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“Solar-like oscillations in Delta Scuti stars”

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1 Introduction

The first chapter's opening paragraph of Sir Arthur Eddington's meanwhile legendary book 'The Internal Constitution of the Stars' (1926) is the following: 'At first sight it would seem that the deep interior of the sun and stars less accessible to scientific investigation than any other region of the universe. Our telescopes may probe farther and farther into the depths of space; but how can we ever obtain certain knowledge of that which is hidden behind substantial barriers? What appliance can pierce through the outer layers of a star and test the conditions within?'. The answer to his question is meanwhile well known, it is asteroseismology. Stars have an inner structure which differs with mass, temperature and luminosity and changes with evolution. Some of them are known to pulsate already before reaching the Zero Age Main Sequence (ZAMS), hence before starting to burn H to He (Zwintz & Weiss 2006). In fact we can find pulsating stars along almost all stages of evolution. Because they oscillate in their natural frequencies determined by their interior, measuring these periodic changes allows to determine the stars' inner structure.

The first pulsating star, Mira, was discovered in 1596 by David Fabricius, who found that the star had disappeared, to be visible again with a period of around 11 months. John Goodricke, in 1784, discovered another type of pulsating variables, the well-known Cepheids. The reason for their variability was found only 1914 by Harlow Shapley to be due to radial pulsation. Due to their tight relation between period and luminosity, discovered by Henrietta Leavitt, these stars are used as standard candles to measure distances to other galaxies. A summary of pulsating stars can be found in, e.g., Handler (2012).

But how does asteroseismology work? When a star is pulsates it contracts and expands periodically causing variations in radius and temperature, which generate periodic brightness changes. The velocity fields produced during contraction and expansion can be measured spectroscopically thanks to the Doppler effect, whereas the periodic temperature and radius fluctuations give rise to luminosity changes. Once the frequencies of pulsation are measured and their geometry identified, modelling of the star can reproduce the sound speed within it which is very sensitive to the temperature and the chemical composition.

1.1 Radial and non-radial pulsations

Stars can pulsate radially and non-radially and are assumed to be spherical (at least when no or slow rotation is implied). To describe the geometry of both, the radial and non-radial pulsations, asteroseismologists use spherical harmonics of the form:

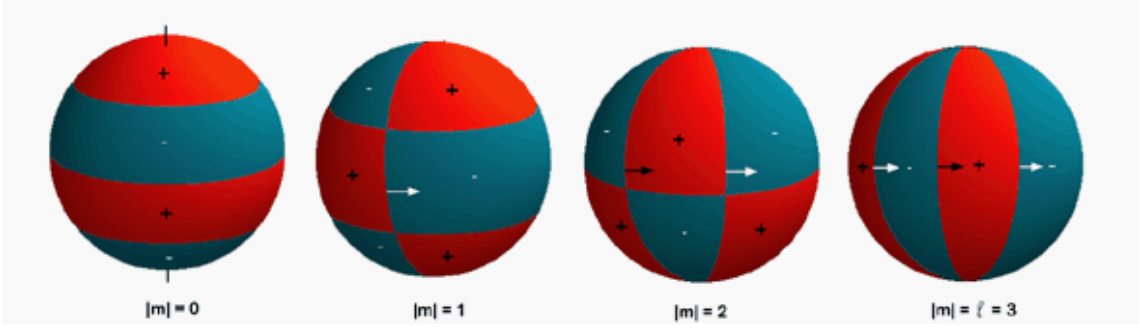


Figure 1.1: Nonradial pulsation of a spherically symmetric star, with all geometrical possibilities for a $\ell=3$ mode. The surface areas denoted by '+' can be imagined moving toward while the '-' away from the observer. This figure was adapted from Wolfgang Zima.

$$Y_\ell^m = (-1)^m c_{\ell m} P_\ell^m(\cos \Theta) e^{im\phi}, \quad (1.1)$$

where Θ is the co-latitudinal angle measured from the pole, and ϕ is the longitude. P_ℓ^m is the associated Legendre polynomial, with ℓ the spherical degree and m the azimuthal order. $c_{\ell m}$ is a normalization constant given by

$$c_{\ell m}^2 = \frac{(2\ell + 1)(\ell - m)!}{4\pi(\ell + m)!}. \quad (1.2)$$

The following three formulae describe the displacement in a spherically symmetric star in the directions r, Θ, ϕ as

$$\xi_r = a(r) P_\ell^m(\cos \Theta) e^{i(m\Theta + \sigma t)} \quad (1.3)$$

$$\xi_\Theta = b(r) \frac{\partial}{\partial \Theta} P_\ell^m(\cos \Theta) e^{i(m\Theta + \sigma t)} \quad (1.4)$$

$$\xi_\phi = b(r) \frac{1}{\sin \Theta} \frac{\partial}{\partial \phi} P_\ell^m(\cos \Theta) e^{i(m\Theta + \sigma t)} \quad (1.5)$$

where r describes the radius, $a(r)$ and $b(r)$ are the amplitudes and σ is the frequency (1/Period). The spherical degree ℓ represents the total number of surface nodes and the azimuthal order m the number of nodes crossing the equator, thus the longitudinal nodes. Therefore we expect $\ell - |m|$ nodes parallel to the equator, i.e. co-latitudinal nodes. The value of m can only be between $-\ell$ and $+\ell$, resulting into $2\ell + 1$ different modes for each spherical degree ℓ . Figure 1.1 illustrates an example for an $\ell = 3$ mode. A mode of degree ℓ with the azimuthal order $m = 0$ is a standing wave, whereas $m \neq 0$ are travelling waves and run with or against the rotation of the star. Radial modes always have only $\ell = 0$ components. The third quantum

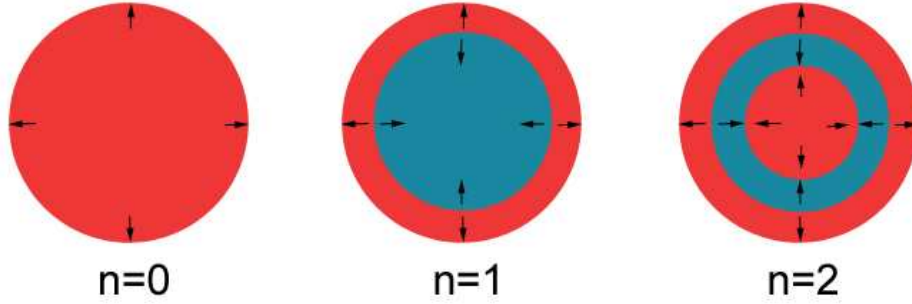


Figure 1.2: The radial overtone of a mode. In 3-D this should be imagined as concentric shells. The radial fundamental mode, $n = 0$, is the simplest mode of pulsation. The star expands and contracts as a whole. For higher overtones on the other hand, there are concentric shells expanding while the ones below contract, indicated in red and green respectively.

number, n (sometimes also referred to as k) describes the number of nodes, or to be more precise concentric shells in radial direction, as shown in Fig. 1.2.

The simplest mode of pulsation is the radial fundamental mode which has no node in the radial direction and therefore is referred to as $n = 0$ (theoretically speaking there is one node which is located at the centre and an anti-node at the surface of the star, analogous to an organ pipe). The first radial overtone has one node in radial direction, so $n = 1$, the second overtone has two nodes hence $n = 2$, and so on (Fig. 1.2). Would the sound speed be homogeneous within the star, which would require the temperature and the chemical composition to be homogeneous, then the ratio between, e.g., the fundamental radial mode and the first overtone (also known as F:1H) would be the same like in an organ pipe, i.e. 0.33 (see, e.g., Aerts et al. 2010 for more detailed explanations). But because the temperature gradient and the chemical composition change within the star, the ratio of these two radial modes can be used as a tool to determine the approximate evolutionary stage of a star. For example, as given in Aerts et al. (2010), δ Sct stars, which are located around the main sequence have a ratio between F/1H of 0.77 and Cepheids of 0.71, the latter being more evolved and therefore having a different inner structure.

For $\ell = 1$ modes the lowest radial order is $n = 1$, meaning that there is at least one radial node inside the star.

So far the stars were assumed to be spherically symmetric and non rotating, meaning that for a nonradial mode, all $|m|$ values have the same frequencies as the central $|m| = 0$ component. Departure from spherical asymmetry, due to e.g. rotation can lift this frequency degeneracy. As a result, all frequencies of azimuthal orders $m \neq 0$ will be different for a given spherical degree ℓ . The traveling waves, influenced by the Coriolis and centrifugal force will have a slightly higher frequency

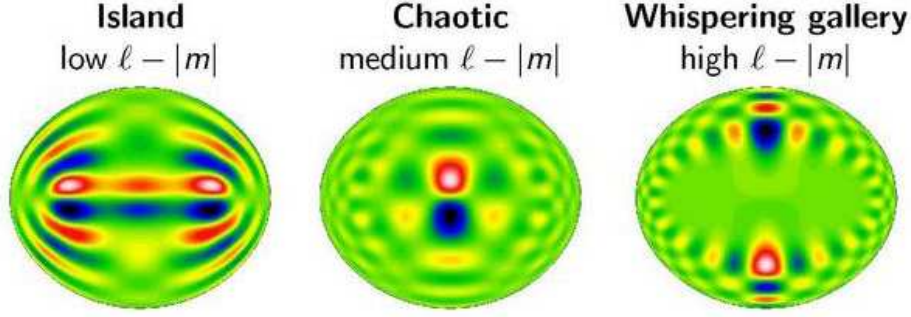


Figure 1.3: Island, chaotic and whispering galleries modes of rapidly rotating stars as characterized by Lignières & Georgeot (2008, 2009). Credit: Daniel Reese (<http://online.itp.ucsb.edu/online/asteroseismo-c11/reese/oh/20.html>).

than the axisymmetric mode ($m = 0$) as they travel with rotation (prograde modes) and a slightly lower frequency when traveling against the rotation (retrograde mode). In case of slow to moderate rotation (see, e.g., Goupil et al. (2000)), the frequencies can then be written as:

$$\omega_{n,\ell,m} = \omega_{n,\ell,0} + m(1 - C_{n,\ell})\Omega + m^2 \frac{D_{n,\ell}\Omega^2}{\omega} \quad (1.6)$$

where the mode n, ℓ, m has the observed frequency $\omega_{n,\ell,m}$, Ω is the rotation frequency rate, $C_{n,\ell}$ and $D_{n,\ell}$ are Ledoux constants describing the effect of centrifugal and Coriolis force and are mode-dependent. These constants are theoretically computed from models. For slow to moderate rotation the rotationally split modes have approximately equidistantly spaced multiplet components, with increasing asymmetry as the rotation increases (Pamyatnykh 2000). As rotational rates increase toward breakup velocities the situation becomes more complicated. The modes of pulsation can no longer be approximated by spherical harmonics and 2-D eigenvalue problems need to be solved (e.g. Reese et al. 2009). Lignières & Georgeot (2008, 2009) classified these modes depending to their organization patterns in several categories such as island, chaotic and whispering gallery modes, as illustrated in Fig.1.3.

1.2 Pressure and Gravity modes

Pulsations in stars are generally of two types: the pressure (p) modes and the gravity (g) modes. The p modes are acoustic modes where pressure is the primary restoring force when a star is perturbed from equilibrium. The gas motion is mostly in vertical direction (Fig. 1.4). The g modes have buoyancy as the restoring force and in this case the motion is mostly horizontal (Fig. 1.4). For completeness it should be



Figure 1.4: Inner structure for modes of pulsation. Left panel: acoustic p modes with pressure as the restoring force. The displacement of a fluid element is mainly in radial direction. Middle panel: g modes having buoyancy as the restoring force, in this case the motion is predominantly horizontally. Right panel: a mixed mode behaves as a g mode in the core but has the properties of p modes in the envelope. Credit: Rich Townsend (<http://shayol.bartol.udel.edu/~rhdt/jobs/UCSB/>)

mentioned that there is another type of modes, the so called f modes, which have frequencies between those of p and the g modes. These modes are surface gravity modes and have no radial node, and can exist only for $\ell \geq 2$.

There are two critical frequencies related to the propagation of oscillation modes. The first one is the Lamb frequency, and determines the inverse time needed to travel a horizontal wavelength at the local sound speed:

$$L_\ell^2 = \frac{\ell(\ell+1)c^2}{r^2} \quad (1.7)$$

where ℓ is the spherical degree, c is the local sound speed at radius r measured from the centre of the star. The second characteristic frequency is the Brunt-Väisälä frequency, which defines the frequency at which a fluid element oscillates around its equilibrium in vertical direction.

$$N^2 = g\left(\frac{1}{H} - \frac{g}{c^2}\right) \quad (1.8)$$

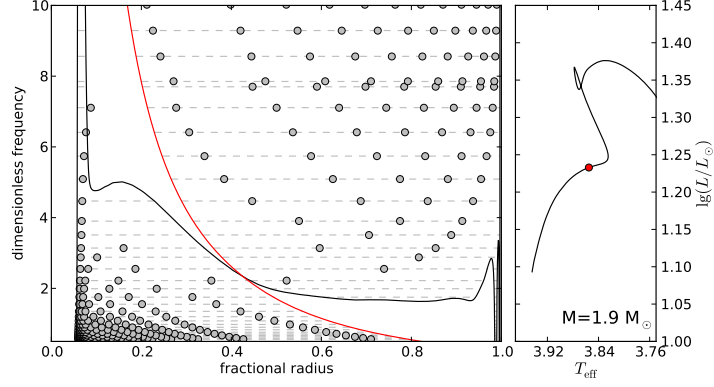


Figure 1.5: Left panel: Propagation diagram of p and g modes in a $1.9 M_{\odot}$ star as a function of depth. Right panel: Evolutionary track of a $1.9 M_{\odot}$, the circle represents the evolutionary stage of model displayed in the right-hand panel. Credit Patrick Lenz.

where g is the local gravity and H the density scale height. These two frequencies, define the regions, or more specifically the cavities in a star where the modes can oscillate. A mode with a frequency ω will be a p mode if $\omega^2 < N^2, L^2$ or will be a g mode and if $\omega^2 > N^2, L^2$. An example for an $\ell = 2$ mode for a $1.9 M_{\odot}$ model can be found in Fig. 1.5, where the mode frequencies are plotted as a function of depth (in the right panel the evolutionary stage of the model is indicated). The region in between the two cavities, where $N^2 < \omega^2 < L^2$, is the so-called evanescent region. The modes in this cavity are damped. As can be seen Fig. 1.5, in this case the p modes are closer to the surface and therefore very likely to be observed, whereas the g modes are trapped deeper in the star and will probably not be excited to observable amplitudes. There are also modes which have radial nodes located in both regions. These modes are the mixed modes (Fig. 1.4), which means they have a bimodal character and act as g modes in the interior and have p modes properties in the outer layers. If the frequencies are close, such an interaction is known as *avoided crossing* (Aizenman et al. 1977) and is a very important tool to probe the deep interior.

When pulsation modes penetrate the stars, they follow certain ray paths. Depending on the spherical degree they penetrate different depths of the star, probing these regions. Figure 1.6 illustrates how the propagation of rays for p modes of different spherical degrees looks like. The dashed circles represent the inner turning point where the wave front is reflected backwards toward the surface, where again it is reflected by the sudden drop in density. The radius where the total internal reflection takes place is where the mode frequency equals the local Lamb frequency.

As the radial order increases the frequency increases for p modes but decreases for g modes. For modes with $n \gg \ell$ the frequencies of consecutive radial orders of same ℓ are approximately equally spaced. The g modes are equally spaced in period

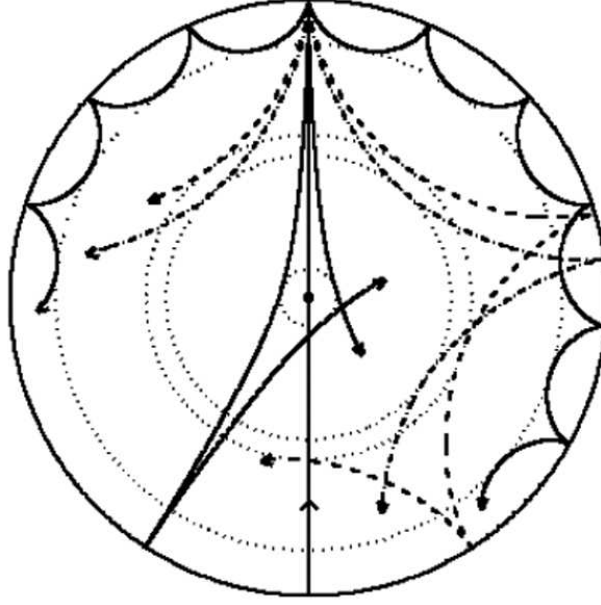


Figure 1.6: Propagation of acoustic p modes. The radius where the wave is reflected depends on the spherical degree ℓ . The ray path reaches an inner turning point, which is due to the increasing sound speed with depth. At the surface the wave gets reflected because of the rapid decrease in density. The acoustic ray path of $\ell = 0$ (the straight line), 2,20,25 and 75 are displayed. © J. Christensen-Dalsgaard, 1997, the Theoretical Astrophysical Centre, Institute of Physics and Astronomy, Aarhus University.

(1/f). From asymptotic theory the following relation was established for p modes by Tassoul (1980, 1990):

$$\nu_{n,\ell} = \Delta\nu\left(n + \frac{\ell}{2} + \tilde{\alpha}\right) + \epsilon_{n,\ell} \quad (1.9)$$

where n and ℓ are the radial order and the spherical degree, $\tilde{\alpha}$ is a constant of order unity, $\epsilon_{n,\ell}$ is a small correction and $\Delta\nu$ is the large frequency separation. The latter is a very important asteroseismic tool because it represents the inverse of the sound speed a wave needs to travel from the surface to the core and back again:

$$\Delta\nu = \left(2 \int_0^R \frac{dr}{c(r)}\right)^{-1} \quad (1.10)$$

with $c(r)$ being the sound speed. Therefore the large frequency separation can be seen as a measure of the mean density of the star.

The asymptotic relation for g modes, which are equally spaced in period is given

by:

$$\Pi_{n,\ell} = \frac{\Pi_0}{\sqrt{\ell(\ell+1)}}(n + \epsilon) \quad (1.11)$$

where n and ℓ are again the quantum numbers, ϵ a constant and Π_0 is

$$\Pi_0 = 2\pi^2 \left(\int \frac{N}{r} dr \right)^{-1} \quad (1.12)$$

where the integral is over the cavity of a given g mode and N is the Brunt-Väisälä frequency. For more details see, e.g, Aerts et al. (2010).

2 δ Scuti stars

2.1 Pulsation mechanisms

Pulsating stars oscillating in p modes, g modes or even in both types simultaneously, can be found in the entire Hertzsprung-Russell diagram (HRD), as illustrated in Fig. 2.1. The latter are called hybrids and can be found in the region of the HRD where the different instability strips overlap. There are several mechanisms driving the oscillations in pulsating variables, one of those being a mechanism acting like a heat engine, converting thermal energy into mechanical energy (e.g. Eddington 1919, Cox 1963). While a star is contracting, pressure and temperature increase. As a consequence the opacity (κ) will increase in certain layers which can block the radiative flux from below. When the star returns to its state of equilibrium the additional stored thermal energy will be transformed into mechanical energy and the stellar layers will shoot past the equilibrium. While the star is expanding the temperature and pressure decrease and so does the opacity, the latter is because the ionized gas is more transparent. The star will stop expanding and contracts, the ions will recombine and κ increases again and the cycle repeats. The specified layers where the thermal energy is stored, are the zones connected to (partial) ionization of abundant elements which can take place only at specific temperatures. The zone where neutral hydrogen (H) and helium (He) are ionized has about 14 000 K and is close to the surface. The second ionization zone of He II is at $\sim 40\,000$ K and the partial ionization zone of iron elements (the Z bump) occurs at approximately 200 000 K. The driving in the He II ionization zone is the main source of excitation in stars placed in the 'classical instability' strip such as the δ Sct stars, RR Lyrae and the Cepheids. The pulsations of the more massive β Cephei and SPB stars are triggered by the κ mechanism acting in the ionization zone of the iron-group elements.

The oscillations in γ Doradus as well as in DA and DB dwarfs are driven by a similar mechanism, only that in this case it is the bottom of the outer convection zone to store the radiative energy (Guzik et al. 2000) and is therefore called *convective driving*. In this case the modes of pulsation are g modes (see Fig. 2.1 for exact location in the HRD).

Another important mechanism especially for the present work, is stochastic driving. In stars like the Sun where the κ mechanism is too weak to act as a valve the modes are intrinsically stable. Nevertheless the acoustic energy of the convective motion, which is comparable to the sound speed, is sufficient to cause resonance at a star's natural frequencies where a part of the energy is transferred into global

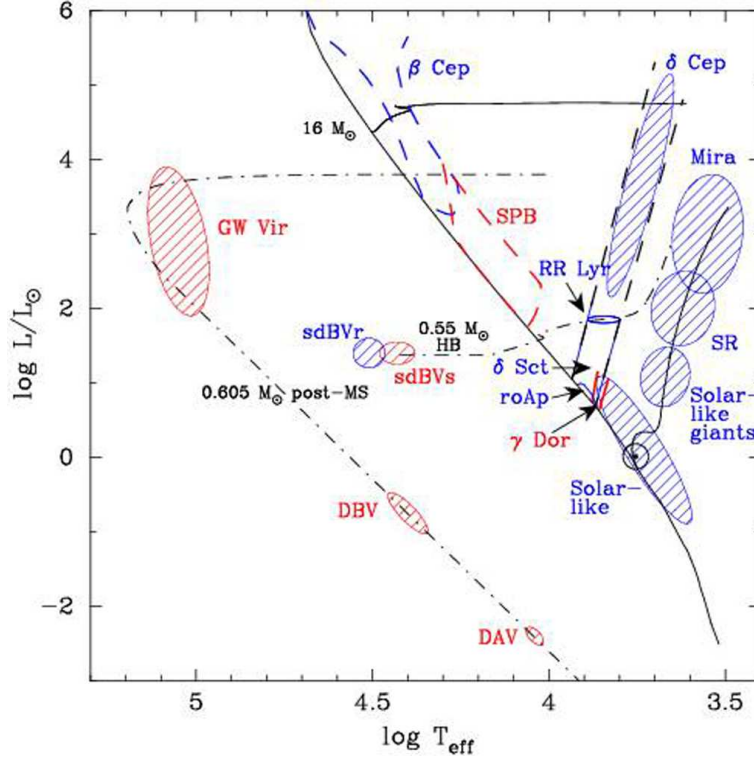


Figure 2.1: Asteroseismic HRD, illustrating all pulsating variable stars. The regions delimited in blue are the regions where p mode pulsations are observed and the regions in red highlight where g modes are expected to have observable amplitudes. Note that some instability strips overlap suggesting that stars exhibit both types of pulsations (meanwhile an observational and theoretical fact). The evolutionary track of the Sun is depicted, predicting already its future. In the higher part of the HRD the evolution of a $16M_{\odot}$ star is shown going through the β Cephei instability strip and therefore might eventually pulsate. The evolution of a star on the horizontal branch is indicated by the dashed dotted line, indicating the cooling sequence of white dwarfs. Credit: updated and adapted from J. Christensen-Dalsgaard by Gerald Handler.

oscillation modes. Because of the large number of convective cells the excitation is random, hence stochastic. Metaphorically speaking, a certain mode of pulsation will be excited by one convection cell and after it turns over, the mode is damped, but immediately after it will be re-excited by the next convective cell at the same frequency but at a different phase. This is very different to the κ mechanism, for example, which excites pulsation coherently. The consequences of this contrast is a very important way of distinguishing between these two types of driving mechanisms in the signal processing (see following chapters for details). Another important at-

tribute of stochastic driving is that all the modes in a certain frequency range are excited to observable amplitudes, allowing mode identification from pattern recognition. This is again in absolute contrast to the heat engine where the mechanism selecting which modes are excited to observable amplitude is not understood (Dziembowski & Krolikowska 1990); one of the main issues to hamper seismic modelling of δ Sct stars. An interesting and entertaining analogy was presented by Peter Goldreich during a colloquium at the University of Santa Barbara, California (broadcasted via: <http://online.itp.ucsb.edu/bblunch/goldreich2/>), who said that stars with stochastically excited modes can be seen as socialist or communist stars because the available energy is distributed to all modes simultaneously, but they have very little energy (hence the amplitudes are small). The stars triggered by the heat engine on the other hand are the capitalistic stars, and all the energy goes to one or few modes which then have large power (amplitude²).

However, a star will only pulsate if the physics inside are just right for a mechanism to work. For the κ mechanism, for example, the He II ionization zone will only be effective to trigger pulsation, if it is not too deep in the star, as the convective layers above will damp the oscillations but it should be also not too high in the atmosphere because at low densities pulsations will be damped too. A mode will only be excited if its period of oscillation corresponds to the thermal time scale of the driving zone (Pamyatnykh 1999). Further, the pulsation periods of pure p modes will always be shorter than the dynamical time scale of a star, which is the time the star needs to return to the state of equilibrium after being perturbed by a given process. The dynamical time scale can be approximated as:

$$\tau_{dyn} \simeq \sqrt{\frac{R^3}{GM}} \simeq \sqrt{\frac{1}{G\bar{\rho}}} \quad (2.1)$$

where $\bar{\rho}$ is the average stellar density. Because the periods of pulsation are related to the dynamical time scale of a star, which depends on the mean density, we can use the observed modes to derive the mean density. The so called pulsational constant Q can be written as:

$$Q = P \left(\frac{M}{M_{\odot}} \right)^{\frac{1}{2}} \left(\frac{R}{R_{\odot}} \right)^{-\frac{3}{2}} = P \sqrt{\frac{\rho_{\odot}}{\bar{\rho}}} \quad (2.2)$$

where P is the period of pulsation. The pulsational constants for the radial fundamental mode will be between 0.03 - 0.04 d for the entire HRD, in particular for the δ Sct stars $Q = 0.033$ d. Acoustic modes will always have a Q value smaller or equal to the radial fundamental mode (NB radial modes are always p modes) and pure g modes always a larger value. Therefore this tool can be used to identify the type of pulsation by using the following empirical relation:

$$\log Q = \log f + 0.5 \log g + 0.1 M_{bol} + \log T_{eff} - 6.456 \quad (2.3)$$

where, f is the observed frequency (see e.g. Breger 2000).

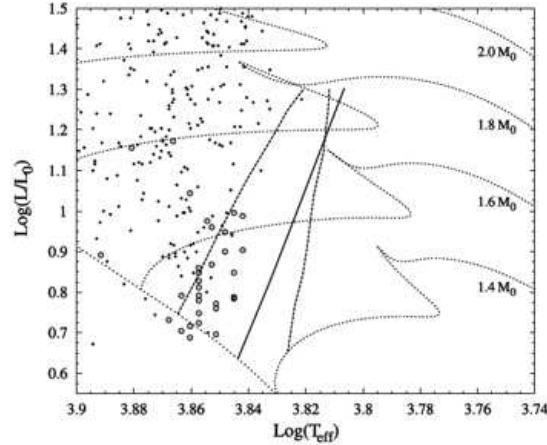


Figure 2.2: The red edge of the instability domain of $\ell = 1$ modes of δ Sct stars (solid line) and γ Dor instability domain (dashed lines). The cool edge of both instability domains was theoretically computed by Dupret et al. (2005), nicely corresponding with the observations. The ZAMS as well as evolutionary tracks for different masses are depicted. The points in the diagram represent observed δ Sct stars, while the circles the γ Dor stars. Figure from Dupret et al. (2005).

2.2 Characterization of δ Scuti stars

In this work the main focus is on the classical instability strip and more precisely on the δ Sct stars. As already mentioned, these stars pulsate due to the κ mechanism acting in the He II ionization zone and are well confined within a region defined by the so called red and blue border, indicating the cooler and hotter edges respectively. Stars with effective temperatures higher than the blue edge cease to pulsate because the He II opacity bump is at a depth where the density is too low to excite pulsation (Pamyatnykh 2000). On the cool site of the instability strip, the oscillations are damped due to the increasing depth of the convective outer layers. These were theoretically derived by Dupret et al. (2005), using time dependent convection, which requires a non-adiabatic treatment that considers the interaction between pulsation and convection as described by Grigahcène et al. (2004). Interestingly, the instability domain of the γ Doradus (γ Dor) stars, pulsating in high radial order g modes, overlaps the one of the δ Sct stars, suggesting that both types of pulsation should be excited simultaneously in stars located there (Fig. 2.2). Handler et al. (2002) found HD 209295 to pulsate in high order g and low order p modes as expected. Nevertheless this specific star turned out to be a close binary system, with g modes tidally excited by the companion. Shortly after Henry & Fekel (2005) indeed found the first 'real' hybrid star. Meanwhile missions like the NASA Kepler satellite (see details in chapter 5.1) have established that the δ Sct and γ Dor

hybrids are a common phenomenon, rather than an exception (Grigahcène et al. 2010, Uytterhoeven et al. 2011).

The δ Sct stars cover masses between 1.5 and 2.5 $M_{\odot}$ and have effective temperatures ranging from 6700 to 8000 K. These stars can be found on the pre main sequence (PMS), main sequence (MS) and on the immediate post MS. The periods of pulsation are the result of low radial order p and g modes, and can range between 15 minutes and 8 hours. δ Sct stars come in many flavours:

1. Population I stars (vast majority)
2. Population II stars, also known as SX Phoenicis stars, best explained as binary stars mergers.
3. The high amplitude δ Sct stars (HADS) are considered to be a subgroup, but more out of historic reasons (see e.g. a review by McNamara 2000). For a long time they were considered to be pure radial pulsators, but extensive observing campaigns have proven the opposite (Poretti et al. 2011). The amplitudes of the dominant modes are of the order of 0.3 mag (which is the main definition of this subgroup) and the vast majority have projected rotational velocities typically lower than 50 km s^{-1} .
4. The λ Bootis stars show solar abundances of light elements but photospheric underabundances of heavy elements, especially of Fe group elements. The present hypothesis is that the peculiarities are due to interstellar matter accreted while passing through a diffuse interstellar cloud (Paunzen et al. 2003).
5. Chemically peculiar AmFm stars, which are observed to have photospheric overabundances in the elements Ba, Y, Sr and underabundances in Sc and Ca (Preston 1974) when compared to the Sun. According to Auriere et al. (2011) these stars do not have any large scale magnetic fields, contrary to the likewise chemically peculiar (rapidly oscillating) Ap stars. The Am phenomenon is related to gravitational settling of heavy elements and levitation of lighter elements that can efficiently operate because of slow rotation (Charbonneau 1993). The pulsating AmFm stars still represent a mysterious group, because the reason why many pulsate is not well understood. It is believed that due to the diffusion of He, there should not be enough in the He II zone for the κ mechanism to drive pulsation. The implementation of diffusion of heavy elements in models can explain pulsation in a very constrained instability region (Turcotte et al. 2000). However, observations from the Kepler satellite (Balona et al. 2011) demonstrate that pulsating AmFm stars are spread over the entire δ Sct instability strip. Also the first δ Sct and γ Dor hybrid, HD 8801, was identified to be an Am star (Henry & Fekel 2005).
6. ρ Puppis stars (earlier also referred to as δ Delphini stars) are overabundant in metals, but more evolved than the Am stars. The hydrogen lines are typical

for F5 standards whereas the Am stars have H lines best matched with those of F2 and earlier (Gray & Garrison 1989). Note that classifications of metallic-line stars, such as Am and ρ Puppis stars, have a special notation: $kX hY mZ$, where X is the spectral classification of the Ca K line, Y is the temperature indicated by the hydrogen lines and Z is the classification of the metallic lines. These stars are suggested to be evolved Am stars (Kurtz 1976) and show anomalous luminosity effects, similar to their progenitors. The anomalous luminosity effect means that different spectral regions are best interpreted by different luminosity classes, making it rather complicated to derive consistent $\log g$ values (Gray & Garrison 1989).

The stars studied in this work are representatives of the last two subclasses of δ Sct stars: ρ Puppis, which is eponymous for the whole group and HD 187547 which was classified as an Am star. This was a fortunate coincidence and allows us to trace the evolution of the Am phenomenon, once the stars have been asteroseismically modelled.

In the earlier days, models of δ Sct stars predicted too many frequencies to be excited but too few were observed. Extensive observing campaigns of the star FG Virginis for example, showed that lowering the detection level is imperative to find additional independent modes, in this case 67 (Breger et al. 2005). Meanwhile in some cases ‘too many’ frequencies are observed, at least for HD 50844, where Poretti et al. (2009) needed around 1000 frequencies (!) to fit the light curve. Mode identification based on spectroscopic data suggested that high modes with $\ell=14$ are excited. Several radial orders of high spherical degree modes split by rotation would be required to explain the large number of observed frequencies. A second CoRoT star (HD 174936, García Hernández et al. 2009), was found to have approximately 500 significant frequencies of pulsation.

Kallinger & Matthews (2010) suggested that the major part of the observed frequencies originates from granulation noise and are not due to pulsation. Their interpretation assumes the presence of non-white granulation noise, as observed in sun-like stars. The granulation time scales found in the two CoRoT stars are perfectly consistent with scaling relations from cooler stars. This hypothesis is strongly supported by earlier spectroscopic measurements, where line profile variations were found to be caused by convective motions in the atmosphere of A and Am stars (Landstreet et al. 2009). In general A type stars have rather high microturbulent velocities¹ which is further evidence for granulation (Montalbán et al. 2007). Balona (2011) also confirms that in the Kepler A type stars (whether variable or not) there is a correlation between the noise level and the effective temperature as expected for the signature of convection. However, there is no reason why we should not observe a combination of both phenomena, high order ℓ modes and granulation noise. The data quality from space may be indeed high enough to also observe higher ℓ modes,

¹This parameter mirrors the velocity fields in the stellar atmosphere, hence can be related to convection.

as was shown by Balona & Dziembowski (1999). They calculated that the amplitude should drop below $50 \mu\text{mag}$ for modes with $\ell \geq 6$ due to geometrical effects, assuming the same intrinsic amplitude of $\Delta T_{\text{eff}}/T_{\text{eff}} \approx 0.01$ for all modes. This is a value which can be detected from space.

Unique modelling of δ Sct stars is hampered by many obstacles, the biggest problem being the mode identification. As already mentioned, it is not yet known why some of the modes observed in δ Sct stars are excited to observable amplitudes while others are not. To clearly determine the geometry of a mode, long observing campaigns are needed, as were organized by the Delta Scuti Network (e.g. Breger 2000). Comparing the amplitude ratios and the phase differences between two filters for a given mode with models allows to identify their geometry (Garrido 2000). Time series spectroscopy can be used for mode identification too, because the line profile variations will be different for different modes. Depending on the projected rotational velocity of a star, the moment method (e.g. Aerts & Eyer 2000) and/or the Pixel by Pixel method (Zima 2009) can be deployed. Daszyńska-Daszkiewicz et al. (2005) combined colour photometry with radial velocity measurements and derived the so-called f parameter which is a semi-empirical variable sensitive to the convection in the envelope. Using this method, they conclude that convection is not efficient in the outer layers of FG Virginis. 44 Tauri is a slowly rotating δ Sct star in which every single observed mode can be explained by models (Lenz et al. 2010). This star was found to be during the contraction phase just after the terminal age main sequence (TAMS), where hydrogen is exhausted in the core and the hydrogen shell burning phase begins. Also in this case the models with inefficient convection fitted the observations best. This star is almost a unique example, as no other δ Sct star could ever be modelled as precisely as 44 Tau.

There are several other parameters which need to be taken into account when employing seismic modelling. Rotation, for example, can cause mode coupling even at moderate rotation (Daszyńska-Daszkiewicz et al. 2002). This means that close modes end up sharing the same characteristics. For example an $\ell = 0$ mode might adopt characteristics of a close $\ell = 2$ mode. An additional uncertainty is convective core overshooting, the primary parameter influencing the life time of a star on the MS which is also not well constrained. And as already mentioned mode identification and inaccurate determination of masses and radii. Why study these stars if so complicated?

The reason why these stars are such interesting astrophysical laboratories is because δ Sct stars occupy a region in the HRD where many physical processes occur. It is in the classical instability strip where the transition between deep and efficient to shallow convective envelopes takes place. The so called granulation boundary (Gray & Nagel 1989) was found from bisector measurements to cross following spectral types: F0V, F2.5IV, F5III, F8II, G1Ib, which is right through the δ Sct instability strip. A summary on convection in A- type stars from the theoretical point of view can be found in Kupka (2004). Smalley (2004) reviewed the same topic with emphasis on observations. More recent studies as already mentioned before, suggest

that convective motions are still present in mid to late type A stars (Landstreet et al. 2009, Kallinger & Matthews 2010). Because convection has an impact not only on pulsational stability but also on stellar evolution, activity, modelling stellar atmospheres, transport of angular momentum, etc., it is of great interest to understand how this transition takes place. When modelling convection, usually the mixing length theory is used (MLT) (Böhm-Vitense 1958, Gough 1977) which gives satisfactory results in many cases, but in some others not. 3-D models to reproduce the physics within convective zones are scarce because of very expensive computing time (e.g. Trampedach & Stein 2011).

Stars later than F5 have very slow rotation rates, in average around $v \sin i < 10 \text{ km s}^{-1}$, with a sharp increase between F0 and F5 (Royer 2009). The measured rotational velocities for the cool stars inside the instability strip are on average higher than 100 km s^{-1} . Royer (2009) also reports observational evidence for differential rotation in A type stars, which is related to magnetic dynamos like in the Sun. Chromospheric activity disappears only for stars hotter than 8300 K (Simon et al. 2002), demonstrating that the instability strip of δ Scuti pulsators is affected by this transition.

2.3 Predictions of solar-like oscillations in δ Scuti stars

Houdek et al. (1999) and later Samadi et al. (2002) predicted that the convection in outer layers of δ Sct stars is still efficient enough to excite solar-like oscillations. Using time-dependent, nonlocal, mixing-length convective treatment, they calculated the intrinsic stability of modes excited by the κ mechanism. Only when modes are intrinsically stable acoustic noise generated by turbulent convection can excite the natural eigenmodes in a given frequency range. Because the amplitudes of stochastic oscillations are the result of the interaction between damping and excitation, taking into account the physical processes involved, resulting from the momentum and the thermal energy balance, predictions can be made. Different models indicate different effects to be the primary reason for the damping of solar-like oscillations, resulting in uncertainties in the predictions, see, e.g., Houdek (2006) for a review. When comparing amplitudes of solar-like oscillations one has to take into account that, especially for the highest radial orders, the amplitudes will differ depending on the observed wavelength range. For the Sun for example the amplitudes vary by 25% between the GOLF and BiSON instruments (Kjeldsen et al. 2005).

As already mentioned before, consecutive high radial order p modes are approximately equally spaced in frequency which gives rise to a comb-like structure in the frequency spectrum of a solar-type star (see Fig. 2.3 for the Sun). The large frequency separation $\Delta\nu$ is the mean separation between high radial order modes of the same degree ℓ and from Equation 1.10 it is evident that it measures the mean density of the star. If scaled to the Sun it can also be written as (Kjeldsen & Bedding 1995):

$$\Delta\nu = \left(\frac{M}{M_\odot}\right)^{\frac{1}{2}} \left(\frac{R}{R_\odot}\right)^{-\frac{3}{2}} \Delta\nu_\odot \quad (2.4)$$

where $\Delta\nu_\odot = 134\mu\text{Hz}$. As can be seen in Fig. 2.3 the oscillation spectrum is described by an envelope with a frequency of maximum power, ν_{max} , at $3090\mu\text{Hz}$ (Huber et al. 2011). The ν_{max} and the shape of the oscillation envelope, determined by damping and driving, are thought to be related to the acoustic cutoff frequency, $\nu_{ac} \propto g/\sqrt{T_{eff}}$ (e.g. Brown et al. 1991). From that Kjeldsen & Bedding (1995) derived the following scaling relation for ν_{max} for any other star:

$$\nu_{max} = \frac{M/M_\odot}{(R/R_\odot)^2 \sqrt{T_{eff}/T_{eff_\odot}}} \nu_{max_\odot}. \quad (2.5)$$

To relate the asymptotic relation for p modes to observables Equation 1.9 can also be written as:

$$\nu_{n,\ell} \simeq \Delta\nu \left(n + \frac{\ell}{2} + \epsilon\right) - \delta\nu_{0\ell} \quad (2.6)$$

where ϵ is a dimensionless offset and $\delta\nu_{0\ell}$ is the so called small frequency separation, which is the frequency difference between modes of the same radial order but of spherical degree ℓ differing by 2. This separation is sensitive to the sound speed gradient and therefore to the chemical composition inside a star and gives a good estimate for the age. Christensen-Dalsgaard (1988) constructed an asteroseismic diagram where for main sequence stars, $\delta\nu$ was plotted as a function of $\Delta\nu$, demonstrating the dependence on mass. Huber et al. (2010) and White et al. (2011) show that also ϵ , which basically determines the absolute position of the $\ell = 0$ ridge in the echelle² diagram. The $\nu_{max} - \Delta\nu$ empirical relation yields the form: $\Delta\nu = \alpha(\nu_{max}/\mu\text{Hz})^\beta$, where $\alpha = 0.263 \pm 0.009$ and $\beta = 0.772 \pm 0.005$ (Stello et al. 2009). The coefficients of α and β vary depending on the literature summarized by Huber et al. (2011).

The damping rate of a mode can be measured from the linewidths³ by fitting a Lorentzian profile to an observed mode (see Fig. 2.3). Because the power of the mode is spread over a certain frequency range the amplitude and frequency cannot be estimated as in the case of coherent pulsation by simply computing the Fourier spectrum and basically reading the numbers off. The frequencies of stochastically excited modes are derived by fitting Lorentzian profiles, where the inverse of the FWHM times π gives the mode lifetime, which according to prediction strongly depend on temperature (Chaplin et al 2009, Baudin et al. 2011). Kjeldsen et al (2008) who showed that the amplitude of solar-like oscillations depends on the wavelength at which the observations are made, proposed a method to derive a

²a diagram where frequency modulo $\Delta\nu$ is plotted as a function of frequency. Peaks equally spaced will follow perpendicular ridges (see Fig. 5.1)

³FWHM of the fitted Lorentzian profile, see Fig. 2.3

homogeneous way to measure the amplitude per radial mode (see chapter 5.1). This value can then be used to compare to theoretical or empirical scaling relations. Predicting the amplitude for stochastic oscillations is possible as mentioned above, but depending on the literature the numbers vary quite a bit. Based on models from Christensen-Dalsgaard & Frandsen (1983), Kjeldsen & Bedding (1995) derived that the velocity amplitudes scale as:

$$A_{vel} \propto \left(\frac{L}{M}\right)^s \quad (2.7)$$

where $s = 1$ and L is the luminosity and M the mass of a star. The same authors derived that the photometric amplitude observed at wavelength λ can be written as:

$$A_\lambda = \frac{v_{osc}}{\lambda T_{eff}^r} \quad (2.8)$$

with the exponent $r = 1.5$ for adiabatic pulsation and 2 for classical pulsators. During the past years s was modified to be between 0.7 and 1.3 for the main sequence stars depending on the literature (Houdek et al. 1999; Houdek 2006; Samadi et al. 2007). A revised empirical scaling relation by Kjeldsen & Bedding (2011) suggests that also the mode lifetime should be taken into account when predicting the amplitude:

$$A_{vel} \propto \frac{L\tau_{osc}^{0.5}}{M^{1.5}T_{eff}^{2.25}} \quad (2.9)$$

where τ_{osc} is the measured mean mode lifetime. More recently, Huber et al. (2011) concluded, based on the Kepler measurements, that the following relation fits better the photometric observations:

$$A_\lambda \propto \frac{L\tau_{osc}^{0.5}}{M^{1.5}T_{eff}^{1.25+r}c_k(T_{eff})} \quad (2.10)$$

where $r = 2$ and $c_k(T_{eff}) = (T_{eff}/5934)^{0.8}$ is the bolometric correction factor for the Kepler passband, from Ballot et al. (2011).

All these tight relations, even if not perfect in some cases, allow nevertheless to perform ensemble asteroseismology of solar-like stars with high accuracy. The derived mass distribution of the Kepler population of Sun-like stars may have a large impact on the models predicted the population of our Galaxy (Chaplin et al. 2011). Can the same be done for δ Sct stars? Are there relations we can use to study these stars as a group? If there are any, Uytterhoeven et al. (2011) who statistically analyzed all the A and F stars in the Kepler FOV, at least did not find any. Figure 2.4, inspired by Fig. 1 from Chaplin et al. (2011) shows δ Sct Fourier spectra organized by increasing temperature and $\log g$ demonstrating the non-uniformity.

The main motivation for the present work was the theoretical prediction of solar-like oscillations to be present in δ Sct stars by Houdek et al (1999) and Samadi et al.

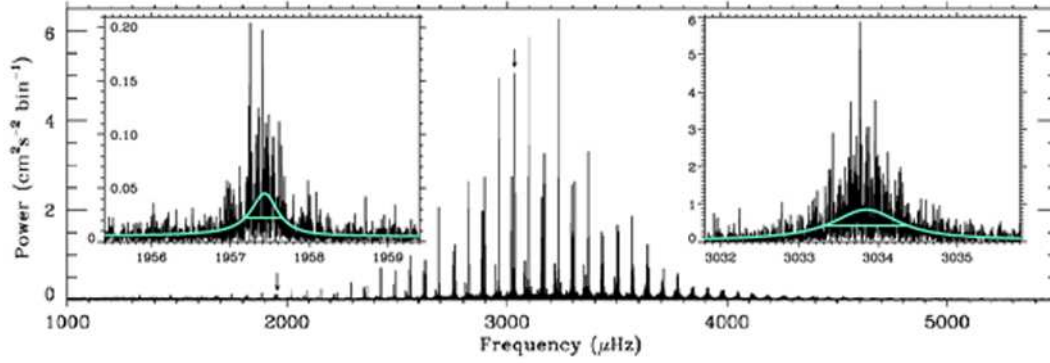


Figure 2.3: The solar oscillation spectrum. The two sub-panels to the left and to the right illustrate two modes in detail, indicated by the arrows. The broad mode structure is the result of the random excitation and damping, which is frequency dependent. From Houdek (2006).

(2002) with the aim to validate or disprove the theory. If detected, that would allow us to perform mode identification for the stochastically excited oscillations from pattern recognition and therefore to also identify the modes of pulsation excited by the κ mechanism. As a result we can reproduce the deep interior of the star by using the δ Sct oscillations and constrain the overshooting parameter α_{OV} , which is the primary factor to influence the lifetime on the MS. The solar-like oscillations on the other hand are most sensitive to outer (convective) envelope, which so far is poorly understood in stars with masses ranging those of δ Sct stars. To search for solar-like oscillations in δ Sct stars, we chose to use radial velocity measurements (chapter 3). The reason for that is that the noise due to granulation is lower in radial velocity measurements than in photometry (see Fig. 4.1 from Aerts et al. 2010).

2.3.1 Solar-like oscillations in F stars

Prior to Kepler, solar-like oscillations were found in several F type stars. For Procyon for example, an extensive ground-based high-precision radial velocity observing campaign was organized (Arentoft et al. 2008). This star is placed at the end of the main sequence or at the beginning of the post-main sequence and most probably shows mixed modes (see Bedding et al. 2010). According to Arentoft et al. (2008) the photometric mode amplitudes at 550 nm were found to be 6.8 ppm for $\ell = 0$ and 8.5 ppm for $\ell = 1$ which is consistent with the observed value of 8.5 ± 2 ppm obtained from observations with the WIRE satellite (Bruntt et al. 2005). Bedding et al. (2010) address an important topic which may be relevant also for some of the δ Sct stars: they say that mixed modes showing g-mode character in the interior and p mode like in the envelope are expected to have lower amplitudes but also longer

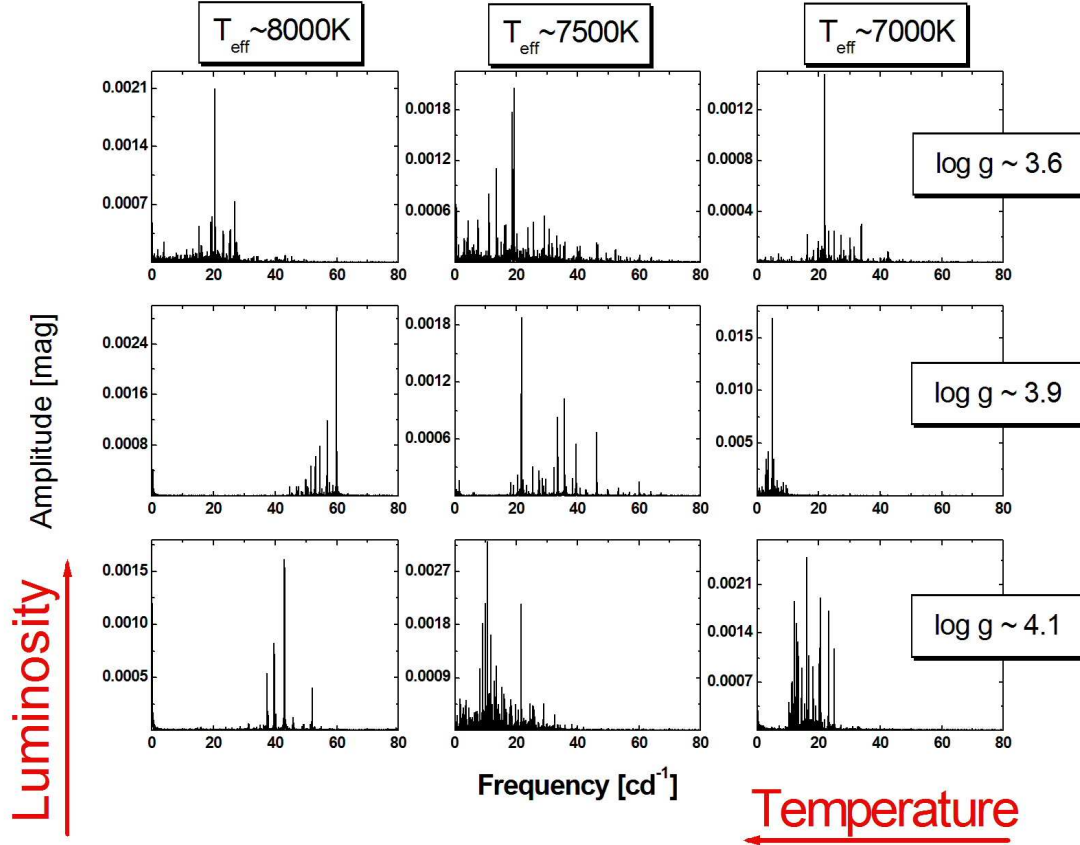


Figure 2.4: Delta Scuti stars from Kepler, an example for their diversity. This figure is inspired by the Chaplin et al. (2011) who show the homogeneity of solar-like oscillations enabling to do ensemble asteroseismology.

mode life time. In the Fourier spectrum such properties would result in higher and narrower peaks.

Mathur et al. (2010, and references therein) list the F-type stars showing solar-like oscillations which were observed with the CoRoT satellite (HD 170987, HD 49933, HD 181420, HD 184420, HD175726) and point out that all observed amplitudes at maximum power were systematically below the predicted values (see section 5.4 Mathur et al. 2010). Houdek et al. (1999) and Samadi et al. (2010) show that the metallicity surface abundance plays an important role on the efficiency of stochastic driving. Less metals result in less effective convection, hence in lower amplitudes. The CoRoT stars mentioned above all have low or solar observed $[\text{Fe}/\text{H}]$ surface abundances. To summarize, for the mentioned F-type stars the amplitudes range from 1.7 to 8.5 ppm, values large enough to be observed in Kepler data, which was clearly proven (see e.g. Chaplin et al. 2011, Huber et al. 2011).

3 Radial velocity measurements

3.1 The iodine technique

Radial velocity measurements are used to measure the velocities with which an object moves toward or away from the observer, based on the Doppler effect. As a star pulsates the outer layers move in and out causing periodic radial velocity shifts. Time resolved spectroscopic observations allow not only to derive the periods of pulsations but also to do identify their geometry (see e.g. Zima et al. 2007).

The radial velocity measurements are as precise and accurate as the instruments themselves and the reduction procedure. To obtain high resolution spectra over a large wavelength region Echelle spectrographs are used. The stability of the instrument and the calibration method is the key to success. Several instruments mounted on telescopes with different sizes exist in the Northern and Southern hemisphere. Instruments such as UCLES at the Anglo Australian Telescope (AAT), the Coudé Spectrograph (TS 23) at the 2.7-m telescope at McDonald Observatory, ESPaDOnS at the Canada-France-Hawaii Telescope (CFHT), CORALIE at the 1.2-m Euler Swiss Telescope at La Silla Observatory, SARG at Telescopio Nazionale Galileo, NARVAL mounted to the Bernard Lyot Telescope at Pic du Midi Observatory, and HARPS at the 3.6-m telescope at ESO La Silla reach a precision of few meters per second per spectrum.

During the latest decades the precision to measure Doppler shifts highly increased. Griffin & Griffin (1973) for example, were the first to use the atmospheric telluric lines superimposed on the stellar spectra to get more accurate wavelength calibrations. Up to date the most common reference method in the visual wavelength region is the Thorium-Argon (ThAr) lamp, emitting emission lines at well determined wavelengths. Usually ThAr calibration frames are taken several times during an observing night to account for instrumental drifts. Nevertheless spectrographs can undergo several changes over time, such as thermal expansion and changes in air-pressure which cause zero-point shifts in the wavelengths scale and dispersion changes (see e.g. Butler et al. 1996). Even if the calibration frames are observed shortly before and immediately after the stellar exposure, this is not sufficient to account for the wavelengths shifts when aiming a precision of few meters per second. The HARPS spectrograph, for example, simultaneously projects the spectrum of the target star and a ThAr lamp onto the same CCD frame, reaching an outstanding precision, and being the most stable instrument so far ($\sim 1\text{m/s}$ for a G type star of 6th magnitude for one minute integration time). For this method the spectrograph is kept in vacuum with a thermal control of milliKelvin.

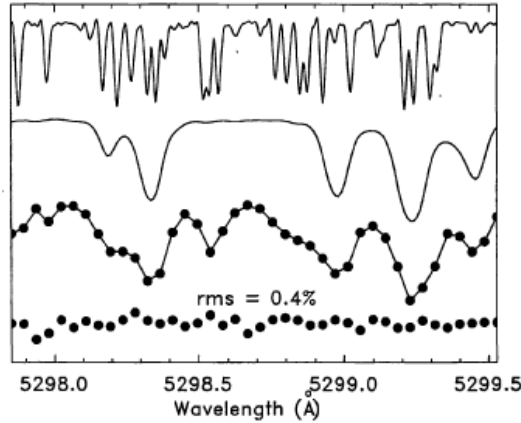


Figure 3.1: Modelling radial velocity observed through an iodine cell. The top spectrum is the I_2 spectrum, the second spectrum is the intrinsic stellar spectrum, the points in the third spectrum represent the star observed through the I_2 cell fit by the model depicted as a solid line. The bottom spectrum shows the differences between the model and the observations multiplied by 10. Figure from Butler et al. (1996).

Another very efficient method for wavelength calibrations is to observe the star through an iodine cell, a method developed by Butler et al. (1996), initially used to detect Doppler shifts caused by planets orbiting their host stars. It is based on the idea that the stellar light and the reference frame should follow the same path through the telescope and the spectrograph, minimizing temporal and spatial error sources on the radial velocity measurements. The iodine cell consisting of 0.001 atmospheres of molecular iodine (I_2), is around 10 cm long with a diameter of 5 cm and is thermally controlled to be at temperatures between 50 and 60°C, which puts the I_2 in a gaseous state. The cell is mounted directly in front of the spectrograph. The reason for choosing I_2 is that it shows a forest of absorption lines between 5000 and 6000Å, a region where stars with a spectral type later than A, have many spectral lines providing the necessary information for precise radial velocity measurements. The wavelengths of the I_2 absorption lines are very well determined by scanning the cell with a Fourier Transform Spectrometer (FTS)¹, a spectrograph with ultra-high precision used in laboratories only.

The negative part about using the iodine cell method, is that there is no publicly available pipeline for data reduction for any of the spectrographs using this methods (UCLES, McDonald, SARG, ...) yet. Of course, radial velocity measurements can be obtained through a simple-cross-correlation between the I_2 spectrum and the

¹see for example the NIST-FTS (National Institute of Standards and Technology-Fourier Transform Spectrometer) with which the I_2 cell used at AAT was scanned, http://physics.nist.gov/Divisions/Div842/Gp1/fts_home.html

observed stellar spectrum through the cell but that would yield a precision between 50 and 100 ms^{-1} only (Butler et al. 1996). For the search of signals with tiny amplitudes of the order of few meters per second a complex reduction method, involving the modelling of the instrumental point-spread-function (PSF) of the spectrograph is needed. The shape of the instrumental profile is influenced by many sources, such as seeing changes during the night, optical elements, dust, etc. A change of only 1% in the PSF shape, which is normally approximated by a Gaussian, can introduce shifts in the precision of the radial velocity measurements up to 20 ms^{-1} (Butler et al. 1996). The following paragraphs will describe in detail the modelling procedure of the observations through an iodine cell, developed and established by Butler et al. (1996).

During the whole reduction process the Echelle orders are divided into so-called chunks of few pixels, covering 2-2.5Å, each delivering a radial velocity measurement. The wavelength region covered by the I_2 is $\sim 1000\text{Å}$ spread over several orders. Depending on the dispersion of the spectrograph and the CCD detector a number of 200-300 of 'individual' radial velocity values can be obtained allowing a high precision of the final value. To derive the radial velocity of a chunk the model is defined by the product of the intrinsic stellar spectrum I_S and the transmission function of the iodine absorption cell T_{I_2} , which then is convolved with the spectrograph's PSF. The result is afterwards binned to the wavelength range of the CCD. The stellar spectrum I_{obs} , is described as follows

$$I_{obs} = k[T_{I_2}(\lambda)I_S(\lambda + \Delta\lambda)] * PSF \quad (3.1)$$

where k is a normalization factor, $\Delta\lambda$ the Doppler shift and $*PSF$ represents the convolution with the PSF of the spectrograph (Butler et al. 1996). T_{I_2} , the transmission function of the iodine cell is the FTS spectrum obtained as described above. The intrinsic stellar spectrum I_S must resemble the spectrum free of any instrumental effects, which is done by deconvolution of the target star (not observed through the iodine cell) and the PSF. For the latter, a rapidly rotating B type star is observed through the iodine cell, mimicking a calibration lamp. It can be assumed that the stellar spectral features are smeared out, thus imaging only the iodine spectrum. From that, the PSF of the instrument can be derived. This procedure is more accurate than measuring a real calibration lamp, because the calibration star light follows the same path as that of the target star. The PSF itself is a sum of several Gaussians at fixed position and widths but with variable height. In this way a possible non-symmetric PSF can be described. For a detailed explanation on how to derive a PSF see Valenti et al. (1995). To preserve the detailed wavelength information provided by the I_2 cell, the stellar spectra are oversampled by a certain factor (at least 4 times) to which also the I_2 cell is resampled. Now having the deconvolved intrinsic stellar spectrum I_S , the PSF of the instrument and the iodine cell spectrum, the observations can be modelled as described in Equation 3.1. For this final step the Doppler shift $\lambda/\Delta\lambda$ becomes an additional free parameter, the one of interest which allows to reproduce the observations. Fig. 3.1 nicely illustrates the procedure described above.

3.2 iSONG

The *Stellar Observations Network Group* (SONG) is an ongoing project which aims to establish a global network of eight robotic 1-m telescopes equipped with high-resolution spectrographs. These should be placed at different observatories covering the Northern and Southern hemispheres, to ensure a high duty cycle. To obtain ultra-precise radial velocity measurements the iodine cell method was chosen. This project was developed by the DASC (Danish AsteroSeismology Centre, Aarhus University, Department of Physics and Astronomy, Denmark) and is designed to keep the costs at a low level, by e.g. using the same setup for all telescopes and spectrographs. This not only saves money and shortens the designing phase but also gives needed homogeneity of the data. The Danish prototype is being built at the moment and is soon to be mounted at Teide Observatory in Tenerife. A detailed description of the project as well as of the telescope and spectrograph can be found at <http://astro.phys.au.dk/SONG/>.

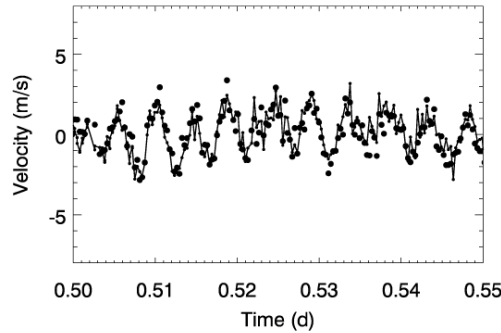


Figure 3.2: Radial velocities of the solar-like star α Cen A, observed with UVES (Butler et al. 1996). Here a comparison is made between iSONG and the method developed by Butler et al. (1996) using the same data set. The black line with small dots represent the data reduced with iSONG whereas the big black points are the data reduced by Butler et al. (1996). Figure from Grundahl et al. (2008).

During the planing phase of the SONG project, Frank Grundahl, the instrument scientist of the Danish prototype, developed a code to extract precise radial velocity measurements of a star observed through an iodine cell. This code is called iSONG, written in IDL and was kindly provided to be used and tested for this work. It is based on the same method described above (Butler et al. 1996). A direct comparison (Grundahl et al. 2008) using the same data set of α Cen A observed with UVES@VLT, demonstrates that iSONG is capable of reaching the same precision as Butler et al. (1996). The difference between the radial velocities derived with iSONG and the ones derived by Butler et al. are shown in Fig. 3.2. Measuring the scatter at high frequencies, a precision per point of 77 cm/s for iSONG and 71 cm/s from Butler et al. (1996) was found.

4 The δ Sct star ρ Puppis

4.1 History

ρ Puppis is a bright star with $V = 2.81$ mag ($RA_{2000} = 08\ 07\ 32.6489$, $DEC_{2000} = -24\ 18\ 15.567$) and was target for many studies as it is eponymous for the metal-rich δ Sct stars. It was first discovered to show light variability by Eggen (1956) and was classified as a δ Sct star. Struve et al. (1956) measured a peak-to-peak amplitude of $10\ \text{kms}^{-1}$ and derived a shift of 0.02 days between maximum brightness and minimum radial velocity. Ponsen (1963) also concluded that ρ Puppis is a mono-periodic star. Danziger & Kuhl (1966) found ρ Puppis to be an intriguing object for its class, pulsating in very high overtones. Bessell (1967) showed that Danziger & Kuhl (1966) had underestimated the line-blanketing of ρ Puppis and therefore measured a far too low $\log g$ and T_{eff} , and concluded that the star is probably pulsating in the first overtone compatible with theoretical prediction of δ Sct stars. Dravins et al. (1977) reported from simultaneous photometric and spectroscopic measurements a transient feature in the Ca II K line attributed to chromospheric activity due to shock waves occurring near maximum outward acceleration of the photosphere. The authors also interpret the observed shifts in epochs as additional variations mixed with the dominant period. Campos & Smith (1980) found that the variability of ρ Puppis is most likely due to a radial mode. Fracassini et al. (1983) have found strong evidence for emission in the Mg II H + K lines ($\lambda\lambda$ 2802.7 and 2795.5) present during the whole pulsation cycle which is a signature of chromospheric activity. Yang et al. (1987) determined different amplitudes of pulsation for the dominant mode in different elements in the spectra of ρ Puppis which they interpreted to be most probably due to beating effects with other pulsation modes. The same authors reported a possible van Hoof effect¹. Mathias et al. (1997) were the first who detected two additional frequencies (at 7.815 and 6.314 cd^{-1} respectively) in new radial velocity measurements. Using the moment method the authors identified the dominant mode as a radial mode and the second one as an axisymmetric one. Mathias et al (1997) also found evidence for a standing wave effect between Fe I $\lambda\lambda$ 6546 and the H α line but did not observe any signature of activity in the Ca II K line as reported earlier by Dravins et al. (1977). Mathias et al. (1999) re-observed ρ Puppis to test the hypothesis of the transient feature but again did not find any evidence. Nevertheless the authors accepted that chromospheric activity must be present in ρ Puppis as the UV observations of Fracassini et

¹The pulsation amplitudes and/or phases measured for different elements can significantly differ, caused either by shock waves but also by running waves (see e.g. Mathias & Gillet 1993)

Table 4.1: Strömgren indices and the effective temperatures of ρ Pup were determined using TEMPLOGG.

$b - y$	0.260 ± 0.002
m_1	0.213 ± 0.008
c_1	0.731 ± 0.005
H_β	2.720
$E(b - y)$	0.036 ± 0.002
$(b - y)_0$	0.223
m_{10}	0.225
c_{10}	0.724
T_{eff} (Napiwotzki et al. 1993)	6700 K
$\log g$ (Napiwotzki et al. 1993)	3.4
T_{eff} (Moon 1985)	7000 K
$\log g$ (Moon 1985)	3.6

al. (1983) clearly showed emission in the Mg II H + K lines as already mentioned. Moon & van Antwerpen (2009) re-analysed all available data and concluded that ρ Pup shows period changes which are attributed to evolution, but the authors did not take into account the multi-periodic nature of the star.

4.2 Fundamental parameters

Strömgren indices were listed by Hauck & Mermilliod (1998) for ρ Pup, allowing to obtain a dereddening coefficients², as well as an effective temperature based on calibrations as summarized in Table 4.1. The same table also displays the c_{10} and m_{10} . For completeness also T_{eff} and $\log g$ based on calibrations of Napiwotzki et al. (1993) and Moon (1985) were calculated (see Table 4.1).

The visual magnitude of ρ Puppis is $m_V = 2.81$. Using the accurate Hipparcos parallax $\pi = 51.33 \pm 0.15$ mas (i.e. a distance of 19.48 ± 0.06 parsec) an absolute magnitude M_V of 1.362 ± 0.006 can be derived (see, e.g., Rodriguez & Breger 2001). The dereddening factor of 0.036 was derived from Strömgren colours. According to Flower (1996) a bolometric correction B.C. = 0.06 was applied, resulting in a bolometric magnitude of $M_{\text{bol}} = 1.302 \pm 0.006$. We derive a luminosity $L/L_\odot = 27.3 \pm 0.2$. Given the proximity of ρ Pup an angular diameter of 1.658 ± 0.03 mas was observed using interferometry (Michael Ireland, priv. comm.) resulting in a radius of $R = 3.47 \pm 0.07 R_\odot$. This is similar to the radius of $R = 3.41 R_\odot$

²It is very unlikely that the $E(b - y) = 0.036 \pm 0.002$ reflects interstellar reddening as ρ Puppis is located at a distance of only 19.48 ± 0.06 parsec. We find it more plausible that the non-zero value originates from the chemical peculiarity of the star, causing many blended absorption lines.

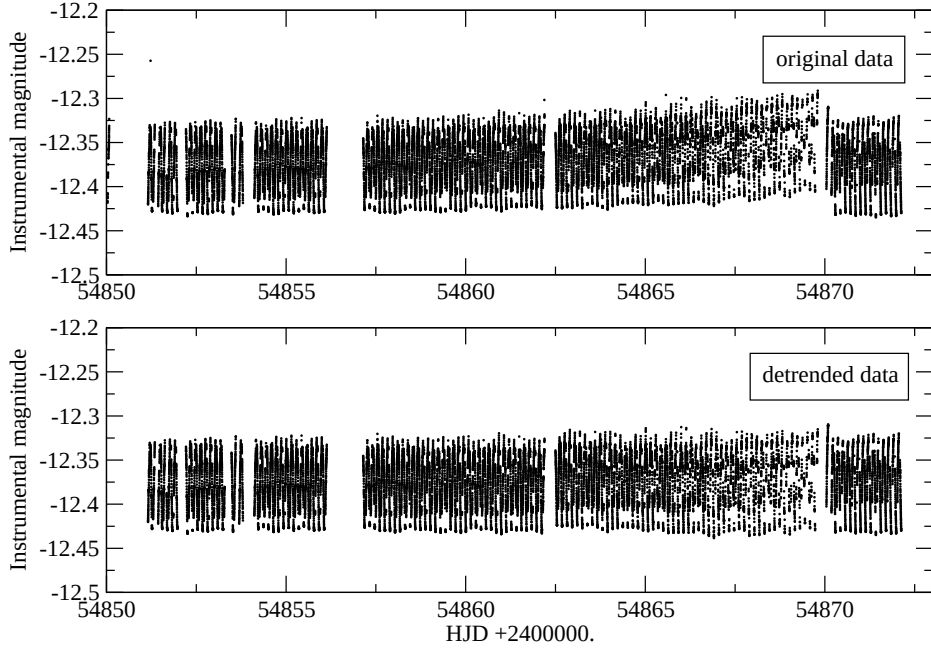


Figure 4.1: Upper panel: MOST data from 2009 with an obvious jump due to thermal adjustments of the spacecraft. Lower panel: data set after trend removal.

mentioned by Rhee et al. (2007). For further analyses we will use the latest value of $R = 3.47 \pm 0.07 R_{\odot}$, which allows to independently obtain an effective temperature of $T_{\text{eff}} = 7080 \text{ K} \pm 80 \text{ K}$ (will be referred to as ‘interferometric T_{eff} ’). This is in agreement within the error bars with values from literature (e.g. photometric values in Table 4.1 and spectroscopic ones from Burkhardt & Coupry (1991)) and with the spectroscopic determination by Antoci et al. (2008).

4.3 Observations and data reduction

To search for solar-like oscillations in ρ Puppis, we organized a multisite campaign spread over two years, involving spectroscopy and photometry. A total of 2763 spectra and 38306 photometric measurements (white light and colour photometry) were collected; a summary can be found in Table 4.2. The photometry is not only useful for mode identification but more importantly for the present case, for accurate determination of the pulsation frequencies.

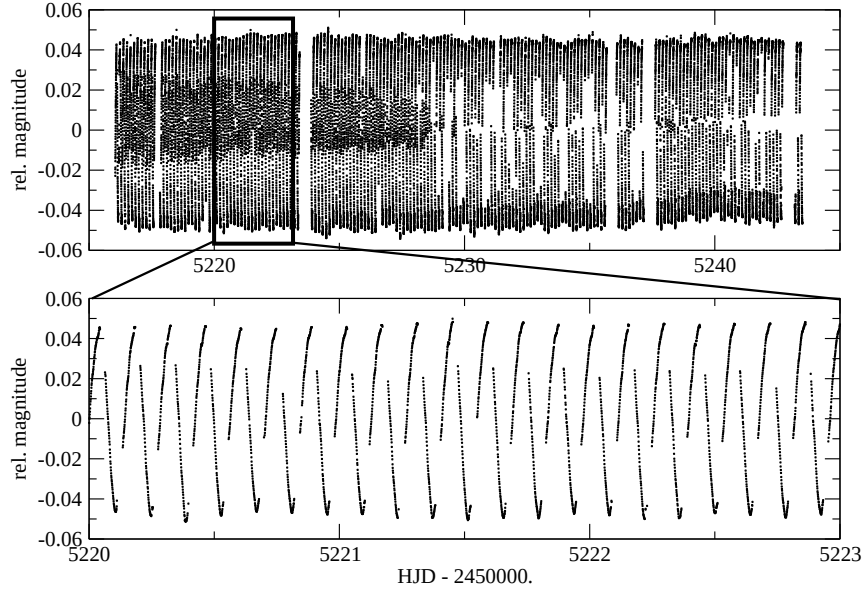


Figure 4.2: Upper panel: MOST data from 2010 showing no trend. Lower panel: close-up of 3 days. The gaps in the data set are due to the orbital period of the MOST satellite. Note that the dominant period of ρ Pup is very close to 2 times the orbital period.

Table 4.2: Multisite campaign for ρ Puppis involving photometry and spectroscopy.

Observatory	Instrument	Method	year-month	Nr. of nights	Nr. of measurements
ESO	CORALIE	ThAr calibration/CCF	2008-01	4	671
AAT	UCLES	I_{12} cell/iSONG	2008-01	5	1165
MOST	photometry	white light	2009-02	21	14274
McDonald	Coude Spectrograph (ES2)	I_{12} cell/iSONG	2010-01	4	424
MOST	photometry	white light	2010-02	27.5	21936
SAAO	PMT	Strömgren $v\&y$	2010-01	21	1136
APT	PMT	Strömgren $v\&y$	2010-01	16	479 (v), 481 (y)
CFHT	ESPaDOnS	ThAr + telluric lines	2010-03	3	503

ρ Pup was the main target during two observing runs of the MOST satellite³, the first during February 2009 (see Fig. 4.1) and the second one during February 2010 (see Fig. 4.2), for details also see Table 4.2. Our target was observed using Fabry imaging (Reegen et al. 2006), the data were reduced by Rainer Kuschnig.

³Canadian satellite MOST (Microvariability and Oscillations of STars); for a detailed technical description, see Walker et al. (2003).

As can be seen from Fig. 4.2, the data quality for 2010 shows no obvious instrumental effects. The jumps visible in 2009 are most probably due to temperature changes in the space craft. The first step to remove this trend was to subdivide the data set in five subsets. For the second (HJD: 2453312-2453317), third (HJD: 2454857-54862) and fourth (HJD:2454862-2454869) segments a linear fit was used to remove the trend. The result can be seen in the lower panel of 4.1. Any signal we might have introduced is not relevant for the present analyses, because it would be in the very low frequency domain, which is not of interest for the present work.

Observations at the SAAO⁴ and APT⁵ were undertaken using the so called three-star-technique (Breger 1993) to minimize instrumental errors as well as to correct for atmospheric influences. The data at the SAAO were taken by Chris Engelbrecht and Gerald Handler, who also reduced the SAAO and APT data. The comparison (C1) and check (C2) stars were HD 60532 and HD 60345, respectively. For the three-star-technique C1 and C2 should have the same or similar spectral type as well as comparable magnitude to the target star. Both stars should be constant, a requirement which is not always easy to achieve (see, e.g., Antoci et al. 2007). The comparison star C1 has a spectral type of F6 IV-V, $V = 4.46$ and is a planet hosting star (Desort et al. 2008). The orbital periods of the two Jupiter-sized planets are 201 days and 604 days respectively, much longer than our entire Strömgren observing run of 42 days, meaning that their signal is irrelevant for our analyses. Desort et al. (2008) also detected variability with a peak amplitude of 5 ms^{-1} which is suspected to be due to pulsation. This can be translated to roughly 0.08 mmag, using the relation from Kjeldsen & Bedding (1995). The noise level of our APT and SAAO data is higher and we can therefore assume HD 60532 as a constant star. C2 has a spectral type A3 III and $V = 5.85$ and no variability has been detected so far.

During January 2008 we obtained data from CORALIE ($R = 50000$) at ESO, observer being Fabien Carrier. These data were reduced using the pipeline available for the spectrograph and the RV measurements were obtained by cross-correlating the observed spectra with a mask represented by a synthetic spectrum. Data reduction, RV extraction, heliocentric and barycentric correction were done by Fabien Carrier. A number of 671 measurements were spread over 4 nights. Fig. 4.3 shows the original data.

Simultaneous observations to minimize aliasing due to day/night gaps were undertaken at the AAT with the UCLES spectrograph. During January 2008 we⁶ obtained 1165 spectra observed through an iodine cell, spread over 5 nights. The exposure times were alternated between 45 and 120 sec to account for seeing variations during the night. With a resolution of 48000 the echelle spectra consist of 47 orders, of which 30 cover the wavelength region of the iodine cell.

The standard reductions were undertaken with *IRAF*, following the cookbook of Churchill (1995). The overscan region on each frame was used for bias corrections.

⁴South African Astronomical Observatory

⁵Vienna Automatic Photoelectric Telescope T6 (0.75 m) at Washington Camp in Arizona

⁶Victoria Antoci and Gerald Handler

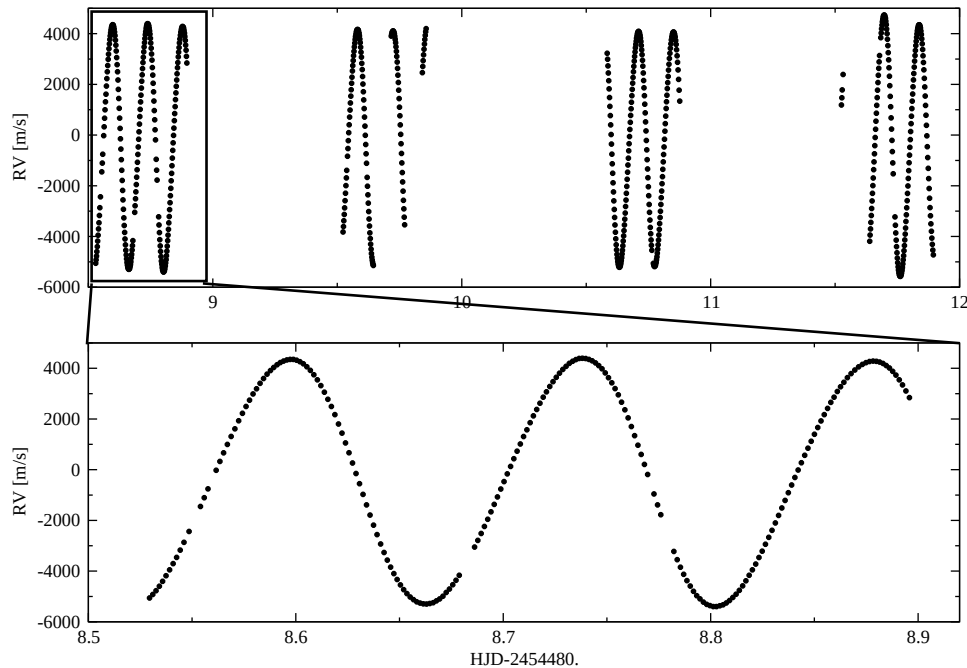


Figure 4.3: Upper panel: RV measurements obtained with the CORALIE spectrograph. Lower panel: close-up showing the first night of observations.

A master flat field out of 20 lamp flat fields carefully checked, was constructed separately for each night. The master flat field was normalized with the package *apflatten*, which models the illumination profiles along dispersion and cross dispersion axes. All frames were flat field corrected. The scattered light along the orders and across dispersion fitted interactively and subtracted using the *apscatter* routine which can be found in the *noao.imred.echelle* package. A model to fit and trace the 47 orders of the echelle spectrum was constructed and applied to each frame when extracting the one-dimensional spectra. For wavelength calibration using the Thorium Argon lamp, the IRAF task *ecidentify* allows after manual identification of some lines in each order, to do an automated identification of the remaining lines. Interactively the best dispersion correction can be fit, which is then stored in a database. The ThAr wavelength calibration should not be applied to the science frames in case iSONG (see Chapter 3.2) is used for extracting the radial velocity measurements. It is nevertheless necessary to export the non-linearized vector which

attributes to each pixel in each order a wavelength value. This needs to be done to have a first guess of the corresponding wavelength region. The science frames are roughly normalized (i.e. corrected for the Blaze-function) before iSONG is employed. The barycentric correction should be applied only after radial velocities were extracted with iSONG.

The McDonald data obtained between January 27, and February 1, 2011 with the Coude Spectrograph also taken through the iodine cell were reduced exactly in the same way as the AAT data.

The data with the ESPaDOnS at CFHT were gathered from March 4-7, 2010 and reduced with the *Libre Esprit* pipeline⁷. The wavelength calibration is done using the ThAr frames as well as telluric lines. According to the spectrograph's specifications⁸, after subtracting the temperature and pressure effects an absolute drift caused by thermal and mechanical relaxation of approximately 20 ms⁻¹ rms per night is expected. Nevertheless when estimating relative stability (the stellar spectrum relative to a ThAr frame) ESOaDOnS performs much better, reaching a value of less than 10 ms⁻¹. The wavelength coverage is approximately from 3500-10000Å. A rough continuum normalization is provided.

4.4 Photometry

4.4.1 MOST data

To perform careful frequency analyses, it is imperative to look at each data set separately and only then to combine those to improve the spectral window. In Fig. 4.4 we show the Fourier spectra of the MOST data taken in 2009 and 2010, respectively. For frequency analyses we used Period04 (Lenz & Breger 2005), a software package which uses Fourier transformations and multiple least-square algorithms. The peak with the highest amplitude in the Fourier spectrum was compared to the window function. Once the signal was found to be intrinsic, it was prewhitened after improving the frequency, amplitude and phase values. Then the residuals were searched for further significant frequencies. Applying a significance criterion of S/N = 4 for independent and 3.5 for combination frequencies (Breger et al. 1999) we find the same eight peaks to be significant in each of the data sets (see table 4.3). The peak at f_5 (9.19 cd⁻¹) coincides with an alias frequency known to originate from the orbit of the MOST satellite and was therefore not flagged to be intrinsic. Only after the same frequency was found to be present in the ground-based data (see Fig. 4.6), f_5 was attributed to ρ Pup. The frequency $f_8 = 7.06$ cd⁻¹ was significant in the MOST data sets 2009 and 2010 respectively, but too close to the dominant mode to be fully resolved. Only when combining the two years this frequency was taken into account as an intrinsic signal.

⁷http://www.cfht.hawaii.edu/Instruments/Spectroscopy/Espadons/Espadons_esprit.html

⁸http://www.ast.obs-mip.fr/projets/espadons/espadons_new/stability.html

Table 4.3: Frequencies, amplitude and phase differences from ground-based Strömgren measurements (SAAO + APT) and MOST data. Note that $f_8 = 7.06 \text{ cd}^{-1}$ was excluded here because it is too close to the dominant mode to be resolved. Only when the entire data sets are combined the f_8 can be resolved (see 4.5). The S/N value was computed by assuming a box size of 5 cd^{-1}

	f_i [cd^{-1}]	$y + \text{MOST}$ mmag	S/N
f_1	$7.098460 \pm 6\text{e-}06$	44.93 ± 0.02	26
$2f_1$	$14.1969 \pm 7\text{e-}05$	3.756 ± 0.02	10
$3f_1$	21.2954 ± 0.0005	0.49 ± 0.02	5
$4f_1$	28.3939 ± 0.0004	0.61 ± 0.02	13
f_2	6.4246 ± 0.0003	0.98 ± 0.02	9
f_3	8.8198 ± 0.0004	0.71 ± 0.02	6
f_4	8.0979 ± 0.0005	0.48 ± 0.02	7
f_5	9.2002 ± 0.0004	0.59 ± 0.02	8
f_6	6.5172 ± 0.0006	0.40 ± 0.02	7
f_7	6.7975 ± 0.0005	0.49 ± 0.02	7
$f_1 + f_3$	15.918 ± 0.001	0.22 ± 0.02	3.5

The amplitude of the dominant mode decreased from 54 mmag (2009) to 45 mmag (2010). The origin of this 20 % change is not clear, as it can be either intrinsic or instrumental. Given that the orbital frequency of the MOST spacecraft is almost twice the value of the dominant mode, the observations cover always the same part of the light curve, in 2009 the ascending and descending branches but never the maxima and minima. Fortunately this changes in 2010 allowing to also observe the extrema of the light curve. This hypothesis is supported by the fact that the amplitudes of almost all frequencies (but f_5 , which stays constant) decrease from 2009 to 2010, which is illustrated in Fig. 4.5. However amplitude variability is not uncommon in δ Sct stars and was observed in several cases (e.g. 44 Tau, Antoci et al. 2007). We therefore cannot rule out a combination of both effects, instrumental and intrinsic.

4.4.2 Ground-based photometry

ρ Pup was also observed in the Strömgren filters v (Fig. 4.7) and y (Fig. 4.8) during February and March 2010 (see Table 4.2). With simultaneous observations, MOST and ground-based, we aim to do mode identification. This can be done by comparing

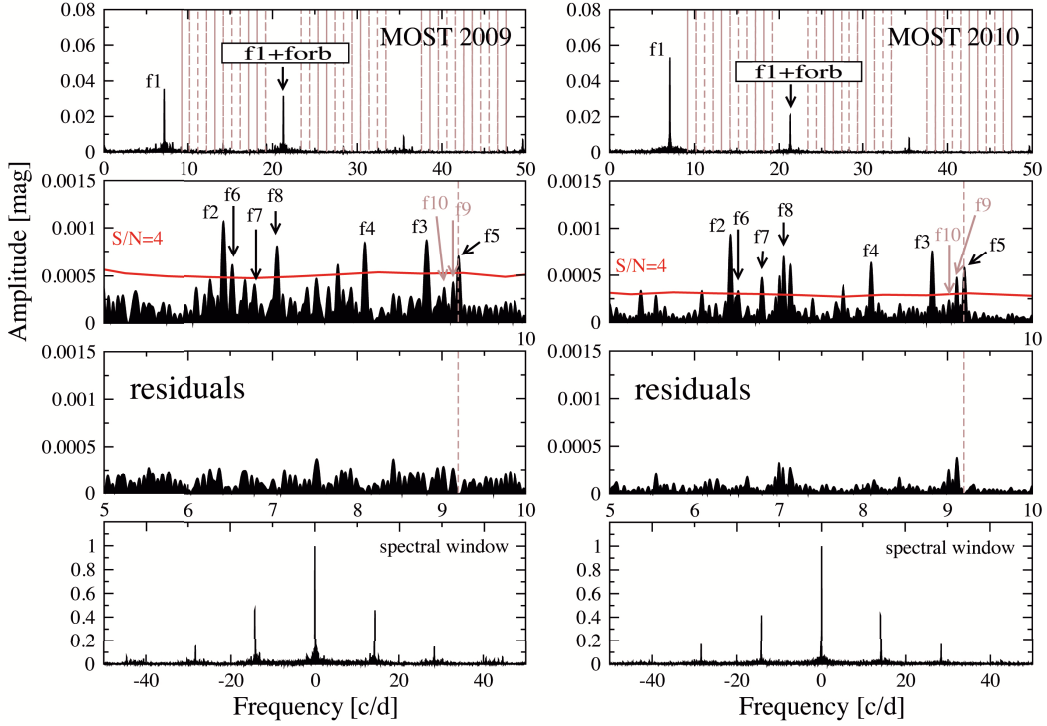


Figure 4.4: Fourier spectra of the MOST data 2009 (left) and 2010 (right). The light brown vertical lines indicate the orbital frequencies of the MOST space craft as well as its harmonics and 1 day aliases. In the first row the dominant mode is clearly visible. Note that f_1 is almost half the orbital frequency (f_{orb}), resulting in combination frequencies between the dominant mode and the orbital frequency. After removing f_1 , the remaining independent frequencies are clearly visible in the second row. In red we depict the significance level of $S/N = 4$. The frequencies denoted in a different colour are only significant when combining both data sets. The third and fourth row show the residuals and the spectral window respectively.

observations with models, where the amplitude ratio of a given mode is plotted as a function of the phase difference (see Fig. 4.9). For accurate mode identification the errors of amplitudes and phases must be as small as possible, which requires large data sets. A unique mode identification is rarely possible, but at least some constraints can be set, by e.g. excluding a mode to be radial or nonradial. For more

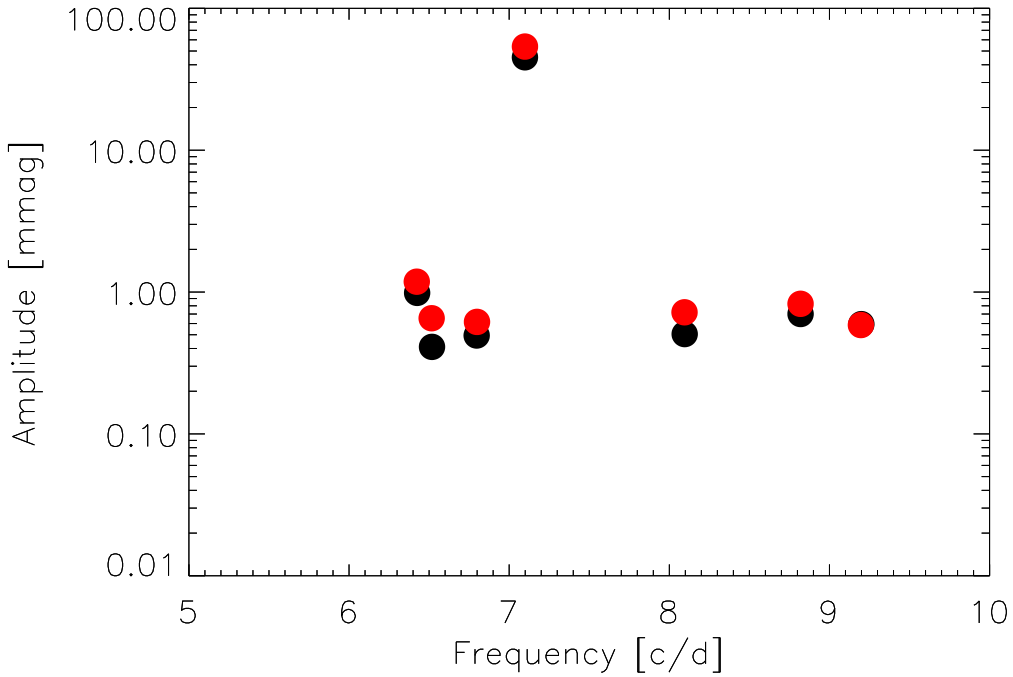


Figure 4.5: Frequencies derived from the MOST data 2009 (red) and 2010 (black). In most cases the error bars are smaller than the symbols. The difference in amplitude between the two observing seasons are very likely not intrinsic to the star. Because the frequency of the dominant mode is almost half the orbital frequency, during 2009, no maxima and minima of the light curve could be observed.

details on this mode identification method see, e.g., Garrido (2000).

The Strömgren data, spread over 42 days, have a lower quality than the MOST data. The white noise level of a data set can be estimated from the high-frequency domain in the Fourier spectrum (Kjeldsen & Bedding 1995), only if no intrinsic signal is present or expected in this frequency region. The noise level in the v filter is at approximately 0.15 mmag whereas in the y filter it is 0.13 mmag. In the ground-based data, only the dominant mode f_1 and its second harmonic $2f_1$ have a significance higher than the common criterion of $S/N = 4$. The amplitudes and phases for six other frequencies (Table 4.4.2) were nevertheless derived, because the same peaks are also present in each of year of the MOST data. The results are presented in Fig. 4.9, which displays the observed amplitude ratios (v/y) as a function of the phase difference (Φ_v/Φ_y). In general it can be said that for radial modes a positive phase difference is expected, which is what is observed for f_1 , consistent with spectroscopic mode identification (Mathias et al. 1997, Antoci et al. 2008). Unfortunately the error bars are very large and a clear mode identification of the remaining modes is not possible. Nevertheless f_5 is likely to be also a radial

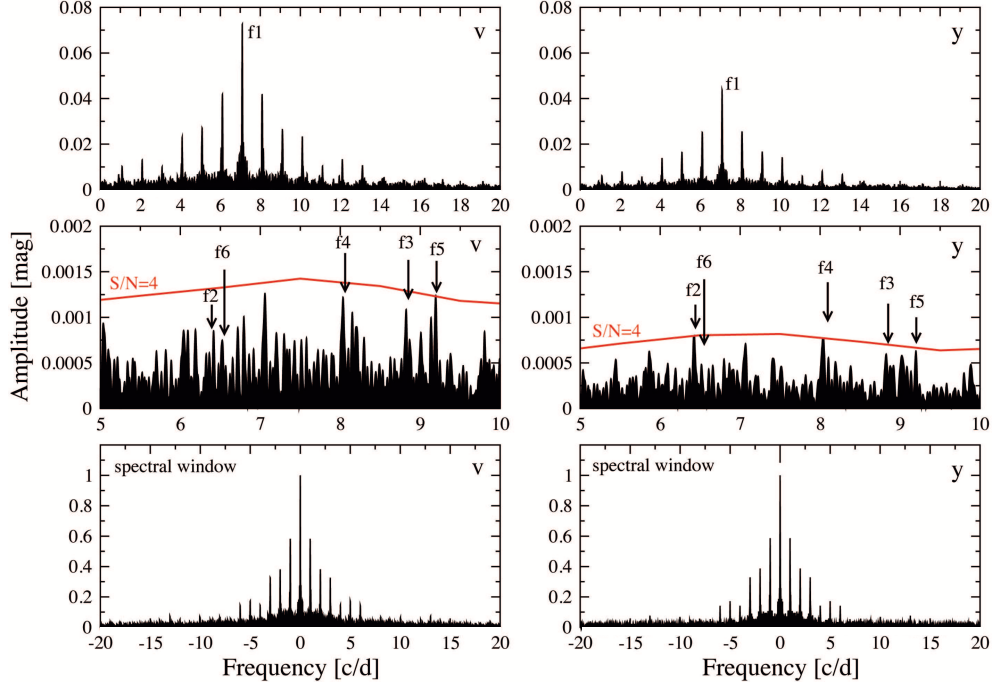


Figure 4.6: Fourier spectra of Strömgren v and y are shown on the left and right side respectively. The upper row shows the dominant frequency. The panels in the second row illustrate the Fourier spectra after f_1 was prewhitened. The lower panels represent the window function of each of the data set.

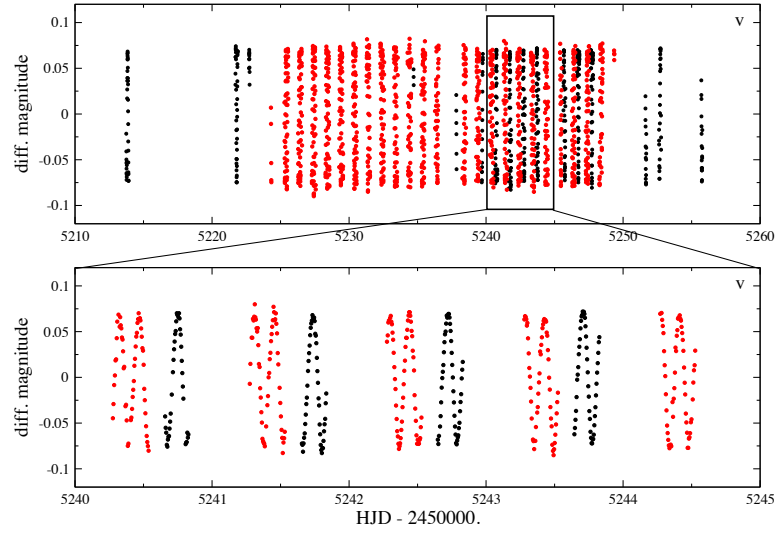


Figure 4.7: Upper panel: Strömgren v data from APT and SAAO. Lower panel: Close-up of few nights.

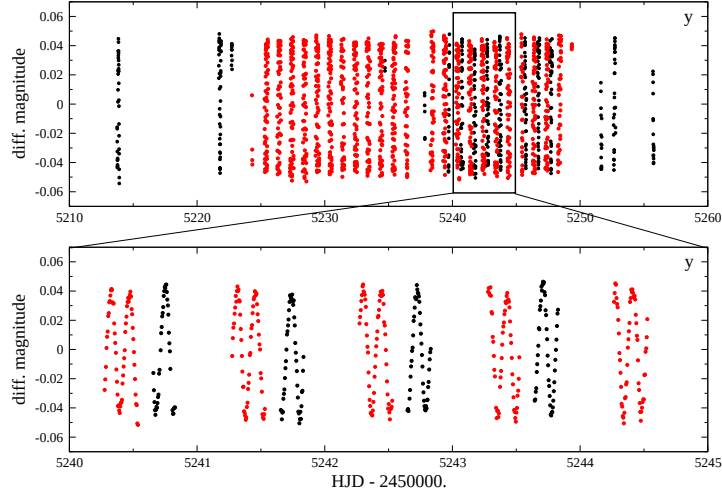


Figure 4.8: Upper panel: Strömgren y data from APT and SAAO. Lower panel: Close-up of few nights.

Table 4.4: Frequencies, amplitude and phase differences from ground-based Strömgren measurements (SAAO + APT). Frequency values were derived from combining all the y data with MOST observations.

	f_i [cd^{-1}]	v mmag	y mmag	$\Phi_v - \Phi_y$ [$^\circ$]
f_1	$7.09846 \pm 3\text{e-}05$	71.4 ± 0.1	42.7 ± 0.2	4.6 ± 0.3
$2f_1$	14.1969 ± 0.0004	5.3 ± 0.1	3.4 ± 0.2	
f_2^*	6.425 ± 0.002	0.9 ± 0.1	1.0 ± 0.2	-9 ± 18
f_3^*	8.820 ± 0.002	1.1 ± 0.1	0.7 ± 0.2	22 ± 15
f_4^*	8.098 ± 0.002	0.9 ± 0.1	0.7 ± 0.2	5 ± 18
f_5^*	9.199 ± 0.002	1.3 ± 0.1	0.7 ± 0.2	6 ± 15
f_6^*	6.517 ± 0.002	0.9 ± 0.1	0.6 ± 0.2	-19 ± 18
f_7^*	$6.797 -$	$-$	$-$	$-$

* The S/N of these frequencies is between 2.8 and 3.9, i.e. lower than the usually adopted significance criterion of $\text{S/N} = 4$. Nevertheless these peaks were independently identified in the MOST data in the years 2009 and 2010.

mode, not only because of the positive phase difference, but also because models of a star with the same parameters as those of ρ Pup predict the first overtone to have

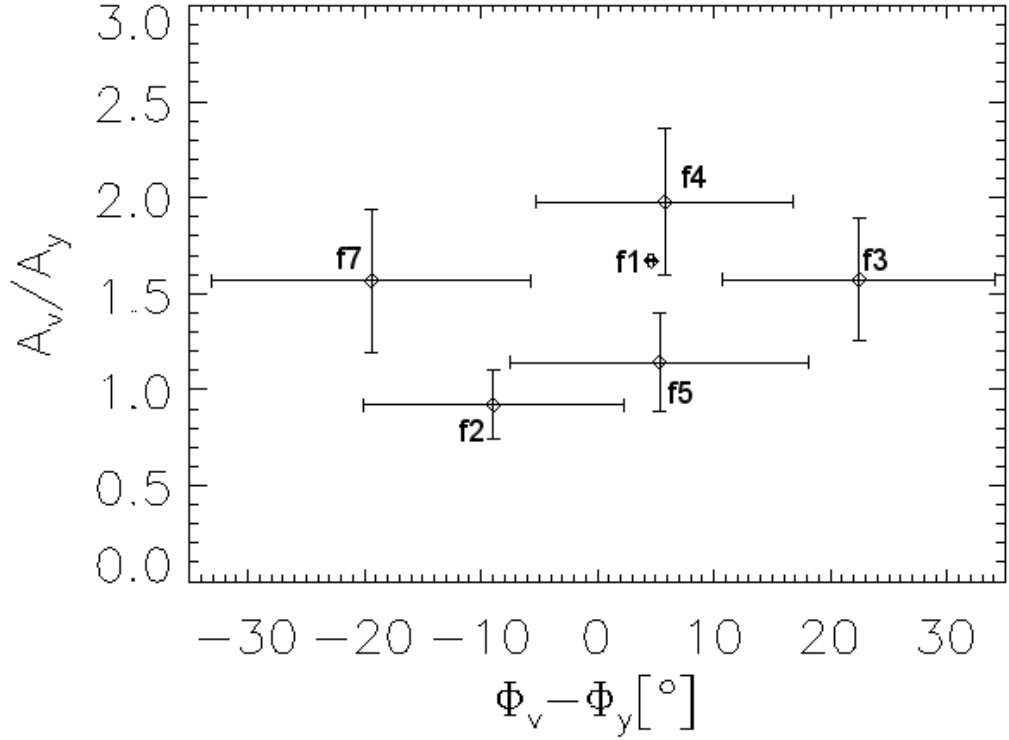


Figure 4.9: Phase shifts versus amplitude ratio for the Strömgren filters v and y . A clear mode identification can be done only for the dominant mode f_1 . The exact frequency and amplitude values as well as the phase differences are given in Table 4.4.2.

a value close to the observed frequency f_5 . Table 4.4.2 summarizes the frequencies for which amplitudes and phases were derived from colour photometry. f_3 has an unusual low phase difference of $-338^\circ \pm 15^\circ$ to which 360° were added resulting in $22^\circ \pm 15^\circ$. This phase shift on the other hand is too high which might indicate that the result should not be trusted given the quality of the data.

As a last step we combined all available photometric data, where all the data were scaled to the y filter, or to be more specific to the amplitude of the dominant mode. The amplitude information from this kind of analyses is of course useless, but it allows to drastically lower the noise level (because it depends on the number of measurements). Finally we obtained 11 significant frequencies, summarized in Table 4.5. The frequency f_{11} is significant in terms of S/N, but it is almost $f_3 + 2\text{cd}^{-1}$, which makes it rather suspicious, and is therefore denoted with a question mark in Fig. 4.10. Nevertheless we decided to keep it in the Table 4.5, but be very cautious when interpreting the data.

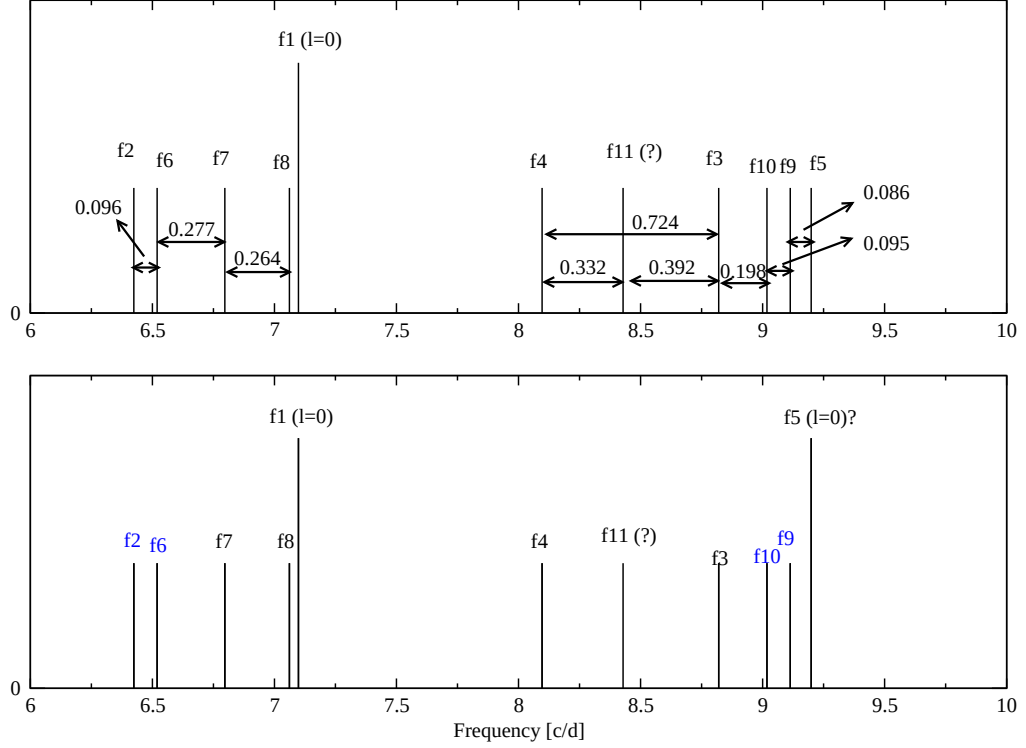


Figure 4.10: Schematic plot of the frequencies of the combined and scaled data. Upper panel: The dominant mode is identified to be the radial fundamental mode. Possible splittings are indicated by arrows, as well as the exact value (in cd^{-1}). Lower Panel: tentative mode identification based on all available information is performed. f_5 is very likely to be the first radial overtone as described in the text. The frequencies labeled in blue could belong to the same multiplet.

4.4.3 Interpretation and discussion

If we assume that f_1 is the radial fundamental mode, then f_5 is most likely the first radial overtone, which is also supported by the ratio f_5/f_1 of 0.772 as well as the pulsational constant Q (Table 4.5). This ratio plotted as a function of the logarithm of the radial fundamental mode is known as the Petersen diagram. This asteroseismic tool can be used to determine the evolutionary stage of a star, as the ratio between the above mentioned modes changes as the star evolves. When computing a Petersen diagram also the rotation, metallicity and overshooting play

Table 4.5: Pulsational constant Q for all observed frequencies derived using spectroscopic ($Q_{spec.}$) and interferometric $Q_{interf.}$, T_{eff} respectively.

	f_i [cd^{-1}]	$Q_{spec.}$	$Q_{interf.}$
f_1	7.09842	0.035	0.036
f_2	6.42405	0.039	0.040
f_3	8.82017	0.028	0.029
f_4	8.09652	0.031	0.032
f_5	9.19897	0.027	0.027
f_6	6.51958	0.038	0.040
f_7	6.79690	0.037	0.038
f_8	7.06139	0.035	0.036
f_9	9.11317	0.027	0.026
f_{10}	9.01777	0.028	0.028
f_{11}	8.42826	0.030	0.030

an important role (see Lenz 2009). Under the assumption that f_1 is the radial fundamental mode and f_5 is the first radial overtone, ρ Pup is most likely in the hydrogen shell burning phase, on the post main sequence.

For completeness we can also assume that f_1 and f_3 are radial modes, as $f_3/f_1 = 0.804$ which is close to what is expected for the ratio of the first to the second radial overtone (0.800). Nevertheless, this hypothesis is very unlikely as that would place the model outside the observational box, inconsistent with the measured parallax. As an example, to fit f_1 and f_3 as first and second radial overtone respectively, for a model with the a mass of $1.85M_{\odot}$, $T_{eff} = 6300$ K and $R = 3.8 R_{\odot}$ are required. The spectroscopic as well as photometric $T_{eff} = 6900 \pm 150$ K and furthermore the very accurate interferometric $T_{eff} = 7080 \pm 80$ K make that scenario very unlikely. We calculate the pulsational constant Q (see Table 4.5) using the relation given in Equation 2.3. $Q_{spec.}$ in table 4.5 denotes the Q value computed using the spectroscopically derived $T_{eff} = 6900$ K and $\log g = 3.8$, whereas $Q_{interf.}$ was calculated using the interferometric temperature of $T_{eff} = 7080$ K. M_{bol} was derived as described in 4.2. Consistent with literature and the present work, f_1 has a Q value of 0.035, which is close to what is expected for the radial fundamental mode for δ Sct stars, i.e. $Q = 0.033$ as described by e.g. Breger (2000). The difference may arise from uncertainties in the spectroscopically derived values of T_{eff} and $\log g$. We can use the knowledge that f_1 is the radial fundamental mode, and fix the associated pulsational constant to be 0.033. Applying the above mentioned relation and using M_{bol} and T_{eff} accurately determined using the Hipparcos parallax and the interferometric radius we can estimate the $\log g$ value of ρ Puppis. This results in $\log g = 3.72$, consistent with the spectroscopic value of 3.80 ± 0.15 .

Another interesting aspect which needs further investigations is the high amplitude ratio of all modes of ρ Pup (Fig. 4.9) when compared to other stars such as 44

Tau (Lenz et al. 2010). There are many reasons for that, e.g the high metallicity or/and the convective outer layers. These effects will be investigated in cooperation with Patrick Lenz in a forthcoming paper.

Fig. 4.10 shows a schematic frequency spectrum of ρ Pup. It can be seen that we observe not only (the) radial (fundamental) mode(s) but also nonradial modes. Given the low frequencies of the nonradial modes we can definitely say that these are mixed modes, consistent with a late evolutionary stage of ρ Pup. In the upper panel of the same figure the frequency differences between various modes are given. The spacings between f_2 and f_6 and f_{10} and f_9 are very similar, 0.096 and 0.095 cd^{-1} respectively, making these peaks possible members of the same multiplet split by rotation, as indicated in blue in the lower panel of Fig. 4.10. Using $R = 3.47 R_{\odot}$ and a $v \sin i$ of 15 kms^{-1} would result in a rotational velocity $v_{\text{rot}} = 17 \text{ kms}^{-1}$ and an inclination angle $i = 63^{\circ}$.

In any case we can set an upper limit for the rotational velocity at 125 kms^{-1} under the assumptions that we do not observe any overlapped frequencies of different multiplets and that there is at least one multiplet present in the frequency spectrum. However, given the fact that this star is a ρ Pup star, which are believed to evolve from Am stars, it is more likely that the upper limit for the rotational velocity is lower than 100 kms^{-1} . This would exclude f_4 to be a member of any multiplet and would further lower the upper limit for v_{rot} down to 70 kms^{-1} (splitting between f_{11} and f_3). However Fig. 4.10 demonstrates that clear mode identification from pattern recognition alone is not possible in this case. Nevertheless, also based on the high amplitude of f_1 , it can be concluded that ρ Pup is most likely a slow or moderate rotator. This is good news, because it means that the modes of pulsation can still be described as spherical harmonics which makes modelling of this star much easier.

To conclude, MOST and colour photometry allowed to determine 10 independent frequencies, with a possible 11th one. The dominant mode is the radial fundamental mode. The frequency f_5 is very likely the first radial overtone making all the other observed frequencies nonradial (mixed) modes. Under the assumption that at least two peaks belong to the same multiplet and that we do not observe overlapping multiplets split by rotation, an upper limit of 70 kms^{-1} for the rotational velocity can be set. This is consistent with its chemically peculiar nature. Because ρ Pup is a bright star, an accurate Hipparcos parallax value, as well as an interferometric radius are available. From that, a bolometric magnitude, luminosity and the effective temperature can be derived. Furthermore, an independent estimate of $\log g = 3.72$, compatible with the spectroscopic value was obtained.

4.5 Radial velocities

Here we describe how the radial velocity measurements (hereafter RV) were extracted using the iSONG code for the UCLES data and for the McDonald data. The RV extraction observations is explained in detail, because it plays an important role for this thesis. The RV from observations gathered with ESPaDONs were extracted using bisectors.

4.5.1 Getting iSONG started

After basic reductions (bias, flat fielding, extraction of spectra, etc), the setup for iSONG can be started. The common information used for all iSONG routines are gathered in one file. Some informations needed for the AAT data are displayed in table 4.6.

Table 4.6: An example for some input parameters for AAT to start iSONG.

parameter	values for AAT
Oversampling factor for Jansson deconvolution	8
Total Number of orders	47
Number of satellite Gaussians	10
Number of pixels in a chunk	71
Number of pixels at the start of each order to be skipped	100
Total number of pixels in an order	2746
Index of the first order to process	10
Index of last order to process	30
Index of first chunk to process	1
Index of last chunk to process	Nr. of last chunk-1

4.5.2 Fitting the instrumental profile

The instrumental profiles of both spectrographs, UCLES and TS23 were derived as described in Chapter 3. To obtain the instrumental profile of UCLES, we observed the rapidly rotating early B type star HD 64740. Fig. 11 shows the spectrum of this star in a region with and without superimposed iodine lines, nicely illustrating the forest of I_2 absorption lines as well as the lack of stellar lines. Fig. 4.12 shows the rapidly rotating B type star HD 67797, which was used to derive the instrumental profile for the McDonald spectrograph. Again, we show a part of the spectrum with and without I_2 absorption lines.

The PSF of each chunk was calculated by first approximating the instrumental profile by a single Gaussian with fixed position. Its values were then used as an initial guess for the multiple Gaussian. Figure 4.13 illustrates an example of six

PSFs of consecutive chunks in the same order. In red we show the single whereas in black the multiple Gaussian, the last being the sum of 10 satellite Gaussians. When comparing the single to the multiple gaussian PSF, a slight asymmetry can be identified, clearly proving the need of multiple Gaussians to model the PSFs. Figure 4.14 show the same but for the McDonald spectrograph.

Even if the B type stars used to derive the instrumental PSF had few absorption lines, some were still present. The chunks covering those wavelengths regions could not be used. In some other cases we obtained strange-looking Gaussians too, but with no obvious reason. This is probably due to numerical problems while fitting the instrumental profile with the IDL MPFIT⁹ routine used by iSONG. An example is shown in Fig. 4.14 and 4.14, for the chunks 14 and 15 of order 13. To avoid losing these chunks, we replaced them by a the mean PSF computed from the good chunks.

4.5.3 Intrinsic stellar spectrum

Now that the instrumental profile was determined, the intrinsic stellar spectrum needs to be modelled (see chapter 3 for details). For that a stellar spectrum of the target star with ideally very high S/N is needed. To obtain such a spectrum, usually many stellar templates without iodine lines are combined. In the case of the AAT data we had too few and all were from different pulsation phases. As there are equivalent width (EQW) variations due to the high amplitude of pulsation, it turned out that not combining them resulted in better RV measurements. To have consistent data sets, the same was done for the McDonald measurements. Finally we chose the spectra with a phase closest to the minimum change in EQW ($\text{phase}_{AAT} = 0.72$ and $\text{phase}_{McD} = 0.86$). Butler et al. (1993) observed a Cepheid which has very large changes in EQW during a pulsation cycle using the same technique. They chose to use more templates, each observed in a specific phase of pulsation. In the case of ρ Puppis however, the differences are minimal, of the order of $1\text{-}3 \text{ ms}^{-1}$ per spectrum.

Examples of how the intrinsic stellar spectrum looks like, after deconvolution with the instrumental profile can be found in Figures 4.15 and 4.16 for the UCLES data and in Figures 4.17 and 4.18 for the McDonald data. The same figures also compare the spectra before and after deconvolution in a given chunk and illustrate the associated PSFs.

4.5.4 Fitting the observations

Using the instrumental profile, the intrinsic stellar spectrum and the information provided by the iodine absorption lines, we can finally derive the RV measurements. This was done by modelling the observations as described in chapter 3. As an initial guess we use the RV obtained by cross-correlating one order without I_2 absorption

⁹<http://www.physics.wisc.edu/~craigm/idl/fitting.html>

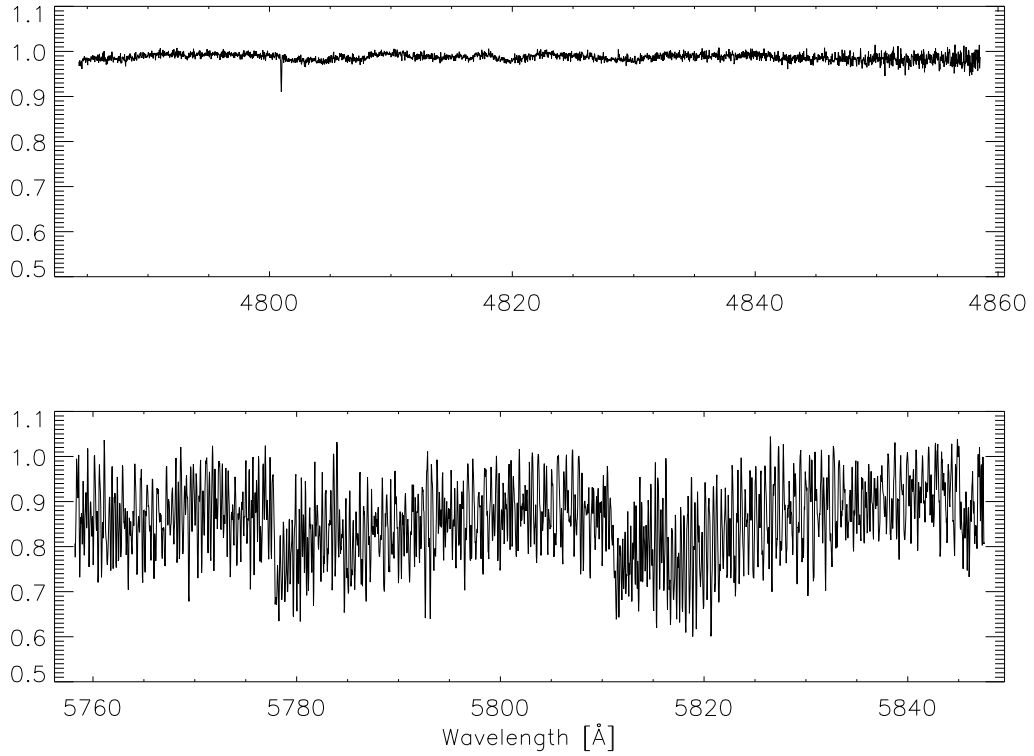


Figure 4.11: The early rapidly rotating B type stars HD 64740 was used to obtain the instrumental profile of the UCLES spectrograph. Upper panel: Echelle order in a wavelength region without the superimposed iodine lines. Lower panel: Example of an echelle order in which the I_2 shows absorption lines.

lines of each of the science spectra with the same wavelength region of the template. As can be seen in Fig. 4.19 and Fig. 4.20 for the UCLES and McDonald data respectively, the quality is not very high, but good enough to act as a starting value.

Because the dominant mode is radial, during a pulsation cycle the lines are periodically blue and redshifted. If the chunk would be fixed at a given position the lines would move in and out and the actual measurement of the RV and would always reflect different parts of the spectrum. Experiments have shown that the scatter decreased when letting the chunks slide with the same part of the spectrum during the whole observing run. In Fig. 4.21 we show the shift in pixels relative to the first spectrum for the AAT and McDonald data respectively. All the RV measurements were derived by using this sliding window technique.

Another factor which influences the results is the oversampling factor. This is usually set to 4 or higher (Butler et al. 1996) and determines by how much the stellar spectra are oversampled with respect to the spectral resolution, to make use of the wavelength information provided by the I_2 cell. The latter is also resampled

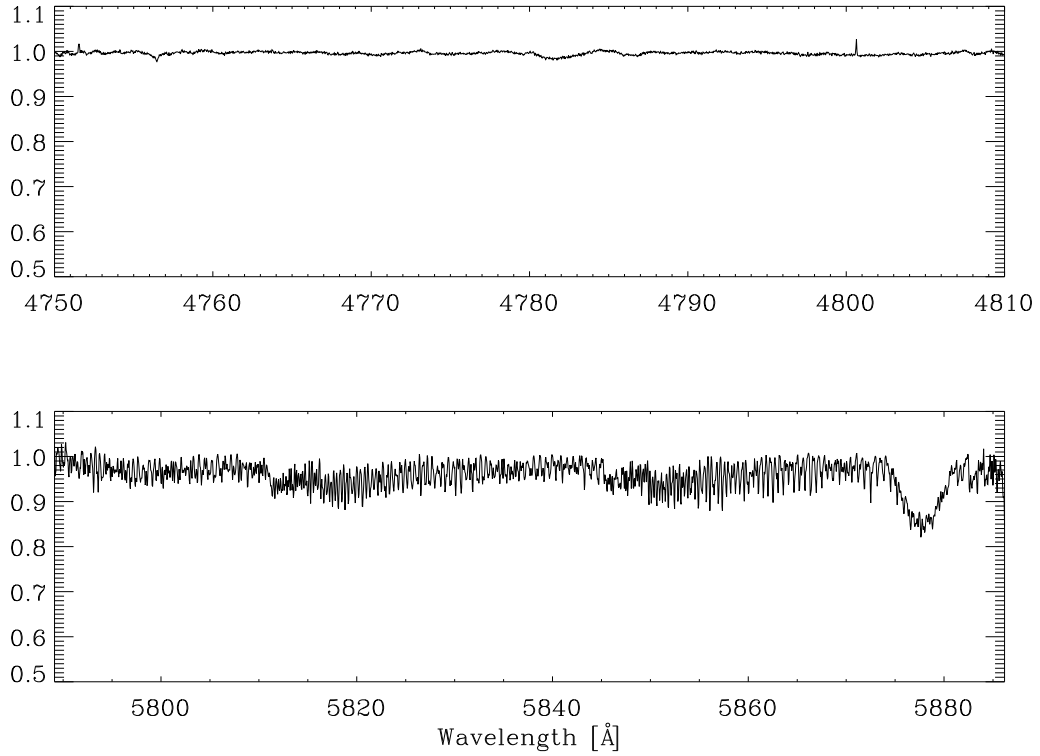


Figure 4.12: The rapidly rotating B type star HD 67797 was used to obtain the instrumental profile of the McDonald spectrograph. Upper panel: Echelle order in a wavelength region without the superimposed iodine lines. Lower panel: Example of an echelle order in which the I_2 shows absorption lines.

to the same scale (see also chapter 3). Increasing this factor also increases the computing time significantly, and can last up to hours for only one science frame. In the case of AAT data, for example, with a total number of 1165 spectra the computations would take several weeks, even if using 5 CPU! Tests with different oversampling factors, 4, 8 and 16, have shown that 8 is the best in keeping the balance between a satisfactory quality and an acceptable duration of computing time, which was also chosen for all further data reductions.

Once the modelling was finished, each spectrum delivered 21 orders x 36 chunks = 756 'independent' RV measurements in the case of the AAT data, whereas each McDonald science spectrum consisted of 13 orders x 22 chunks = 286 RV. Excluding the outliers and combining the remaining values to a mean value should then result in a very precise RV measurement. Unfortunately, identifying the outliers in an objective way is not straightforward. More importantly, we also tried to disentangle the factors which mostly influence the precision: RV information originates from stellar absorption lines, that are not uniformly distributed across the spectrum.

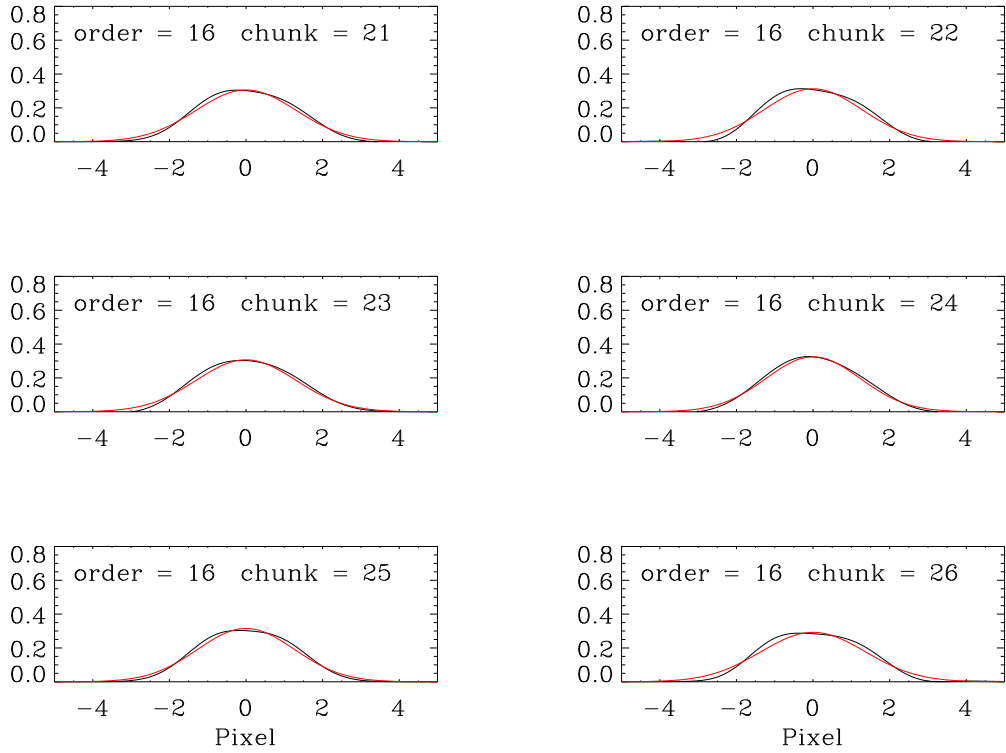


Figure 4.13: Instrumental PSFs of some of chunks for the UCLES spectrograph. The black line represents the PSF constructed from multiple Gaussians, whereas the red line is the single Gaussian.

The wavelength region that can be used is restricted to approximately 5000-6200Å when using the I_2 technique. There are several chunks which do not show any stellar lines and therefore are not expected to carry any RV information. Also the density of the I_2 lines is getting lower when approaching the wavelength limits given above. The upper panel of Fig. 4.22 shows the EQW¹⁰ of a given spectrum as a function of wavelength as well as a linear trend, clearly illustrating that the number of lines decreases with increasing wavelength. This is consistent with what is expected for A and F type stars. Nevertheless it should be kept in mind that at higher wavelength also telluric lines start to appear in the spectrum, in other words a high EQW does not necessarily mean a stellar line. This is illustrated in the lower panel of Fig. 4.22, where the RV measurements of each chunk of a given spectrum are plotted as a function of EQW of the chunk. There is a clear trend showing that chunks having a higher EQW cluster around a RV value of 2000 ms⁻¹, but we can also see outliers.

The goodness of the fit is expressed by the factor 'sigma fit' and represents the residual value between the observations and the model in percent. In principle, the lower the value the better the model fits the observations. Figure 4.23 shows the

¹⁰The EQW for a given chunk was measured by integrating the area covered by absorption lines.

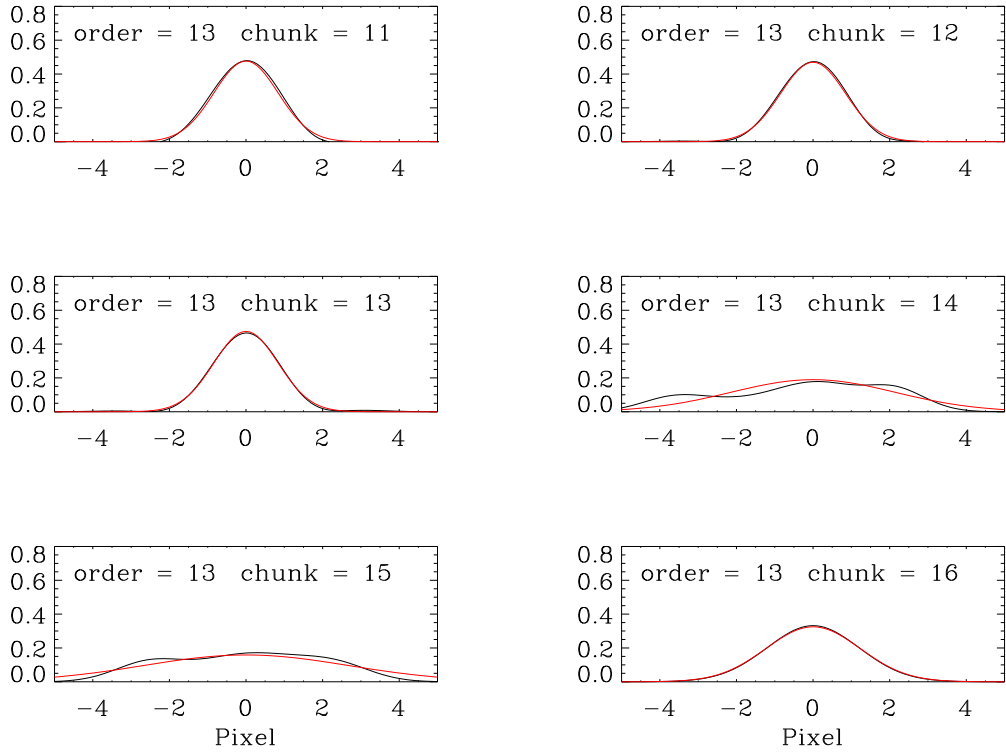


Figure 4.14: Instrumental PSFs of some of chunks for the McDonald spectrograph. The black line represents the PSF constructed from multiple Gaussians, whereas the red line is the single Gaussian.

sigma fit as a function of EQW, with a cutoff at a sigma fit value of ~ 0.25 , only few outliers can be found above. Chunks with an EQW larger than ~ 0.2 also tend to have a larger sigma. As already mentioned a large EQW does not necessarily mean a stellar line, but can be attributed to telluric lines or to a mixture of both.

The errors per measurements (i.e. per spectrum) were estimated by fitting the RV as a function of wavelength (WL), to a linear fit and taking the square root of the standard deviation of the residuals. To obtain the lowest error and to find out which parameter has the largest impact on the quality of the measurements, experiments varying three different parameters restricting the number of chunks used, were undertaken. As a first parameter, a lower limit for the EQW was introduced, with the following possible values: 0.01, 0.05, 0.1, 0.15, 0.2. The second attribute was the allowed wavelength region starting with 5000Å, where the largest number of stellar lines can be found but with different upper limits (5500Å, 5700Å, 5900Å, 6100Å, 6300Å). And finally as a last delimiter for selecting the 'best' RV measurements, we used the sigma fit with upper limits at 0.1, 0.15, 0.2 and 0.25.

The errors per measurement were then calculated for each spectrum using the RV information from the selected chunks depending on EQW, WL range, sigma fit.

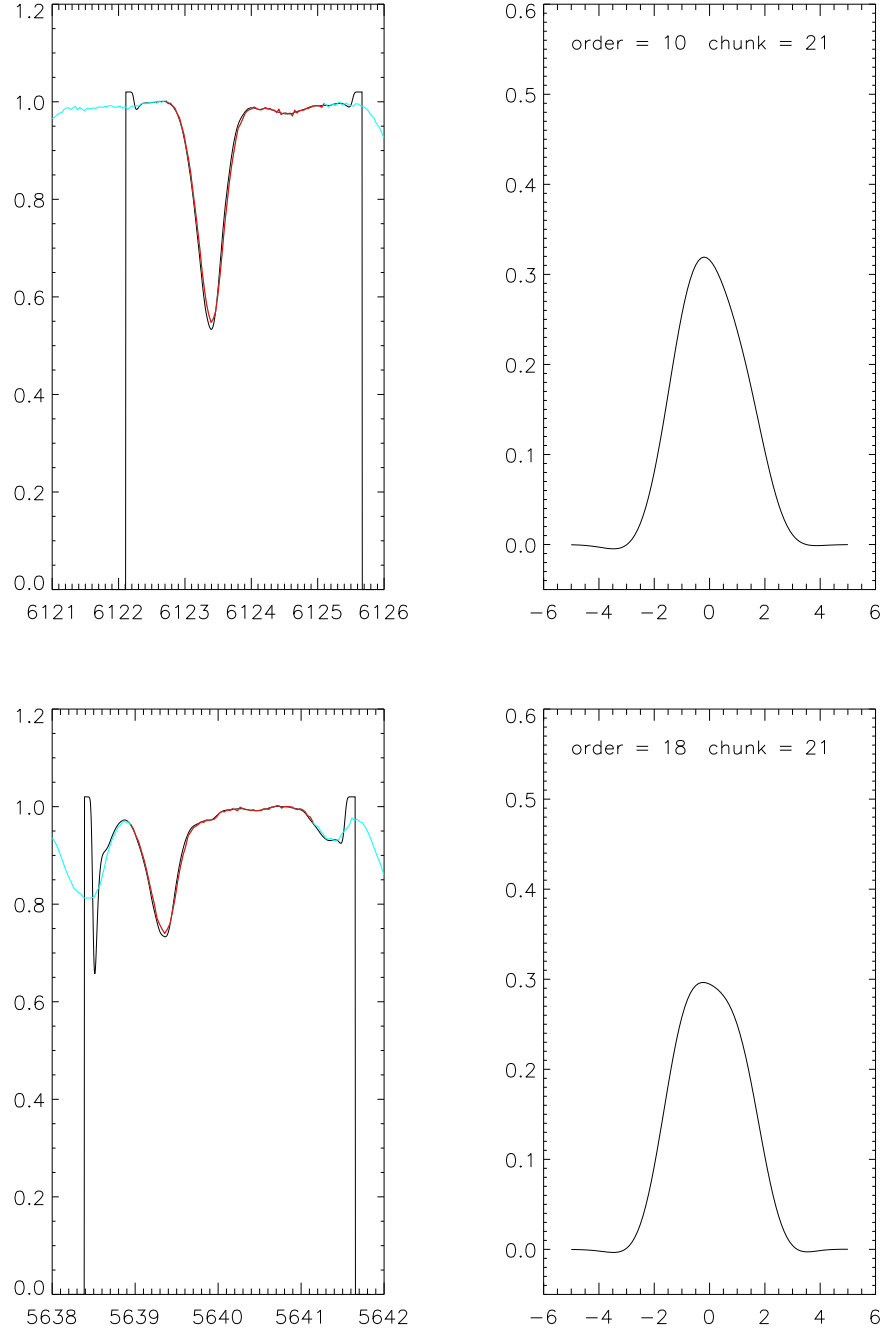


Figure 4.15: Intrinsic stellar spectrum after deconvolving the observed template with the instrumental profile. Left panel: Deconvolved UCLES stellar spectrum in red, in purple the observed spectrum and in black the chunk size. Right panel: associated PSF in pixel as well as order and chunk number. Each row represents the same part of the spectrum.

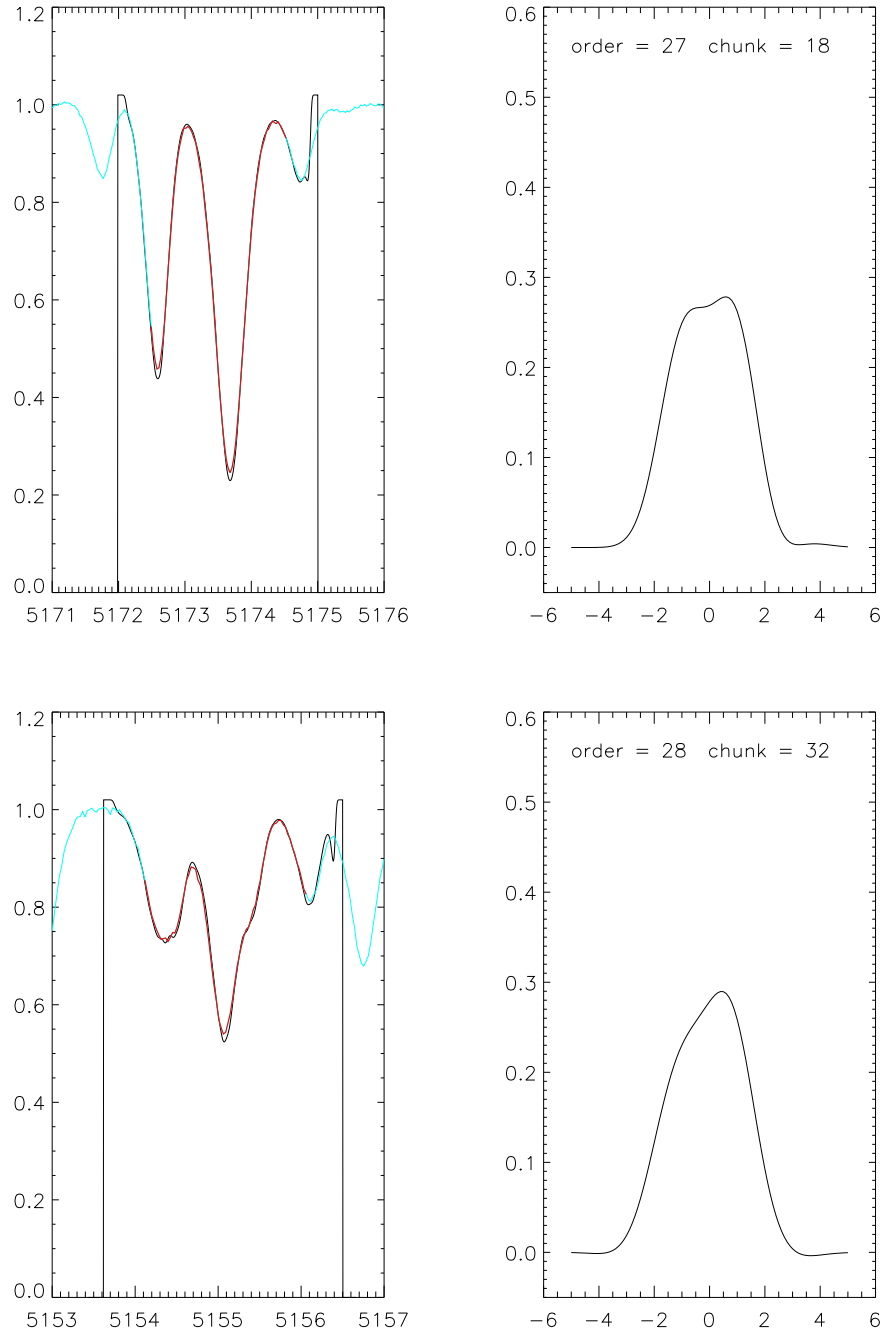


Figure 4.16: Intrinsic stellar spectrum after deconvolving the observed template with the instrumental profile. Left panel: Deconvolved UCLES stellar spectrum in red, in purple the observed spectrum and in black the chunk size. Right panel: associated PSF in pixel as well as order and chunk number. Each row represents the same part of the spectrum.

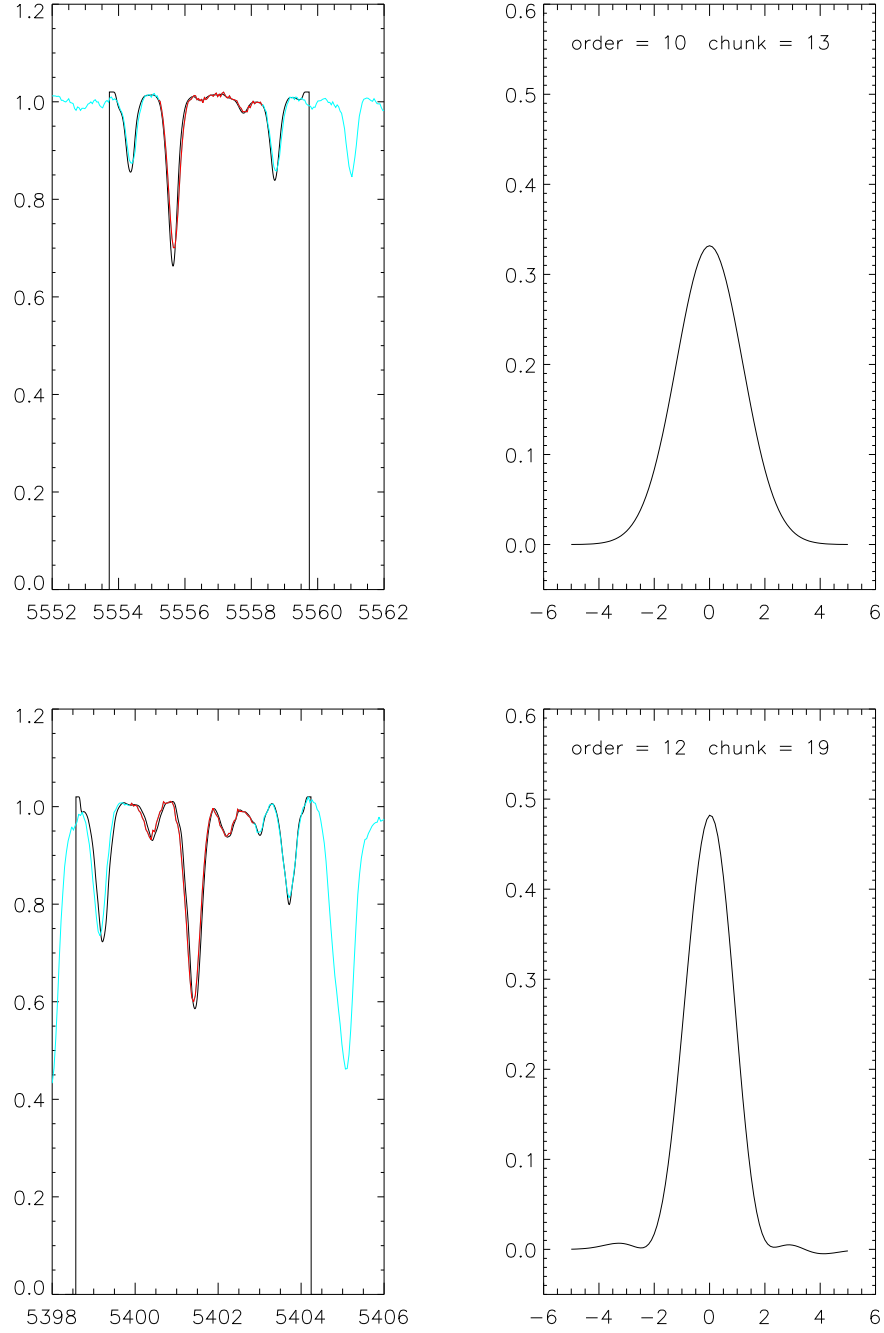


Figure 4.17: Intrinsic stellar spectrum after deconvolving the observed template with the instrumental profile. Left panel: Deconvolved McDonald stellar spectrum in red, in purple the observed spectrum and in black the chunk size. Right panel: associated PSF in pixel as well as order and chunk number. Each row represents the same part of the spectrum.

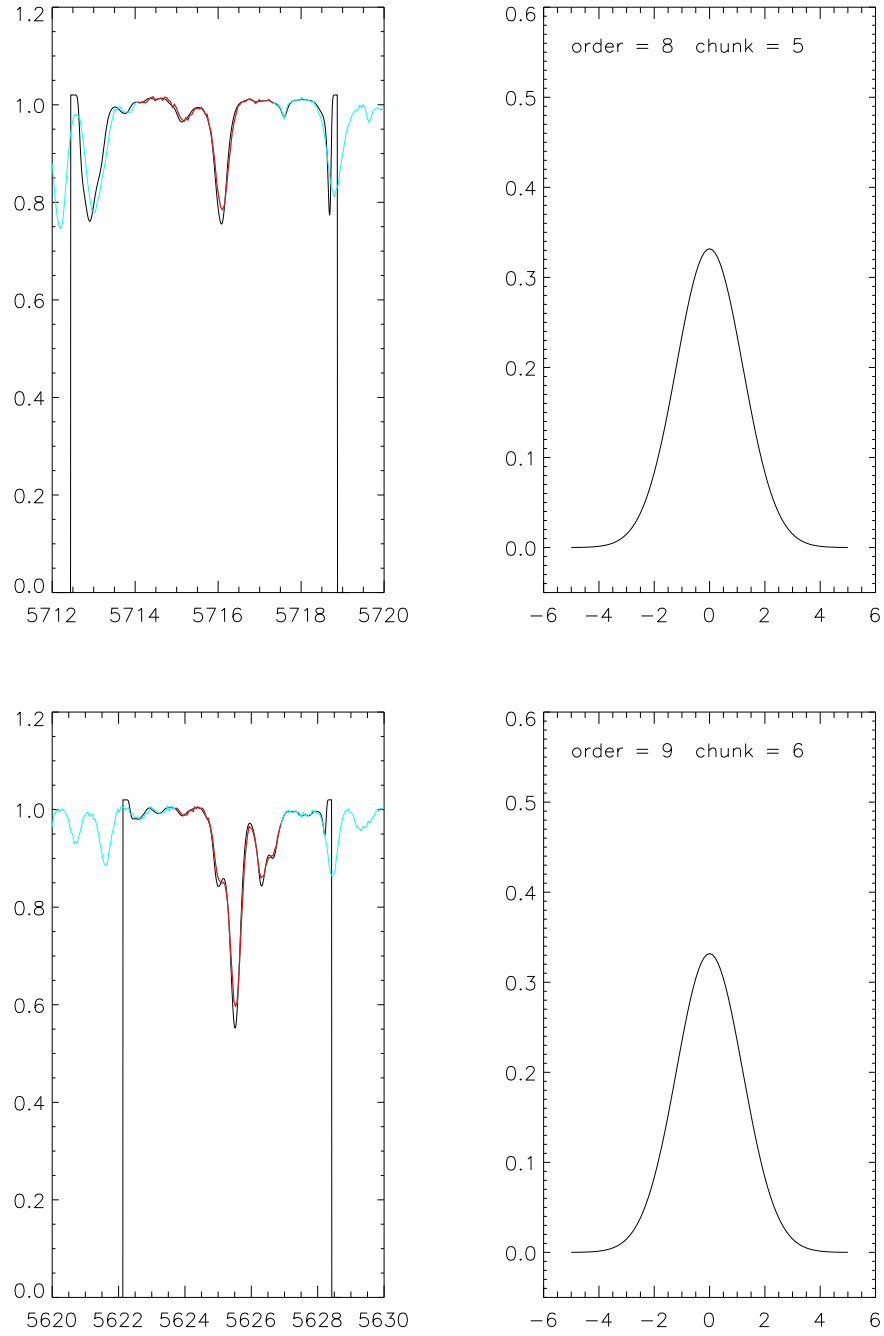


Figure 4.18: Intrinsic stellar spectrum after deconvolving the observed template with the instrumental profile. Left panel: Deconvolved McDonald stellar spectrum in red, in purple the observed spectrum and in black the chunk size. Right panel: associated PSF in pixel as well as order and chunk number. Each row represents the same part of the spectrum.

To decide which parameter constellation delivered the best data set, a ‘lowest mean error’ was introduced, by averaging the errors per measurement for the entire data set (for AAT 1165 errors). The best mean error (14.5 ms^{-1}) was found when all the chunks with wavelengths $\leq 5900\text{\AA}$, EQW ≤ 0.2 and with a sigma fit value ≤ 0.25 were used (see Fig. 4.35). After prewhitening the frequencies found photometrically, the noise level derived from the high frequency domain (e.g. between 100-150 cd^{-1}) is $\sim 6 \text{ ms}^{-1}$, too high for detecting possible solar-like oscillations. Figures 4.24, 4.25, and 4.26 display the mean error for different data sets using the selection criterions mentioned above as a function of maximum wavelength, minimum EQW and maximum sigma fit, respectively. The minimum EQW seems to have the largest impact on the errors, which is not surprising because chunks with very low EQW values carry little or no RV information. The Figures 4.27 to 4.29 show the errors per measurement averaged using different chunks based on the selection parameters indicated in the caption of each figure. The upper panel of those figures display a RV curve to indicate that the quality of the measurement changes with pulsation cycle, being lowest at maximum and minimum amplitude. Figures 4.31 to 4.34 show that the slope of the linear fit also changes depending on the selection criteria as well as on the pulsation phase.

Eliminating all possible errors, we concluded that the amplitude of the dominant mode intrinsically varies from chunk to chunk, i.e. from line to line. That was confirmed by the McDonald and CFHT data sets. The latter did not use using an iodine cell, which proved that the amplitude variations are intrinsic to ρ Puppis (see next chapter for details). An example of several RV curves derived from different chunks for the UCLES as well as for the McDonald data can be found in Fig. 4.36. The amplitudes differ up to 2000 ms^{-1} peak to peak amplitude which translates to approximately 20% of the pulsation amplitude. When combining all the chunks, the scatter in amplitude is too high to allow a possible detection or a significant null-result of the predicted solar-like oscillations.

In the end it turned out that a visual inspection of all the RV curves for all the chunks (UCLES and McDonald data) was the best method. We selected the best curves based on their scatter, some illustrated in Fig. 4.36. After the barycentric correction, the frequencies derived photometrically where prewhitened (the amplitudes and phases were free parameters) from each of the RV curves independently and only then the residuals where combined allowing to increase the precision significantly (see next chapter for details).

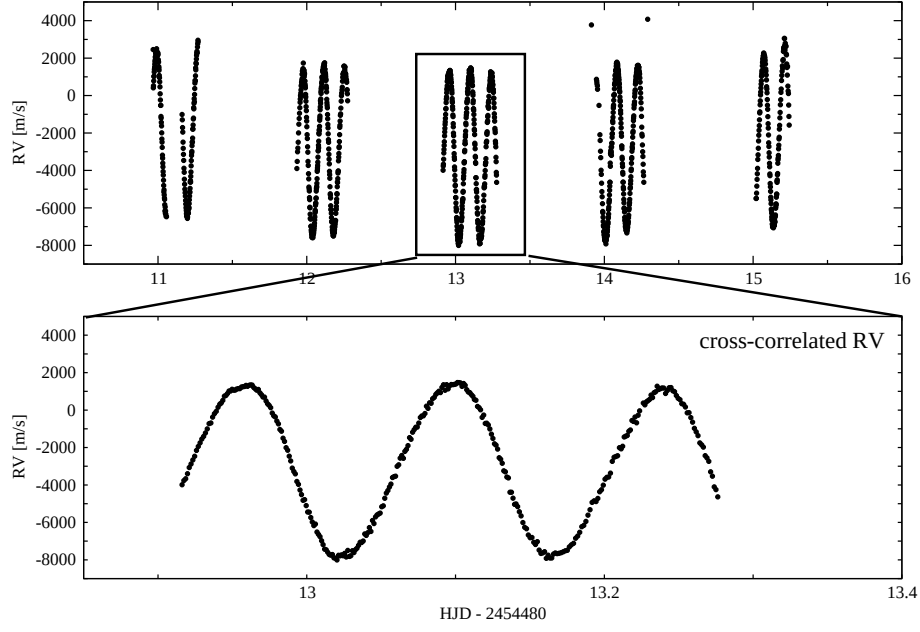


Figure 4.19: Cross-correlation RV curve of the UCLES data. Note that the barycentric correction was not done for this data set, as the cross-correlated

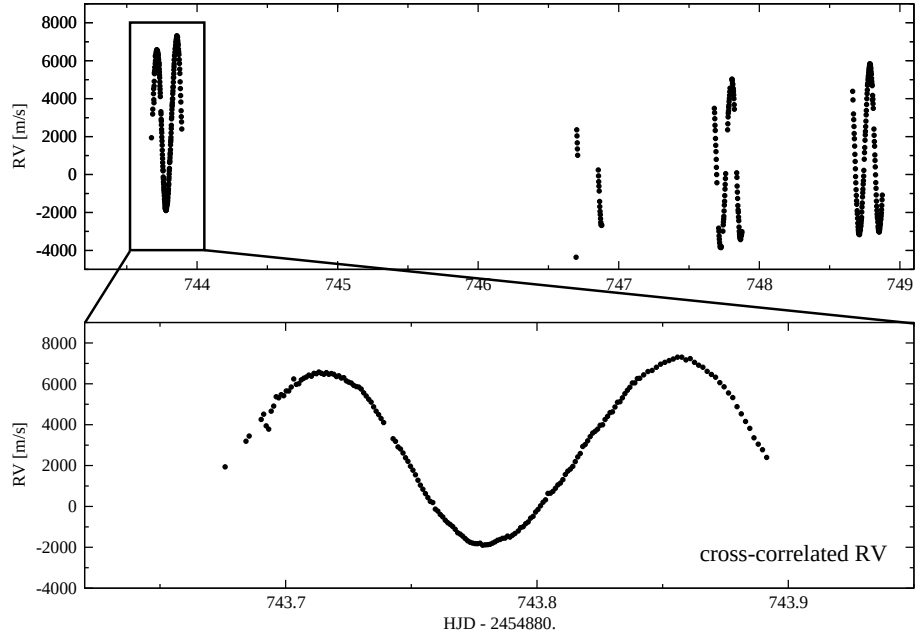


Figure 4.20: Cross-correlation RV curve of the McDonald data. Note that the barycentric correction was not done for this data set, as the cross-correlated RV serve only as a starting values for iSONG.

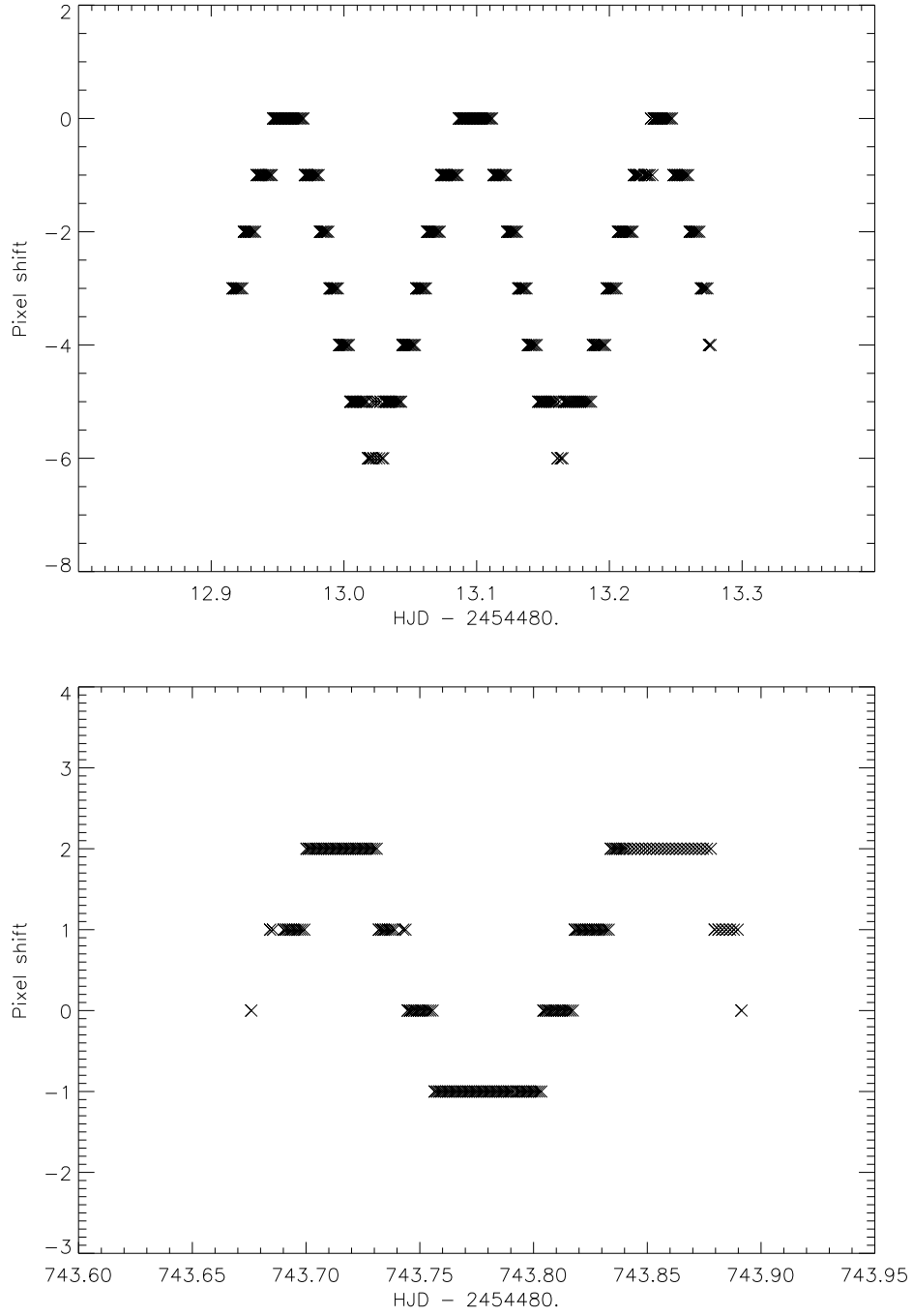


Figure 4.21: Upper panel: Pixel shift relative to the template (UCLES data). Lower panel: Pixel shift relative to the template (McDonald data).

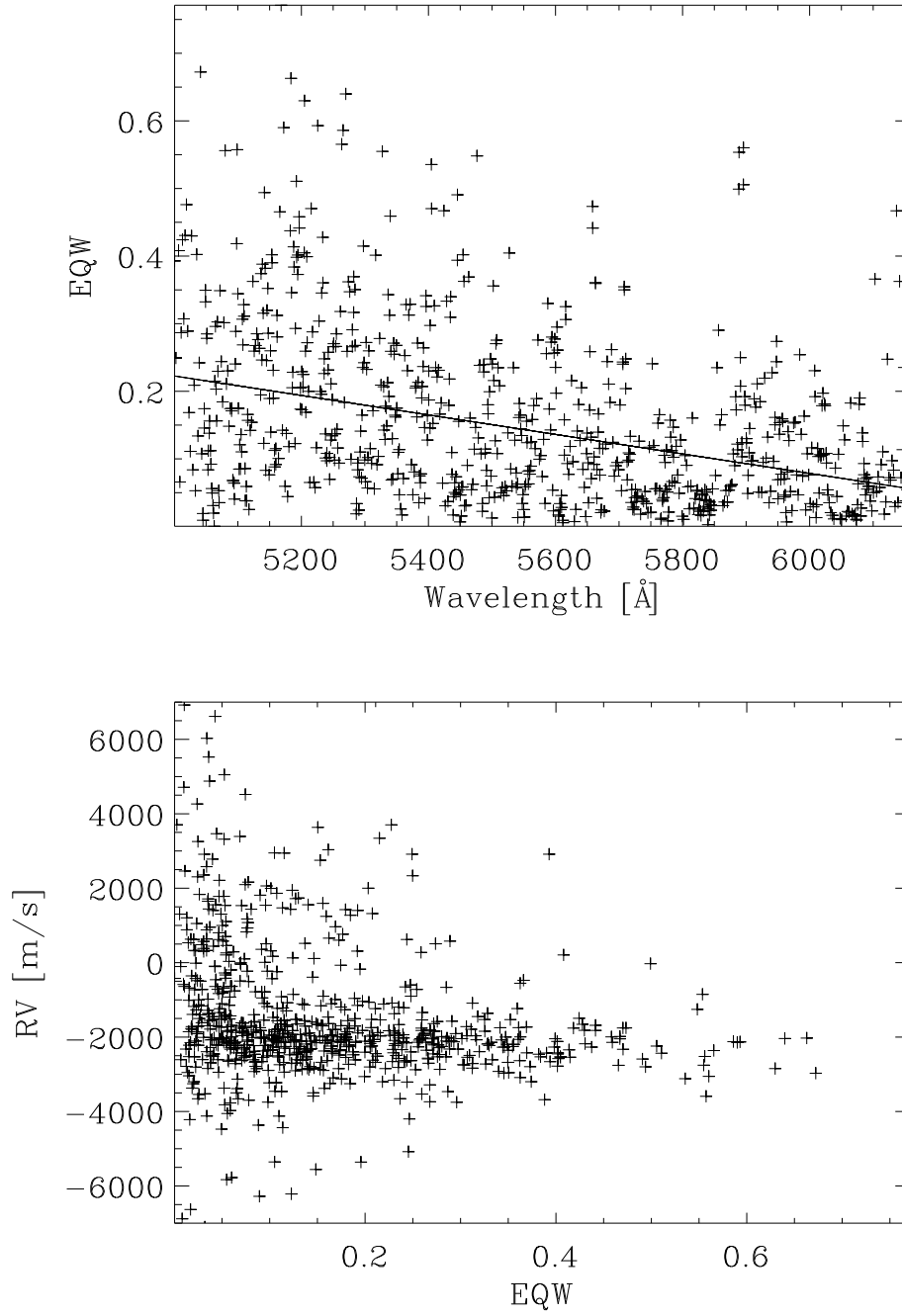


Figure 4.22: Upper panel: EQW in a chunk as a function of WL of one measurement (UCLES data). Lower panel: RV as a function of EQW in a chunk.

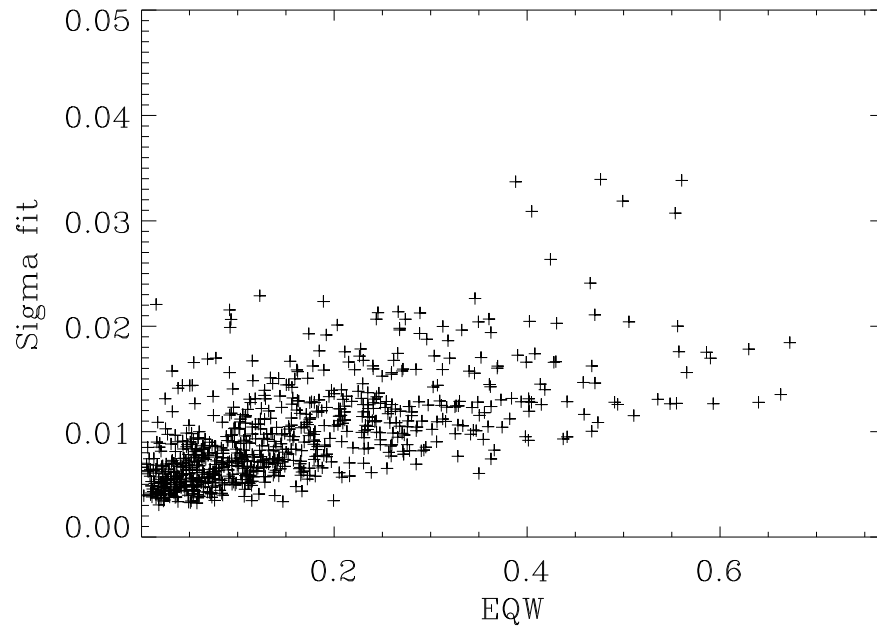


Figure 4.23: The goodness of the fit (sigma fit) as function of the EQW in a chunk.

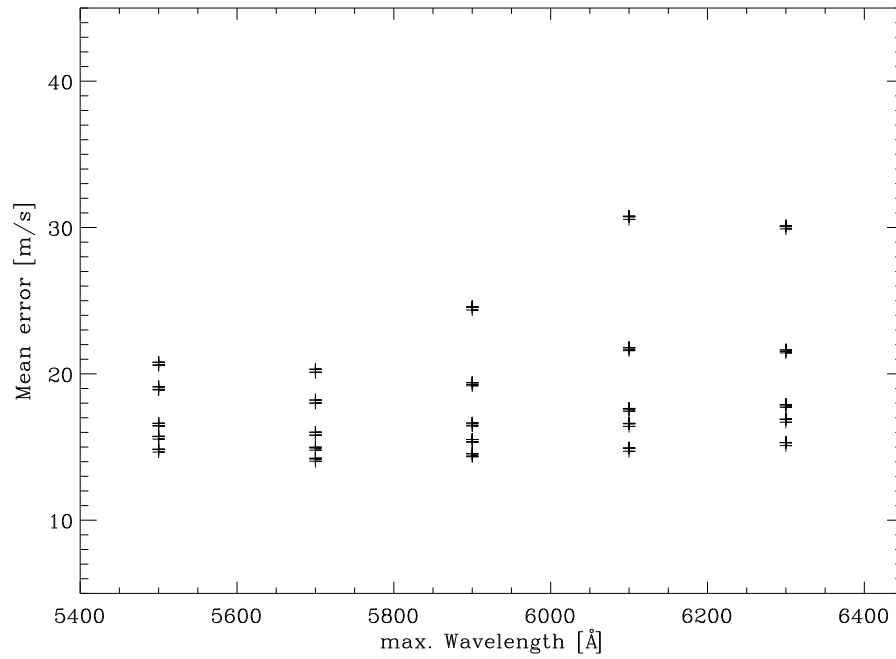


Figure 4.24: Mean error for the UCLES data as a function of maximum WL.

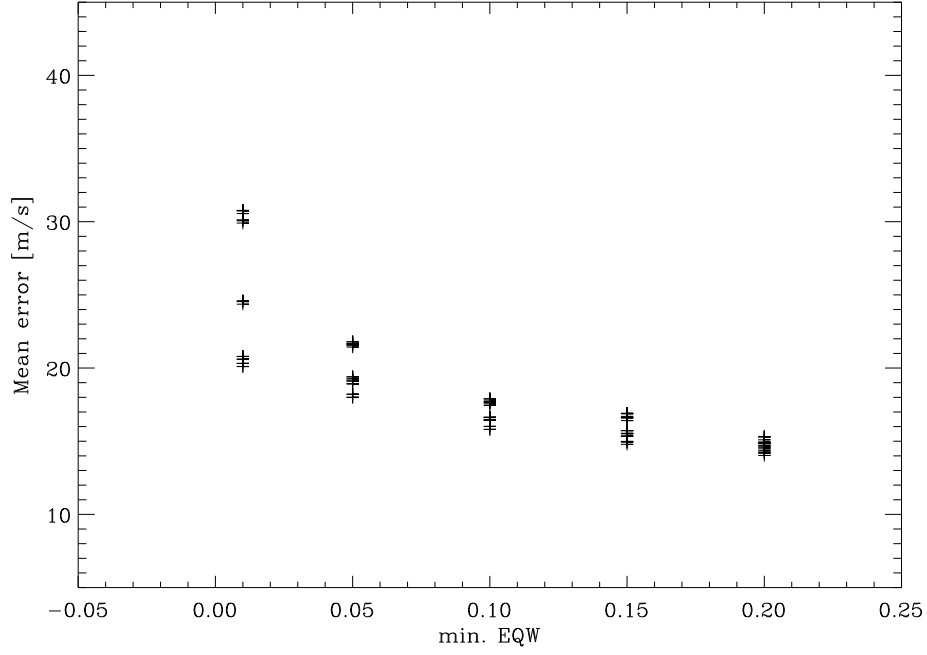


Figure 4.25: Mean error of the UCLES data as a function of minimum EQW. The choice of lower EQW cutoff has the largest impact on the mean error. In other words, the deeper the lines the more accurate the RV measurements are.

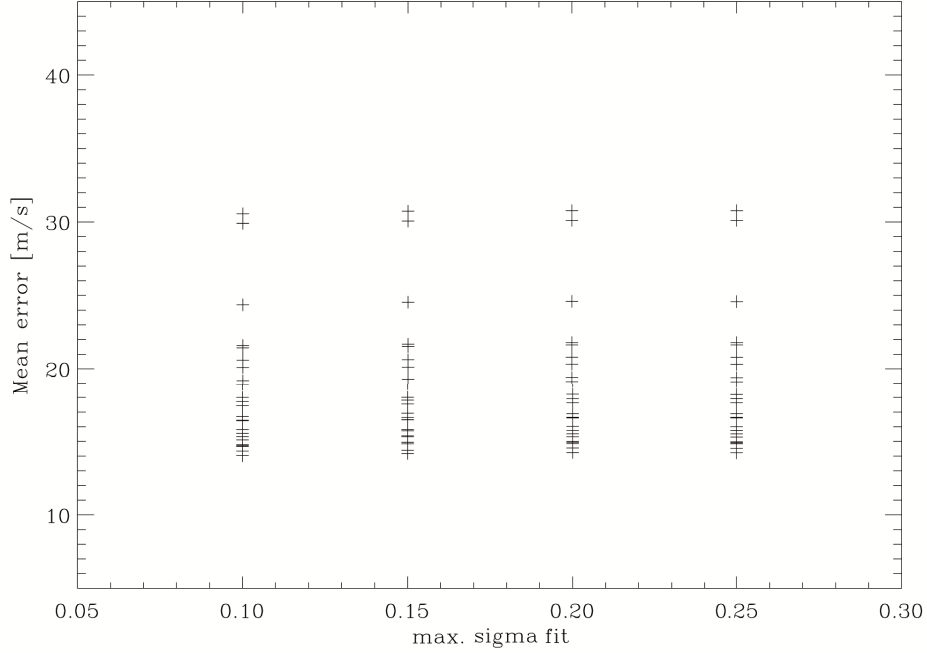


Figure 4.26: Mean error of the UCLES data as a function of the sigma of the fit. The sigma fit describes how well the observations were reproduced. This also shows that the template has not such a large impact as the EQW. This factor has the lowest impact on the mean error.

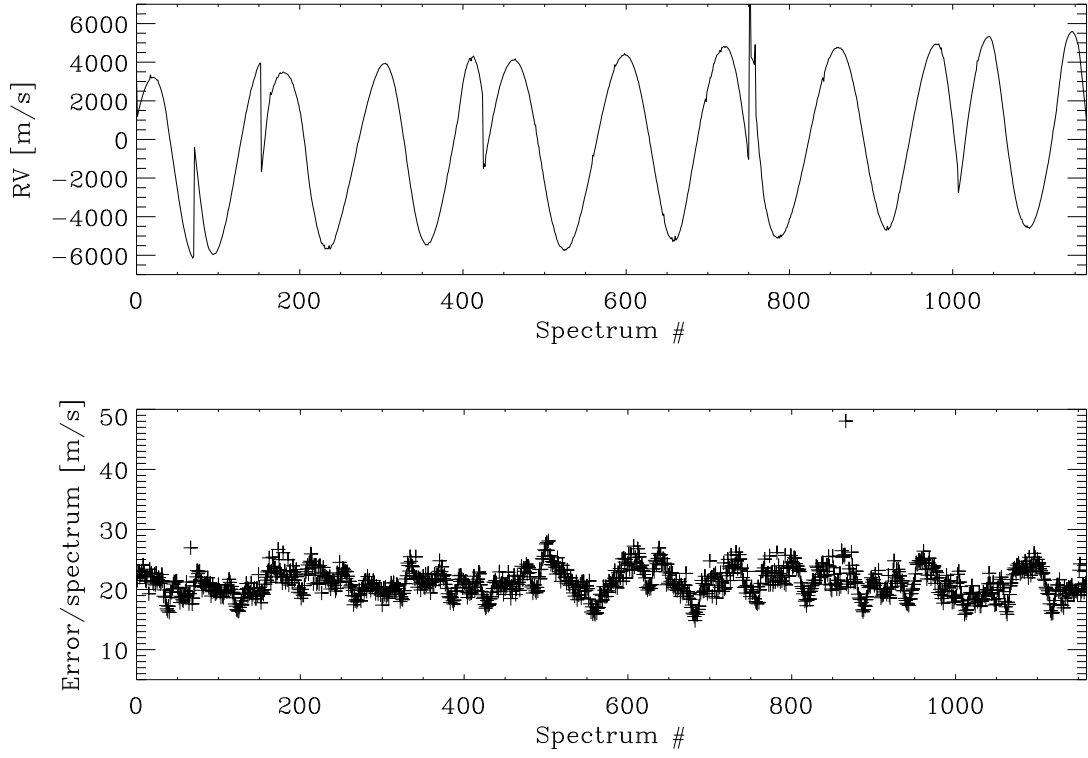


Figure 4.27: Upper panel: UCLES data. Lower panel: Error per spectrum, to be compared to the phase of pulsation. In this case the entire WL range where I_2 lines are present, was used. EQW greater than 0.05 and the cutoff for the sigma fit parameter was 0.22.

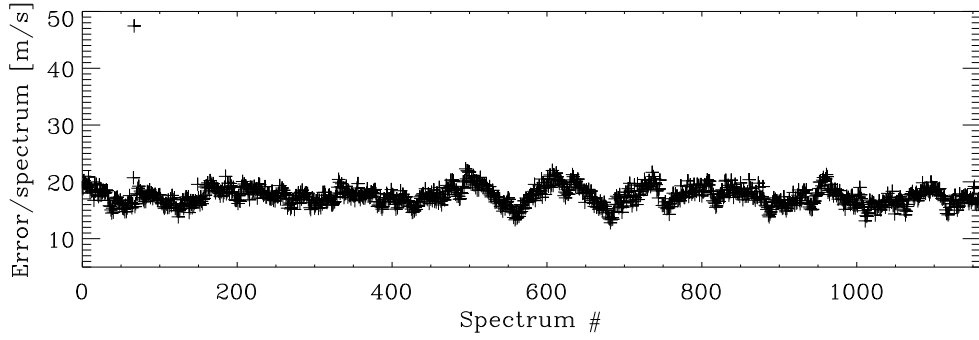


Figure 4.28: The entire WL range where I_2 lines are present, was used. EQW greater than 0.5 and the cutoff for the sigma fit parameter was 0.22.

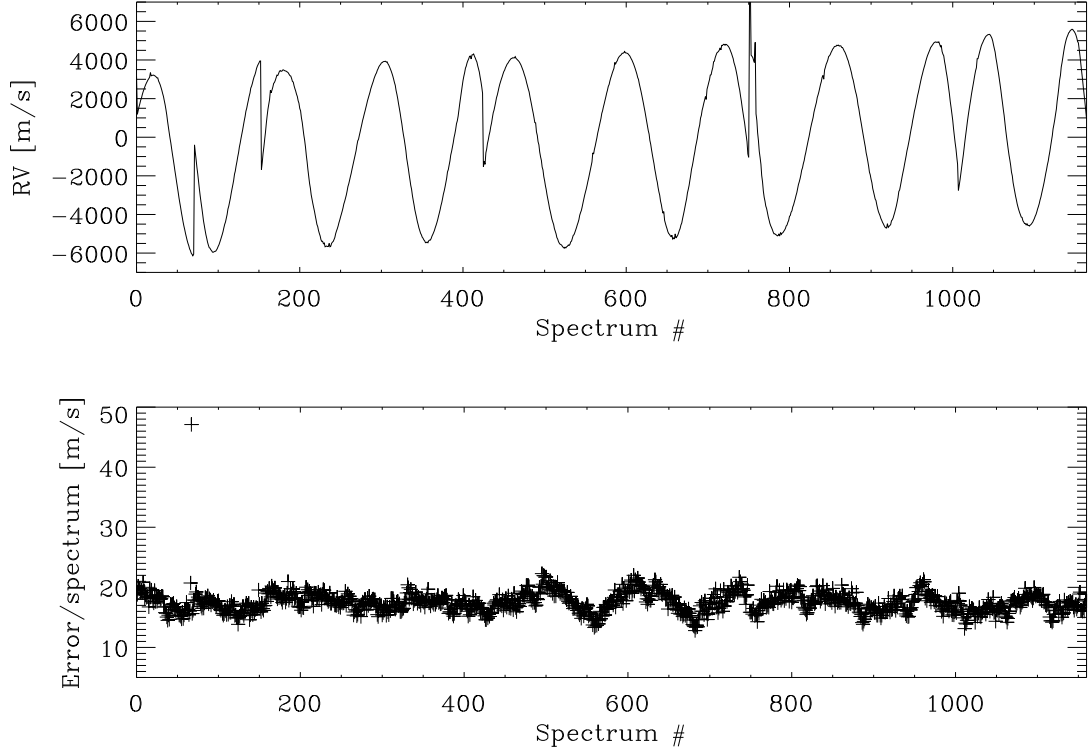


Figure 4.29: Upper panel: UCLES data. Lower panel: Error per spectrum, to be compared to the phase of pulsation. The entire WL range where I_2 lines are present, was used. EQW greater than 0.1 and the cutoff for the sigma fit parameter was 0.1.

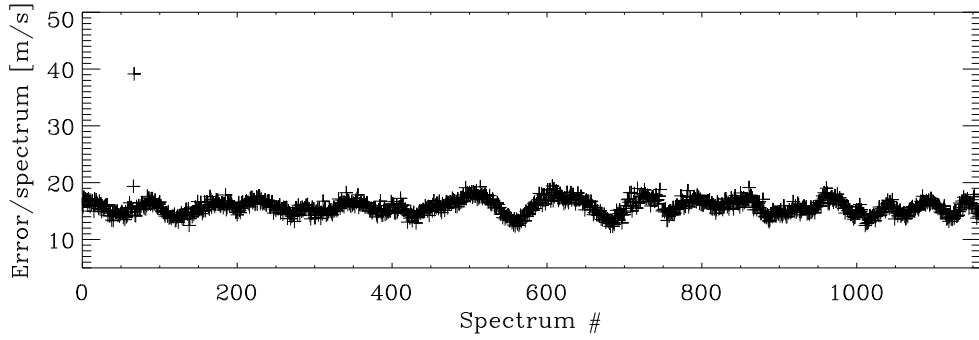


Figure 4.30: In this case the RV measurements only in the WL range between 5000 and 5800 Å were used. EQW greater than 0.1 and the cutoff for the sigma fit parameter was 0.22.

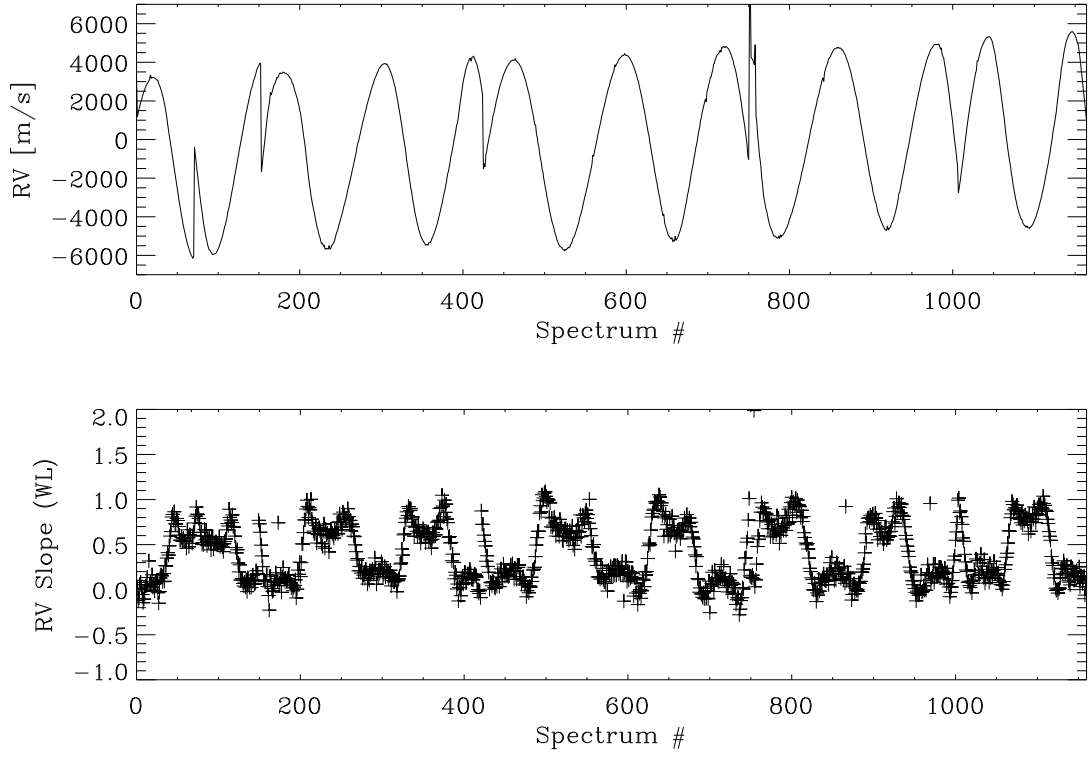


Figure 4.31: Upper panel: UCLES data. Lower panel: The slope of the RV measurements as a function of WL compared to the data. It can be seen that the slope changes with pulsation phase. The slope is also dependent on the chunks, i.e. RV used (compare with the following plots). In this case the measurements within the entire WL region (5000-6300 Å), with an EQW greater than 0.05 and with a sigma fit factor lower than 0.22 were used.

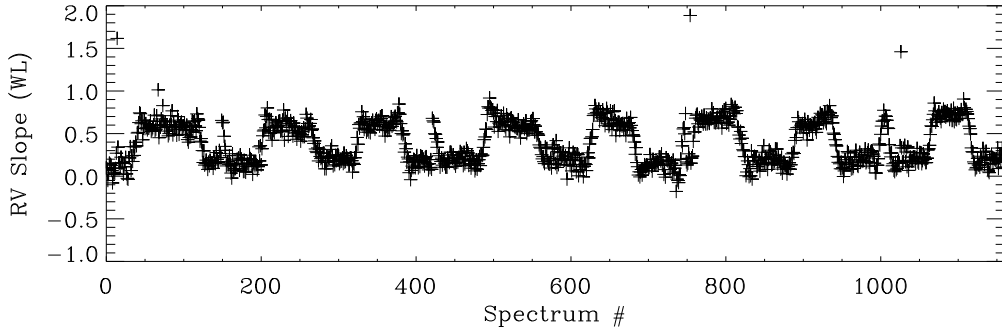


Figure 4.32: The slope of the RV measurements as a function of WL. The slope is dependent on the chunks, i.e. RV used. In this case the measurements within the entire WL region (5000-6300 Å), with an EQW greater than 0.1 and with a sigma fit factor lower than 0.22 were used.

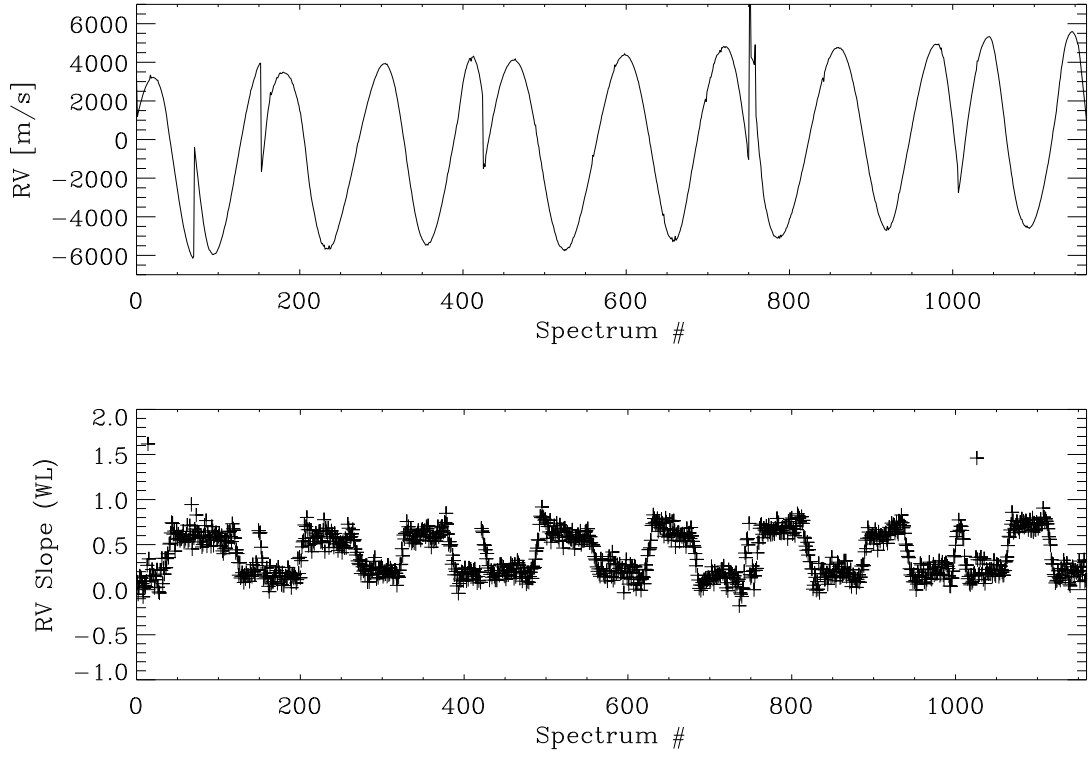


Figure 4.33: Upper panel: UCLES data. Lower panel: The slope of the RV measurements as a function of WL compared to the data. It can be seen that the slope changes with pulsation phase. The slope is also dependent on the chunks, i.e. RV used. In this case the measurements within the entire WL region (5000-6300 Å), with an EQW greater than 0.1 and with a sigma fit factor lower than 0.1 were used.

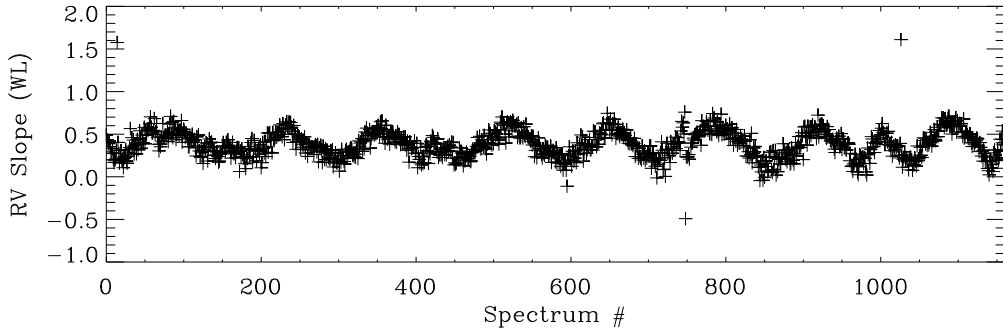


Figure 4.34: The slope of the RV measurements as a function of WL. The slope is dependent on the chunks, i.e. RV used. In this case the measurements within the WL region 5000-5800 Å, with an EQW greater than 0.1 and with a sigma fit factor lower than 0.22 were used.

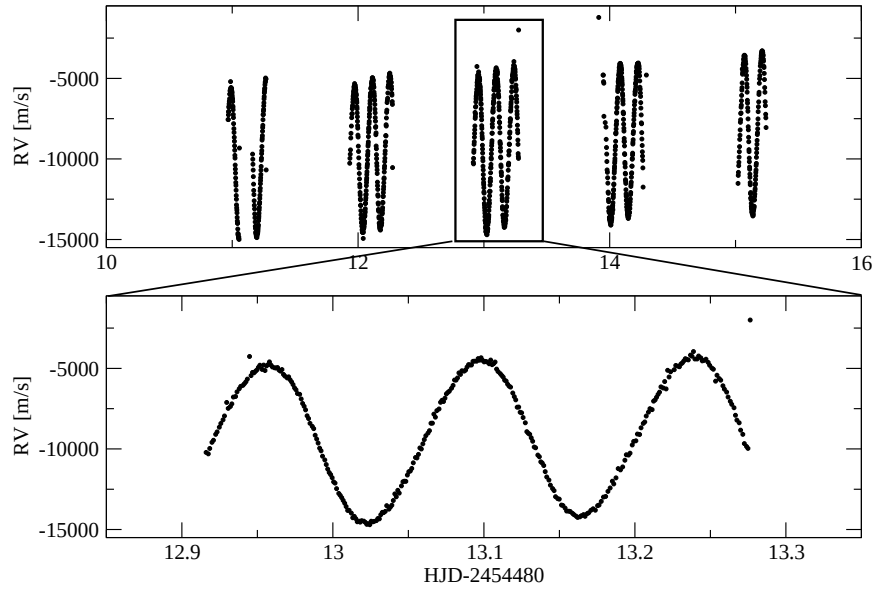


Figure 4.35: UCLES RV data derived by using only certain chunks selected as a function of wavelength, EQW and sigma fit. This RV curve has the smallest mean error ($= 14.5 \text{ ms}^{-1}$). The quality is still not sufficient for our purpose.

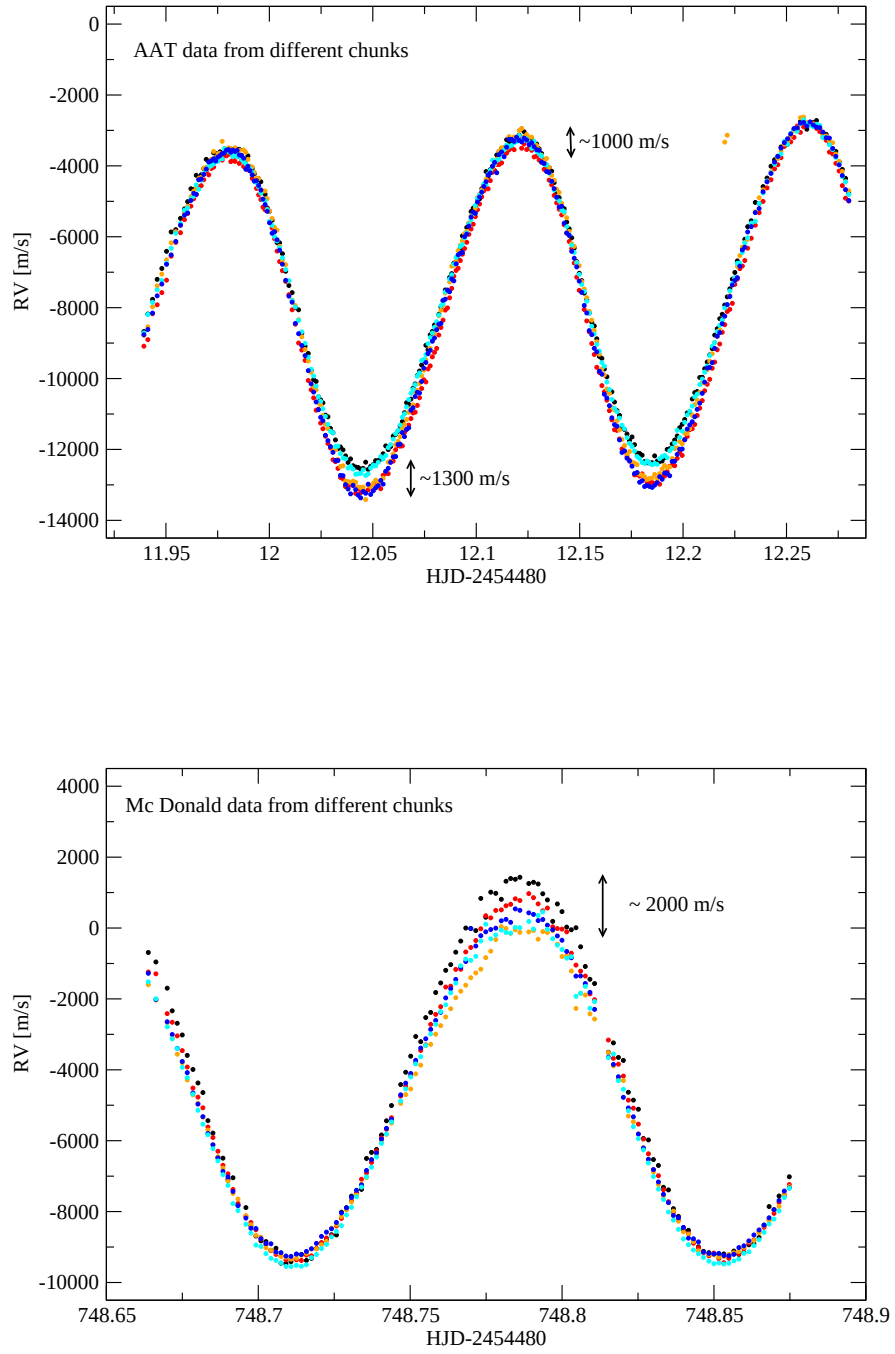


Figure 4.36: Upper panel: UCLES RV measurements for one night derived from different chunks. There are clear variations in amplitude. Lower panel: same plot but for the McDonald data.

4.5.5 ESPaDONs radial velocities

The radial velocities measured with ESPaDONs@CFHT were extracted using bisectors, which are usually used to study line asymmetries. The latter can be caused by different mechanisms, such as pulsation, stellar rotation, magnetic fields, mass loss, granulation, etc. A bisector is constructed by connecting the blue and the red line component of an absorption line at the same height and taking its middle point. If the line is symmetric a vertical straight line will be the result, whereas non-symmetric lines will cause different shapes depending on the velocity fields occurring in the photosphere of a star. This method has been extensively used to, e.g., study convective motions in cool stars (see e.g. Gray 2005) as well as to map the photospheres of roAp stars (e.g. Elkin et al. 2008). This can be done because the core of an absorption line is formed in higher photospheric layers relative to its wings. The shape, the span of velocity as well as the absolute position in wavelength of a bisector display important depth information (see, e.g., Gray 2009).

Depending on the position in the HRD the bisector is dominated by different physical phenomena. For cool stars (early F type and later) it is mainly the convection which governs the asymmetry of the line. The Sun's net bisector for example, can be described as the letter C. This means that the convective velocities do not penetrate the highest part of the atmospheres (described by the line cores). In the layers slightly below, the velocities get higher, are more blue-shifted than the deepest part, the line wings, which are slower and therefore more red-shifted. In other words we observe the rising granules, being blue-shifted and dominating the bisector and the in-falling material which moves away from the observer and is therefore redshifted. In stars hotter than the Sun the core of the line is also blue-shifted which suggests that the granules penetrate into higher atmospheric layers.

When moving on the main sequence to higher temperatures an inversion of the bisector shape can be observed, where the wings are blue and the core is red-shifted (e.g., Gray 2005). This is because the rising material becomes more luminous and dominates the fraction of intensity in the bisector. The velocity span covered for an A type star can be several kms^{-1} , compared to the Sun which shows only a few hundred ms^{-1} shift. Because of the higher temperature the convection transports energy less effectively, leading to higher convective velocities. The so-called granulation boundary on the main sequence can be found on the cool side of the δ Sct instability strip, between late A and early F type stars (see e.g. Royer 2009). According to, e.g., Kupka (2004) and Landstreet et al. (2009) granulation signatures can be found also in A type stars up to 8300K.

For the present work, we were not interested in disentangling the velocity fields originating from pulsation from those caused by granulation. This means that we were not restricted to unblended lines when constructing bisectors but could also use blended ones. For line identification we used the synthetic spectra computed for the abundance analyses of ρ Pup as described by Antoci et al. (2008). The code to derive the line bisectors was kindly provided by Luca Fossati and was written in IDL.

After analyzing several lines we found strong amplitude variability depending on the line depth. To minimize scatter when averaging the bisector to one RV value, we chose to use only lines showing constant amplitude over a large part of the bisector. Figure 4.37 illustrates the difference between a line displaying no and one showing strong amplitude variability (from line core to wing up to 4 km s^{-1} peak to peak amplitude). The majority of all absorption lines displays asymmetric variability when plotting all bisectors. Even if the dominant mode is a radial mode, that causes the line to only blue and red shift periodically, there are also contributions from the low-amplitude nonradial modes (Chapter 4.4) to the bisectors. So far we have no clear explanation for all these significant changes (could be due to non-linearities in the atmosphere), especially why we see such different behaviour from line to line (even within the same element), but find it very unlikely to have introduced any artificial signals when extracting the bisectors. The data were reduced using the *Libre Esprit* pipeline, which has been tested extensively. The normalization of the spectrum has a very high impact on the bisector, because it can introduce or cancel asymmetries in the spectral line. We have tested lines which have a clear continuum to the blue and red part of the line, hence allowed an accurate normalization. The amplitude asymmetry as a function of line depth still existed. Further in-depth analyses of this phenomenon are planned for the near future, but are out of the scope of the present work.

For the search for solar-like oscillations we have extracted the RV from the following lines: NaI D1 $\lambda\lambda$ 5895.9A, NaI D2 $\lambda\lambda$ 5889.9, FeI FeI blend $\lambda\lambda$ 5139.2/5139.4, FeI FeI $\lambda\lambda$ 5107.4/5107.6. As mentioned above, blended lines are not a problem, but we nevertheless chose to use lines which were blended by the same element. All the measurements from a given bisector in the parts where the amplitude was constant as a function of depth were averaged. One of the used lines is shown in the left part of Fig. 4.37. For this particular line the values between line depth 0.4 and approximately 0.8 were used. To be consistent with the AAT and McDonald data, also in this case the photometrically derived frequencies were prewhitened first. Only then the residuals were averaged to a final RV curve, which has a noise level of only 50 cm s^{-1} in the Fourier spectrum.

4.6 Searching for solar-like oscillations

Now that all the RV measurements were extracted, the data were carefully analysed. First we performed separate analyses of each data set, meaning that we prewhitened the signal at frequencies lower than 20 cd^{-1} and then combined the residuals. From tests on artificial data sets (see chapter 5.1) containing coherent and non-coherent¹¹

¹¹The artificial data sets to mimic the solar-like oscillations were generated using the *Aarhus simulator*, where the frequency of maximum power, the amplitudes and the mode lifetimes are scaled to the Sun. The artificial data sets were kindly provided by Torben Arentoft for a star with parameters (see Chapter 4.2) as those of ρ Puppis. These data were used to test our analysis methods.

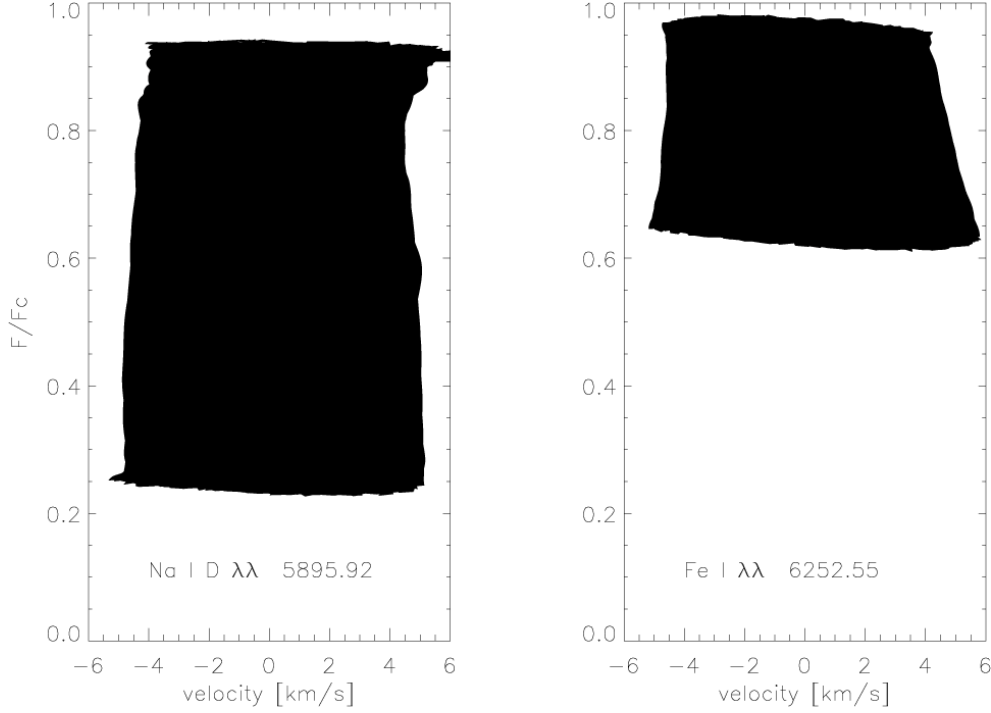


Figure 4.37: Left panel: Bisectors derived from the Na D1 line plotted for the entire pulsation cycle. In this case the amplitudes are almost constant. To extract the RV the values between F/F_c 0.4 and 0.8 were averaged. Right panel: The Fe I $\lambda\lambda$ 5253.5 line, with very weak contributions from other Fe I and Fe II lines was used. Note the clear but asymmetric variation in amplitude with depth. The amplitude changes on the red part from ~ 6 to $\sim 4 \text{ km s}^{-1}$ from core to the wings respectively, whereas for the blue part of the line shifts from almost -5.5 km s^{-1} to -4.5 and increases again to -5 km s^{-1} .

signals, representing the κ -mechanism driven and the stochastic oscillations respectively, it was shown that prewhitening a coherent signal does not change a possible non-coherent one. In other words, the low-frequency signals observed in ρ Puppis could be removed without affecting the detectability of possible solar-like oscillations. Note that due to the short time-base of the individual data sets most of the frequencies derived photometrically cannot be resolved in this case. This is not important because we are not interested in the δ Sct pulsation here, but rather want to get rid of it to lower the noise and to unveil possible low-amplitude solar-like oscillations. Also it is very likely that some of the frequencies we removed are rather of instrumental origin or artefacts due to aliases effects left from the prewhitening process- which also serves our purpose.

The amplitudes of solar-like oscillations for a star with the parameters of ρ Puppis (see Chapter 4.36) were predicted to be between 1 and 2 ms^{-1} (i.e., 2500-5000 times lower than the amplitude of the dominant mode!) depending on the approach used

(Houdek & Gough 2002 or Samadi et al. 2005). If we use the significance criterion from Kjeldsen & Bedding (1996) of $S/N = 2.5$ a noise level of 0.40 ms^{-1} is needed to detect a signal with a 1 ms^{-1} amplitude. If we adopt the significance criterion of Carrier et al. (2007) of $S/N = 3.05$, the noise level needs to be at 0.3 ms^{-1} . According to the authors, $S/N = 3.05$ is required to unambiguously detect solar-like oscillations, with a confidence level of 99%.

Usually when analyzing RV measurements of solar-type stars, an error per measurement can be computed after combining all the RV extracted from the different chunks. These errors can then be used to weigh the data such that less precise measurements affect the results less. In the present case, however, better precision has been achieved when first prewhitening the dominant signal at low frequencies and only then combining the residuals of the individual RV, as already mentioned. This means that we do not have an error per measurement to weigh the data accordingly. In their extensive observing campaign for Procyon, Arentoft et al. (2008) used noise-optimized weights, where they combined the usual method ($w_i = 1/\sigma_i^2$) with the one of Butler et al. (2004)¹², but also introduce a new method to better identify the outliers and to down-weight these. To do so they employed a high-pass filter to identify which measurements contribute most to the signal at very high frequencies. This is possible because, as was shown by e.g. Butler et al. (2004), it can be assumed that the signal in the high-frequency domain gives very good information about the noise in the data. Inspired by these methods, we have used the high-pass filtering technique to estimate the uncertainties of each measurement, in the residual RV curve. To do so we used the Butterworth filter deployed in Fourier space, which is available as an IDL routine and is described by the following formula:

$$\frac{1}{\sqrt{1 + \frac{\Omega}{\Omega_c}^{2N}}} \quad (4.1)$$

where Ω is the frequency in Fourier space, Ω_c the cut-off frequency and N the order of the exponent determining the shape of the filter. Experimenting with different values for the cut-off frequency, we find that the signal higher than 75 cd^{-1} represents the noise level best. In Figures 4.38, 4.39, lower left-hand panel the Fourier spectra of the high as well as the low-pass filter are shown. The latter was not used, but was plotted for completeness. This filter was designed such that the spectral leakage from the 'unwanted' frequency region is as small as possible. Ideally a pass band filter should have a so-called *brick wall* shape, which should not touch the signal in the pass band but filter out the signal in the stop band. The higher the order of the Butterworth filter the more a *brick wall* shape is approximated. In the present case

¹²a method to down-weight outliers by using the condition $\sigma_{amp}^2 \sum_{i=1}^N \sigma_i^2 = \pi$, where σ_{amp} is the noise level in the amplitude spectrum, N the number of measurements, σ_i the uncertainty of the velocity measurement.

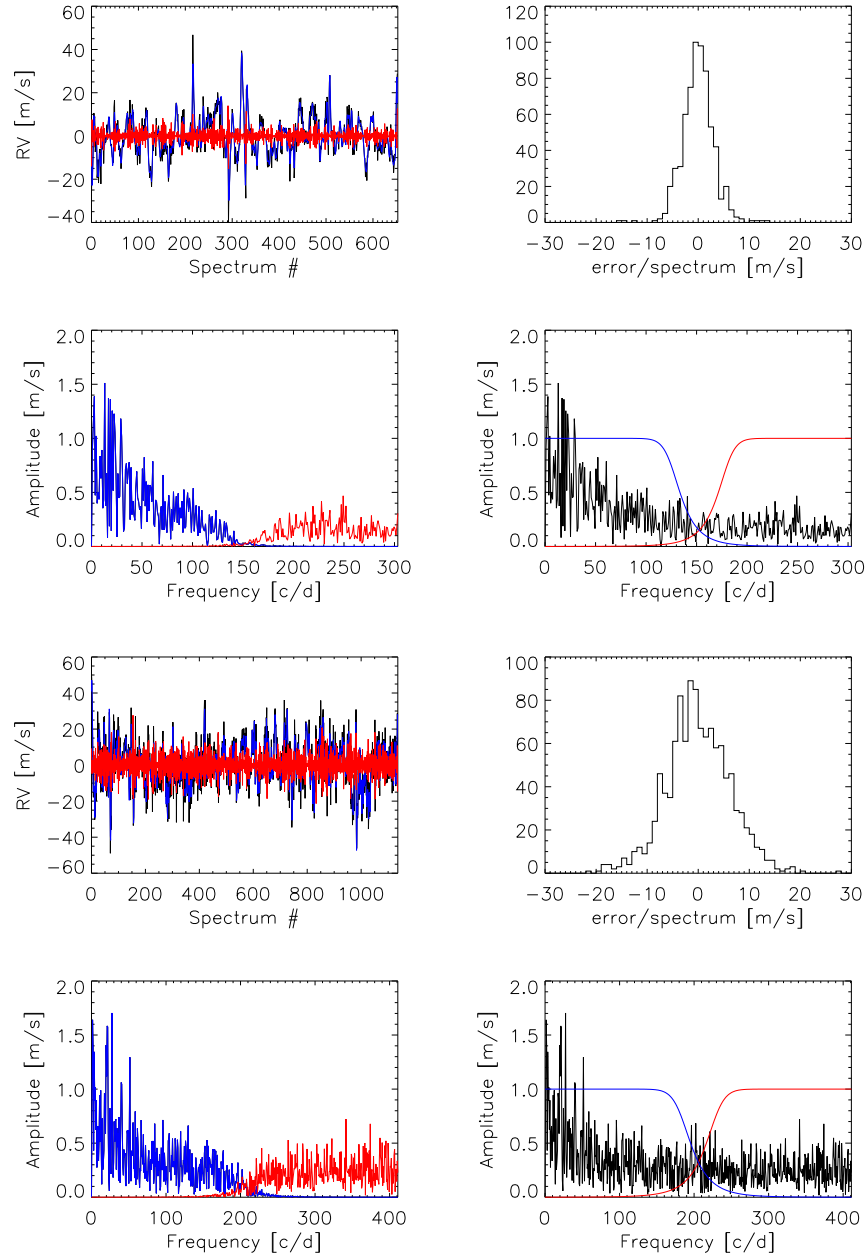


Figure 4.38: High pass filtering using a Butterworth filter to determine the error per measurement for the CORALIE (upper four panels) UCLES data (lower four panels). Upper left panel: observed residuals in black, in red the signal after high pass filtering, in blue the low pass filtered data. Lower left panel: Fourier spectrum of the high (red) and low (blue) pass filtered data. Lower right panel: Fourier spectrum of the observed residuals (black) together with both high and low pass filters. Upper right panel: histogram of the derived uncertainties.

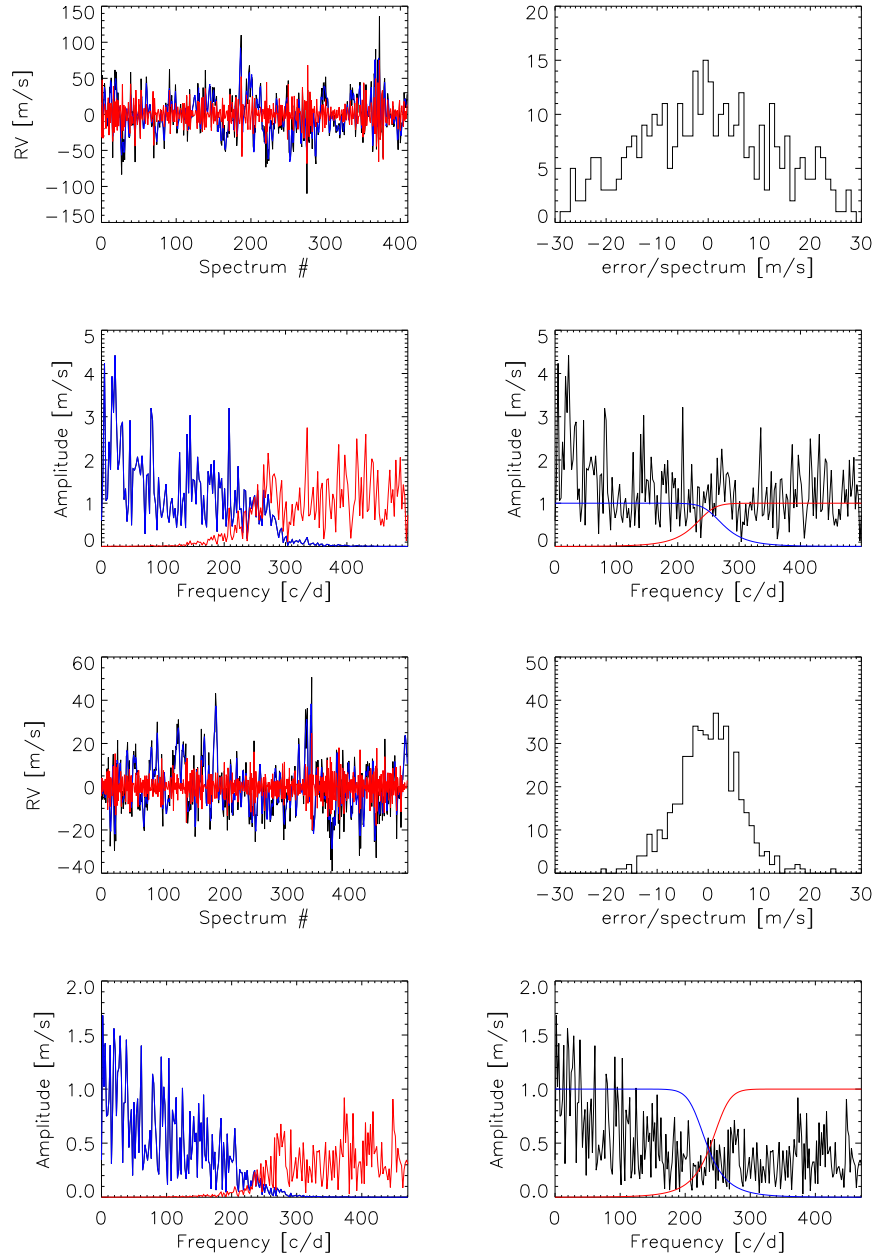


Figure 4.39: High pass filtering using a Butterworth filter to determine the error per measurement for the McDonald data (upper four panels) and CFHT data (lower four panels). Upper left panel: observed residuals in black, in red the signal after high pass filtering, in blue the low pass filtered data. Lower left panel: Fourier spectrum of the high (red) and low (blue) pass filtered data. Lower right panel: Fourier spectrum of the observed residuals (black) together with both high and low pass filters. Upper right panel: histogram of the derived uncertainties.

an order of 10 was used. For details see e.g. http://www.electronics-tutorials.ws/filter/filter_8.html.

The high-pass filtering was done for each data set separately, because the Nyquist frequency for each observing run is different. In Figures 4.38, 4.39, we illustrate the filters used as well as the signal after high-pass but also after low-pass filtering. The filter was constructed in frequency space, then the signal passing through the filter was transformed back to the time domain, allowing to determine the amplitude of the signal originating from high-frequencies mirroring the noise behaviour of the data set. The same figures also show the uncertainties derived from this method as a histogram, giving a clear idea which are the better data sets. For further analyses we then computed a mean error and weighted the measurements as follows:

$$\begin{aligned} \sigma_{RV} \leq 1\sigma : w_i &= 3 + \frac{1}{\sigma_{RV}^2}. \\ 1\sigma \geq \sigma_{RV} \leq 2\sigma : w_i &= 1 + \frac{1}{\sigma_{RV}^2}. \\ \sigma_{RV} \geq 2\sigma : w_i &= \frac{1}{\sigma_{RV}^2}. \end{aligned} \tag{4.2}$$

where σ_{RV} is the error of the individual measurements estimated from the high-pass filtering and σ the standard deviation. When inspecting each RV curve prior to the filtering only very obvious outliers were omitted. Even if there were more points with lower quality we chose to down-weight, rather than to delete them.

In case of the CORALIE data, displayed in Fig. 4.40 together with the uncertainties, the errors per measurement were delivered together with the data, and were determined using the CORALIE pipeline. Sometimes such pipelines can underestimate the errors. At least that is what seems to be the case if we compare the pipeline errors to the error estimated by using the high-pass-filtering. If we use the formula given by Kjeldsen & Bedding (1995), to estimate the error per spectrum by measuring the noise level in the power spectrum:

$$\sigma_{PS} = 4\sigma_{rms}/N \tag{4.3}$$

where σ_{PS} is the noise level in the power spectrum, N the number of measurements and σ_{rms} their rms scatter, we obtain for the measured noise around 0.5 ms^{-1} , if squared $0.25 \text{ m}^2/\text{s}^2$, a σ_{rms} of $\sim 2.5 \text{ ms}^{-1}$. This is in better agreement with what we obtain from the high-pass filtering (i.e. 3 ms^{-1}) than with the values delivered from the pipeline (Fig. 4.40). For further analyses, we therefore use the errors derived from the Butterworth filter illustrated in Fig. 4.38. The Fourier spectrum of the residuals is displayed in Fig. 4.41.

For the UCLES data, 104 residual RV curves were combined by averaging the measurements originating from the same spectrum. This resulted in a noise level of 0.6 ms^{-1} in the Fourier spectrum when using the noise-optimized point weights as described above (see Fig. 4.38 and Fig. 4.41). The same was done for the McDonald data set, by combining the RV curves of 27 different chunks yielding a noise level of

2.2 ms^{-1} . The ESPaDOnS RV were derived by using the line bisectors as described in detail in Chapter 4.5.5. Also in this case the dominant signals at low frequencies were first removed and only then the residuals combined. The noise level in the Fourier spectrum (see Fig. 4.41) is 0.7 ms^{-1} .

Finally all the data sets were combined, lowering the noise level down to 0.4 ms^{-1} when using the weighted data (lower panel of Fig. 4.41). For comparison, the unweighted data result in only slightly higher noise of 0.5 ms^{-1} . Even if the difference may not be huge, in terms of significance criterion it helps to set a lower limit. In the lower panel of the same figure, the grey arrow indicates where the frequency of maximum power, computed according to Equation 2.5 is expected to be ($\sim 37 \text{ cd}^{-1}$). The solar-like oscillations are damped and re-excited at the same frequency but with different phases. This allows us to collapse the HJD of our data, such that the sampling of each data set is preserved but the gaps removed (see, e.g., Kallinger & Matthews 2010). This procedure, of course changes the window function, suppressing the daily aliases. The trade-off is the lower frequency resolution, which in the present case is less important. The results of the 'stacked' data are illustrated and compared with the 'original' data in Fig. 4.42. In both cases there is no obvious signal where ν_{max} is expected, which could be interpreted as solar-like oscillations. This might lead to the straightforward conclusion that there are no solar-like oscillations in ρ Puppis. However, there is clearly a signal at lower frequencies around 22 and 29 cd^{-1} , which can, if intrinsic to the star, either be due to (a) combination frequencies from the δ Scuti pulsation or (b) independent high order κ mechanism driven pulsation.

Nevertheless let us assume as an example the possibility that we do observe solar-like oscillations in ρ Puppis, not with a maximum amplitude at the predicted ν_{max} of $\sim 37 \text{ cd}^{-1}$, but at around 29 cd^{-1} where power is observed. If we apply the relation from Kjeldsen & Bedding (1995):

$$\frac{\nu_{max}}{\nu_{max\odot}} = \frac{M/M_{\odot}}{(R/R_{\odot})^2 \sqrt{T_{\text{eff}}/5777\text{K}}} \quad (4.4)$$

and use the radius derived from interferometry ($R = 3.47R_{\odot}$) together with the T_{eff} of 7080 K (see chapter 4.2) we obtain a mass of $\sim 1.5 M_{\odot}$. This is indeed rather low, but as was shown by Pamyatnykh (2000), changing the chemical composition of a star results in a rather drastic shift of the evolutionary track in the HRD diagram. For lower metallicities the evolutionary track of a model at a given mass moves towards higher luminosities. In other words, a given star with a measured luminosity and temperature can have a lower mass if the (global) abundance of heavy elements is decreased. In the case of ρ Puppis this is not necessarily supported by its chemically peculiar nature, because the higher metallicity can indeed be just an atmospheric phenomenon. Under the assumption that the signal observed at 29 cd^{-1} is stochastically excited and is ν_{max} , using the empirical scaling relation from Stello et al (2009) we derive a large frequency separation of $\Delta\nu = 2.15 \text{ cd}^{-1}$. This means that if we observe alternating $\ell = 0$ and 1 modes, we should detect half this

value, which is 1.08 cd^{-1} . If the signals at 29 cd^{-1} is ν_{max} , then the rather smooth transition, as observed in HD 187547 (next chapter), between the κ mechanism and the stochastically excited pulsation can be interpreted as further evidence for this hypothesis. For completeness we did the same exercise but this time assuming that the signal at $\sim 21 \text{ cd}^{-1}$ is ν_{max} . To fit this value for the same radius and temperature as above, a mass of $\sim 1.2 M_{\odot}$ is required, which is definitely too low. Nevertheless, because we know that the dominant mode is the fundamental radial mode with $Q = 0.033$, we get $M/R^3 = 0.055$. If we assume the mass to be $1.5 M_{\odot}$ we obtain $R = 3.01 R_{\odot}$ and for $1.2 M_{\odot}$, $R = 2.80 R_{\odot}$. Both are clearly inconsistent with the accurate interferometric radius.

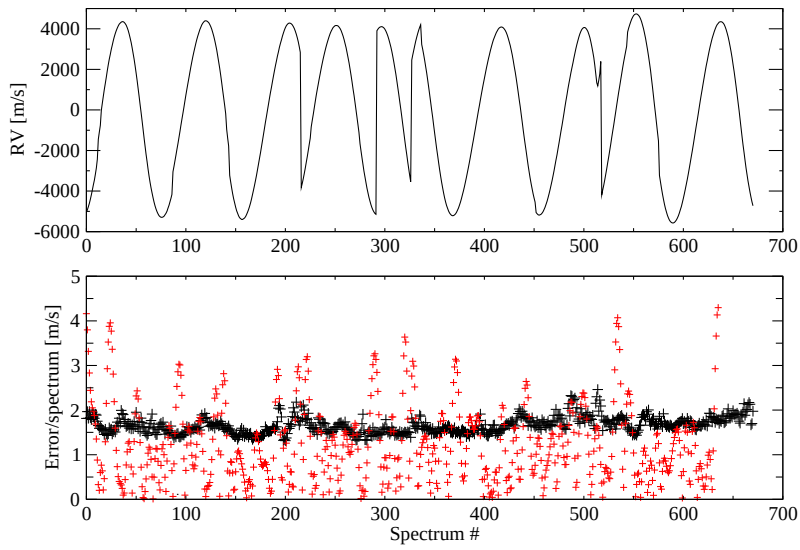


Figure 4.40: Upper panel: RV curve observed with CORALIE. Lower panel: Errors per spectrum delivered by the pipeline when extracting the RV (black) and the errors determined from the Butterworth filter in red. Also in this case a slight dependence of the errors on the pulsation cycle can be detected, even if more subtle than in the UCLES data.

To conclude, we have no clear evidence of solar-like oscillations in ρ Puppis at the predicted frequency of maximum power of 37 cd^{-1} with amplitudes higher than 1 ms^{-1} , assuming a significance criterion of $S/N = 2.5$, but of 1.6 ms^{-1} using the criterion of $S/N = 4$, typically used for coherent pulsators. The higher signal at lower frequencies and the more or less sudden drop at around the expected frequency of maximum power at 37 cd^{-1} (see Fig. 4.41) suggests that we might observe granulation signature.

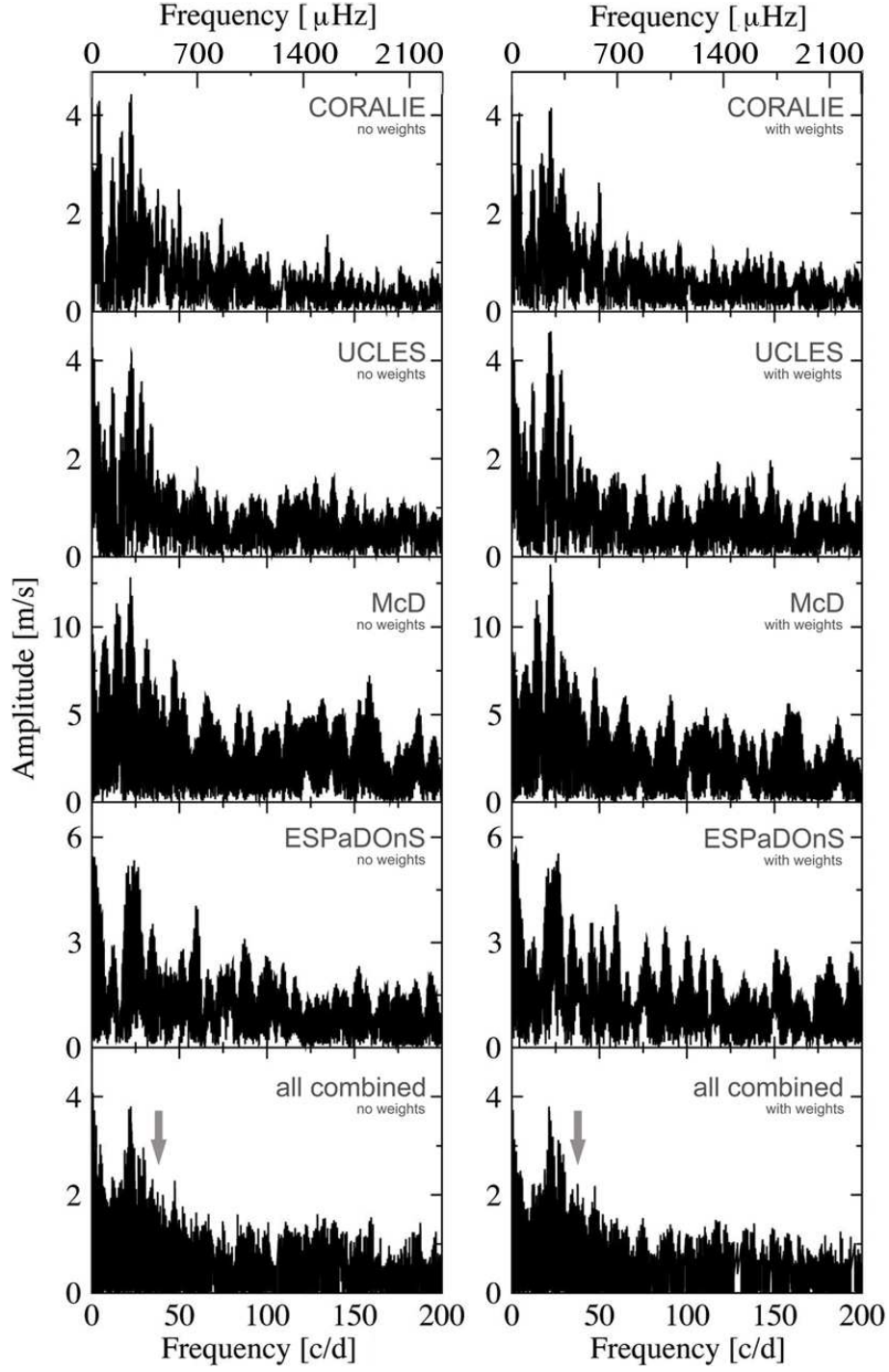


Figure 4.41: Fourier spectra for all individual data sets, with and without using noise-optimized weights. The lower panel shows the amplitude spectra of the combined data sets. The grey arrow indicates the predicted frequency of maximum power ν_{max} .

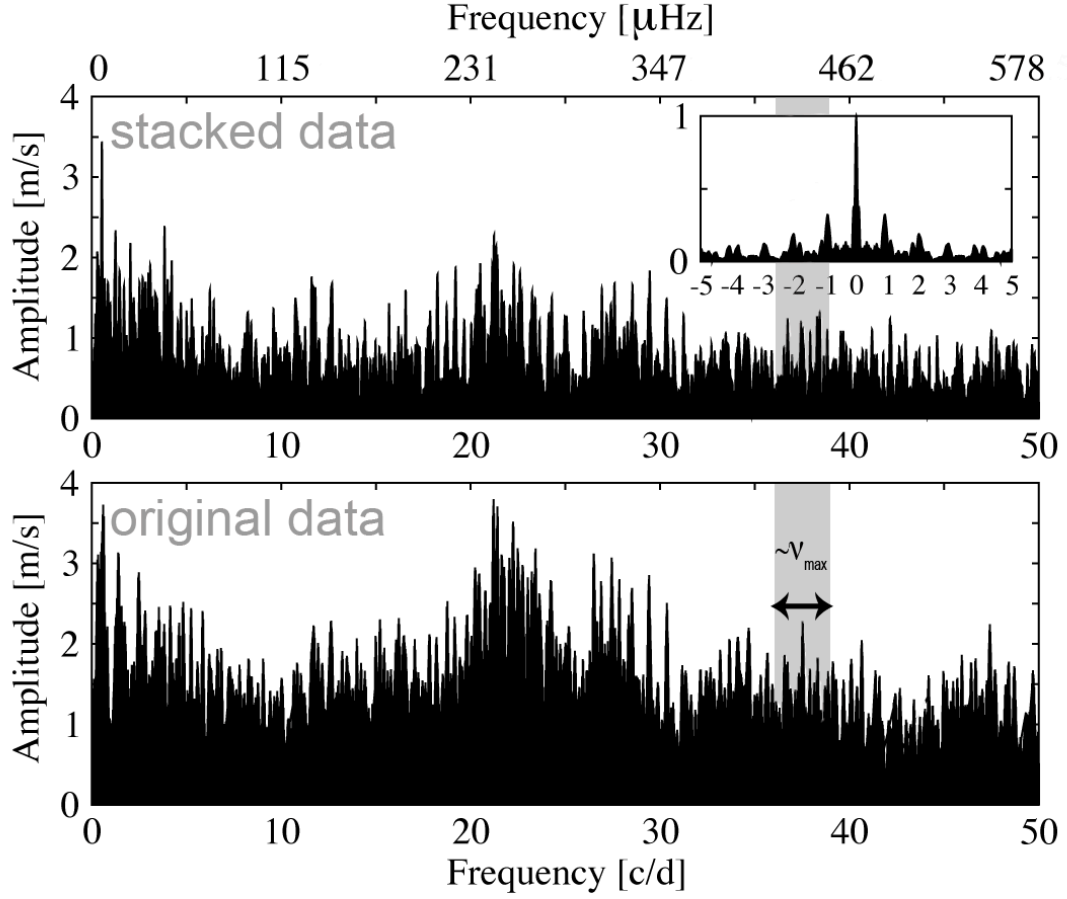


Figure 4.42: Upper panel: A solar-like mode at a given frequency is damped and re-excited at a different phase, which means preserving the phase information is not absolutely necessary as in the case of a coherent signal. Therefore the gaps can be removed without losing altering the result. In this case the combined data were stacked to 15 days. Lower panel: for comparison again the Fourier spectrum of all combined data, with the original HJD, hence the name 'original' data. In grey we depict the region where $\nu_{\max}$ is expected.

5 The Kepler satellite

The NASA Kepler mission was designed to search for earth-like planets around sun-like stars (Koch et al. 2010 and references therein). The satellite was launched on March 6, 2009 in an Earth trailing orbit and has gathered almost uninterrupted data of approximately 150000 stars. The mission length is 3.5 years, since at least 3 eclipses are needed to characterize a planet and its orbit, but is designed such that the space craft could be operated for at least a further 10 years. The 1-m class Schmidt telescope with a FOV with a diameter of 16 degrees is targeted to the constellation of Cygnus looking toward the Galactic plane (see Fig. 5.1). The data are provided in two modes, long cadence (LC) where the measurements of 30 minutes are co-added to one value and short cadence (SC) with only 1 minute in between the observations. The Nyquist frequency for LC is at $\sim 24 \text{ cd}^{-1}$ whereas for SC at 694 cd^{-1} . Therefore only the latter can be used for the present work. The data are delivered in quarters which consists of 3 month each (except Q0 and Q1).

Even if the satellite was originally designed for the search of terrestrial planets, the link to asteroseismology is rather obvious since the same observing precision is required. Furthermore asteroseismology of solar-like stars can provide precise basic stellar parameters of planet-hosting stars (e.g., Gilliland et al. 2010b). The asteroseismic part of the mission is the KAI (Kepler Asteroseismic Investigation) which delivers the observed data through the KASOC (Kepler Asteroseismic Science Operations Center), a data base designed to manage the investigations. The KASC (Kepler Asteroseismic Science Consortium: <http://astro.phys.au.dk/KASC/>) is a collaboration of many international investigators making use of the observations and are supposed to complement the KAI.

Prior to the mission the stellar population in the FOV¹ was characterized and compiled into the Kepler Input Catalogue (KIC), as described by Batalha et al. (2010). Based on colour photometry similar to the Sloan Survey basic stellar parameters such as temperatures, $\log g$ values, masses and radii were derived. Even if the error bars are rather large in certain cases it gives at least a good starting point to attribute a star to a group of pulsating stars.

During the past years many outstanding results based on Kepler data of pulsating stars were published. Grigahcène et al. (2010) summarized some early results on δ Sct and γ Dor hybrids, showing that hybridity in these type of stars is more a common characteristic rather than an exception. Balona et al. (2010) have shown that pulsating Am stars can be found all over the δ Sct instability strip, although present theory suggests that these stars should pulsate only in a very restricted area

¹Field of View

of the instability strip (Turcotte et al. 2000). Uytterhoeven et al. (2011) have performed a comprehensive study of A and F type stars suggesting that δ Sct/ γ Dor hybrids are not restricted in a certain part of the instability strip as expected. Chaplin et al. (2010) showed the possibility of doing 'ensemble asteroseismology' of solar-type stars also allowing a characterization of the stellar population. Bedding et al. (2011) reported the detection of g-modes in red giants allowing for the first time to distinguish between pre and post He flash stars by measuring the period spacings of $\ell = 1$ mixed modes. Huber et al. (2011) demonstrated that the scaling relations for, e.g., amplitudes and mode lifetimes published so far needed to be revisited and nicely illustrated how the pulsation amplitudes change with evolution. The latter was not new but the large amount of homogeneous data allowed to derive new scaling relations. That was just to name some examples.

If there is any possibility of observing stochastically excited pulsation in δ Sct stars photometrically, it is only with Kepler. For the present work all stars observed (over 1000) during Q0 and Q4 with T_{eff} values between 6200 and 8000 K were analysed. First the constant stars were pre-selected and then the remaining variable stars were inspected by eye, one by one.

Following the scaling relation to predict the frequency of maximum power from Kjeldsen & Bedding (1995), the values were calculated for all δ Sct, or to be more specific the range of maximum power, since the error bars of the fundamental parameters are huge. This was done to give an idea in which part of the frequency spectrum (e.g. $\leq$ or $\geq 100 \text{ cd}^{-1}$) the stochastic pulsation is expected.

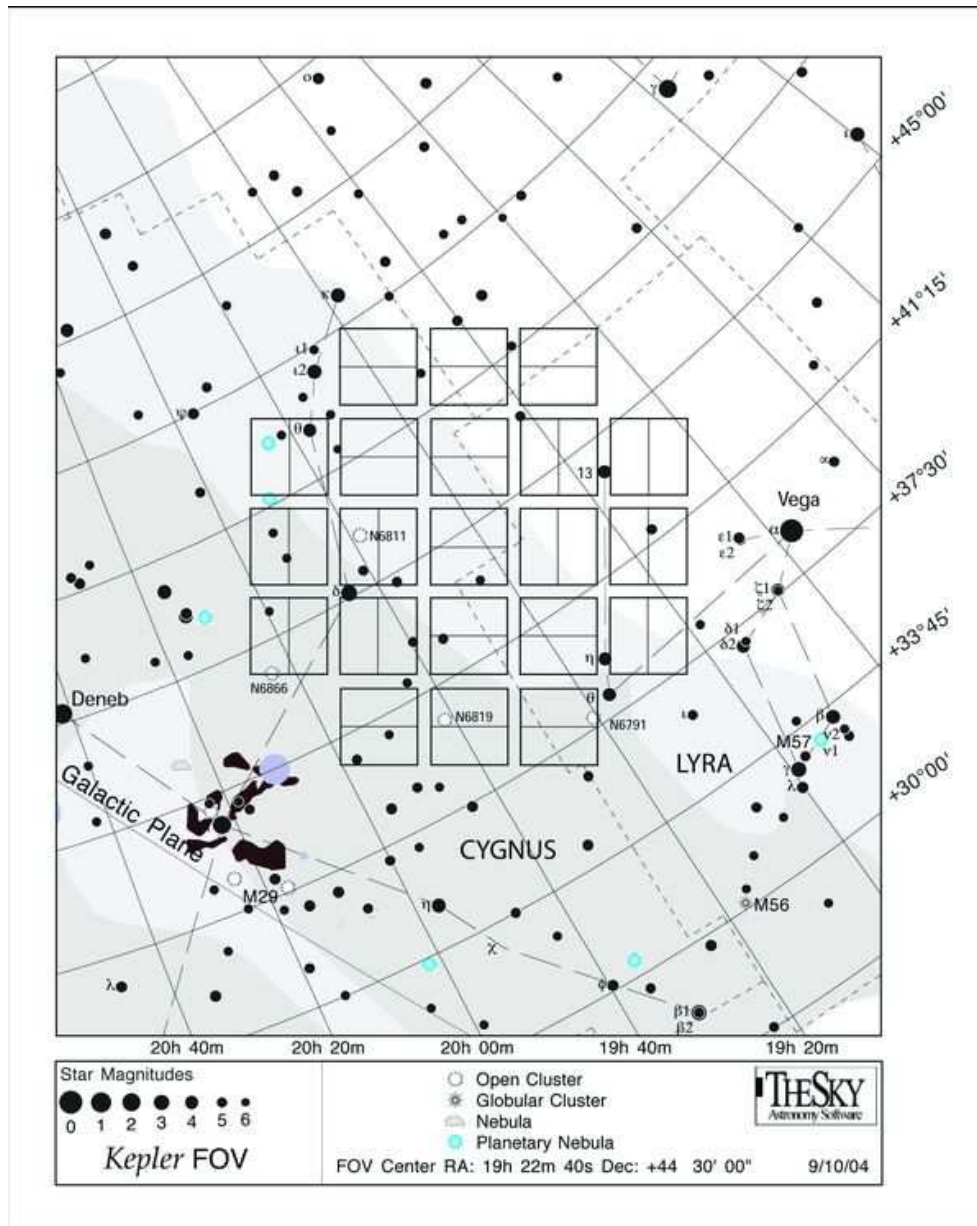


Figure 5.1: The Kepler FOV star chart covering around 100 square degrees of the sky. The rectangles represent the 42 CCDs, summing up to 92 megapixel. Credit: Software Bisque.

5.1 Nature publication on HD 187547

In this chapter we present the analyses and results of HD 187547, one of the Kepler δ Sct stars, which were recently published in Nature. The article reports the findings of the predicted solar-like pulsations, demonstrating that the outer convective layers in a chemically peculiar Am star are effective enough to stochastically excite modes. Due to copyright issues we must not reproduce the Nature edited version, but the one which was published on the astro.ph archive. The paper was accepted on July 16, 2011 and was published online September 14, 2011. Finally it was printed in the issue from September 29th, 2011: Nature, 477, p. 570 - 573, with doi:10.1038/nature10389. The contribution of each author can be found at the end of the article in section 5.1, as it is mandatory information to accompany the publication. Figure 5.2 was part of the press release text.

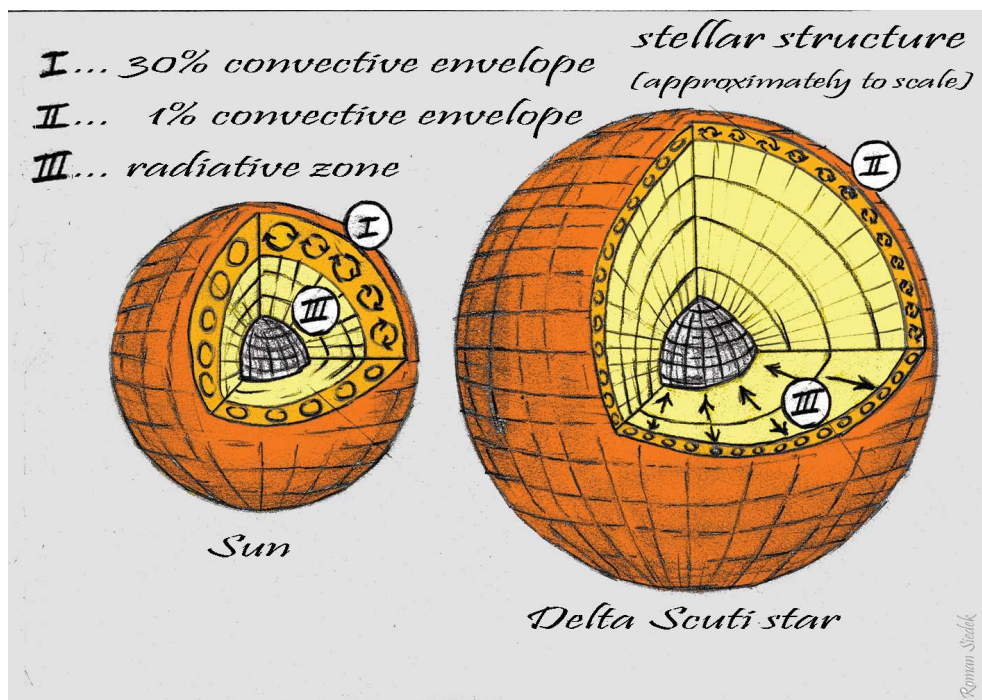


Figure 5.2: Press release figure, comparing the inner structure of the Sun with that of a δ Sct star. Credit: Roman Siedek, Victoria Antoci.

Solar-like oscillations in a Delta Scuti star excited by an efficient convective envelope

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Abstract: Delta Scuti (δ Sct)¹ stars are opacity-driven pulsators with masses of 1.5-2.5 times solar with their pulsations resulting from the varying ionization of helium. In less massive stars² like the Sun, convection transports mass and energy through the outer 30 per cent of the star and excites a rich spectrum of resonant acoustic modes. Based on the solar example, with no firm theoretical basis, models predict that the convective envelope in δ Sct stars extends only about one per cent of the radius³, but with sufficient energy to excite solar-like oscillations^{4,5}. This was not observed before the Kepler mission⁶, so the presence of a convective envelope in the models has been questioned. Here we report the detection of solar-like oscillations in the δ Sct star HD 187547, implying that surface convection operates efficiently in stars about twice as massive as the Sun, as the ad hoc models predicted.

Thirty days of continuous observations of HD 187547 (KIC 7548479) by the *Kepler* mission⁶ with a cadence of one minute led to its identification as a δ Sct pulsator (Fig. 1a, b). In contrast to the non-uniformly distributed signals at low frequencies the observed regularly spaced peaks at high frequencies (Fig. 1c) suggest that we also observe high-radial overtones as expected for stochastically excited solar-like oscillations. For such oscillations the observed comb-like frequency structure (with the large frequency separation $\Delta\nu$ indicating the frequency separation between consecutive radial overtones of like degree) is the result of mainly radial and dipolar pulsation modes, whereas for δ Sct stars it is not clear which modes are excited to observable amplitudes. The strikingly broadened structures observed only at high frequencies (Fig. 1f, Fig. 2b, c) suggest that each are either due to single damped and stochastically re-excited oscillations, or very close unresolved frequencies of coherent oscillations.

Based on spectroscopic observations we derive an effective temperature $T_{\text{eff}} = 7500 \pm 250$ K, a surface gravity of $\log g = 3.90 \pm 0.25$ dex [cgs], and a projected rotational velocity of $v \sin i = 10.3 \pm 2.3$ km s⁻¹ (see Supplementary Information for details). We identify HD 187547 as an Am star from chemical element abundance analysis, consistent with the observed low $v \sin i$ typical for these stars. Am stars are stars of spectral type A showing atmospheric under-abundance when compared to the Sun in the chemical elements Sc, Ca and overabundance of Ba, Sr and Y⁷. We compute a photospheric metallicity (all elements but H and He) of $Z = 0.017$ which is larger than the solar value of $Z = 0.0134$ ⁸.

About two-thirds of Am stars are primary components of spectroscopic binary systems⁹. The Am phenomenon is connected to slow rotation, not common in A type stars. Binarity is believed to act as a braking mechanism slowing down the rotation and allowing spectral peculiarities to occur due to element diffusion¹⁰. Pulsating Am stars still represent a challenge to theory, as He is expected to gravitationally settle and should only partially be present in the HeII ionization zone where the δ Sct pulsations are excited. In other words theoretical models predict that the hottest and youngest A-type stars should not pulsate¹⁰, which is in contradiction

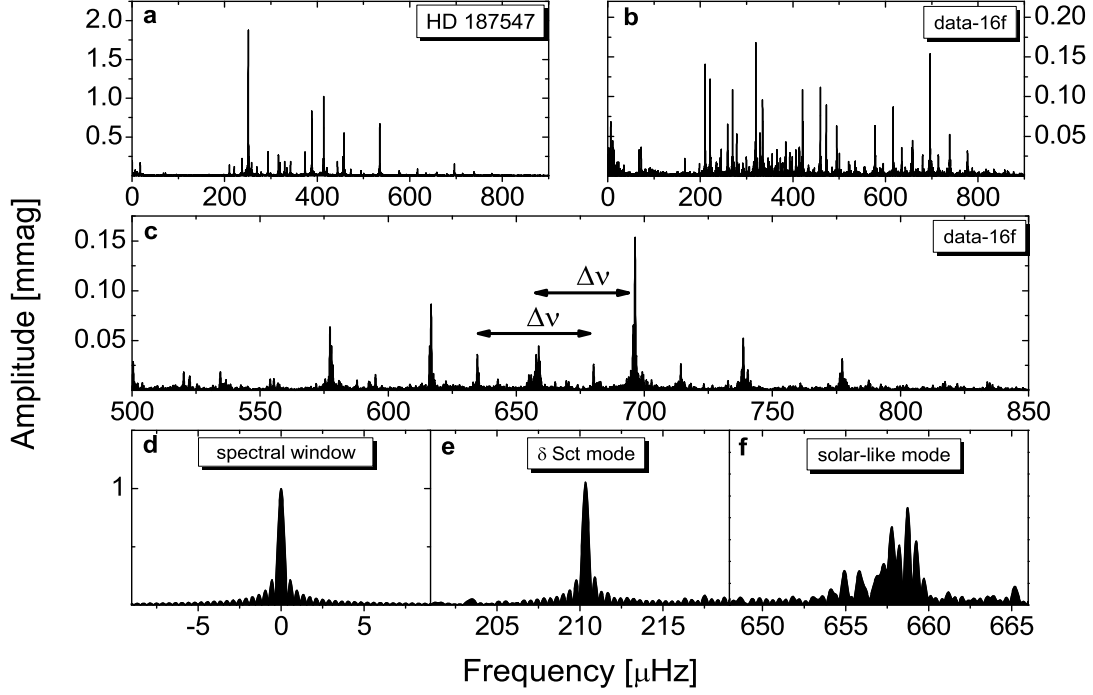


Figure 1: **Fourier amplitude spectra of the *Kepler* light curve of HD 187547.**

a, Fourier spectrum covering the entire frequency range in which significant signals were observed with a dominant frequency at 251 μHz and an amplitude of 2 mmag, typical for a δ Sct star. **b**, The multi-mode oscillations of HD 187547 are shown by subtracting 16 sinusoids corresponding to the most prominent oscillations, revealing a large number of additional significant frequencies. **c** The region between 500 and 870 μHz shows a clear pattern of roughly equally spaced peaks, which we interpret as high-order consecutive radial overtones. The comb-like structure expected for high-order radial overtones is clearly visible. The broadened peaks suggest damped/re-excited solar-like oscillations. The black arrows denoted by $\Delta\nu$ indicate the large separation between consecutive radial and dipole modes. **d**, Spectral window. The shape of the window function is defined by the length and sampling of the data set. Any coherent signal will have the same profile. **e**, Example for one of the modes driven by the opacity mechanism in HD 187547. **f**, A supposed solar-like oscillation mode observed in HD 187547, displaying a broadened structure suggestive of a short mode lifetime.

with recent observations¹¹. As the stars evolve their convective envelopes deepen and efficiently mix the stellar matter erasing the observed chemical peculiarities in the atmospheres, allowing the opacity-mechanism to drive pulsation in the HeII

ionisation zone. Using the observed solar-like oscillations reported here, the depth of the convective envelope can be derived (hence the mixing length), probing the diffusion of He and heavy elements in this star. This will contribute significantly to revise the interaction between pulsation and diffusion in models of Am stars.

Seven radial velocity measurements of HD 187547, spread over 153 days, give no evidence for a short-period binary system. In addition, the absence of any detectable contribution by a potential close companion to the spectrum implies a considerably less luminous star of spectral type G or later. The expected amplitudes and frequency of maximum oscillation power for such a star are inconsistent with the observations, leading to the conclusion that the signal observed in Fig. 1c cannot originate from a companion. The observed amplitude spectrum of HD 187547 is not affected by a background star because the fraction of light in the aperture from neighbouring stars is only 1.5%. Another type of chemically peculiar pulsating stars situated, as the δ Sct stars, in the classical instability strip in the Hertzsprung- Russell diagram¹² are the rapidly oscillating Ap stars. Their high-radial-order pulsation modes are triggered by the opacity mechanism acting in the hydrogen ionization zone, often showing equidistant multiplets in the frequency spectrum as a result of the alignment of the pulsation axes with strong magnetic fields¹³. The strong magnetic fields as seen in rapidly oscillating Ap stars are however not observed in Am stars¹⁴. We therefore exclude that HD 187547 is a hybrid of a δ Sct and a rapidly oscillating Ap star.

In Fig. 3 we show an échelle diagram which compares the observed frequencies to a model of a star similar to HD 187547, demonstrating again the clear structures separated by $\Delta\nu$ at high frequencies and the non-structured distribution at lower frequencies. For the high-frequency modes we derive a mean large frequency separation, $\Delta\nu$, to be $40.5 \pm 0.6 \mu\text{Hz}$. Using the empirical relation¹⁵ $\Delta\nu = (0.263 \pm 0.009)\mu\text{Hz}(\nu_{\text{max}}/\mu\text{Hz})^{0.772 \pm 0.005}$ we obtain a frequency of maximum power $\nu_{\text{max}} = 682_{-43}^{+41} \mu\text{Hz}$. This is in very good agreement with the highest amplitude mode in the supposed stochastic frequency region at $696 \mu\text{Hz}$. The possibility that what we observe is $0.5\Delta\nu$ in the frequency spectrum is ruled out because this would require a ν_{max} at approximately $1673 \mu\text{Hz}$, where no signal is observed. We can also exclude to observe $2\Delta\nu$ because that would place ν_{max} at $277 \mu\text{Hz}$, close to the dominant opacity-driven mode at $251 \mu\text{Hz}$.

The amplitudes of solar-like oscillations are determined by the interaction between driving and damping defined by different physical processes², such as modulation of the turbulent momentum and heat fluxes by pulsation. The exact contribution to driving/damping by each of these processes is still not well understood, resulting in uncertainties in the predictions of the stochastically excited mode amplitudes¹⁶, particularly in hotter stars^{2,3} in which the convective envelopes are shallow. We expect the mixing length, the amplitudes and mode lifetimes to constrain the anisotropy of the convective velocity field, parameters that all semi-analytical convection models rely on¹⁷.

For HD 187547 we measure a peak-amplitude per radial mode¹⁸ for the assumed

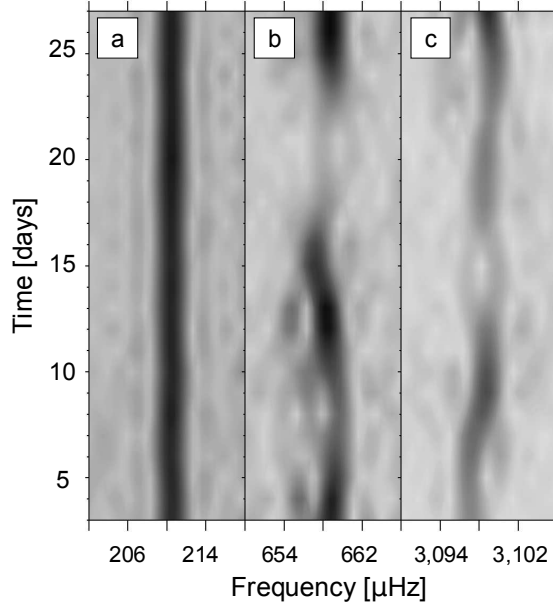


Figure 2: **Time-Fourier spectrum.** Here we highlight again the difference in temporal variability between the modes interpreted as stochastic modes and the coherent, opacity-driven peaks at low frequencies. The time-fourier spectrum was computed with a running filter of $\text{FWHM} = 5$ days, comparable to the mean mode lifetime. **a**, An opacity-driven mode (the same as displayed in Fig. 1e) showing temporal stability in the δ Sct frequency region. **b**, Stochastic mode observed in HD 187547, displaying an erratic behaviour as expected for solar-like oscillations (the same as displayed in Fig. 1f). **c**, For comparison, a stochastic oscillation mode observed in the Sun. The solar data were obtained from the SOHO VIRGO instrument. The data set has the same length and sampling as HD 187547, i.e. 30 days and one minute respectively. Further details of frequency analyses and tests on artificial data sets (Supplementary Fig. 1) to verify our interpretation can be found in the Supplementary Information.

stochastic signal of 56 ± 2 ppm, which after bolometric correction¹⁹ results in 67 ± 3 ppm (see Supplementary Information for details). From the empirical scaling relation²⁰ and using a bolometric solar peak-amplitude of 3.6 ppm²¹ we obtain a predicted peak-amplitude of $A = 14 \pm 9$ ppm. The mean mode lifetimes are measured²² to be 5.7 ± 0.8 days. Empirical relations predict a mode lifetime for a star with $T_{\text{eff}} = 7500 \pm 250\text{K}$ of the order of one day²³ or shorter²⁴, which is not in agreement with what we measure for HD 187547. However these scaling relations (for amplitude and mode lifetimes) are based on few observed stars and none of them are calibrated in the temperature domain of our target where the physical conditions in the convection zone are expected to be very different. Furthermore, given

that HD 187547 is metal over-abundant when compared to the Sun, the observed amplitude is expected to be higher^{3,25} than predicted from simple scaling which is indeed the case. The power of a mode is directly proportional to the mode lifetime provided the energy supply rate over the mode inertia is constant²⁶, which further supports the higher amplitude as the observed mode lifetimes are also longer than expected. An additional factor which is not considered in any scaling relations is the chemical peculiarity of our target. In summary, these factors make HD 187547 an intriguing case for further theoretical analyses of stochastic oscillations and the potential interaction with the opacity mechanism in δ Sct stars.

The amplitude distribution for stochastic pulsation can be described as a Rayleigh distribution, provided the examined time series are much shorter than the mode lifetimes. The relation between the mean amplitude $\langle A \rangle$ and its standard deviation $\sigma(A)$ can then be written as²⁷ $(4/\pi - 1)^{0.5} \langle A \rangle \simeq 0.52 \langle A \rangle$. This is not valid for opacity-driven pulsation. In the case of HD 187547 we therefore expect to obtain two different regimes of the ratio $\sigma(A)/\langle A \rangle$ for the two groups of oscillation modes (Supplementary Fig. 2). Indeed, we see that the δ Sct frequencies have a lower value of $\sigma(A)/\langle A \rangle$ compared to the supposed solar-like modes, giving further evidence for the stochastic nature of the latter (see Supplementary Information for details).

We cannot strictly rule out that the signals between 578 and 868 μHz are due to unresolved modes of pulsation excited by the opacity mechanism, since high-radial-order acoustic modes can also be observed in hot δ Sct stars. Nevertheless, as shown in Fig. 1 this would imply that δ Sct pulsation *continuously* covers the region between 205 and 870 μHz . According to current theory, the opacity mechanism acting in the HeII ionization zone, cannot excite modes spanning 16 radial orders for a star with parameters like those of HD 187547²⁸. Further support for the discovery of solar-like oscillations comes from spectroscopic observations that also indicate the presence of convective motions in the atmospheres of A and Am stars²⁹. Additionally, signatures of granulation noise in δ Sct stars have been reported from photometric measurements³. Opacity-driven pulsations are also observed in more massive stars (8-16 $M_{\odot}$), known as β Cephei stars (in this case the opacity-mechanism acts in the iron-group elements ionization region). The unexpected detection of solar-like oscillations in such a star³⁰ (with a mass of 10 $M_{\odot}$), suggests that both types of pulsations, opacity-driven and stochastically excited, can coexist and can have overlapping frequency domains. The similar time scales of the different oscillation types imply a possible interaction between the two mechanisms.

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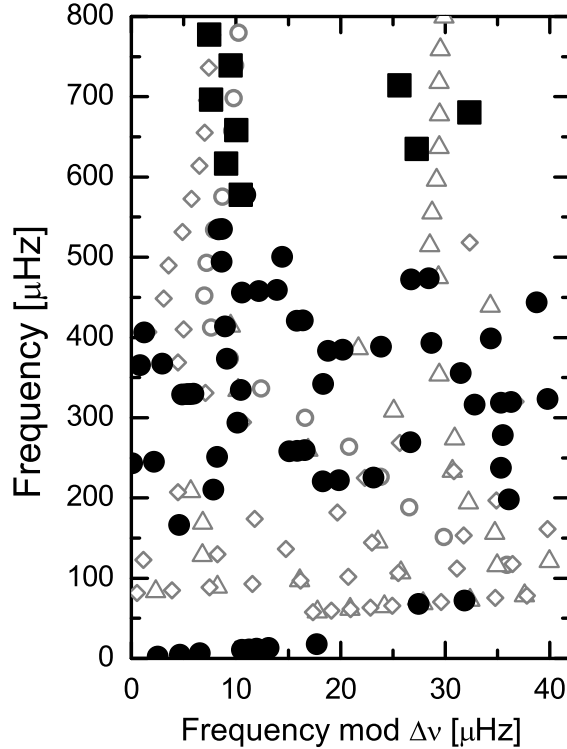


Figure 3: **Échelle diagram of HD 187547.** Here we plot 69 extracted frequencies as a function of frequency modulo the large separation ($\Delta\nu = 40.5 \mu\text{Hz}$). Frequencies equally spaced by $\Delta\nu$ will form vertical ridges in the échelle diagram. To guide the eye, we show theoretically predicted frequencies of pulsation modes for a $1.85 M_{\odot}$ stellar model. Ridges of $l = 0$ modes are represented by open circles, $l = 1$ by open triangles and $l = 2$ by open diamonds. Note that detailed modeling of the star is beyond the scope of this paper. The supposed solar-like modes (filled squares) between 500 and $870 \mu\text{Hz}$ exhibit clear ridges as expected for high-order acoustic oscillations similar to what is observed in solar-like stars. The lower frequencies that we attribute to δ Sct pulsation (black filled circles) excited by the opacity mechanism show no obvious regular patterns.

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Supplementary Information is linked to the online version of the paper at www.nature.com/nature.

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Author contribution

V.A. discovered the star among the *Kepler* targets, analysed it and found the solar-like oscillations (as a part of her PhD thesis), did spectroscopic analyses, frequency analyses, the test on the stochastic nature of the signal, interpretations and wrote the paper. G.H. had the idea for this project and supervised V.A., helped with analyses, interpretations and writing the paper. T.L.C. contributed to the analyses of the stochastic modes and also to the test on the stochastic nature of the signal. A.O.T. observed the target spectroscopically at NOT, identified the star as an Am star and did spectroscopic analyses. A.M. contributed to the statistical test on the nature of the stochastic signal. T.K. helped interpretations, data analyses, writing the paper and delivered the mode lifetimes. D.S. helped with data analyses, writing the paper and did Fig. 2. A.G. helped with theoretical interpretations and the

time-fourier analyses. T.B. helped with interpretations and writing the paper. H.K. contributed to the analyses, also by supervising V.A. and is member of the KAI Steering Committee (Kepler Asteroseismic Investigation Steering Committee). J.C-D. helped with the theoretical support, writing the paper and is member of the KAI Steering Committee (Kepler Asteroseismic Investigation Steering Committee). T.L. confirmed the Am identification, excluding the Ap character of the star. G.C., A.F., and A.K. did spectroscopic analyses. P.DC. was PI and observer for the spectroscopic data from McDonald observatory. K.U. was CoI of the McDonald data and was coordinating the ground-based observations. H.B. was PI for the NARVAL spectrum and did spectroscopic analyses. G.Ho. and P.L. helped with theoretical interpretations and writing the paper. D.W.K. helped with the Am classification, writing the paper and is leader of the delta Scuti working group of the KASC (Kepler Asteroseismic Science Consortium). J.VC., C.A. and B.D.C. are part of the Kepler team and were involved in designing and operating the satellite. All co-authors contributed to discussions and commented on the manuscript.

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Supplementary Information

Observations

The *Kepler* satellite gathered 30 days of uninterrupted data for HD 187547 (KIC 7548479) between October 19 and November 18, 2009, corresponding to *Kepler*'s observing quarter 3, month 2 (Q3.2). We use the short cadence (roughly 1 minute) 'raw' pipeline-reduced data³¹. To determine the star's effective temperature (T_{eff}) and surface gravity ($\log g$) follow-up ground-based observations were performed. We have obtained one spectrum in June 2010 with the Sandiford Cass Échelle Spectrometer attached to the 2.1 m telescope at McDonald Observatory in Texas with a resolution of $R = 60000$. A second spectrum was measured in July 2010 with the NARVAL spectrograph at the Telescope Bernard Lyot (TBL) atop Pic du Midi in France with a resolution of $R = 81000$. An additional five spectra spread over the months October to December, 2010, were obtained with the FIES spectrograph at the Nordic Optical Telescope (NOT) with a resolution of $R = 67000$. Colour information ($uvby\beta$) was gathered with the 2.1 m telescope at McDonald Observatory in Texas.

The T_{eff} and $\log g$ values of HD 187547 were determined using the method of spectral synthesis. LTE atmospheric models were calculated with ATLAS9³² and synthetic spectra by using SYNTHE³³. We also used the VWA code^{34,35} and the ROTFIT code³⁶. In addition, the LLMODELS code³⁷ was applied, synthetic spectra based on these models were calculated with synth3³⁸ and atomic parameters used for spectrum synthesis were extracted from the VALD database³⁹. Average surface elemental abundances were determined from equivalent width measurements and an adapted version of the WIDTH9 code⁴⁰.

Data analyses

Modes excited by the opacity mechanism are expected to have temporally stable oscillations, whereas stochastically excited modes have short lifetimes of the order of days²³. Therefore, in the frequency spectrum, one would expect narrow peaks for δ Sct type pulsation, but broadened peaks for solar-like pulsation. Frequency analyses carried out on artificial data sets (Fig. S1), injected with both types of pulsation, demonstrate that non-coherent signals, which simulate the stochastic pulsation, are still recoverable after subtracting the coherent signal corresponding to the δ Sct type pulsation.

Non-sinusoidal light curves, often observed in δ Sct stars, generate peaks in the Fourier spectrum at combination frequencies with values of $nf_i \pm mf_j$, $nf_i \pm mf_j \pm pf_k$, $nf_i \pm mf_j \pm pf_k \pm \dots$, etc, where m, n, p are integer numbers and f_i, f_j, f_k are frequency values. If the pulsation spectrum is dense and the time resolution is poor, it is very difficult to distinguish clearly between independent modes and combina-

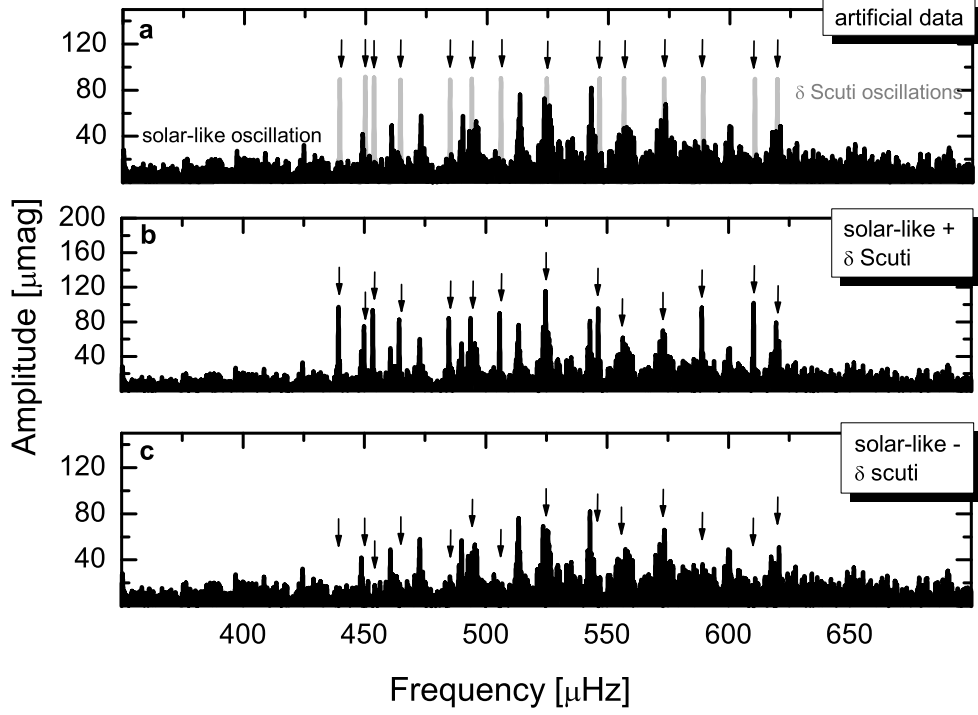


Figure S1: **Testing the coexistence of coherent and non-coherent signals.**

a, The black curve illustrates the Fourier spectrum of artificial data simulating stochastic pulsation, whereas the grey curve depicts the artificial δ Sct oscillations. Note that the non-stochastic signal was injected to be exactly on top of the Lorentzian profiles and in-between. **b**, Fourier spectrum of the combined stochastic and non-stochastic data, the latter is identified by the black arrows. **c**, Residual spectrum after removing the δ Sct pulsation, demonstrating that the stochastic signal, simulating solar-like oscillations survives almost unaffected. The black arrows again identify the frequency values of the subtracted coherent signal.

tion frequencies, also considering accidental matches. Frequency analyses, using Period04⁴¹, showed that considering the 16 strongest δ Sct pulsation modes two out of nine supposed stochastic signals have similar values within the time resolution to second order combination frequencies. Even if these peaks are removed there is still significant signal left due to the broad shapes in the Fourier spectrum. Furthermore, from probability calculations it can be shown that at least one out of the nine derived supposed stochastic signals should be accidentally fit by a second-order combination frequency taking into account 16 parent modes. The four strongest supposed stochastic modes cannot be fit by second-order combinations. The amplitudes for third-order combination frequencies are expected to be lower than for second-order, which makes it very unlikely that third-order combinations cause such strong peaks in the Fourier spectrum. We therefore conclude that the supposed stochastic signals are very likely due to independent modes and are not the result of a non-sinusoidal shape of the light curve.

The amplitude per radial mode was calculated by convolving the power density spectrum ($\text{ppm}^2/\mu\text{Hz}$) with a Gaussian (FWHM of $4\Delta\nu$) minus the noise and then multiplied by $\Delta\nu$ divided by spatial response function¹⁹. Finally we then take the square root¹⁸ to convert to peak-amplitude. Using a new scaling relation²⁰ with a peak-scaled bolometric solar amplitude²¹ of 3.6 ppm ($= 2.55\sqrt{2}$) and the following parameters: $L/L_\odot = 18 \pm 11$, mass $= 1.85 \pm 0.25 M_\odot$, mode lifetime $= 5.8 \pm 0.8$ [d], $T_{\text{eff}} = 7500 \pm 250\text{K}$, $r = 1.5$, we obtain a peak-amplitude of $A = 14 \pm 9$ ppm. For the bolometric correction¹⁹ we compute a correction factor of $ck = 1.2$ for $T_{\text{eff}} = 7500$ K which is then multiplied with the observed amplitude resulting in 67 ± 3 ppm.

Testing statistical properties of stochastic signals

To prove the properties of the supposed solar-like oscillations of HD 187547 we applied a statistical test^{42,43}. For that we subdivided the light curve into 30 segments, each of a length of 24 hours, for which the amplitudes for several peaks were derived. The short subsets have a poor resolution and a higher noise level. Beating effects of close unresolved frequencies of δ Sct type can, in some cases, result in high values of the ratio $\sigma(A)/\langle A \rangle$, leading to a wrong conclusion about the nature of the signal. To minimize these effects we therefore removed the signal within a range of $11.57 \mu\text{Hz}$ (i.e. the resolution in a 1- day segment) of the frequency of interest before computing the amplitudes. If there are two different types of pulsation with long and short mode lifetimes, respectively, we would expect to obtain two different values of the ratio $\sigma(A)/\langle A \rangle$. As illustrated in Fig. S2a, this is indeed the case when comparing the supposed stochastic with the high amplitude δ Sct frequencies (filled circles), with mean ratio values of 0.38 ± 0.09 and 0.13 ± 0.12 respectively. The cut-off value to discriminate between high and small amplitudes is $160 \mu\text{mag}$, defined by the height of the main ‘stochastic’ mode at $696 \mu\text{Hz}$. However, the distinction is less clear when we compare with the low amplitude δ Sct modes (empty circles), which is probably

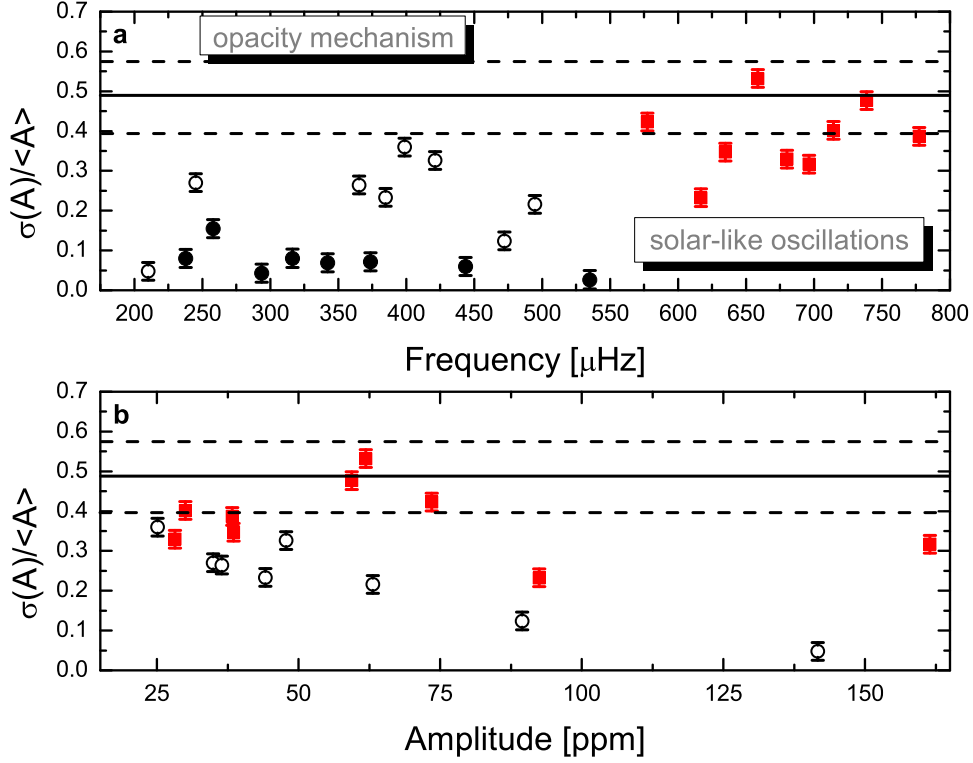


Figure S2: **Testing the statistical properties of the pulsation modes.** **a**, The ratio $\sigma(A)/\langle A \rangle$ as a function of frequency. The red filled squares symbolize the supposed stochastic modes whereas the black circles show the δ Sct frequencies. The filled circles represent the δ Sct frequencies with high amplitudes whereas the empty circles the lower amplitude δ Sct frequencies. It can clearly be seen that the group of peaks in the δ Sct regime are lower than the supposed stochastic oscillations. The solid line at 0.48 is the average value for a stochastic signal derived from 50,000 simulations, and the dashed lines indicates their rms scatter. The error bars are s.e.m. **b**, $\sigma(A)/\langle A \rangle$ as a function of amplitude for the supposed stochastic signal and the low amplitude δ Sct modes.

due to the larger impact of noise on the low amplitude values (mean ratio is 0.27 ± 0.11). Fig. S2b shows $\sigma(A)/\langle A \rangle$ as a function of amplitude illustrating that for δ Sct modes the higher the amplitude gets the lower the ratio is. The same effect is not observed for the supposed stochastic frequencies. The majority of the solar-like modes can be found within 1σ around the expected value for a stochastic signal. From simulations of 50,000 Monte-Carlo non-coherent light curves with the same length and mode lifetimes as observed for HD 187547 we get a value of $\sigma(A)/\langle A \rangle = 0.48^{+0.07}_{-0.09}$ (black solid line in Fig. S2, the dashed lines represent the 1σ error bar). Related simulations were performed to test the impact of high noise on the $\sigma(A)/\langle A \rangle$ assuming a coherent signal. Consistent with Fig. S2b, the ratio is increasing with

increasing noise, hence with decreasing amplitude, but does not reach the same mean $\sigma(A)/\langle A \rangle$ value as expected for stochastic oscillations. As an example, a mean signal-to-noise of 3.8 in each segment results in a value of $\sigma(A)/\langle A \rangle = 0.19 \pm 0.02$, demonstrating the robustness of this statistical test. The fact that the δ Sct frequencies as an entire group have a lower ratio of $\sigma(A)/\langle A \rangle$ compared to the supposed solar-like modes provides further evidence for the stochastic nature of the latter.

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6 Conclusions & Discussion

The aim of this project was to search for solar-like oscillations, which have been predicted to be excited in δ Scuti stars by Houdek (1999) and Samadi et al. (2002). A positive or a significant null result would tell us more about the convective outer layers of these stars, which occupy the region of the HRD, where the transition from deep and effective to shallow convective envelopes takes place. How exactly this happens is not well understood, but has an important impact on stellar evolution models. Fast rotation, for example, common in δ Sct stars combined with differential rotation are suggested to influence the depth of the convective outer layers such that solar-like oscillations might be excited in stars in which otherwise the convection would not be effective enough (MacGregor et al. 2007). On the other hand theoretical modelling of the stars FG Vir (Daszyńska-Daszkiewicz et al. 2005) and 44 Tau (Lenz et al. 2010) suggest insignificant convection in their envelopes. Carrier et al. (2007) have searched for solar-like oscillations in the spectroscopic binary Am HD 209625 star (which is not classified as a δ Sct star), but did not detect any. It is true that all sun-like stars observed with sufficient accuracy show solar-like oscillations but should all the δ Sct stars behave alike? Sun-like stars are, compared to more massive stars like the δ Sct stars, more homogeneous when it comes to rotation for example. The stars located in the instability strip have rotational velocities from very slow (44 Tau has a projected rotational velocity, $v \sin i = 2 \pm 1 \text{ kms}^{-1}$, Zima et al. 2009) to almost break-up velocity (Altair, e.g. Monier et al. 2007). In the case of Altair the difference in temperature between the pole and the equator is more than 1500K (!). This is not only to show the diversity of δ Sct stars, but more importantly to emphasize the *inhomogeneity* which may cast some doubts on whether *all* δ Sct stars with a given temperature and luminosity should show solar-like oscillations.

The star ρ Puppis was the first target to be searched for stochastic oscillations. There were several reasons to select this object: (1) the star is very bright and therefore the exposure times can be kept very short (between 45 and 120 seconds) to ensure a good sampling of the pulsation cycle; (2) ρ Puppis is located at the red border of the classical instability strip where the outer convective envelope should be deeper than in hotter stars; (3) it is overabundant in metals and therefore has more absorption lines containing the needed radial velocity information; (4) the dominant mode was known to be the radial fundamental mode; (5) the amplitudes of solar-like oscillations are expected to be higher with higher metallicity (e.g. Samadi et al. 2007). A photometric multi-colour and multi-site campaign revealed 10 independent modes of pulsation with a possible 11th one. The mode identification was

nevertheless possible only for the dominant mode, confirming the radial nature. The basic parameters measured for ρ Puppis are precise (e.g. interferometric radius to a precision of only 2 %, Ireland, priv. comm.) and constrain the models significantly.

With more than two thousand spectra obtained at four different observatories and with different techniques we obtained a noise level in the Fourier spectrum of 0.4 ms^{-1} , the best RV data set ever obtained for a δ Sct star. Based on that, we can exclude the presence of solar-like oscillations in ρ Puppis with amplitudes higher than 1 ms^{-1} , when using a significance criterion as used for stochastic signals, i.e. $S/N = 2.5$ (Kjeldsen & Bedding, 1995). If the significance criterion for classical pulsators of $S/N = 4$ is applied, solar-like oscillations with amplitudes higher than 1.6 ms^{-1} can be excluded. We conclude that ρ Puppis does not show solar-like oscillations at the predicted frequency of maximum power at $\sim 37 \text{ cd}^{-1}$.

The NASA Kepler satellite observed hundreds of δ Scuti stars at a precision where solar-like oscillations, if present, should be detected. One of these observed stars was HD 187547 (Antoci et al. 2011), at first glance a typical δ Sct star. At high frequencies, we detected modes approximately equidistantly spaced, as expected for high radial order p-modes, which are not combination frequencies. The κ mechanism cannot excite a continuous frequency region as observed in HD 187547 ($18\text{--}70 \text{ cd}^{-1}$). The identification as an Am star consistent with the low $v \sin i$, makes it very unlikely to be a hybrid between a δ Sct star and a roAp star, because large-scale magnetic fields, a necessity for roAp pulsators, have never been detected in Am stars. Spectroscopic observations also exclude that the peaks at high frequencies originate from a possible companion, because such a star would be an A or F-type star and would be visible in the spectrum but it is not. The measured large separation $\Delta\nu$ predicts ν_{max} to be exactly where the mode with the highest amplitude in the supposed stochastic region is detected. The statistical properties of the supposed solar-like modes in HD 187547 are very similar to what is expected for stochastic signals. The measured amplitude per radial mode is $67 \pm 3 \text{ ppm}$ and the mean mode lifetimes are $5.8 \pm 0.8 \text{ days}$. From predictions the amplitude as the mode lifetimes are expected to be ~ 4 times lower. This is not a problem because the empirical relations as well as theoretical calculations were done for a different temperature regime. Also the peculiar nature of HD 187547 was never considered. We therefore conclude that HD 187547 presents the first observational evidence for the existence of hybrid oscillators exhibiting δ Sct and stochastically driven pulsation simultaneously. This interpretation is supported by the striking similarities between the observed signal at high frequencies and the properties of stochastically excited pulsation.

To summarize, ρ Puppis very likely does not show solar-like oscillations, but HD 187547 does. This is not easy to understand and will certainly need further investigation. Interestingly, the star showing solar-like oscillations is an Am star, which are believed to be the progenitors of ρ Puppis stars. In other words, we have the same type of star but in different evolutionary stages. The Am phenomenon is related to slow rotation leading to diffusion of heavy elements but also of He. So far, it is not understood why some of the observed Am stars do pulsate at

all. The observed element abundance pattern of Am stars is probably erased by convection as it evolves, which in fact should excite solar-like oscillations. The height of amplitudes of solar-like oscillations is determined by the interaction of damping and excitation, but the extent to which physical process such as the modulation of turbulent momentum and heat fluxes by pulsation contribute is still under debate (Houdek 2009). Maybe during the evolution of an Am star this interaction changes leading to damping of the solar-like oscillations.

The smooth transition between δ Sct pulsation and the solar-like oscillations in HD 187547 suggests an interaction between these two types of excitation mechanisms because the time-scales are very similar. So far there is no theoretical work to investigate to which extent and how the κ mechanism may influence the acoustic oscillations driven by the turbulent motion of convection, but the fact that even in the Sun the κ mechanism plays a role (Houdek, priv. comm.), even if minor, shows the necessity to consider this. Maybe solar-like oscillations are only excited in δ Sct stars where the two regions overlap, because the convection might not be effective enough to excite these pulsations alone but gets additional power from the κ mechanism which acts at similar time scales. At the moment this hypothesis is purely speculative but it needs to be tested, both from theoretical point of view but also observationally. The discovery of HD 187547 is a first step, but one star alone is not enough to validate a theory. Future work will be to go back to the beginning and search again every single Kepler δ Sct star for solar-like oscillations. Both stars, HD 187547 and ρ Puppis, need to be modelled also taking into account diffusion theory. Meanwhile several months of data observed by the Kepler satellite are available for HD 187547; analyzing those is going to be the very next step.

7 Abstract

The present work is based on theoretical predictions (Houdek et al. 1999, Samadi et al. 2002) stating that the outer convective envelopes of δ Sct stars are still effective enough to excite solar-like oscillations. To search for these oscillations we have organized a photometric and spectroscopic multisite campaign, including ground-based as well as observations from space for the δ Sct star ρ Puppis. This star is eponymous for the metal-rich δ Sct stars and its dominant mode is the radial fundamental mode. From photometry we have derived 10, possibly 11 frequencies which we attribute to independent radial and nonradial modes of pulsation. To search for solar-like oscillations high-precision, high-resolution spectroscopic measurements from four different observatories were gathered. Two data sets were obtained through an iodine cell, an observing technique used to detect planets and to observe the variability of sun-like stars. Combining all the radial velocity data we reach a noise level of 0.4 ms^{-1} in the amplitude spectrum. We can exclude to observe solar-like oscillations in ρ Puppis with an amplitude higher than 1 ms^{-1} at the predicted frequency of maximum power, if we use the significance criterion of $S/N = 2.5$ as described by Kjeldsen & Bedding (1995). The predicted amplitudes for ρ Puppis were between 1 and 2 ms^{-1} depending on the approach used.

The second part of this project presents the results of the Kepler δ Sct star HD 187547, recently published in Nature (Antoci et al. 2011). Additional to the typical δ Sct pulsation, this star shows equidistantly spaced peaks at high frequencies, which we interpret as solar-like oscillations. We find the spacing between the peaks at high frequencies to be consistent with the expected large frequency separation $\Delta\nu$. We can exclude that these peaks are the result of combination frequencies or that they originate from a possible companion. The shape of the peaks attributed to stochastically excited modes are broadened, indicating either short mode lifetimes or very close unresolved frequencies. The scaling relation from Stello et al. (2009) predicts the frequency of maximum power ν_{max} to be at the value where we observe the mode with the highest amplitude within the assumed stochastic frequency region. The observed amplitudes and mode lifetimes are higher than predicted but within the expected order of magnitude. The statistical behaviour of the solar-like modes is compatible with what is expected for a damped and re-excited stochastic signal. The κ mechanism in δ Sct stars cannot excite the entire frequency range observed in HD 187547. We conclude that the most plausible explanation for what we observe in HD 187547 is the presence of solar-like oscillations as expected from theory.

To summarize, we have a positive detection of solar-like oscillations in HD 187547,

but based on the present data a null result for ρ Puppis. We have made the first step, but to validate a theory more than one positive result is needed. We plan to address this question in the very near future.

8 Zusammenfassung

Das Ziel dieser Dissertation war es, sonnenähnliche Oszillationen in δ Sct Sternen zu finden, basierend auf theoretische Vorhersagen von Houdek et al. (1999) und Samadi et al. (2002). Dafür wurde für den δ Sct Stern ρ Puppis eine photometrische und spektroskopische Beobachtungskampagne organisiert. Dieser Stern ist namensgebend für eine Untergruppe der δ Sct Sterne, die eine hohe Metallizität aufweisen. Die photometrischen Messungen, sowohl bodengebunden als auch von MOST-Satelliten, haben 10 signifikante Frequenzen mit einer möglichen elften hervorgebracht, die eindeutig das Resultat radialer und nichtradialer Pulsationen sind. Um aber nach sonnenähnlichen Pulsationen zu suchen, haben wir hochaufgelöste Zeitserienspektroskopie von vier verschiedenen Observatorien verwendet. Zwei dieser Datensätze wurden durch eine Jodzelle gewonnen, eine Beobachtungstechnik die sehr genaue Daten liefert und Standard ist für die Suche nach Planeten und Variationen in sonnenähnlichen Sternen. Durch das Kombinieren aller Radialgeschwindigkeitsmessungen konnte ein Rauschniveau von 0.4 ms^{-1} im Amplitudenspektrum erreicht werden. Das ist genug um sonnenähnliche Pulsationen mit einer Amplitude von 1 ms^{-1} auszuschließen, wenn ein Signifikanzkriterium von $S/N = 2.5$ (Kjeldsen & Bedding 1995) angenommen wird. Die Amplituden für ρ Puppis wurden, abhängig vom verwendeten Ansatz, zwischen 1 und 2 ms^{-1} vorhergesagt.

Der zweite Teil dieser Arbeit besteht aus der Analyse des Kepler δ Sct Sterns HD 187547. Ein Artikel dazu wurde vor kurzem in der Fachzeitschrift Nature publiziert (Antoci et al. 2011). HD 187547 weist zusätzlich zu den für einen δ Sct Stern typischen Pulsationen, Signale im hochfrequenten Bereich auf, die von uns als sonnenähnliche Oszillationen interpretiert wurden. Der Frequenzunterschied zwischen den Moden in diesem Bereich ist genau der Wert der für die sogenannte ‘large frequency separation’ $\Delta\nu$ erwartet wird. Es wird einerseits ausgeschlossen, dass diese Signale das Resultat von Kombinationsfrequenzen sind und andererseits, dass sie von einem möglichen Begleiter stammen. Die verbreiterten Signale im Fourierspektrum lassen entweder auf kurze Lebensdauer oder auf nichtaufgelöste Peaks schließen. Die Skalierung von Stello et al. (2009) um die ‘frequency of maximum power’ ν_{max} auszurechnen, liefert einen Wert der gut mit der Frequenz der beobachteten Mode mit der höchsten Amplitude übereinstimmt. Auch wenn die beobachteten Amplituden und die Lebenszeit dieser Moden höher bzw. kürzer als angenommen sind, stimmt die Größenordnung in etwa. Die statistischen Eigenschaften der sonnenähnlichen Pulsationen stimmt mit dem Charakteristika von gedämpften und wieder angeregten stochastischen Signale überein. Da der κ Mechanismus nicht im Stande ist Pulsationsmoden über einen so großen Frequenzbereich anzuregen, schließen wir

daraus, dass der δ Sct Stern HD 187547 sonnenähnliche Oszillationen aufweist.

Zusammenfassend können wir sagen, dass wir eine Detektion und eine Nichtdetektion haben. Wir haben den ersten Schritt gemacht um die Theorie zu überprüfen, aber um Sie endgültig zu bestätigen brauchen wir mehr als nur diesen einen Stern, ein Projekt das anschließend an diese Dissertation weitergeführt wird.

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10 Curriculum Vitae

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June 1998	Graduation 'Matura' at RG/WRG Feldgasse 8-12, 1080 Vienna
1998-2006	University of Vienna, graduated Astronomy (Title of Thesis: 'Der δ Scuti Stern 44 Tau')
Oct. 2006 -current	PhD student at the University of Vienna

Astronomy related employments:

2000- 2001	Research grant within the FWF-project S7300 PI O.Prof.Dr. Breger
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Research visits:

Nov. 2000	observing at the Mt. Suhora Observatory, Poland (one week)
April 2003	observing at the SAAO (South African Astronomical Observatory) South Africa (three weeks)
Oct. 2003	observing at the Piskeszetöbobservatory, Hungary (one week)
Sept. 2005	'PhD Conference on Astrophysics of Variable Star' in Pecs, Hungary
Nov. 2006	observing at the SAAO (South African Astronomical Observatory) South Africa (three weeks)
Jan. 2008	observing at the AAT (Anglo-Australian- Telescope) at SSO (Siding Spring Observatory), Australia (5 nights)
June 2008	Hands-on-practice tutorial in spectroscopic mode identification with FAMIAS in Leuven, Belgium
Nov. 2008	Research visit in Aarhus, Denmark
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Conferences and colloquia:

July 2001	Conference 'Observational Aspects of Pulsating B- and A Stars' in Brussels, Belgium (poster)
July 2004	IAU Symposium 224, 'The A-Star Puzzle' in Poprad Slovakia (poster)
Aug. 2007	HELAS II International Conference, Helioseismology, Asteroseismology and MHD Connections (poster)
June. 2008	Interpretation of Asteroseismic Data, Wroclaw, Poland
July 2008	2nd BRITE Workshop, Vienna, Austria (poster)
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Sept. 2008	JENAM conference, Vienna Austria (poster)
Feb. 2009	CoRoT meeting, Paris, France (poster)
March 2009	SONG meeting, Aarhus, Denmark (contributed talk)
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March 2010	SONG meeting, Beijing, China (contributed talk)
June 2010	3rd Kepler Asteroseismology Workshop: 'Kepler Asteroseismology in Action', Aarhus, Denmark (contributed talk)
Oct. 2010	The Power of Helio- and Asteroseismology: A conference in honour of J. Christensen-Dalsgaard on the occasion of his 60th birthday

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2002	became a member of OGA ² (österr. Gesellschaft für Astronomie und Astrophysik)
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2003-2005	chairwoman of the student's representatives of Astronomy, University of Vienna

Teaching

Tutor for the 'Introductory Lab in Astronomy' (1 semester)
Hands-on workshop: 'Reducing Echelle spectra with IRAF'

Computer Skills

IDL, PERIOD04, IRAF, LaTeX, FAMILAS, Windows, Linux, etc

Additional Skills

Language Knowledge:

Romanian: native speaker
German: fluent
English: fluent

Italian: intermediate

Non-scientific qualifications

Different types of full-time jobs during master studies:

waitressing

database administration

data acquisition in a bank
