On the origin of cyclical variability in the winds of massive stars

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Chapter 1

Introduction and summary

1.1. Introduction

The goal of this thesis work is the search for the origin of the widely observed cyclical variability of winds of hot, massive stars. This is one of the most challenging problems in the research of massive stars during the past 15 years. We first describe the considerations that lead us to this investigation, and highlight in the following sections the background and importance of this research.

At present, two different mechanisms are proposed as a possible cause of the variability of winds of massive stars: non-radial pulsations (where the phase of the oscillation varies over the surface) and magnetic fields, both of which being surface phenomena that are very difficult to observe in these stars. The observational support is very scarce. At present there are only 6 confirmed O stars with non-radial pulsations, two of which were found during this thesis work (as the result of 8 years of progress in theory and techniques of analysis after the data had been obtained), and there is no O star at all with a magnetic field detection. However, the evidence that the periodicity of the wind variability is directly related to the rotation period of the star is overwhelming. This implies that some surface phenomenon must play a dominant role in modulating the wind, and the presence of (small) magnetic structures anchored to the surface is the most obvious candidate, although non-radial pulsation modes can in principle do the same job.

Non-radial pulsations are expected to occur in basically all stars. The theory predicts this kind of instabilities over a large part of the HR diagram, but the predictions of the pulsation periods or amplitudes for hot, massive stars are only qualitative so far. It is difficult to find non-radial pulsations in these stars because non-radial pulsations can only be detected as moving, very small perturbations in the line profiles, often less than 0.1% of the intensity. This requires 2m-class telescopes equipped with high-dispersion spectrographs, even for the brightest stars. The observational problem is complicated even more because the timescales for pulsation, outflow and rotation are all of the order of hours to days, and any serious attempt to study these phenomena requires the simultaneous effort of several observatories around the globe. Presently the (Fourier) techniques to detect non-radial pulsations in rotating stars are reasonably well developed (see Teltzing 1996, Schrijvers 1999), but the bottleneck remains to obtain a homogeneous dataset with sufficient coverage (typically a few observations per hour) over a long enough time interval (typically a week).

Although at first sight it may seem obvious that magnetic fields must play a major role in modulating the outflowing stellar wind, the difficulties with magnetic fields are manyfold. First of all, there is no theory that predicts the occurrence of a specific magnetic field configuration on the surface of massive stars, mainly because these stars have no outer convection layer such as in solar-type stars. The observational problems are at least as severe. One needs a specialized instrument of which there are only very few available. The present detection techniques, based on the Zeeman effect, make use of the fact that the difference in wavelength of the oppositely shifted Zeeman components of a spectral line is a measure of the strength of the magnetic field. For small fields this difference is at the border of what can be detected above the noise. Modern multiplexing techniques use the accumulated signal of all the observed lines together. This works very well for cool stars which have thousands of lines, but hot stars have only a few tens of lines at most, which strongly limits the advantage of multiplexing. Another complication is that this Zeeman technique only measures the projected component of the field in the line of sight, and the true field can be 10 times larger. In this thesis we describe the best effort ever to search for a magnetic field in one of the brightest O stars, but report only an upper limit. We also describe the discovery of the magnetic field in the B1 III star β Cephei, the hottest star found sofar with a significant field, which clearly demonstrates that massive stars can have a magnetic field (the origin of which, however, remains unclear), and that the techniques are available, but that apparently the sensitivity of the instrumentation is not yet high enough for the application to O stars.

From the above it is clear that the problem of cyclical wind variability can only be solved with a large observational effort. In the last 10 years a number of multisite campaigns has been conducted, organized from Amsterdam (principal investigator H.F. Henrichs), and included space-
and ground-based observatories to study a few carefully selected bright O stars. This thesis concentrates mainly on the analysis of the acquired data on the 4th magnitude O7.5 III star ξ Persei, which is the most suitable target for this purpose on the Northern Hemisphere. Such campaigns not only involve the logistics of proposal approval and schedule synchronization of sometimes a dozen observatories (all with their own procedures), but also the non-trivial and time-consuming task of reducing the data from equally many different sources. The reduction has to be done in one place to ensure the required homogeneity, which appeared essential for a sound Fourier analysis. Several new techniques have been developed, in particular to extract quantitative information on periodicities with their uncertainties. This analysis will therefore serve as a case study for the further analysis of other O stars, for which data has been obtained.

In this introduction we outline the importance of the study of massive stars, and review the present insights on stellar winds and their variability. We conclude with a summary of this thesis.

1.2. The role of O and B stars

The most massive stars, with spectral type O and B, and masses ranging from 8 to 100 M☉, play an important role in the universe. First of all they are hot and luminous with temperatures between 20,000 and 50,000 K and luminosities ranging from 10⁵ to 10⁶ L☉. With these luminosities they contribute to a major part of a galaxy’s luminosity. The brightest supergiants are visible as individual stars in other galaxies up to the Virgo cluster (at 20 Mpc). These stars have a strong wind, which is driven by the radiation pressure of the star. Mass-loss rates of 10⁻⁵ to 10⁻⁴ M☉yr⁻¹ are typical for O and early B stars. This material is expelled with velocities up to 3000 km s⁻¹, which makes them very important contributors to the energy and momentum budget of the interstellar medium. This mass loss also has a large impact on their evolution. The most luminous stars can lose half of their initial mass during their lifetime. After various stages of evolution the ongoing mass loss finally leads to the exposure of the hot stellar core when the star becomes a Wolf-Rayet star. Ultimately, these stars end their active lives with a violent supernova explosion and enrich the interstellar medium with heavy elements. The shock waves from these explosions trigger new star formation, whereas the remnants, in the form of neutron stars and black holes, are responsible for many energetic phenomena in the universe.

In order to understand the evolution of massive stars knowledge about mass loss and stellar winds is essential. It is therefore important to study in detail the mechanisms at work in radiatively driven stellar winds. Similar physical processes act in other outflows like in quasi-stellar objects (QSOs) and active galactic nuclei (AGNs). Like in many other astrophysical problems, the observed variability provides an important diagnostic for the study of these processes, deriving the relevant physical parameters and to test current theories.

1.3. Radiatively driven stellar winds: a brief history

Massive stars were long suspected to have dense stellar winds driven by the radiation pressure of the star. Milne (1924) predicted the high-speed ejection of atoms from stars and noted the instability of line-driven outflows and their susceptibility to line-shocking (see the review of Lucy 1998). In the C III λ5896 emission line of the O9.5 Ia star α Cam Wilson (1958) detected wings which extend up to 1500 km s⁻¹, and interpreted this as being due to high-speed outflow.

The most important evidence for hot star winds was provided by the discovery of P-Cygni type profiles in the UV resonance lines of C IV, N V and Si IV in the spectra of O and B supergiants obtained with rocket experiments by Morton (1967). These profiles are characterized by a blue-shifted absorption part convolved with an emission profile centered at rest wavelength. The blue-shifted absorption trough is formed by material in front of the star flowing towards the observer, whereas the emission part originates in the outflowing gas all around the star. The most negative velocity at which still absorption is found (called the velocity edge) is identified with the terminal velocity (v∞) of the wind. Since the observed v∞ is several times larger than the escape velocity (vesc), it became immediately clear that these stars are losing mass. Abbott (1982) found that the mass-loss rate \( M \propto L^{1.8} \) and that v∞ scales with vesc. This gave strong support to the idea that radiation pressure provides the driving force.

It can easily be shown that electron (Thomson) scattering alone is not sufficient for providing the radiative acceleration. Lucy & Solomon (1970) showed that the line opacity from strong lines formed in the wind makes an important contribution to the driving of stellar winds. Castor, Abbott & Klein (1975, CAK) further developed the radiation-driven wind theory by including the contribution of weak lines. They provided a theoretical basis for the observed relation between \( M \) and \( L \) and \( v_\infty \) and \( v_\text{esc} \). Integration of the equation of motion results in the widely used velocity law for the relation between velocity \( v \) and distance \( r \) to the center of the star, which takes the form

\[
v(r) = v_\infty \left(1 - \frac{R_\ast}{r}\right)^{\beta}
\]

According to the CAK-theory \( \beta = 0.5 \). Later improvements (Friend & Abbott 1986, Pauldrach et al. 1986) resulted in \( \beta = 0.8 \), which is in good agreement with observations. Also the predicted mass-loss rates and terminal velocities are in fair agreement with the observations. Furthermore, a comparison between observed and predicted line profiles reveals fundamental parameters such as mass, radius, and luminosity of the star (see Kudritzki & Hummer 1990 and Kudritzki 1998 for reviews). Under certain
conditions these fundamental parameters can also be derived from Hα line profiles (Puls et al. 1996, Petrenz & Puls 1996). Since Hα can even be observed in O stars in external galaxies they provide an excellent standard candle for distance measurements (Kudritzki 1998).

1.4. Wind variability

After the pioneering work by Morton (1967) a systematic study of UV spectra was initiated with the launch of the Copernicus satellite. In the ultraviolet P Cygni profiles of many OB stars unexpected features were discovered, the so called high-velocity narrow absorption components (e.g. Underhill 1975, Morton 1976, Snow & Morton 1976, Lamers et al. 1982), of which the nature was totally unclear, although they were obviously formed in the wind. With the launch of the International Ultraviolet Explorer (IUE) satellite in 1978, operated jointly by NASA from Goddard Space Flight Center in Greenbelt, and by ESA from Villafrance near Madrid, a new very fruitful era of UV spectroscopy started. It soon appeared that these narrow absorption components could vary in strength and shape on timescales of a few hours and that they occurred in the majority of OB and Be stars (Henrichs 1984). Throughout the operational lifetime of the IUE satellite (1978 – 1996) the study of variability of these UV lines has been one of the focal points and several thousands of UV spectra of OB stars have been recorded. From the obtained time series it became clear that the variability is not chaotic, but occurs in regular patterns (e.g. Prinja et al. 1987, Henrichs et al. 1988). Broad absorption features appear at low or intermediate (0.2-0.5v∞) line-of-sight velocity and narrow in width when they approach the terminal velocity. Because of their distinct appearance these features were since then called discrete absorption components (DACs).
At first sight, such a strong variability is not expected in radiation-driven winds, in which the dynamics is determined by the \( \sim \) constant luminosity and gravity of the star. However, a line-driven wind is expected to show random fluctuations due to a potent instability: a small-scale increase in the flow speed Doppler-shifts the local line frequency out of the absorption shadow of the underlying material, leading to an increased radiative force which then tends to further increase the flow speed (Lucy & Solomon 1970, Owocck & Rybicki 1984). However, these fluctuations most likely end up at small-scale variability and not to the large-scale regular DAC variability. The black troughs in UV resonance lines and the observed X-ray emission from O stars are, however, well explained by this kind of instability (Lucy 1982, Owocck et al. 1988, Puls et al. 1993).

As first suggested by Prinjja (1988) and Henrichs et al. (1988) and later confirmed by other studies, in particular by the extensive study of the DAC properties in ten different O stars (Kaper et al. 1996, 1999a), it was found that the DAC variability is cyclic and that the recurrence times are proportional to the reciprocal of the projected rotational velocity (\( \text{vsini} \)). Figure 1.1 shows some examples of developing DACs in progressively faster rotating stars. This strongly suggests that the variability is caused by some structure which corotates with the star. The possibility of the presence of Corotating Interaction Regions (CIRs) in hot-star winds, in analogy to what is observed in the inhomogeneous solar wind was first proposed by Mullan (1984, 1986). In this model the emergent wind flow is perturbed by some inhomogeneity at the surface of the star, which causes an azimuthal asymmetry. Such a structure produces a local change in the wind flow properties. Further-out in the wind, the slow material is caught up by faster wind coming from below and collides, thus forming shock-fronts which corotate with the star. Prinjja & Howarth (1988) suggested CIR-like structures to explain the DAC behavior in the O7.5 III star 68 Cyg. Cranmer & Owocck (1996) performed the first hydrodynamical computations of a CIR model (see Fig. 1.2), and were able to reproduce the behavior of the DACs. They did not specify the nature of the perturbation at the bottom of the flow. One could think of non-radial pulsations (which divide the star in oppositely moving sectors) or magnetic field configurations (with different temperature and brightness).

**1.5. Observational strategies**

A number of extensive timeseries of UV spectra of OB stars have been obtained, showing the detailed evolution of DACs, following a pattern typical for a given star (e.g. Massa et al. 1995 presenting the IUE MEGA campaign including \( \zeta \) Pup, HD 64760 and HD 56980), Kaper et al. 1996, 1999a), but these observations gave no clue about the origin of the DACs. For this purpose one needs to study the wind structure as a function of distance to the star, which requires elaborate multiwavelength observations. In Fig. 1.3 a schematic map of the line-forming regions in the wind is given. The UV resonance lines (Si IV, N V and C IV) are formed throughout the wind, while e.g. the sub-ordinate lines of N IV and H\( \alpha \) are formed closer to the star. Several other optical lines are formed in the photosphere and in the transition region. The photospheric lines are used to study the stellar surface, e.g. for the presence of non-radial pulsations. Polarization measurements to search for magnetic fields can also be done using optical lines.

The first campaign to study the O7.5 III star \( \xi \) Per, the main target of this thesis, was organized in 1989, which included IUE observations with ground-based support from the Calar Alto Observatory in Spain and Kitt Peak. This yielded the insight that the variability of the wind is already detected near the stellar surface (Henrichs et al. 1994). Furthermore, the pulsational properties of the star could be determined (de Jong 2000b, Chapter 5). The latter was only possible after many modeling efforts to describe and anal-
use the pulsational properties of rotating stars. More co-
ordinated optical and UV observations were carried out
in 1991 (Kaper et al. 1997), including Hα measurements.
This study showed that the wind variability by DACs is also
reflected by the variations in the Hα line. In October
1994 an extensive campaign of 10 days of IUE observ-
ations and simultaneous multi-site groundbased observa-
tions of ξ Per (and a few other O stars) was organized. This
star has a DAC period of 2 days. This campaign provided
a wealth of information about the wind structure (de Jong
2000a, Chapter 2). All the UV lines and the Hα line show
a periodicity of 2.09 d and are strongly correlated. We could
only explain these observations by the presence of multiple
CIRs and a stellar rotation period of 4.18 d. This is remark-
able because the implied radius of the star, given the ob-
erved projected rotation velocity, has to be in this case at
least 17 R⊙, which is rather large for a luminosity class III
giant (Kaper et al. 1999a, de Jong et al. 2000a, Chapter 2).
Model atmosphere calculations should show whether this
conclusion is justified.

Since the IUE satellite was switched off in 1996 (be-
cause of budgetary reasons), only the optical lines (espe-
cially Hα) can be observed for further studies of O star
winds. In principle the Hubble Space Telescope could be
used for this purpose as well, but in practice it is not feasible
to obtain continuous observations with the HST for a num-
ber of days. In order to get more insight in the optical line
profile variability we conducted a new multi-site (MuSi-
CoS, “MultiSite Continuous Spectroscopy”) campaign on ξ
Per in 1996 (Henrichs et al. 1998b, Chapter 3). This time all
telescopes were equipped with échelle spectrographs which
covered the whole optical range. Unfortunately the IUE
satellite was taken out of service just before the start of the
campaign (although observing time was allocated). During
these campaigns an attempt to measure the magnetic field
was made, but only upper limits could be obtained.

1.6. A search for the origin of wind variability

Although the CIR model is now widely accepted as the
proper model for the UV wind variability, the origin of the
perturbations is still unknown. As described above, non-
radial pulsations or magnetic fields are both still valid op-
tions, the latter of which still being the strongest candidate.

Several B stars are known to have a magnetic field. The
He peculiar B stars are all thought to have magnetically
confined winds (e.g. Shore & Brown 1990). Also some β
Cep stars, which share their position in the HR diagram
overlaps with the He-strong stars were suspected to have
a magnetic field because the phenomenology of the stellar
wind variations is similar to that of the Bp stars as far as the
UV is concerned (Henrichs et al. 1993). We report in Chap-
ter 5 the detection of a magnetic field of 90 G in the slowly
rotating star β Cep (B1 IiIe), which is modulated with the
stellar rotation period of 12 days. This is the hottest upper
main-sequence star for which a magnetic field has been dis-
covered so far. The field in this star is very weak (the second
weakest among all B and A stars with a detected field), but
apparently strong enough to control the wind up to 10 stel-
lar radii. For most O stars it is not likely that their winds are
magnetically controlled, which also constrains the strength
of the field. As an interesting conclusion regarding β Cep
we note that this slowly rotating star, which shows intermit-
tent Hα emission similar to the enigmatic Be stars (Mathi-
has et al. 1991, Kaper & Mathias 1995), provides an exam-
ple in which the Hα emission is not due to rapid rotation
such as in other Be stars, but rather due to the presence of a
strong enough magnetic field.

It is therefore tantalizing that no magnetic fields have
been detected yet in O stars. The O7 V star θ1 Ori C is
strongly suspected to have a magnetic field, since the phe-
nomenology of the variations is very similar to that of mag-
netic rotators of the Ap and Bp group (Stahls 1998). Do-
nati & Wade (1999b) and Mathys (1999) attempted to mea-
sure the field of θ1 Ori C, but only found an upper limit of
250 G in the longitudinal component, which means that
the polar field strength can be up to 2.6 kG. We made
several attempts to measure the field of the O7.5 III star
ξ Persei (October 1994 campaign: Henrichs et al. 1998a,
de Jong et al. 2000a, Chapter 2; November 1996 MUSI-
COS: Henrichs et al. 1998b, Chapter 3; December 1998 Pic
du Midi: de Jong et al. 2000b, Chapter 5), but our best result
is an upper limit of 47 G on the disk-averaged longitudi-
nal component of the field. From this we estimate an upper
limit of 400-500 G on the polar field strength (de Jong et al.
2000b, Chapter 5). We predict that with at least 4m-class
telescopes and very good weather conditions a field detec-
tion should be possible with the current instrumentation.
The new generation of polarimetric instruments developed
for spectrographs like ESPADONS should make the detec-
tion of apparently weak fields possible.

The second candidate for the surface perturbations is the
presence of non-radial pulsations (NRP) in which neigh-
boring segments of the star oscillate in different phases. A
NRP mode is determined by the parameters ℓ and m. The
value of ℓ indicates the total number of node lines on the
surface of which m node lines cross the equator. There are
three types of NRP: sectoral (ℓ = |m|), zonal (m = 0) and
tesseral (ℓ > |m|, m ≠ 0). Examples of these NRP types
are shown in Fig. 1.4.

NRP will cause velocity and density perturbations at the
base of the wind, but the velocity with which NRP bumps
move with respect to the stellar surface depends on the NRP
mode and frequency. This velocity has to be added to the
rotation velocity in order to derive the timescale it takes for
a feature on the surface to cross the visible disk of the
star. Until now NRP have been confirmed in six O stars
and are suspected in two more (see Henrichs 1999b for an
overview). We report in Chapter 4 the discovery of NRPs in
the O stars ξ Per (P=3.45 h, ℓ=3) and λ Cep (P=12.3 h, ℓ=5
and P=6.6 h, ℓ=5). The NRP in ξ Per can most probably not
account for the DAC period of 2.09 d, because its pattern
speed and time scale are incompatible. However, other variability in the wind, visible in Hα on time scales of hours, could well be due to NRP (de Jong et al. 2000b, Chapter 5). Beating effects between multiple NRP modes has shown in some Be stars to provide a mechanism to enhance the mass-loss rate at certain pulsation phases (Rivinius et al. 1998). Whether this can give rise to wind variability in O stars is not known. Further studies are obviously needed.

1.7. Towards modeling the wind structure

Extensive time series were also obtained of the Hα line, which maps the inner part of the wind, of most (~40) bright O stars during several years (Kaper et al. 1998). Especially the O supergiants show very complicated line profile variations, which also differ very much from star to star. Main sequence stars do not show such variations in the Hα line, probably because their wind is too weak. This variability is cyclical and is also most likely related to corotating structures. No good model is currently available to explain this behavior in detail. As a first attempt to understand these variations we modeled the Hα variability using a 2D kinematic model in which spiral like structures are accounted for (de Jong et al. 2000c, Chapter 7). We developed a code based on genetic algorithms to search for the best parameters to describe this structure. Due to the limitations of the model only a qualitative agreement could be obtained. This is an essential first step in trying to understand what happens close to the stellar surface in the transition region between the photosphere and the wind.

1.8. Contents of this thesis

In the next three chapters we describe the results of three major campaigns on ξ Persei. Each campaign has its own focus. The first one in October 1994 was the most extensive global campaign, which included UV timeseries of spectra (Chapter 2). We concentrated on obtaining a long period of observations to study the phase relation between the different spectral lines. In the MuSiCoS campaign in November 1996 (Chapter 3) we searched for magnetic fields (simultaneously with line variability) with better instrumentation, but this campaign was hampered by bad weather. The third describes the discovery of non-radial pulsations in the O stars ξ Persei and λ Cephei, based on data obtained in 1989. In Chapter 5 we present the results of the best attempt so far to search for a magnetic field in ξ Per, using the MuSiCoS polarimeter at Pic du Midi in France. Chapter 6 describes
the discovery of the magnetic field in $\beta$ Cephei. In the last chapter we present the results of extensive modeling of the inner part of the wind by means of 2D calculations.

References


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