universitas leodiensis
UNIVERSITÉ de Liège

Faculté des Sciences

Département
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Asteroseismology of β Cephei stars: effects of microscopic diffusion.

par

Pierre-Olivier Bourge

Promotrice :
Dr. Anne Thoul

Dissertation présentée en
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> Je ne me souviens que d'un mur immense
> Mais nous étions ensemble
> Ensemble, nous l'avons franchi
>
> *Chanson pour les pieds*
> – Jean-Jacques Goldman (2001)

Certes le mur *immense* est quelque peu exagéré en parlant du doctorat, néanmoins l'idée développée par Goldman dans sa chanson résume bien ma reconnaissance envers l'aide que vous tous, qui avez croisé et partagé ma vie depuis quatre ans, m'avez apportée. Sans *vous*, je n'y serais pas arrivé. Un très grand **Merci !**

J'aurais voulu être plus long mais pris de court par le temps et vous ayant déjà (pour certains) imposé la lecture de ma thèse, j'irai droit au but. Merci *Arlette* pour ton accueil si chaleureux au sein de ton service, *Anne* pour ton suivi, lors de ces trois années et demie de doctorat, mais aussi avant, lors du DEA, et enfin particulièrement pour ton gros coup de main lors du dernier coup de collier et ta patiente lecture de mon anglais souvent difficile, *Richard* pour les mille et une réponses à mes non moins innombrables questions, *Sylvie* pour ton "marrainage" et ton aide quasi quotidienne à bord de la "galère" diffusion, *Andrea*, Grazie mile !, tu es le compagnon idéal de bureau, toujours des plus agréable et serviable (y compris à la dernière minute) et puis la Lombardie, c'est quand même la plus belle région d'Italie qui soit, tu ne me contrediras certainement pas, non?, *Josefina* pour le "mélange turbulent" versus la perte de masse mais aussi pour tes intéressants débats parfois contradictoires mais d'où je ressors toujours enrichi, *Mélanie* pour ta gentillesse et le sourire que tout le monde te connaît, *Patrick*, nouveau venu mais déjà pas mal de discussions où je découvre un autre monde (qu'il soit rotationnel ou suisse), et j'inclurai encore *Maurice* et *Nicolas*, qui ont atteint la sagesse des retraités (⌣̈) et ne la gardent pas pour eux ! Merci encore à *vous* qui m'avez chacun tellement appris en astrophysique et en astérosismologie, et avec qui il fut tellement agréable de "rechercher" chaque jour …

Je voudrais également remercier mes autres collègues du +1 qui font de cet étage un endroit vraiment sympa et j'étends mes remerciements aux nombreux collègues de l'institut qui ont toute ma sympathie, et sans oublier une mention spéciale á Martine, Denise et Angela (nos travailleuses de l'ombre).

Conny, *Joris*, en *collega's van Leuven*, het was een waar genoegen om al die tijd met jullie samen te werken en zo de "duistere kant van de Kracht" te leren kennen: "de waarnemers", met hun observaties die nooit kloppen met onze modellen, wat erg frustr. . . , nee, boeiend was. Ik had het gevoel door mijn werk in de BAG deel uit te maken van een echte familie, hartelijk bedankt ! (en bedankt Eva voor de hulp in de vertaling.)

Georges, un grand merci pour ton aide, ta disponibilité et pour l'impulsion précieuse que tu m'as communiquée lors des calculs préliminaires sur la diffusion.

Je terminerais par vous qui êtes toujours là et qui à votre façon m'avez chacun soutenu : la famille et les proches, parents, beaux-parents, frère et soeur, cousin(e)s, tantes et tontons, filleul(le)s, grands-parents, amis proches et moins proches, merci. Finalement, *Catherine*, ton soutien, bien plus immense que le mur de Goldman, si je l'ai franchi, c'est bien grâce à toi et à ton support (et dans les deux sens du terme) de tous les jours, tout au long de ce parcours et de sa longue dernière ligne droite.

À vous tous encore et à tous ceux que je n'ai pas cités, merci.

Can you find Alfirk? [1]

and the Cepheus constellation?

---

[1] This figure and the figure on page 185 were obtain by using the free software PP3 v.1.3.3 for celestial chart generation from Torsten Bronger (avalaible at `http://pp3.sourceforge.net`).

Contents

Chapter 1

Introduction

Het zien van de sterren
    zet me altijd aan tot dromen ...
Looking at the stars
    always makes me dream ...
        – Vincent Willem van Gogh (1853-90)

Contents

1.1 Preamble

If you look at the sky, night after night, you will notice that the stars are not all of constant brightness. Some stars brighten and dim, some with precise regularity. Those are called *variable stars* by astronomers [1]. Variable stars can be classified in two main groups: intrinsic and extrinsic variables.

Intrinsic variables are stars whose luminosity changes because of changes in their physical properties themselves. Among intrinsic variable stars, we distinguish three main subgroups: *pulsating* variables are stars whose radius expands and contracts, *eruptive* variables are stars which experience eruptions at their surface like flares or mass ejections, and *cataclysmic or explosive* variables are stars that undergo a cataclysmic change in their properties like novae and supernovae.

Extrinsic variables are stars whose variability is caused by orbital effects or by their own rotation. The *eclipsing* binaries are stars which belong to double or multiple systems and which occasionally eclipse one another as they orbit. The *rotating* variables are stars whose variability is caused by their own rotation, such as spotted stars (i.e. with extreme 'sunspots'), or stars that rotate so fast or in such close orbit, that they become ellipsoidal in shape. The fluctuations in apparent magnitude occur due to the change in the light emitting area visible to the observer as the star rotates.

Variable stars can also be classified in terms of their periodicity (periodic, semiregular, irregular or non-periodic, ...) or their position in the Hertzsprung-Russell diagram [2].

The problem for astronomers is that stars are essentially opaque, so that we can only see their surface and we have no access to the internal layers. By studying the variability of stars, it is possible to get informations on their orbits (in multiple systems) and on their distances, and to constraint some

---

[1] Note that as the observational instruments and techniques were developed and improved, the term 'variable stars' was extended to stars showing a significant variation with time of any of their observable physical properties, such as their luminosity, surface temperature, spectroscopic variations, etc.

[2] The Hertzsprung-Russell diagram (or HR diagram) is named after Elnar Hertzsprung and Henry Norris Russell, the two astronomers who created it independently circa 1910. It plots the magnitude or apparent brightness of a star as a function of its colour or spectral type, which reflects its surface temperature. Note that theoreticians prefer to use the luminosity and the effective temperature, physical quantities which are obtained directly from the stellar models.

of their physical properties such as their mass, their radius, their age. It is also possible to deduce informations on their internal properties. Indeed, just as we can recognize a violin from a piano by the sound that they produce, stellar pulsations depend on the detail of their internal structure. The study of stars through their pulsational properties is called *asteroseismology*. It is a powerful tool to test our current theory of stellar evolution, i.e. how stars are born, evolve and die. Our knowledge of variable stars has increased dramatically during the last decades, thanks to better observational data.

For more details about the theory of asteroseismology or variable stars, we refer the reader to the references mentioned in the bibliography and more particularly Unno et al. (1989), Gautschy and Saio (1995, 1996), Scuflaire (2000, 2002), Christensen-Dalsgaard (2003), Rauw (2003), Aerts (2004), Thoul (2004) and Shibahashi (2005).

1.2 Variable main sequence stars in the HR diagram

Stars spend about 95 % of their lifetime burning hydrogen into helium in their center. This stage of their evolution is called the main sequence. In what follows we will only deal with main sequence stars.

Variable stars are found all over the HR diagram. This is illustrated in Fig. 1.1 where different types of variable stars are shown. Theses variable stars are distinguished and classified by their periods of pulsation, the shapes of their light curves, and the excitation mechanisms of their pulsations. These are functions of the mass of the star and its evolutionary state.

The main sequence pulsating stars are called, in increasing mass, solar-like, γ Dor, roAp, δ Scuti, SPB (Slowly pulsating B stars), and finally β Cephei, the class of stars which we will deal with in this work. These stars are multiperiodic and exhibit radial and non-radial pulsations. During radial pulsations, the star oscillates around an equilibrium state by changing its radius while maintaining a spherical shape. In non-radial pulsations, some parts of the stellar layers move inward, while others move outward.

Radial oscillations are characterised by the radial wavenumber n or *radial order*, which represents the number of nodes of the eigenfunction of the

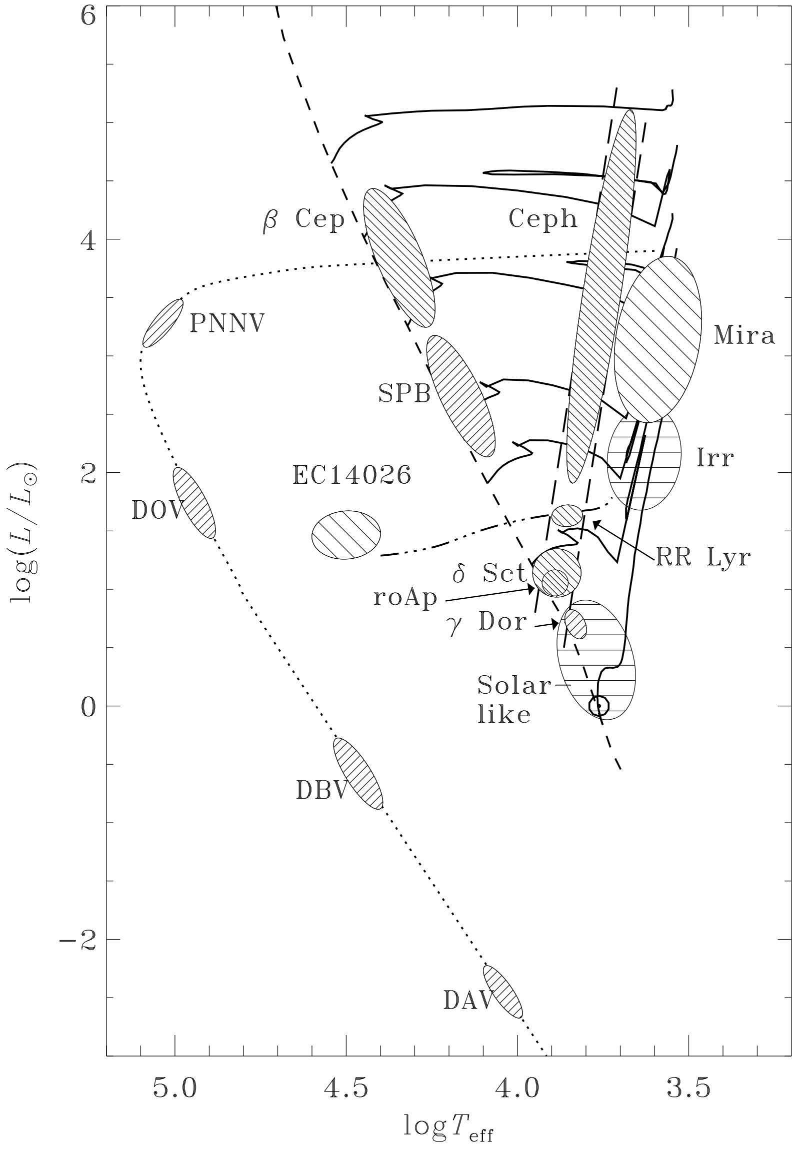


Figure 1.1: Pulsating stars in the HR diagram (from Christensen-Dalsgaard 2003).

oscillation mode between the center and the surface of the star. It is similar to the number of nodes of a vibrating string, which tells us in which harmonic the string vibrates (fundamental mode, first harmonic, ...). In the case of a star, there is a succession of expanding and collapsing spherical layers (shells). Non-radial oscillation modes in pulsators are described in terms of *spherical harmonics* $Y_l^m(\theta, \phi)$ of co-latitude θ (i.e. angular distance from the polar axis) and longitude ϕ. The wavenumber l is called the *degree* of the mode and represents the number of surface nodal lines, while the wavenumber m, called the *azimuthal order*, accounts for the number of surface nodal lines that pass through the rotation axis of the star. An illustration of non-radial oscillations is given in Fig. 1.2.

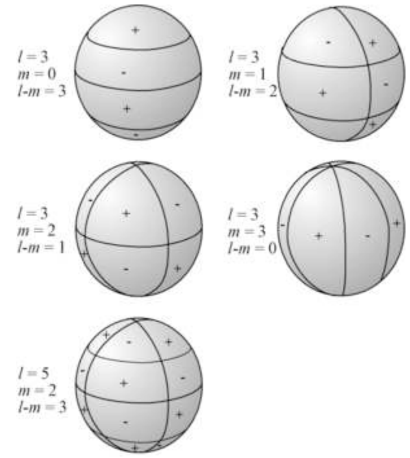


Figure 1.2: Different examples of non-radial oscillations. Schematic representation of Y_l^m on the unit sphere. Y_l^m is equal to 0 along m great circles passing through the poles, and along $l - m$ circles of equal latitude. The function changes sign each time it crosses one of these lines. (Figure from Wikipedia web site).

1.3 β Cephei stars

In this work we will focus on β Cephei stars, the hottest of the variable main sequence stars. We briefly review their main observational and theoretical properties. For more details, we refer the reader to the following good reviews from: Sterken and Jerzykiewicz (1993), Aerts and De Cat (2003) and Stankov and Handler (2005).

1.3.1 A little bit of history

> It is certainly astonishing in working on this star [β Cep] to find that plates taken in immediate succession, with the epoch of mid-exposure separated by less than half an hour, show marked differences of radial velocity, at times reaching 10 kilometers.
>
> *Yerkes Observatory*
> – Edwin Brant Frost (1906)

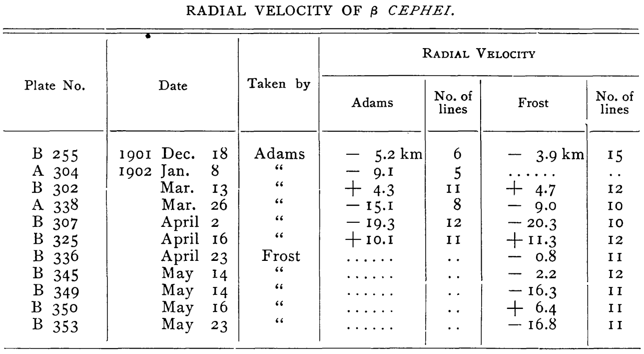
In 1955, Struve published a review paper on β Cephei stars entitled "An interesting group of pulsating stars" [3]. In fact the interest for β Cephei stars started much earlier at the dawn of the 20th century. In the winter of 1901-1902, Edwin B. Frost and Walter S. Adams were taking spectrograms [4] of β Cephei, a bright B-type star. The measures on the third plate suggested a variability in the radial velocity of the star. They assumed a long period but Frost's brilliant suspicion led him to take two spectrograms on the night of May 14, 1902. He found that, during an interval of five hours and a half, the velocity changed by nearly half of the whole range observed so far (see Fig. 1.3). Unable to conclude on the period of the star at that time, Frost continued his observations, and four years later he announced a period of $4^h34^m11^s$, with a velocity curve nearly symmetrical and an amplitude of 34 km/s. In September 1913, P. Guthnick announced a variation in the light curve of β Cephei with a period identical to the one found by Frost (Guthnick 1914, see Fig. 1.4). For those interested about these pionneers' works, we suggest the papers by Frost (1902, 1906), Guthnick (1914) and Struve (1955)

β Cephei gave its name to a whole class of pulsating stars. During the first part of the 20th century, the observations were based on photographic spectroscopy. With the introduction of photo-electric photometry, a very

---

[3] Please note that the β Cephei variables have also been called "β Canis Majoris stars" because of β Canis Majoris which became the first well studied member of the group. Nowadays, the more historically correct designation used is "β Cephei stars".

[4] A spectrogram is basically a photograph of a spectrum, but the term may be taken to mean any representation of a spectrum, digital or otherwise. A spectrum is the result of dispersing a ray of light into its constituent colors. The importance of spectroscopy is that as light is broken into its components, spectral features – such as absorption and emission lines – may be identified, which tell us a great deal about a celestial body's velocity, composition, etc.



RADIAL VELOCITY OF *β CEPHEI.*

Plate No.	Date	Taken by	Radial Velocity			
			Adams	No. of lines	Frost	No. of lines
B 255	1901 Dec. 18	Adams	− 5.2 km	6	− 3.9 km	15
A 304	1902 Jan. 8	"	− 9.1	5	......	..
B 302	Mar. 13	"	+ 4.3	11	+ 4.7	12
A 338	Mar. 26	"	− 15.1	8	− 9.0	10
B 307	April 2	"	− 19.3	12	− 20.3	10
B 325	April 16	"	+ 10.1	11	+ 11.3	12
B 336	April 23	Frost	......	..	− 0.8	11
B 345	May 14	"	......	..	− 2.2	12
B 349	May 14	"	......	..	− 16.3	11
B 350	May 16	"	......	..	+ 6.4	11
B 353	May 23	"	......	..	− 16.8	11

Figure 1.3: A tribute to history. (Table from Frost 1902).

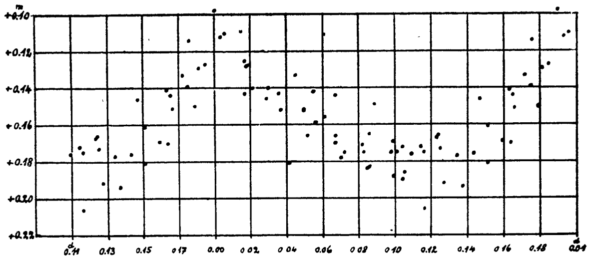


Fig. 2. *P. Guthnick.* β Cephei. Einzelmessungen.

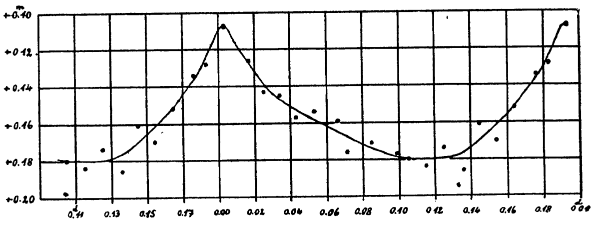


Fig. 3. *P. Guthnick.* β Cephei. Mittlere Lichtkurve.

Figure 1.4: A tribute to history. The top panel represents the observed data points of the light curve of β Cephei. The bottom panel represents the mean light curve of β Cephei. (Figure from Guthnick 1914).

different strategy for the search of variable stars began: large systematic surveys were undertaken during the second half of the 20th century, so that numerous new β Cephei stars were discovered. Meanwhile, the continuous improvements in spectroscopy led to higher resolution and NRP (Non Radial Pulsations) investigations became possible, opening a new field called "line profile fitting" [5], initiated in the mid-1970s. From those it is possible to perform pulsation mode identification (Smith 1977).

In the review of Sterken and Jerzykiewicz (1993), 59 β Cephei stars were identified. According to Stankov and Handler (2005), 40 more new β Cephei stars were discovered and confirmed in the last decade. Pigulski (2005), using the ASAS-3 data [6], unambiguously classifies 14 stars as new β Cephei stars, and Narwid et al. (2006), using the catalog of 200 000 stars from Wozniak et al. (2002) based on OGLE-II data [7], estimate that more than 100 short-period variables could be β Cephei stars. The interest for these stars in the astronomical community is growing rapidly as reflected by the rate of publications on this topic: more than 900 papers were written on this topic since Frost's discovery, and nearly one third of them were published in the last decade [8]!
For more on the history of β Cephei stars, we refer the reader to the very clear papers by Struve (1955), Lesh and Aizenman (1978), Sterken and Jerzykiewicz (1993), Aerts and De Cat (2003), and Stankov and Handler (2005).

---

[5] The velocity field caused by the NRPs leads, through Doppler displacement, to periodic variations in the spectral lines profiles.

[6] ASAS-3 is the third stage of the *All Sky Automated Survey* conducted by G. Pojmański (Pojmański 2004). The ASAS-3 survey monitored over 10 millions stars and its catalogue includes over 38 000 variable stars brighter than ∼14 mag in V.

[7] OGLE-II is the second stage of the *Optical Gravitational Lensing Experiment* project. OGLE is a long term project with the main goal of searching for the dark matter with microlensing phenomena (Udalski, Kubiak and Szymanski 1997).

[8] Based on a quick search made on February, 26th 2007 in the database of the ADS website. The results since Frost's publication in 1902 returned 667 references in the paper's title and 937 in the abstracts, with 293 of them since 1997.
The ADS (NASA Astrophysics Data System)'s website is available at `http://adswww.harvard.edu/`

1.3.2 β Cephei stars from an observational point of view

> Pour qu'une chose soit intéressante,
> il suffit de la regarder longtemps.
>
> Anything becomes interesting
> if you look at it long enough.
> – Gustave Flaubert (1845)

β Cephei stars are young population I main sequence stars with spectral types between B0 and B3. They are found in OB associations and in young galactic clusters. Their position in the HR diagram suggests that they are 10 to 20 solar mass stars on the main sequence phase. So far, 107 stars are confirmed β Cephei stars (Stankov and Handler 2005, Pigulski 2005).
They have periods between 1.6 and 7.7 hours with a median of 4.1 hours (Stankov and Handler 2005). Their amplitudes, usually smaller than 0.1 magnitude, range from 0.01 to 0.2 in the visible, with BW Vul (HD 199140) having the largest semi-amplitude of about 85 mmag (Stankov and Handler 2005, and references therein). We show in Fig. 1.5 a semi-amplitude-period diagram for β Cephei stars (Pigulski 2005). About 60 % of the confirmed β Cephei stars are multiperiodic (Stankov and Handler 2005, Pigulski 2005). Additional pulsation periods may still be undetected so far. A modulation in the light curve is present for many of these variables, due to multiple neighbouring periods. As illustration, in Fig. 1.6 we show the colour and brightness variations of the star DD Lacertae (12 Lac), displaying night-to-night amplitude variability caused by the beating between different oscillation modes of almost equal amplitude.

Most of the β Cephei stars pulsate in the radial fundamental mode and, for many of them, there is strong evidence from spectroscopic and multiphotometric observations that some of their pulsation modes are non-radial, with a small degree l and a low radial order n (see e.g. Stankov and Handler 2005). With the exception of the stars BW Vulpeculae (Crowe and Gillet 1989, Aerts et al. 1995) and σ Scorpii (Mathias, Gillet and Crowe 1991), the pulsation of β Cephei stars is well described by the linear theory (the light curves or similarly the phase diagrams for individual frequencies are sinusoidal). The pulsation periods are stable, although variations of the order of a second or less per century have been observed in δ Ceti (Cuypers 1986).

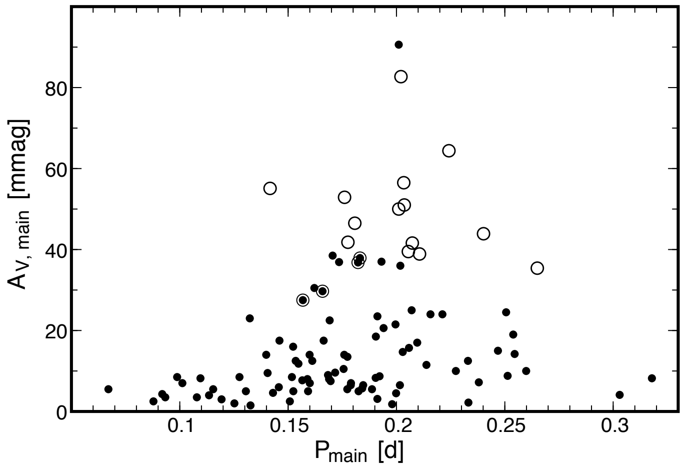


Figure 1.5: V semi-amplitudes of the dominating mode plotted against the period of this mode. Dots denote stars from the catalogue of Stankov and Handler (2005), open circles, those reported in Pigulski (2005). Encircled dots are four already known β Cephei in the ASAS-3 photometry. (Figure from Pigulski 2005).

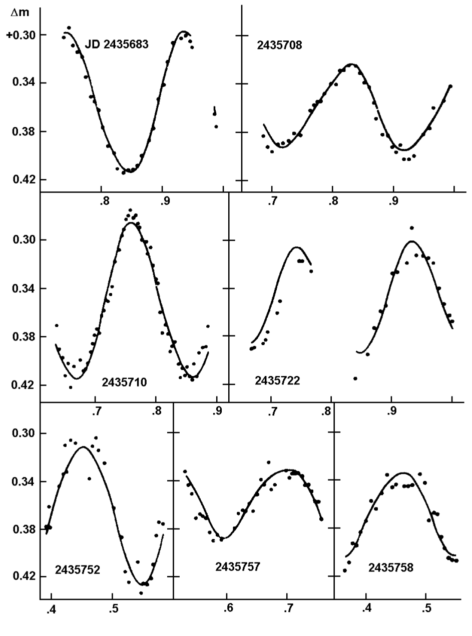


Figure 1.6: DD Lacertae (12 lac) light curves (from Jerzykiewicz 1978).

The variations of light have larger amplitudes at blue wavelengths than at red wavelengths, and a phase difference of about 0.25 with the radial velocity variations (see Fig. 1.7). Such a phase difference is expected when the star is the hottest at its smallest radius. Note that this is in agreement with the adiabatic theory of oscillations, which predicts that the maximum of luminosity corresponds to a minimum of radius.

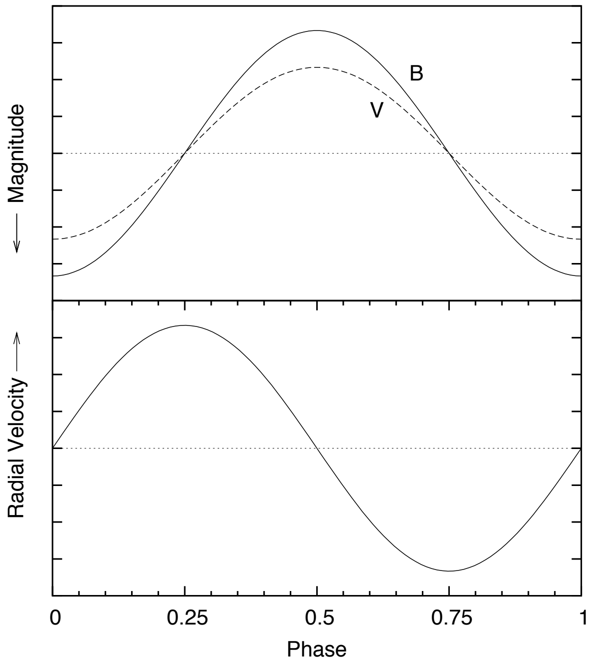


Figure 1.7: Schematic light and radial velocity variations of a typical β Cephei star.

β Cephei stars usually show photometric as well as spectroscopic variations. However more and more β Cephei stars have line profile variations without detectable corresponding photometric variations (Aerts and De Cat 2003), such as ω^1 Sco (Telting and Schrijvers 1998), as illustrated in Fig. 1.8.

Among the hundred of confirmed or suspected β Cephei stars, slow rotators as well as rapid rotators have been observed. The range of projected rotational velocity, $v \sin i$, extends from 0 to 300 km/s as can be seen in Fig. 1.9 (Stankov and Handler 2005). Most confirmed β Cephei stars seem to be rather slow rotators with an average $v \sin i \sim 100$ km/s. But as quoted by Aerts and De Cat (2003) and Stankov and Handler (2005), this could in part

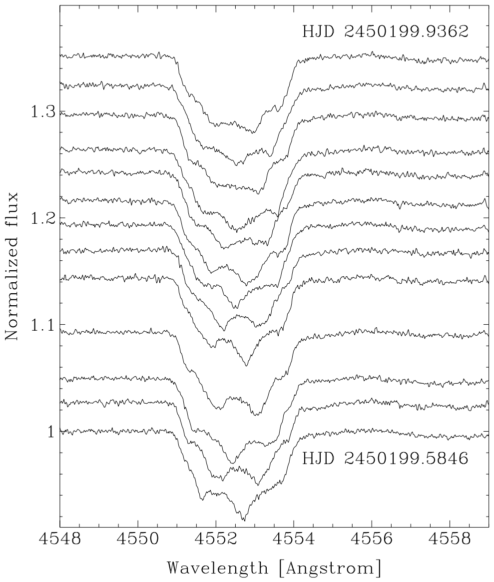


Figure 1.8: Line profile variability of ω^1 Sco: one night of data showing the variation in the Si III triplet 4552 Å line. (Figure from Telting and Schrijvers 1998).

be due to a selection effect as the highest-amplitude pulsators are slowly rotating stars, with the exceptions of HD 203664 (Aerts 2000, Aerts et al. 2006) and HD 52918 (Balona et al. 2002).

A few β Cephei stars with magnetic fields have been detected. It has been known for a long time that β Cephei itself is a magnetic star (Rudy and Kemp 1978). The most recent work by Donati et al. (2001) shows that its magnetic field can be approximately described by a dipole with a dipolar strength of 360 ± 30 G. Neiner et al. (2003) detected a magnetic field in V2052 Oph with a strength of 250 ± 90 G and Hubrig et al. (2006) measure a magnetic field of 306 ± 31 G in ξ^1 CMa.

Despite searches for photometric variability of O-type stars (e.g. Pigulski and Kołaczkowski 1998), so far no β Cephei stars have been found with $M > 20\ M_\odot$ and $log(L/L_\odot) > 5$, even though they could theoretically exist. The reason is probably a shift of the instability strip from the main sequence towards more evolved stars. Their evolution becomes so fast that it is statistically hard to find stars in such an evolutionary state. Furthermore, even though O-type β Cephei stars could exist, their pulsation amplitude would

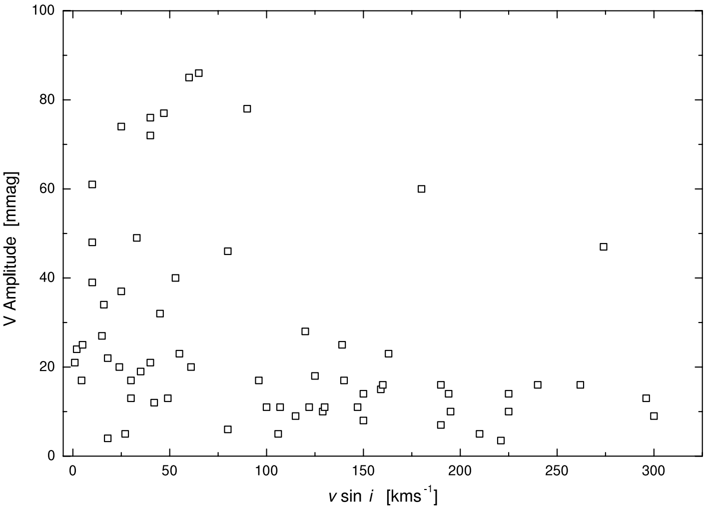


Figure 1.9: Photometric amplitude of confirmed β Cephei stars depending on their projected rotational velocity. (Figure from Stankov and Handler 2005).

be small and therefore not yet detectable. The only known O-type β Cephei variable candidate is HD 34656 (O7 II) which shows radial velocity variations with a period of 8.18 hours and semi-amplitude of 3 km/s (Fullerton, Gies and Bolton 1991), but the authors are still uncertain on its β Cephei nature, and the reported radial velocity variations of the star may not be statistically significant (Stankov and Handler 2005). The hottest and most luminous confirmed β Cephei star is HD 165174, with a B0 IIIn spectral type (Stankov and Handler 2005).

Hot stars have significant mass loss in the form of line-driven stellar winds, which renders the observation of oscillations difficult. The theoretical calculations for these high luminosity stars are also uncertain. Indeed, due to their large radiative pressure, they undergo instabilities giving rise to oscillations of a different nature than those of the classical β Cephei stars. They are called "strange modes" (for more about them, see Scuflaire 2002 and references therein).

For an up-to-date catalog of confirmed β Cephei stars, we refer the reader to the online catalog from De Cat (2006). Note that the author lists only stars for which Geneva photometry is available to enable a homogeneous determination of the stellar parameters. The catalog provides lists of confirmed and candidate β Cephei and Slowly Pulsating B stars. Slowly Pulsating B stars, or SPB in short, are late B-type stars (B2-B9) showing light and line-profile variations, that are multiperiodic with periods of pulsation of the order of days (about 0.5 to 5 days).

For more on the observational characteristics of β Cephei stars, we refer the reader to the reviews in the papers of Struve (1955), Lesh and Aizenman (1978), Sterken and Jerzykiewicz (1993), Aerts and De Cat (2003), and Stankov and Handler (2005).

1.3.3 β Cephei stars from the theoretical point of view

> It is thus quite possible that, by the single stroke of augmenting the heavy element opacities by factors of 2-3, we can bring into line with the theory of stellar structure and evolution not only for the double-mode and bump Cepheids, but the β Cephei pulsators as well.
>
> – Norman R. Simon (1982)

Though β Cephei stars have been known for more than 100 years, their variability has long been an enigm for the astronomy community. Soon after Frost's discovery, it was clear that, in the binary hypothesis, the radial velocity curve of β Cephei led to an incredibly small orbit – only 45 000 km – and with an inclination close to 0° (Frost 1906). When Guthnick (1914) found a light curve variability, the mystery deepened as the light curve did not resemble those of ordinary eclipsing variables. And so the puzzle remained for many years.

Several internal mechanisms can trigger pulsations in stars. Radiative transport leads to excitation if the perturbation in opacity is such that the radiation is held back at compression and released at expansion (as in the heat engine in thermodynamics). In order to be efficient, this must happen in a region of localised opacity increase which coincides with the transition region from the nearly adiabatic to the strongly non-adiabatic pulsations. This is called the κ-mechanism as introduced by Baker and Kippenhahn (1962).

A major step in the good direction was made by Simon (1982). He showed that if the contribution of the heavy elements to the opacity was increased by a factor of 2 to 3, classical Cepheid models could then reproduce the observed ratios of first- and second-overtone periods over the fundamental period. He suggested that this increase might also solve the problem of the excitation mechanism of the β Cephei pulsators.

Indeed the κ-mechanism, acting within the partial ionisation zone of the iron-group elements, induces oscillations in β Cephei stars. But at that time, the driving effect was not sufficient. The breakthrough came in the early 1990s, when the stellar opacities, near the opacity bump around 200 000 K due to the partial ionisation of the iron-group elements, increased by a factor 3 in the new OPAL [9] determinations of Iglesias and Rogers (1991) [10]. This opacity enhancement resulted in an enhancement of the driving effect of the excitation. This was quickly presented by Cox et al. (1992), Moskalik and Dziembowski (1992), Kiriakidis, El Eid and Glatzel (1992) and Dziembowski and Pamiatnykh (1993) as the answer to the long unsolved problem of the excitation of the pulsations in early B-type stars. The iron abundance in those stars seems indeed to be a crucial parameter for the existence of the instability (see e.g. Pamyatnykh 1999) and this could explain why not all B stars are pulsating.

There are two different types of oscillation modes. Pressure modes (p-modes) are standing acoustic modes, i.e. sound waves quite similar to those of musical intruments. The restoring force for p-modes is the pressure. Gravity modes (g-modes) are internal gravity waves. The buoyancy force is the restoring force for these modes. Pressure modes are high frequency modes, while gravity modes have longer periods. The p-modes have large amplitudes in the outer layers of the star while g-modes generally have large amplitudes in the deep layers of the star. For more details about p- and g-modes, we refer the reader to Scuflaire (2002) and Thoul (2004).

The β Cephei stars oscillate with periods between 2 and 8 hours. These short periods are well explained by κ-driven [11] low-order p- and/or g-modes. The theoretical instability strip of standard models of β Cephei stars is shown in Fig. 1.10 (Stankov and Handler 2005), where the confirmed (*filled circles*)

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[9] OPAL is the acronym for *Opacity Project at Livermore*. The offical home page is avalaible at `http://www-phys.llnl.gov/Research/OPAL/opal.html`.

[10] Their new calculations took into account the previously neglected effects of spin-orbit interactions (Iglesias, Rogers and Wilson 1992). The main impact of the spin-orbit interaction is to enhance significantly the opacity in the region of the Z bump (the opacity peak due to iron-group elements) but only at low densities.

[11] i.e. oscillations that are excited (driven) by the κ-mechanism.

and candidate (*open circles*) β Cephei stars as well as the poor and rejected candidates (*plus signs*) are shown in a theoretical HR diagram. The slanted solid line is the ZAMS [12], the thick dashed line describes the boundaries of the theoretical β Cephei strip for a metallicity $Z = 0.02$, the thin dashed lines are the β Cephei boundaries for radial modes, and the dotted lines those of the SPB stars. Several stellar evolutionary tracks, labeled with their evolutionary masses, are also plotted. All the theoretical results were adopted from Pamyatnykh (1999).
We see that the instability strips of β Cephei and SPB stars are overlapping. Thus some hybrid pulsators should exist having the simultaneous occurrence of high-order g-modes and low-order p- or g-modes in a B-type star. Only a handful of hybrid pulsators have been discovered up to now, such as ν Eri (Handler et al. 2004, Jerzykiewicz et al. 2005) and γ Peg (Chapellier et al. 2006), or 19 Mon (Balona et al. 2002) and 12 Lac (Handler et al. 2006), for which one low frequency have been reported.

As we said in Section 1.3.2, though they are theoretically predicted, there is no observational evidence for hot and luminous β Cephei pulsators, with the possible exception of HD 34656 (see Fullerton, Gies and Bolton 1991).
Although the blue part of the strip is not well populated, observed β Cephei stars agree more or less with the theoretical instability strip. From the standard stellar evolution theory and from Fig. 1.10, we see that it is reasonable to conclude that all known β Cephei stars are main sequence objects. The mass distribution of confirmed and candidate β Cephei stars peaks sharply at about 12 $M_\odot$ (Stankov and Handler 2005).

β Cephei stars have a rather simple internal structure: they have a convective core, surrounded by a radiative envelope. They are 'middle' main sequence stars and their convective core weights about 20 % of their total mass. Note that two tiny superficial convective layers also exist very close to the surface. These are associated with the opacity bump due to the partial ionization of the iron-group elements and the second ionization of helium. Their masses are extremely small (less than 10^{-8} and 10^{-10} stellar mass fraction).
For more details on the structure and the evolution of β Cephei stellar models, we refer the reader to Bourge (2004).

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[12] ZAMS is a common acronym used for 'Zero Age Main Sequence'. This line represents the position of stars that have begun burning hydrogen in their core.
Note that the term TAMS is also commonly used and is the acronym for 'Terminal-Age Main Sequence', used to describe stars at the point in their lifetimes where they have finished burning hydrogen in their cores.

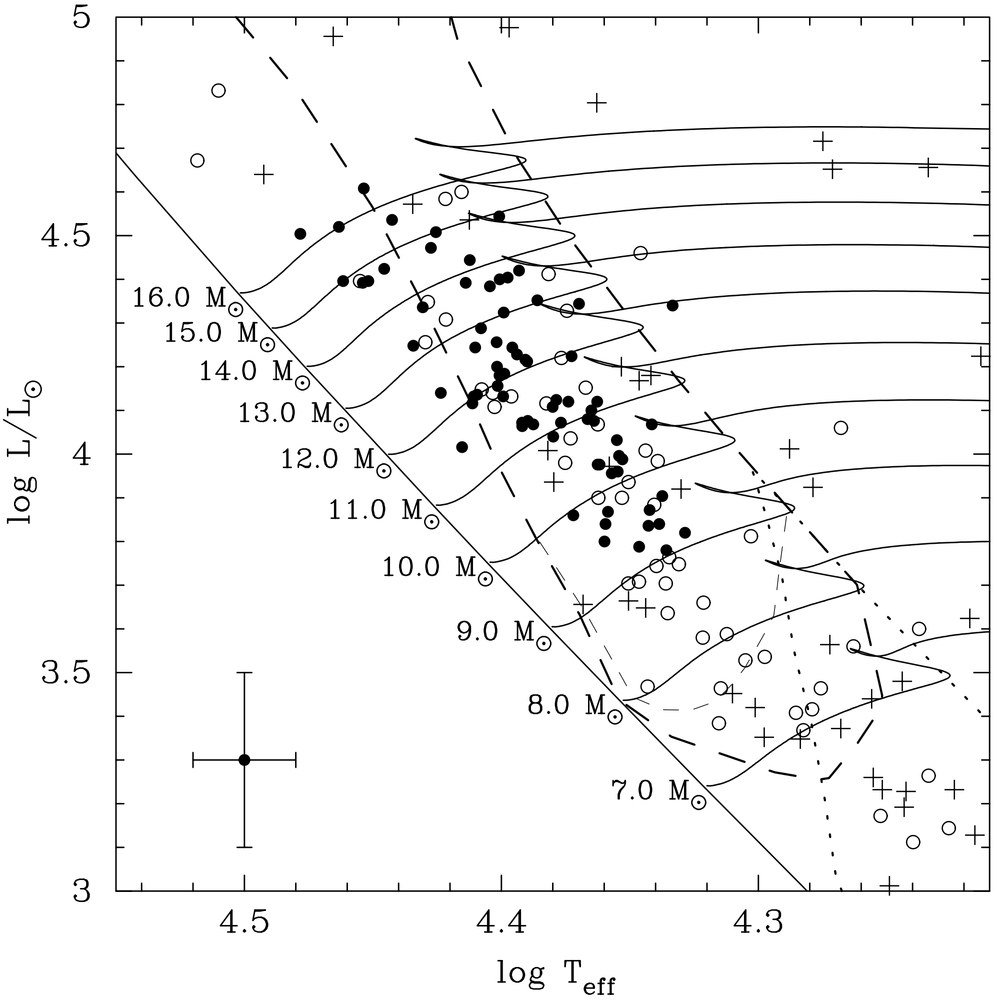

Figure 1.10: Theoretical HR diagram of the confirmed (*filled circles*) and candidate (*open circles*) β Cephei stars as well as the poor and rejected candidates (*plus signs*). The filled circle with the error bars in the lower left corner indicates the rms accuracy of each point in this diagram. The slanted solid line is the ZAMS, the thick dashed line describes the boundaries of the theoretical β Cephei instability strip for standard models having $Z = 0.02$, the thin dashed lines are the β Cephei boundaries for radial modes, and the dotted lines those of the SPB stars. Several stellar evolutionary tracks, labeled with their evolutionary masses, are also plotted. All the theoretical results were adopted from Pamyatnykh (1999). (Figure from Stankov and Handler 2005).

1.4 Current status and problems

> A biologist, a statistician, a mathematician and an astrophysicist are on a photo-safari in Africa. As they're driving along the savannah in their jeep, they stop and scout the horizon with their binoculars.
> The biologist: "Look! A herd of zebras! And there's a white zebra! Fantastic! We'll be famous!"
> The statistician: "Hey, calm down, it's not significant. We only know there's one white zebra."
> The mathematician: "Actually, we only know there exists a zebra, which is white on one side."
> The astrophysicist: "Oh, no! A special case!"
> – anonymous

β Cephei stars have a sparse spectrum (as an example, the amplitude spectrum of HD 129929 is shown in Fig. 1.11) which can often be matched to the theoretically calculated frequencies, and we can obtain information about their global stellar parameters such as their mass, metallicity, radius, age, as well as some information on their internal structure such as the size of their convective core (overshoot), or the internal rotation law. Several stars have been extensively studied with success, such as 16 Lacertae (Thoul et al. 2003), HD 129929 (Aerts et al. 2003, Dupret et al. 2004, Thoul et al. 2004) and θ Ophiuchi (Briquet et al. 2007, submitted).

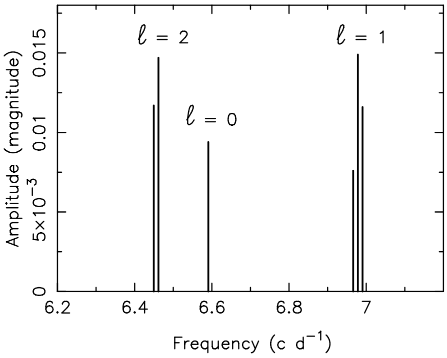

Figure 1.11: Amplitude spectrum of the Geneva U data for HD 129929 (from Aerts et al. 2003).

However several recently observed β Cephei stars such as ν Eri and 12 Lac (Handler et al. 2006) present new challenges for the asteroseismologists. A rich oscillation spectrum of ν Eri was obtained from a large multisite campaign (Handler et al. 2004, Aerts et al. 2004a, De Ridder et al. 2004, Jerzykiewicz et al. 2005). While trying to fit four clearly detected pulsation modes in ν Eri, it was found (Ausseloos et al. 2004, Ausseloos 2005) that standard stellar models fail to reproduce the observed frequency spectrum. It was necessary to significantly increase the amount of iron in the star (by a factor of 4) or decrease the initial hydrogen mass fraction X (almost by a factor of 2) in the whole star to account for the observations. Another possible explanation to solve the problem was proposed by Pamyatnykh, Handler and Dziembowski (2004). They showed that a local enhancement by a factor 4 of the iron-group elements in the opacity bump region of those elements could help reproduce the observed frequencies.

A global enhancement of iron or a low initial hydrogen mass fraction are hard to justify, even though recently Chuzhoy (2006) has shown that element diffusion could produce large fluctuations in the initial helium abundance in stars. Microscopic diffusion refers to the relative displacements in a fluid medium of different chemical species due to the driving effect of the abundances, pressure and temperature gradients or external forces. In the case of protostellar clouds, Chuzhoy (2006) showed that the diffusion time scale can fall below 10^8 years. The amplitude of the helium abundance variations depends on many factors such as the magnetic field, the outside pressure, the turbulence. Diffusion may also produce spatial variations of the deuterium and lithium abundances. The author suggests that helium diffusion could maybe explain the large fluctuations of primordial helium abundances inferred from the recent observations of globular clusters (Bedin et al. 2004, Norris 2004, Piotto et al. 2005). According to Chuzhoy's calculations, the element abundances can also change before the onset of stellar nucleosynthesis in stars. A low hydrogen mass fraction might perhaps be acceptable in some cases.

For the local enhancement of iron, as was first suggested by Cox et al. (1992), Pamyatnykh, Handler and Dziembowski (2004) proposed the radiative levitation [13] of iron as an explanation since it is shown to be already at work in sdB stars [14] (Charpinet et al. 1996, 1997). The pulsating sdB stars have

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[13] For more details on microscopic diffusion and radiative forces, we refer the reader to appendices A and B and the references therein.

[14] sdB stars, or sub-dwarf B stars, are evolved, compact stars with low-mass core in the helium burning phase. They have typical masses of about 0.5 $M_\odot$ and $\log g \sim 5,8$. Some sdB stars pulsate and are called EC 14026 objects, after the prototype. They have low-order radial and non-radial pulsations with periods of about 2 to 3 minutes (Charpinet

the same driving mechanism for the oscillations than β Cephei stars, i.e. the κ-mechanism due to the iron-group opacity bump, and the same range of effective temperatures as the β Cephei stars. Charpinet et al. (1996, 1997) and Fontaine et al. (2003) have shown that such an accumulation of iron due to radiative levitation is needed to explain the excitation of oscillations in sdB stars. In stars with effective temperatures lower than 6 000 K, the radiative accelerations are negligible. Because of the gravitational settling, the elements heavier than hydrogen simply sink towards the central regions of the star while hydrogen goes up for hydrostatic balance. In hotter stars, the radiative accelerations can become large and compete with gravitational settling. They can prevent elements from falling down and can even push them towards the external layers. Michaud et al. (1976), Vauclair, Vauclair and Michaud (1978) and Richer, Michaud and Turcotte (2000) have shown that this process can explain at least qualitatively the observed chemical anomalies in Am-Fm stars. According to results from Richard, Michaud and Richer (2001), the radiative accelerations also lead to the accumulation of iron-peak elements around 200 000 K in late B, A and F stars. This accumulation results in a substantial opacity increase which can lead to the appearance of a convectively unstable region.

The problem of the excitation of the pulsations of β Cephei stars is even more puzzling if we consider the existence of β Cephei stars in the Large Magellanic Cloud (LMC) (Pigulski and Kołaczkowski 2002, and Kołaczkowski et al. 2004) and even a few ones in the Small Magellanic Cloud (SMC) (Kołaczkowski et al. 2006), since Pamyatnykh (1999) showed that the lower part of the instability strip of β Cephei stars in the HR diagram should almost vanish for metallicities below 0.01. Here again the radiatively-driven diffusion of iron and its accumulation in the transition region could provide an explanation for the existence of these low metallicity β Cephei stars.

As we said above microscopic diffusion can explain qualitatively the observed chemical anomalies in Am-Fm stars. Recently, Morel et al. (2006, 2007a,b) have discovered that some β Cephei stars present chemical abundance anomalies at their surface. Indeed their nitrogen abundance is enhanced by up to 0.6 dex while He, C, O, Mg, Al, Si and Fe are typical of values found in OB dwarfs in the solar neighbourhood.

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et al. 1997).

1.5 Purpose of this work

β Cephei stars are very interesting to study because they have a simple structure and a simple oscillation spectrum, and yet they present some unsolved issues, such as an unexplained wide range of observed frequencies (ν Eri, 12 Lac), the existence of low metallicity β Cephei stars, and unusual carbon, nitrogen and oxygen abundance ratios if compared to solar or nearby OB-type stars values (δ Cet, β Cep, ξ^1 CMa, V2052 Oph and to a lesser extent ν Eri).

A possible solution to the first two problems could be an enhancement of iron in the driving region of the pulsation modes. Only three physical processes can cause this: nuclear reactions, mass accretion and microscopic diffusion.
The first one is easily ruled out as β Cephei stars are in their main sequence phase of evolution, i.e. the central (core) burning of hydrogen into helium, which does not produce iron.
Mass accretion (such as the swallowing of a telluric planet), would leave a signature in the element abundances (relative enhancement of refractory elements and lithium with respect to H, He, C, N, O abundances) which is not observed (e.g. Gonzalez 1998).
The last solution is microscopic diffusion, i.e. the segregation of chemical elements through their differential transport, due to the existence of gradients of temperature, pressure, concentration, and to different radiative forces.
Microscopic diffusion including radiative forces could also produce a segregation between carbon, nitrogen and oxygen at the surface and provide an explanation for Morel et al.'s results.

Microscopic diffusion including radiative forces in β Cephei stars is the main topic of this thesis. In Chapter 2 we present the physics of microscopic diffusion and its implementation in the stellar evolution code CLES, as well as the results on the evolution of a 10 $M_\odot$ stellar model. In Chapter 3 we present the effects of the diffusion of iron on the excitation of pulsation modes in β Cephei stars. In Chapter 4 we present the results that we obtained for the radiatively-driven diffusion of carbon, nitrogen and oxygen, and its effects on their surface abundances.