Pulsation, rotation, wind and magnetic field in early B-type stars

Neiner, C.L.

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Introduction

This thesis is concerned with variable phenomena observed in hot massive B stars, in particular rotation, pulsations and winds, which have typical timescales from hours to days. We also investigate the presence and role of magnetic fields in these stars, a rather new area of research. Studying these phenomena enables us to better understand the physical processes involved in these stars. This will hopefully cast new light on the explanation of the enigmatic Be phenomenon, and significantly extends the observational platform for asteroseismology in B stars, the only means to study their internal structure. This works consists of four new in-depth case studies. Such studies are very elaborate and telescope time consuming but are essential to make progress in this field, as statistical properties of the behavior of these stars have not revealed a coherent picture. This introduction starts with describing the scientific background and context within which this research was carried out. We conclude with a summary of the content of the thesis, along with the major conclusions, and propose future work to be done.

1.1 Early B-type stars

Variability is found in all kinds of stars throughout the Hertzsprung-Russell (H-R) diagram. In this thesis we concentrate on three groups of early B-type stars, namely the Be, \( \beta \) Cephei and Slowly Pulsating B (SPB) stars.

Be, \( \beta \) Cep and SPB variables are all pulsating B stars, but they occupy different regions in the H-R diagram, as shown in Fig. 1.1. These three classes have significantly different properties, which are summarised in Table 1.1. More details are given in the following sections (see also Sterken & Jaschek 1996).

1.1.1 Be stars

Be stars are non-supergiant B stars that at least once have displayed Balmer line emission. This property applies to about 20% of all B-type stars. Some late O and early A stars also show such emission and are considered as an extension of the Be stars. The early (i.e. more massive and hotter) Be stars exhibit strong variable winds evidenced by the rapidly variable UV resonance lines of highly ionised species, as well as by spectral and light variations on timescales from hours to decades. The phases of emission in the optical and infrared lines
of hydrogen and several ions, called the Be phenomenon, most likely reflect changes in the structure of the circumstellar disk created by episodic ejections of mass. The visual inspection through a spectroscope of the first Be star $\gamma$ Cas was described in 1867 (Secchi 1867). The origin of this phenomenon is, however, still unknown.

Figure 1.2 shows examples of H\(\alpha\) spectra of the Be star 60 Cyg taken at different times, compared to a synthetic spectrum for a star of similar spectral type. This star goes from a phase with the H\(\alpha\) line in absorption to a phase with strong double-peaked emission within 6 years.

It is generally accepted that the envelope of Be stars is flattened by their high rotational velocities. Recent interferometric observations (e.g. Quirrenbach et al. 1997; Stee 2000) provided direct evidence for the presence of such a disk (see Fig. 1.3). The rotation rates of Be stars, however, are always lower than the critical velocities at which the centrifugal force balances gravitation at the equator. Thus, the centrifugal force by itself is inadequate to explain the formation of a disk around these stars.
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<table>
<thead>
<tr>
<th>Class</th>
<th>Be</th>
<th>β Cep</th>
<th>SPB</th>
</tr>
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<tr>
<td>Type</td>
<td>O8-A2</td>
<td>B0.5-2</td>
<td>B2-B8</td>
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<td>Luminosity class</td>
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<td>III-IV</td>
<td>III-V</td>
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<td>Typical mass</td>
<td>8 M☉</td>
<td>12 M☉</td>
<td>5 M☉</td>
</tr>
<tr>
<td>Typical radius</td>
<td>6 R☉</td>
<td>7 R☉</td>
<td>5 R☉</td>
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<tr>
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</tr>
<tr>
<td>Line-profile var.</td>
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<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>Rotation rate</td>
<td>high (some low)</td>
<td>low (some high)</td>
<td>low (some high)</td>
</tr>
<tr>
<td>Specifics</td>
<td>Balmer emission</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Main pulsations</td>
<td>non-radial</td>
<td>radial</td>
<td>non-radial</td>
</tr>
<tr>
<td>Pulsation periods</td>
<td>0.2-2 days</td>
<td>0.1-0.3 days</td>
<td>0.5-3 days</td>
</tr>
<tr>
<td>Modes</td>
<td>p, g (or r)</td>
<td>p (or f)</td>
<td>g</td>
</tr>
</tbody>
</table>

Table 1.1: Comparison between different types of early B-type stars.

The key problems in understanding this phenomenon are then: (i) how to enhance the specific angular momentum of ejected material so that it can attain a stable orbit, and (ii) how to eject quantities of mass in the observed nonsteady fashion.

A few explanations have been proposed: beating of non-radial pulsations (NRP) modes, presence of magnetic fields, hot spots, photospheric shocks and/or mass transfer in interacting binaries (see e.g. Baade 2000; Balona 2000). Up to now, however, observational facts and theories did not converge towards a conclusive explanation.

1.1.2 β Cephei stars

β Cep variables, known since 1902, are early-B subgiants or giants (B0.5 to B2, luminosity class III or IV) that exhibit coherent short-period light and radial velocity variations (Fig.1.4), successfully explained in terms of pulsations. Pulsation periods of β Cep variables range from about 3 to 8 hours. Most of them are discovered photometrically, although the amplitude of light variation is rather small. The full amplitude of radial velocity variations range from about 10 to 50 km s⁻¹.

The driving mechanism was not understood for a long time. In contrast to several other variable classes of stars (e.g. δ Scuti, RR Lyrae), the region of ionisation of He I cannot destabilise β Cep stars. It was not until 1993, when new atomic data became available, that it became clear that the classical κ mechanism is the cause of the pulsations in these stars, i.e. that it is an effect of the opacity of iron-peak elements deep in the envelope of the star. (Dziembowski & Pamiatnykh 1993; Dziembowski et al. 1993).

The small range of spectral types and luminosities among the β Cep stars make them cluster in a small region in the H-R diagram, called 'the β Cep instability strip'. Some β Cep stars also show Balmer emission, which makes them Be stars. β Cep itself, the prototype of this class, is a Be star, but slowly rotating. This latter point is relevant, since most of the theoretical efforts to explain Be stars have been concentrated on rapid rotation. The amplitude
of pulsation of the $\beta$ Cep stars has its peak at the center of the instability strip, next to the main sequence, and decreases towards both directions of luminosity. However, $\beta$ Cep stars are normal main-sequence or slightly evolved stars in the core hydrogen burning stage.

$\beta$ Cep stars were first thought to be restricted to slow rotators, but Shobbrock et al. (1969) discovered rapidly rotating examples. The fact that only slow rotators were first discovered was due to selection effects (see also Schrijvers 1999).

Smith (1980) has argued that the main pulsation mode of $\beta$ Cep stars is radial. Nevertheless non-radial pulsations were also detected in some of them. Their presence could generate multi-period beating, a mechanism which can, in principle, cause long term phenomena.
1.1.3 SPB stars

Slowly Pulsating B (SPB) variables are B2 to B8 stars that show both light and line-profile variability. Typical periods are 0.5 to 3 days, thus too long and too unstable to be associated with $\beta$ Cep variability. SPB variables are situated just below the $\beta$ Cep stars in the H-R diagram. Their line-profile variations are interpreted in terms of non-radial pulsations.

The SPB stars were considered to be slow rotators, but, similar to $\beta$ Cep stars, a few rapidly rotating ones have recently been discovered.

The recent observation of a rapid filling of the equivalent width of H and He i lines in the B2.5 IV star 53 Psc (Le Contel et al. 2001) seems to indicate that some of the SPB stars also show the Be phenomenon.

Note that the majority of the stars previously classified as mid-B variables or 53 Per stars...
Figure 1.4: Radial velocity variations of the He I 4921 line for the β Cep star V 2052 Oph (chapter 5), explained in terms of pulsations and rotational modulation.

are now considered to be SPB stars, since Waelkens (1991) discovered that they all show the same kind of variations and are all slow non-radial pulsators.

1.2 Pulsations

1.2.1 Theory

Two types of stellar oscillations are distinguished: radial and non-radial. The radial pulsation is the simplest type in which a star oscillates around its equilibrium state by expanding and contracting in a periodic way, while keeping its spherical shape. In the case of general NRPs the total volume is conserved, but not the sphericity, as neighboring segments of the star oscillate in different phases. Theoretically, radial pulsations can be treated as a special case of NRPs.

NRP modes are characterised by three main parameters: the pulsation degree $l$, the az-
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**Figure 1.5**: Examples of non-radial pulsations modes (Schrijvers 1999). Black areas move outward, whereas the white areas move inward.

Imuthal order $m$ and the radial order $n$. The stellar surface is divided into parts oscillating in antiphase defined by $l$ border lines, of which $|m|$ are spaced equally in azimuth for constant longitude. Thus $l - m$ is the number of border lines of equal latitude and $-l \leq m \leq l$. $n$ is the number of nodes from the center to the surface of the star. Examples of pulsations modes are shown in Fig. 1.5. For further reading and mathematical formulations, the book by Unno et al. (1989) is recommended.

It should be noted that pulsation periodicities of rotating stars are difficult to predict by theory, because many physical effects cannot yet be taken into account in the theory of stellar structure, especially in case of rapid rotation. In a real star, the amplitude of pulsations is limited by non-linear processes, which cannot be calculated yet either.

### 1.2.2 Observations

NRPs are expected to occur in basically all stars, but it is difficult to find them, because NRPs can only be detected as very small perturbations moving through the line profiles, affecting often less than 0.1% of the intensity (see Fig. 1.6). This requires at least 2m-class telescopes equipped with high-dispersion spectrographs, even for the brightest stars. The observational problem is further complicated by the timescales of pulsation, outflow and rotation, which are all of the order of hours to days, close to the 1-day rotation period of the Earth. Therefore, any serious attempt to study these phenomena requires the simultaneous effort of several observatories around the globe, or satellites.

Especially the detection of a beating effect between two close frequencies is very difficult. Yet, Rivinius et al. (1998) obtained the first and up to now only evidence for pulsation beating,
in the Be star $\mu$ Cen. They could relate the beating period to epochs of strong emission events (outbursts), and thus successfully predict the time of future outbursts.

### 1.3 Magnetic fields

It is well known that solar-type (low-mass) stars have magnetic fields, generated in the convective outer layer of the star. Massive stars, however, have only a very thin convective region near the surface (apart from the convective core) and no mechanism is known that can generate a substantial field in these stars, in spite of the fact that a number of magnetic B stars are known.
1.3.1 Zeeman effect

When studying the formation of spectral lines in the presence of a magnetic field, it is necessary to take into account the state of polarisation of the light. The state of arbitrarily polarised radiation can generally be represented by a set of four parameters, first introduced by Stokes (1852). Chandrasekhar (1950) introduced the present form of the Stokes parameters: I, Q, U and V. I is the total intensity of the radiation, Q and U characterise the linearly polarised light, and V represents the circularly polarised light.

In the presence of a magnetic field, an atomic level is characterised by three fundamental quantities: its energy, the total angular momentum quantum number $J$ and the Landé factor $g$. Because of the magnetic field, the atomic level is split into $(2J + 1)$ atomic states, each of them having a magnetic quantum number $M$ which varies from $-J$ to $J$ in steps of one. This splitting is called the Zeeman effect.

This description is valid in the weak field limit, i.e. when the quadratic Zeeman effect is negligible and the magnetic splitting of the level is small compared to the fine structure. For more details and applications to astronomical settings, see Mathys (1989).

1.3.2 The magnetic oblique rotator

In the magnetic oblique rotator model (Stibbs 1950) the magnetic field structure is not symmetric about the rotation axis of the star. For the most simple case of a dipole field, this means that the axis of the dipole and the axis of rotation do not coincide. The observed stellar configuration can then be characterised by the inclination angle $i$ between the observer’s line-of-sight and the stellar rotation axis and by the magnetic field angle $\beta$ between the magnetic axis and the rotation axis (see Fig. 1.7).

The magnetic field determines the properties of surface features, such as the distribution of the chemical abundances over the star. Therefore, in case of stars with a wind, such as the ones studied in this thesis, as the star rotates, the aspect of its visible hemisphere changes. This leads to variations in various observables, such as the shape and equivalent width of wind-sensitive UV resonance lines. The period of these variations is the stellar rotation period.

1.3.3 Observations

Over the past years an increasing number of observations has been obtained, which provide indirect evidence that hot stars must have magnetic fields, in particular because their winds are modulated or perturbed by the rotation. However, direct detection of weak magnetic fields in hot stars is particularly challenging. A high-resolution spectropolarimeter mounted on a large telescope is needed, and only very few such configurations exist. The present detection technique uses the difference in wavelength of the oppositely shifted Zeeman components of a spectral line as a measure of the strength of the magnetic field. For weak fields this wavelength difference is at the limit of what can be detected with present instrumentation.

The result can be improved by accumulating the magnetic signal of all the observed lines together, with the Least Square Deconvolution (LSD) technique (Donati et al. 1997). This
technique has provided many detections of magnetic fields for cool stars which have thousands of lines. However, the number of spectral lines in hot stars is much lower and their line profiles are often broadened by fast rotation and other mechanisms (e.g. pulsations). Another complication is that the Zeeman technique only measures the projected component of the field in the line of sight, which can be much weaker than the polar field, especially when high order fields are involved.

Yet, Henrichs et al. (2000) have reported the detection of a weak magnetic field in $\beta$ Cep, the prototype of $\beta$ Cep stars which is also a Be star, but with an unusually low rotational velocity (Fig. 1.8). The magnetic field of this star is well understood in the frame of an oblique rotator model.

1.4 Overview of the thesis

In this thesis we study early B-type stars by concentrating on the two presently most favored explanations for the Be phenomenon, i.e. the beating of non-radial pulsations and the presence of magnetic fields.

In Chapter 2, we report on the Multi Site Continuous Spectroscopic (MuSiCoS) campaign held in 1998. We find multiperiodicity in the Be star $\omega$ Ori from line-profile variations and identify the associated pulsation modes. We observed a dense cloud orbiting around the star, and propose two scenarios to explain its behavior in relation with the outburst of the star.

In Chapter 3, we re-investigate $\omega$ Ori by combining our MuSiCoS 1998 dataset with data
taken in 1999 by Balona et al. (2001) and in 2001 at the Pic du Midi, to try to improve the frequency determination. We report on the probable discovery of a magnetic field in this star, which makes it the first magnetic classical Be star.

In Chapter 4, we perform a line-profile variability search in the Be star 66 Oph and find multiperiodicity. We have also searched for the presence of a magnetic field in this star, but further study is necessary.

The multiperiodicities detected in these two Be stars build confidence in the possibility that a beating effect occurs in more Be stars than μ Cen, which could be the explanation of the Be phenomenon. The presence of a magnetic field could also play an important role.

In Chapter 5, we report on the discovery of a non-radial pulsation mode in the β Cep star V 2052 Oph, in addition to the already known radial mode. From UV observations, we obtained a precise determination of the rotational period and showed the presence of rotational modulation of several observables. Moreover a weak magnetic field is discovered in this star, together with associated phenomena such as chemical peculiarities. We discovered that this star belongs to the He-strong class of objects. This is the first discovery of a magnetic field in a β Cep star without emission lines.

In Chapter 6, we present the first discovery of a magnetic field in a SPB star: ζ Cas. Again pulsations and rotational modulation are studied, in the framework of the oblique magnetic dipole model.
The discoveries of weak magnetic fields in $\omega$ Ori, V 2052 Oph and $\zeta$ Cas raise the number of known magnetic early-B stars from one ($\beta$ Cep) to four. Specific UV variability and chemical abundance peculiarities are found in all these stars and can be used as selection criteria for forthcoming observations. These conclusions are summarised in Chapter 7.

1.5 Future work

Magnetic pulsating early-B stars are apparently rather rare. Shibahashi & Aerts (2000) showed, although the mathematical formulation needs improvement, that studying the pulsation properties of a rotating magnetic star gives strong constraints on its stellar parameters and its evolutionary stage, which is of high asteroseismological importance. Confirmation of the above results and finding more such stars is needed.

The EsPaDonS spectropolarimeter, which will be soon available on the 4-meter telescope at the Canada France Hawaii Telescope (CFHT), and which will be at least 10 times more efficient than the Musicos spectropolarimeter at the Pic du Midi, France, will certainly make a breakthrough in the discovery of magnetic fields in early B-type stars.

In addition, the satellite CoRot, which will be launched in November 2005, will provide long-term continuous observations of many B stars and is expected to discover new pulsations periods in these stars, especially beating periods.

Theoretical modeling of the associated phenomena should go hand in hand with these advancements.

Bibliography

Mathys, G. 1989, Fundamentals of Cosmic Physics, 13, 143
Schrijvers, C. 1999, PhD thesis, Universiteit van Amsterdam
Secchi, A. 1867, Astron. Nachr., 68, 63
Stokes, G. G. 1852, Trans. Cambridge Phil. Soc., 9, 399
Unno, W., Osaki, Y., Ando, H., Saio, H., & Shibahashi, H. 1989, Nonradial oscillations of stars (University of Tokyo Press, 2nd ed.)
"In theory, there is no difference between theory and practice. But, in practice, there is."

Jan L.A. van de Snepscheut