen.gt.$clip4"

out=$file.senmsk4
rm -rf $file.mom1tmp2
moment in=$file.senmsk2 out=$file.mom1tmp2 region=$vrange mom=1
rm -rf $file.mom1tmp3
moment in=$file.senmsk3 out=$file.mom1tmp3 region=$vrange mom=1
rm -rf $file.mom1tmp4
moment in=$file.senmsk4 out=$file.mom1tmp4 region=$vrange mom=1
else
rm -rf $file.senmsk2
rm -rf $file.senmsk3
rm -rf $file.senmsk4
maths exp=$file mask="$file.gt.$clip2"

```

```

out=$file.senmsk2
maths exp=$file mask="$file.gt.$clip3"

out=$file.senmsk3
maths exp=$file mask="$file.gt.$clip4"

out=$file.senmsk4
rm -rf $file.mom1tmp2
moment in=$file.senmsk2 out=$file.mom1tmp2 region=$vrangle mom=1
rm -rf $file.mom1tmp3
moment in=$file.senmsk3 out=$file.mom1tmp3 region=$vrangle mom=1
rm -rf $file.mom1tmp4
moment in=$file.senmsk4 out=$file.mom1tmp4 region=$vrangle mom=1
endif
rm -rf $file.2s.mom1
maths mask="$file.mom1tmp2.ge.$vmin.and.$file.mom1tmp2.le.$vmax"

exp=$file.mom1tmp2 out=$file.2s.mom1
mv $file.2s.mom1/mask $file.2s.mom1/mask1
cgdisp in=$file.2s.mom1 device=$device nxy=1 options=full,beamb1

range=$vmin,$vmax,lin,3 labtyp=arcsec region=$xyreg
rm -rf $file.3s.mom1
maths mask="$file.mom1tmp3.ge.$vmin.and.$file.mom1tmp3.le.$vmax"

exp=$file.mom1tmp3 out=$file.3s.mom1
mv $file.3s.mom1/mask $file.3s.mom1/mask1
cgdisp in=$file.3s.mom1 device=$device nxy=1 options=full,beamb1

range=$vmin,$vmax,lin,3 labtyp=arcsec region=$xyreg
rm -rf $file.4s.mom1
maths mask="$file.mom1tmp4.ge.$vmin.and.$file.mom1tmp4.le.$vmax"

exp=$file.mom1tmp4 out=$file.4s.mom1
mv $file.4s.mom1/mask $file.4s.mom1/mask1
cgdisp in=$file.4s.mom1 device=$device nxy=1 options=full,beamb1

range=$vmin,$vmax,lin,3 labtyp=arcsec region=$xyreg
rm -rf $file.mom1tmp2
rm -rf $file.mom1tmp3
rm -rf $file.mom1tmp4
rm -rf $file.senmsk2
rm -rf $file.senmsk3
rm -rf $file.senmsk4
# MOMENT 2:
# doing clips at 2 sigma, 3sigma, 4 sigma
echo "Clipping at $clip2, $clip3, $clip4 for Moment 2 (3 files)" | tee -a $log
if ($mosaic == "y") then
rm -rf $file.senmsk2
rm -rf $file.senmsk3

```

```

rm -rf $file.senmsk4
maths exp=$file mask="$file/$file.sen.gt.$clip2"

out=$file.senmsk2
maths exp=$file mask="$file/$file.sen.gt.$clip3"

out=$file.senmsk3
maths exp=$file mask="$file/$file.sen.gt.$clip4"

out=$file.senmsk4
rm -rf $file.2s.mom2
moment in=$file.senmsk2 out=$file.2s.mom2 region=$vrangle mom=2
rm -rf $file.2s.mom3
moment in=$file.senmsk3 out=$file.3s.mom2 region=$vrangle mom=2
rm -rf $file.2s.mom4
moment in=$file.senmsk4 out=$file.4s.mom2 region=$vrangle mom=2
else
rm -rf $file.senmsk2
rm -rf $file.senmsk3
rm -rf $file.senmsk4
maths exp=$file mask="$file.gt.$clip2"

out=$file.senmsk2
maths exp=$file mask="$file.gt.$clip3"

out=$file.senmsk3
maths exp=$file mask="$file.gt.$clip4"

out=$file.senmsk4
rm -rf $file.2s.mom2
moment in=$file.senmsk2 out=$file.2s.mom2 region=$vrangle mom=2
rm -rf $file.2s.mom3
moment in=$file.senmsk3 out=$file.3s.mom2 region=$vrangle mom=2
rm -rf $file.2s.mom4
moment in=$file.senmsk4 out=$file.4s.mom2 region=$vrangle mom=2
endif
mv $file.2s.mom2/mask $file.2s.mom2/mask1
cgdisp in=$file.2s.mom2 device=$device nxy=1 options=full,beamb1

range=0,0,lin,3 labtyp=arcsec region=$xyreg
mv $file.3s.mom2/mask $file.3s.mom2/mask1
cgdisp in=$file.3s.mom2 device=$device nxy=1 options=full,beamb1

range=0,0,lin,3 labtyp=arcsec region=$xyreg
mv $file.4s.mom2/mask $file.4s.mom2/mask1
cgdisp in=$file.4s.mom2 device=$device nxy=1 options=full,beamb1

range=0,0,lin,3 labtyp=arcsec region=$xyreg
rm -rf $file.senmsk2
rm -rf $file.senmsk3
rm -rf $file.senmsk4

```

```

goto end
#-----
# Method 2. Reduce noise by masking with a smoothed dataset.
# This eliminates most of the noise but not residual sidelobes.
#-----
mask:
# Mask using 3 sigma level in smoothed dataset:
if ($mosaic == "y") then
rm -rf $file.sencm
maths exp=$file.cm/$file.sen out=$file.sencm
set incube=sencm
else
set incube=cm
endif
rm -rf $file.smo
convol map=$file.$incube fwhm=$fwhm pa=0 out=$file.smo
echo "" | tee -a $log
echo "Making moment-0 map for $file using masking" | tee -a $log
echo "Smoothed $file.cm by fwhm=$fwhm" | tee -a $log
if ($mosaic == "y") rm -rf $file.sencm

set srms='histo in=$file.smo region='image(1,3)'|grep Rms|awk 'print $4','
set clip='calc -f f7.5 "$srms*3'
echo "Masking at value: $clip" | tee -a $log
rm -rf $file.msk
rm -rf $file.msk.res
maths exp=$file.cm out=$file.msk mask=$file.smo.gt.$clip
maths exp=$file.cm out=$file.msk.res mask=$file.smo.lt.$clip
if ($interact == "y") then
cgdisp in=$file.msk device=$device region=$xyreg type=p

options=full,3value labtyp=arcsec nxy=4,3 range=0,0,lin,3
cgdisp in=$file.msk.res device=$device region=$xyreg type=p

options=full,3value labtyp=arcsec nxy=4,3 range=0,0,lin,3
endif
### OPTIONAL: Require real emission to be in 2 or more consecutive
### channels. (Note this may still leave sidelobes in).
if ($interact == "y") then
echo ""
echo -n "Use vblank to mask pixels isolated in velocity [n]? "
set resp = "$/t"
if ($resp == "y") then
echo "Used vblank to mask pixels isolated in velocity" gtgt $log
rm -rf $file.mskr
reorder in=$file.msk out=$file.mskr mode=312
vblank in=$file.mskr tol=1
rm -rf $file.msk
reorder in=$file.mskr out=$file.msk mode=231
cgdisp in=$file.msk device=$device region=$xyreg type=p

```

```

options=full,3value labtyp=arcsec nxy=3,2 range=0,0,lin,3
endif
endif
# MOMENT 0: use 1 sigma clipping
rm -rf $file.mmom0 $file.mmom1
moment in=$file.msk out=$file.mmom0 clip=$rms region=$vrangle
moment in=$file.msk out=$file.mmom1 mom=1 clip=-99999,$rms region=$vrangle
mv $file.mmom0/mask $file.mmom0/mask1
cgdisp in=$file.mmom0 device=$device nxy=1 options=full,beamb1

range=0,0,lin,3 labtyp=arcsec region=$xyreg
set sum='histo in=$file.mmom0 region=$xyreg | grep Flux | awk 'print $6''
echo -n "### Total masked flux (Jy km/s):" | tee -a $log
calc -f f7.1 $sum | tee -a $log

goto end
#-----
# Method 3, Part I. Fit Gaussians to all profiles.
# This is the most time consuming but often gives good results.
#-----
gaufit:
# Since a single run of gaufit often leaves bad pixels, in this
# implementation there are two runs, with different initial estimates
# for the profile fwhm (30 and 60 km/s). You can change the estimates
# by editing the script, or hash out the following line to just run once.
set step=1
# SET PARAMETERS:
set cutoff='calc -f f7.5 "$rms*1.5"' # Min. allowed amplitude ( $gt=1.5$  sigma)
set wrange=5 # Min. allowed fwhm, in km/s
set rmsest=$rms # Estimated rms noise
set estim=0,0,30 # Default values for AMP,VEL,DISP. Use 0 for AMP and
# VEL to put initial estimate at peak of profile.
# Best to give an estimate for DISP (fwhm in km/s).
set options=relax # options=relax often gives better results,
# options=supbad only writes actual fits to log
dogaufit:
rm -rf $file.gaupar $file.gaures $file.gaumod $file.gaulog
gaufit in=$file.cm velest=$vest estim=$estim params=$file.gaupar

log=$file.gaulog rmsest=$rmsest cutoff=$cutoff

wrange=$wrange region=$xyreg options=$options
# model=$file.gaumod residual=$file.gaures
echo "" | tee -a $log
echo "gaufit on $file with estim=$estim cutoff=$cutoff vest=$vest"

| tee -a $log
# AMPLITUDES (Jy/bm)
split:
rm -rf $file.gauamp

```

```

imsub in=$file.gaupar out=$file.gauamp region='image(1)'
cgdisp in=$file.gauamp device=$device nxy=1 options=full,beaml,wedge

range=0,0,lin,3 labtyp=arcsec region=$xyreg
# VELOCITY CENTROIDS (km/s)
rm -rf $file.gauvel
imsub in=$file.gaupar out=$file.gauvel region='image(2)'
puthd in=$file.gauvel/bunit value='KM/S' type=ascii
puthd in=$file.gauvel/btype value='velocity' type=ascii
cgdisp in=$file.gauvel device=$device nxy=1 options=full,beaml,wedge

range=$vmin,$vmax,lin,3 labtyp=arcsec region=$xyreg
# DISPERSIONS (FWHM, km/s)
rm -rf $file.gaudis
imsub in=$file.gaupar out=$file.gaudis region='image(3)'
cgdisp in=$file.gaudis device=$device nxy=1 options=full,wedge

range=0,0,lin,3 labtyp=arcsec region=$xyreg
# VELOCITY ERROR (km/s)
rm -rf $file.gauerr
imsub in=$file.gaupar out=$file.gauerr region='image(5)'
# INTEGRATED INTENSITY (Jy/bm km/s)
rm -rf $file.gaint
maths exp="1.064*$file.gauamp*$file.gaudis" out=$file.gaint
puthd in=$file.gaint/bunit value='JY/BEAM.KM/S' type=ascii
mv $file.gaint/mask $file.gaint/mask1
cgdisp in=$file.gaint device=$device nxy=1 options=full,beaml,wedge

range=0,0,lin,3 labtyp=arcsec region=$xyreg
set sum='histo in=$file.gaint region=$xyreg | grep Flux | awk 'print $6''
echo -n "### Flux prior to clipping (Jy km/s):" | tee -a $log
calc -f f7.1 $sum | tee -a $log
# Planes 4-6 of $file.gaupar are formal errors in amp, centroid, width.
# Plane 7 of $file.gaupar is rms of residual cube.
# REPEAT WITH DIFFERENT PARAMETERS OR MERGE:
if ($?step) then
set step = 'expr $step + 1'
if ($step == 2) then
rm -rf $file.gaupar1
mv $file.gaupar $file.gaupar1
set estim=0,0,60
goto dogaufit
else if ($step == 3) then
rm -rf $file.gaupar2
mv $file.gaupar $file.gaupar2
goto merge
else
goto end
endif
else
goto end

```

```

endif
merge:
echo "" | tee -a $log
echo "Consolidated two runs of gaufit" | tee -a $log
delhd in=$file.gaupar1/mask
delhd in=$file.gaupar2/mask
rm -rf $file.gaupar3
maths exp=$file.gaupar2 mask="$file.gaupar1.eq.0" out=$file.gaupar3
delhd in=$file.gaupar3/mask
rm -rf $file.gaupar
maths exp="$file.gaupar1+$file.gaupar3" out=$file.gaupar
goto split
#-----
# Method 3, Part II. Clip out Gaussians which were fitted to noise.
#-----
# Clip out Gaussian fits with integrated fluxes less than fluxclip.
# This reduces positive noise bias resulting from all Gaussians being
# positive, and is preferable to using a large amplitude cutoff in
# GAUFIT which would preferentially remove broad emission lines.
# Also clip out Gaussians with large velocity errors.

gauclip:
# Define mask:
if ($mosaic == "y") then
if !(-e $file.senmom0) moment in=$file.sen mom=-1 out=$file.senmom0
set mask = $file.gauint/$file.senmom0.gt.$fluxclip.and.$file.gauerr.lt.$velclip
else
set mask = $file.gauint.gt.$fluxclip.and.$file.gauerr.lt.$velclip
endif
rm -rf $file.gamp
maths exp=$file.gauamp out=$file.gamp mask=$mask
cgdisp in=$file.gamp device=$device nxy=1 options=full,beaml,wedge

range=0,0,lin,3 labtyp=arcsec region=$xyreg
mv $file.gamp/mask $file.gamp/mask1
rm -rf $file.gmom0
maths exp=$file.gauint out=$file.gmom0 mask=$mask
cgdisp in=$file.gmom0 device=$device nxy=1 options=full,beaml,wedge

range=0,0,lin,3 labtyp=arcsec region=$xyreg
mv $file.gmom0/mask $file.gmom0/mask1
rm -rf $file.gmom1
maths exp=$file.gauvel out=$file.gmom1 mask=$mask
cgdisp in=$file.gmom1 device=$device nxy=1 options=full,beaml,wedge

range=$vmin,$vmax,lin,3 labtyp=arcsec region=$xyreg
mv $file.gmom1/mask $file.gmom1/mask1
rm -rf $file.gmom2
maths exp=$file.gaudis out=$file.gmom2 mask=$mask
cgdisp in=$file.gmom2 device=$device nxy=1 options=full,wedge

```

```

range=0,0,lin,3 labtyp=arcsec region=$xyreg
rm -rf $file.gmom1err
maths exp=$file.gauerr out=$file.gmom1err mask=$mask
cgdisp in=$file.gmom1err device=$device nxy=1 options=full,wedge

range=0,0,lin,3 labtyp=arcsec region=$xyreg
# to get the .gmom-1 file for determining the rotation curve
rm -rf $file.gmom-1
maths exp=$file.gmom0/$file.gauvel out=$file.gmom-1 mask=$mask
cgdisp in=$file.gmom-1 device=$device nxy=1 options=full,wedge

range=0,0,lin,3 labtyp=arcsec region=$xyreg
# Flux calculation
set sum='histo in=$file.gmom0 region=$xyreg | grep Flux | awk 'print $6''
echo "" | tee -a $log
echo "Clipped pixels with flux lt $fluxclip and vel. error gt $velclip"

| tee -a $log
echo -n "*** Flux after clipping (Jy km/s):" | tee -a $log
calc -f f7.1 $sum | tee -a $log
#goto end
#=====
echo "reached plotting"
# Fancy plotting (contour levels must be set manually)
set plotfile=gmom0
cgdisp in=$file.$plotfile,$file.$plotfile type=c,p

slev=a,2 levs1=1,2,3,4,5,6,7,9,11,13,15

range=0,40,lin labtyp=arcsec options=beamb1,full

device=/vps nxy=1 region=$xyreg
mv pgplot.ps $file.$plotfile.ps
ghostview $file.$plotfile.ps &
#goto end
set plotfile=gmom1
cgdisp in=$file.$plotfile,$file.$plotfile type=p,c slev=a,10

levs1=32,34,36,38,40,42,44,46,48,50,52,54,56,58,60,62,64,66,68,70,72

range=$vmin,$vmax,lin,3 labtyp=arcsec options=beamb1,wedge,full

region=$xyreg cols1=1 device=/vcps
mv pgplot.ps $file.$plotfile.ps
ghostview $file.$plotfile.ps &
goto end
#=====

```

Appendix C

Deutsche Zusammenfassung

Die vorliegende Arbeit basiert auf CALIFA, dem “Calar Alto Legacy Integral Field Area survey”. Dabei handelt es sich um eine Auswahl von 600 Galaxien mit Rotverschiebungen zwischen $z=0.005$ und $z=0.03$. Innerhalb dieses Bereichs, ist das Sample statistisch repräsentativ. CALIFAs Aufgabe besteht darin, Sternpopulationen, Alter, Metallizitäten, Gasverteilungen, Mechanismen zur Gasanregung, chemische Zusammensetzungen sowie kinematische Eigenschaften der Sterne und des ionisierten Gases genauestens zu analysieren. Eine Schlüsselkomponente zum Verständnis der Sternentstehung entzog sich bisher allerdings der Untersuchung: das kalte, molekulare Gas – Treibstoff der Sternentstehung. Das ist Gegenstand dieser Arbeit, welche als vorbereitende Studie dient, um in Zukunft interferometrische Karten mit ALMA, PdBI und CARMA zu gewinnen. Ziel ist dabei, dass die räumliche Auflösung von $2''$ von CALIFAs optischen Integralfeldspektrographen (IFS), entsprechend 200–760 pc, auch im *submm* Bereich erreicht wird. Im Rahmen dieser Arbeit, wurde eine ausführliche Recherche verfügbarer Datenarchive durchgeführt und es konnte festgestellt werden, dass für 159 Galaxien aus CALIFAs *mothersample* (bestehend aus 939 Galaxien) bereits Beobachtungsdaten und Analysen publiziert wurden. Weiters konnten Infrarot-Daten, aufgenommen mit dem IRAS und WISE Satelliten für 497 beziehungsweise 924 Galaxien, aus Archiven entnommen werden. Die Datensätze wurden zusammengeführt, sodass letztendlich für *alle* Galaxien des CALIFA *mothersamples*, Sternentstehungsraten abgeleitet werden konnten. Darüberhinaus wurden zwei verschiedenen Quellen (Springob et al. 2005 und HYPERLEDA) Beobachtungen des atomaren Wasserstoffs entnommen, um atomare Gasmassen für zumindest $2/3$ des CALIFA Samples ableiten zu können. CO Daten aus mehr als hundert unterschiedlichen Publikationen und Katalogen wurden homogenisiert, um daraus die gesamte Masse der in den Galaxien befindlichen Molekülwolken zu berechnen. Dies geschah unter Berücksichtigung einer aufwändigen *Apertur – Korrektur*. Zusätzlich war es möglich für 26 Galaxien, für welche Sánchez et al. (2013) Metallizitäten veröffentlichten, den CO Konversionsfaktor, X_{CO} , abzuschätzen, um für jene Galaxien, ebenfalls eine *metal-*

lizitäts-abhängige molekulare Masse bestimmen zu können. Alle erwähnten Werte wurden in einer MySQL Datenbank zusammengefasst und der CALIFA-Kollaboration über ein Web-Interface zur Verfügung gestellt. Für eine spätere, interferometrische Analyse, wurde ein Sub-Sample von 65 Galaxien definiert. Die Galaxienauswahl geschah dabei mit einem eigens programmierten Algorithmus basierend auf den folgenden Parametern: stellare Masse, Sternentstehungsrate und Morphologie. Weiters wurden Beobachtungen an verschiedenen Sub-Millimeter Teleskopen beantragt, darunter: APEX, IRAM und PdBI. In der vorliegenden Arbeit, werden alle Methoden und Berechnungen beschrieben und diskutiert, wie etwa die Kennicutt-Schmidt Beziehung, Sternentstehungs-Effizienzen oder Zeitskalen der Gas-Erschöpfung für molekulare und gesamte galaktische Gasreserven. Daraus konnten vor allem drei Schlüsse gezogen werden: 1) Die galaktische Sternentstehungsrate steht in linearer Beziehung zur molekularen Masse, sogar wenn das meiste Gas in atomarer Form vorliegt. 2) Es gibt ein Gas-Dichte-Limit, welches unabhängig von der beobachteten Skala besteht und mit dem Übergang vom atomaren in den molekularen Zustand des Gases einhergeht. 3) In erster Näherung ist das Verhältnis der Sternentstehungsrate zur molekularen Masse in normalen Spiralgalaxien gleichbleibend. Diese Ergebnisse wurden aus unaufgelösten Daten gewonnen, was also vergleichbar ist mit Beobachtungen von Galaxien im frühen Universum und somit in Zukunft hilfreich sein wird, wenn Daten hochrotverschobener Galaxien interpretiert werden sollen. Neben, dieser globalen Analyse, wurde ein einzelnes Objekt im Detail studiert, NGC2623. Dabei handelt es sich um einen *merger*, der sich zu einer elliptischen Galaxie entwickeln wird. Hervorzuheben ist dabei die Entdeckung eines molekularen Gasklumpens und die Ableitung seiner Kinetik. Die Beobachtung bestätigt das Modell ausströmenden, heissen Gases, bei gleichzeitigem Einfall von kaltem, molekularem Gas.

Appendix D

Curriculum Vitae



Johannes Puschnig

Curriculum Vitae

Date of birth: 01.08.1980

Place of birth: Wels, Austria

Education

1991–2000 **Secondary School & trade apprenticeship**, *Werkschulheim Felbertal*, 5323 Ebenau, Austria, A-level exam ("Matura") - pass with merit, complete practical training in Mechatronics.

11/2012 **Bachelor of Science, BSc.**, University of Vienna, Department of Astrophysics, Austria.

Publications

Title *The night sky brightness at Potsdam-Babelsberg*
Journal Journal of Quantitative Spectroscopy & Radiative Transfer (JQSRT)
Preprint arXiv
Authors Puschnig J., Posch T., Schwöpe A., Schwarz R.
Year 2013

Title *Photometric and Spectroscopic Night Sky Brightness Measurements performed at the Vienna University Observatory*
Journal Journal of Quantitative Spectroscopy & Radiative Transfer (JQSRT)
Preprint arXiv:1304.7716
Authors Puschnig J., Posch T., Uttenthaler S.
Year 2013

Title *CALIFA, the Calar Alto Legacy Integral Field Area survey: II. First public data release*
Journal Astronomy and Astrophysics (A&A)
Volume 549, id.A87, 25 pp.

Authors Husemann et al.

Year 2013

Title *Towards ensemble asteroseismology of the young open clusters Chi Persei and NGC 6910*

Journal Astronomical Notes (AN)

Volume 331, Issue 9/10, p.1080-1083

Authors Saesen et al.

Year 2010

Title *Photometric multi-site campaign on the open cluster NGC 884. I. Detection of the variable stars*

Journal Astronomy and Astrophysics (A&A)

Volume 515, id.A16, 18 pp.

Authors Saesen et al.

Year 2010

Title *Photometric multi-site campaign on massive B stars in the open cluster Chi Persei (NGC 884)*

Journal Journal of Physics: Conference Series (JPhCS)

Volume 118, Issue 1, id. 012071

Authors Saesen et al.

Year 2010

Conference Proceedings

Conference Light Pollution Theory, Modeling, and Measurements, April 15-18 2013, Smolenice, SK

Title *Night Sky Brightness Measurements and Night Sky Spectroscopy performed at the Vienna University Observatory*

Authors Posch T., Puschnig, J.

Notes in print

Conference Ist die Welt rund um die Uhr geöffnet? Chancen und Risiken künstlicher Beleuchtung. Feb 2nd to 4th 2012, Linz, Austria

Title *Geschichte und Gegenwart: Öffentliche Beleuchtung und Lichtverschmutzung im Grossraum Wien.*

Authors Posch T., Puschnig J.

Notes published in: Studien zur Kulturgeschichte Oberösterreichs Folge 33. Hg. von Ute Streitt und Elisabeth Schiller. Hg. von den Oberösterreichischen Landesmuseen, p. 75-88

Talks

- 04/2013 CALIFA Busy Week 5, AIP - An der Sternwarte, Potsdam, Germany
Title *CALIFA database presentation*
- 04/2012 Wissenschaftliche Jahrestagung und Jahresversammlung der Österr. Gesellschaft für Astronomie und Astrophysik
Title *Monitoring night sky brightness at Vienna, Mt. Mitterschöpfel and Berlin-Babelsberg*
- 02/2012 Oberösterreichisches Landesmuseum
Title *Ist die Welt rund um die Uhr geöffnet? Chancen und Risiken künstlicher Beleuchtung*

Proposals with substantial Contribution

- 04/2013 SWEDEN (Onsala) APEX SHeFi, 15 Aug 2013 - 31 Dec 2013 (ACCEPTED)
Title *Searching for Molecular Gas Reservoirs in CALIFA Galaxies*
PI Dr. Helmut Dannerbauer
- 03/2013 ESO APEX SHeFi, Period 92A, 1 Oct 2013 - 31 Mar 2014 (ACCEPTED)
Title *Searching for Molecular Gas Reservoirs in CALIFA Galaxies*
PI Dr. Helmut Dannerbauer
- 03/2013 IRAM 30m EMIR, Period 01 June 2013 - 30 Nov 2013 (ACCEPTED)
Title *Census of Molecular Gas Reservoirs in CALIFA Galaxies: I. Search of CO*
PI Dr. Helmut Dannerbauer
- 03/2013 IRAM PDBI Period 01 June 2013 - 30 Nov 2013 (REJECTED)
Title *Census of Molecular Gas Reservoirs in CALIFA Galaxies: II. Mapping of CO*
PI Dr. Helmut Dannerbauer
- 02/2013 MPG APEX SHeFi, Period 20 Mar 2013 - 13 Aug 2013 (ACCEPTED)
Title *Searching for Molecular Gas Reservoirs in CALIFA Galaxies*
PI Dr. Glenn van de Ven
- 09/2012 IRAM PDBI, Period 01 Dec 2012 - 31 May 2013 (REJECTED)
Title *Census of the Cold Molecular Gas Reservoir of CALIFA Galaxies*
PI Dr. Helmut Dannerbauer

