O AND B-STAR SURFACE MAPPING

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1. Introduction

The massive O and B-type stars will be among the first targets of the new generation of long baseline optical interferometers (such as the CHARA Array, a 400-m diameter distributed array of five 1-m telescopes). Many of these objects are binary stars for which joint astrometric and spectroscopic observations will provide masses and distances (e.g., 15 Mon; Gies et al. 1993), but there is also great interest in resolving disks of single stars. Early interferometric observations have already resolved the flattened circumstellar disks around some Be stars (Quirrenbach et al. 1994).

There is circumstantial evidence from stellar wind studies that some type of surface structure should be present. Most O stars display time variable optical depth enhancements in their UV P Cygni wind profiles (now known as discrete absorption components) that originate in spatial structures in the wind that extend to near the photosphere (see references in Fullerton, Gies, & Bolton 1996 [FGB]). Prinja (1988) and Kaper (1993) suggest that the recurrence time scales of these features are related to the rotation period of the underlying star. This connection with rotation is seen dramatically in *IUE* spectra of the B-supergiant HD 64760 (Prinja, Massa, & Fullerton 1995) and the O-giant ξ Per (Henrichs et al. 1995).

Although these observations suggest that the wind variations have their source in photospheric structures, there is no consensus yet on the nature of these structures. Little is known about the strength or geometry of magnetic fields in normal OB-stars, since observations have yielded only upper limits of a few hundred Gauss (Bohlender 1994). However, the discovery of periodic Hα and wind variations in the O6 dwarf θ^1 Ori C which are apparently cyclic with the rotation period (Stahl et al. 1993; Walborn & Nichols 1994) potentially offers one example of magnetically controlled activity. The other leading contender for structure is photospheric nonradial

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pulsation (NRP) which is an attractive model because it can readily account for many kinds of photometric and line profile variability (Gies 1991, 1994) and because pulsations are expected theoretically (Kiriakidis et al. 1993). Here I review the observational evidence for NRP in hot stars and the methods that are used to relate profile variations to NRP models. Special attention will be given to models for the rapidly rotating O star, ζ Oph, which has played a pivotal role in this young field.

2. Profile Variations and Surface Structure

Systematic line profile variations were discovered in several key O and B stars early in the 1980s (see reviews of Smith 1986, Walker 1991, Baade 1988, Gies 1991). In a seminal paper, Vogt & Penrod (1983) described the nature of these line profile variations (*lpv*) in the prototype star ζ Oph (O9.5 V; $V \sin i = 400$ km s^{-1}). The *lpv* take the form of "bumps" which generally cross the absorption lines from blue-to-red on time scales of hours. Vogt & Penrod showed that the crossing times of these features are too rapid to be caused by stellar rotation (the star would be rotating much faster than the critical, break-up velocity); nor could they be caused by transits of clumps of orbiting circumstellar gas (since the observed photometric variations are too small). Rather they argued that the *lpv* arise in photospheric nonradial pulsations that can act to re-distribute the flux in a rotationally broadened profile through the creation of sectors of differing velocity and temperature in the visible hemisphere of the star.

These early studies provided the motivation for surveys of *lpv* in a variety of early-type stars, and it is now clear that the incidence of *lpv* is widespread (see the excellent review by FGB). A systematic, high S/N spectroscopic survey of the O stars has recently been made by FGB who have developed statistical, objective methods to assess the presence of *lpv*. They find that *lpv* is present in 77% of their sample (23 of 30 stars), and the incidence and amplitude of variability increase with increasing stellar radius and luminosity (all the supergiants display *lpv* but none of the dwarfs earlier than O7). Recent and impressive studies of individual O stars have been made by Howarth & Reid (1993; HD 93521) and Reid & Howarth (1996; ζ Pup). A survey similar to that of FGB has been conducted for early B-type, non-emission line stars by Fieldus & Bolton (1994). (The completion of this work has been delayed by the tragic death of Michael Fieldus.)

A great deal of work has been devoted to *lpv* in Be stars which has been motivated in part by Penrod's (1986) suggestion that NRP could play a defining role in the creation of the circumstellar emission disk. It is now clear that the winds of Be stars are important in disk formation (Bjorkman

& Cassinelli 1993; Owocki, Cranmer, & Blondin 1994), but there is emerging evidence that mass loss processes related to NRP are also important. Much of the work on Be stars has taken the form of coordinated, multiwavelength observing campaigns on selected targets (Peters 1994; Gies 1994; Stefl et al. 1995). Most of the target stars display variability consistent with an $l = -m = 2$ NRP mode with periods on the order of a day, and the associated light curves are consistent with the pulsation periods, amplitudes, and phases derived from spectroscopy. The variability appears strongest in the line wings which only agrees with the NRP prediction that horizontal motions should exceed vertical motions for g-mode pulsations. The same periods are found in variations of the C IV λ1550 P Cygni line, which strongly suggests that NRP modulates the local stellar wind.

Early analyses of the *lpv* were made by direct comparison of the observed profiles with calculated NRP model profiles (see Smith, Fullerton, & Percy 1987). While this approach is useful where one or perhaps two NRP modes are present, it becomes unwieldy in the presence of multiple modes. Gies & Kullavanijaya (1988) introduced a time series analysis method in which power spectra are calculated at each wavelength point across a profile (aliases in the power spectra can be removed using the CLEAN algorithm). They showed how periodic signals can be identified in the periodograms and how variations in complex phase across the profile can be related to the order of the NRP mode. Furthermore, the distribution of power across the profile at a signal frequency can provide estimates of the ratio of horizontal to vertical velocity amplitude. They applied this technique to the *lpv* star ϵ Per (B0.7 III) and found convincing evidence for 4 periodic signals.

This approach is based on the Doppler imaging approximation ($v_{\rm NRP} << V \sin i$), and the limits and extensions of this approach have been investigated by several authors. Kennelly, Walker, & Merryfield (1992) have shown that if the profiles are transformed from a radial velocity scale to one based on stellar longitude, then a second Fourier transform of the collected profiles (in the axis across the profile) yields the power distribution according to NRP order m. Reid & Aerts (1994) have investigated the pitfalls associated with the usual assumption that the modes are sectorial ($l = |m|$, distributed like sections of an orange), and they question the accuracy of the spheroidal modes for rapidly rotating stars. Telting & Schrijvers (1995) address the issue of mode identification and suggest that a careful analysis of the power and phase distribution across the profile at both the fundamental and first harmonic signal frequencies can lead to reliable estimates of both l and m. Clement (1994) suggests that the amplitudes may become more focused towards the equator in rapidly rotating stars. Taken together, these studies suggest that time series analysis techniques offer an appropriate basis for the study of *lpv* from multimode NRP.

3. A Model for Zeta Oph

Since Vogt & Penrod's (1983) pioneering study of *lpv* in ζ Oph, two other detailed investigations have appeared. Kambe, Ando, & Hirata (1990) made a time series analysis of observations of ζ Oph from 1987 and 1988, and they found evidence for 2 - 3 periods in the star's *lpv*. The most extensive observations to date were made in a coordinated optical/UV campaign staged in the spring of 1989 (Reid et al. 1993; Howarth et al. 1993). The character of the *lpv* during this campaign is illustrated in Figure 3 of Reid et al. which shows the line fluctuations in a gray-scale format as a function of line position and time. The familiar bump patterns are seen to migrate through most of the absorption lines. Reid et al. used time series analysis to find 4 periodic signals that appear to originate in NRP.

Reid et al. (1993) noted, however, that the variations were undetectable in several lines, notably He II $\lambda\lambda4542, 4686$. These lines weaken significantly with advancing spectral type (decreasing temperature) at type O9.5 V, and Reid et al. suggest that these lines are formed predominantly in the polar regions of ζ Oph. Such rapidly rotating stars will have hot polar caps and cooler, extended equatorial regions, and lines formed in the hotter polar regions will display less net rotational broadening. Indeed, Reid et al. find that the He II $\lambda4686$ line is much narrower than other lines, and they argue that the absence of *lpv* in He II indicates that the pulsations are concentrated at the equator (as expected for sectorial mode NRP).

I have made a numerical model for the geometry and line profiles of ζ Oph that can reproduce the relative constancy of the He II lines provided that the star is rotating close to the critical break-up speed. The model profiles are based on stellar parameters given by Howarth et al. (1993, Table 1). The code assumes Roche geometry and calculates the pole-to-equator temperature and radius variation. The range of the temperature variation will increase as the rotation rate is set closer to the critical limit. The model profiles are based on the flux profiles published by Auer & Mihalas (1972) and Mihalas et al. (1974), and the results reported here should be considered illustrative rather than definitive because ideally one should use intensity profiles that account for center to limb changes. The run of equivalent width for He I $\lambda4471$ and He II $\lambda4542$ is shown in Figure 1. I calculated a series of models with no pulsation to determine the values of inclination (68°) and polar temperature (38000 K) that gave the best match to the observed mean profiles. The star rotates at 95% of the critical rate in this provisional model, and the range in temperature with latitude is indicated in Figure 1. The equivalent width of He II vanishes at the equator where the NRP amplitude is largest, and so the amplitude of the He II *lpv* will be much reduced from the uniform temperature case.

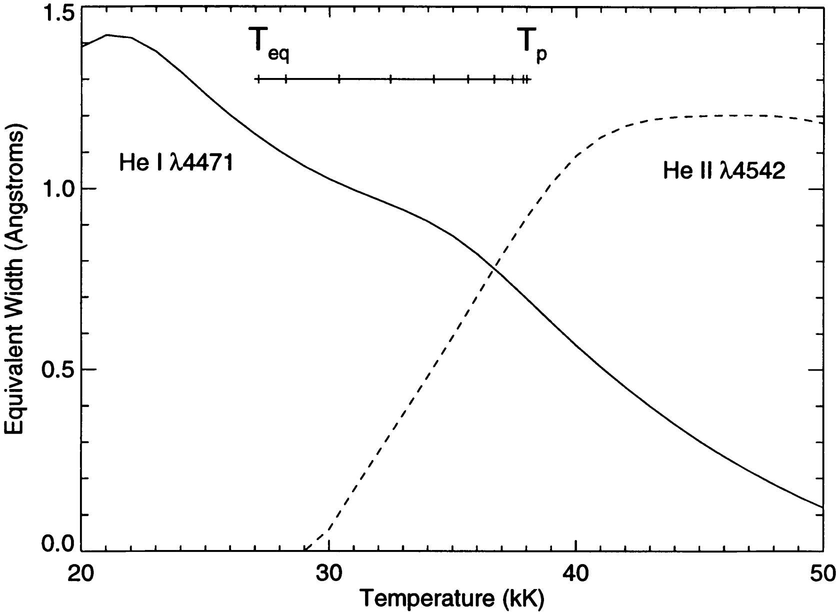

Figure 1. He equivalent widths for log $g = 4$ models as a function of effective temperature. The range of temperature in the ζ Oph model is also shown (each tick corresponds to 10° in latitude).

The resulting *lpv* from several sources are illustrated in Figure 2 for both He I and He II. These are difference profiles (after subtracting the no pulsation profile) for an $l = -m = 4$ mode with a maximum vertical velocity amplitude of 10 km s^{-1} and for NRP phase 0.25 (cool, extended sector crossing the central meridian). The *lpv* resulting from NRP velocity fields only are shown as dotted lines; the *lpv* in He II are small because of the line's weakness in the equatorial zone. There are temperature variations associated with NRP (Buta & Smith 1979) which influence the *lpv* in two ways. First, cool regions (like the one on the meridian in this case) will contribute less flux to the profile, and thus the absorption contribution from this region is weakened (the dashed lines show the result for NRP velocity and continuum flux variations). However, the line equivalent width also varies as a result of the NRP temperature fluctuations, and the final solid line shows the *lpv* with all these factors included. In the case of He I, a cooler zone will produce stronger absorption, but the reverse is true for He II. In fact, it is this equivalent width variation that dominates the net *lpv* of He II and causes them to appear opposite from those seen in He I.

I used such difference profiles to estimate the NRP vertical velocity

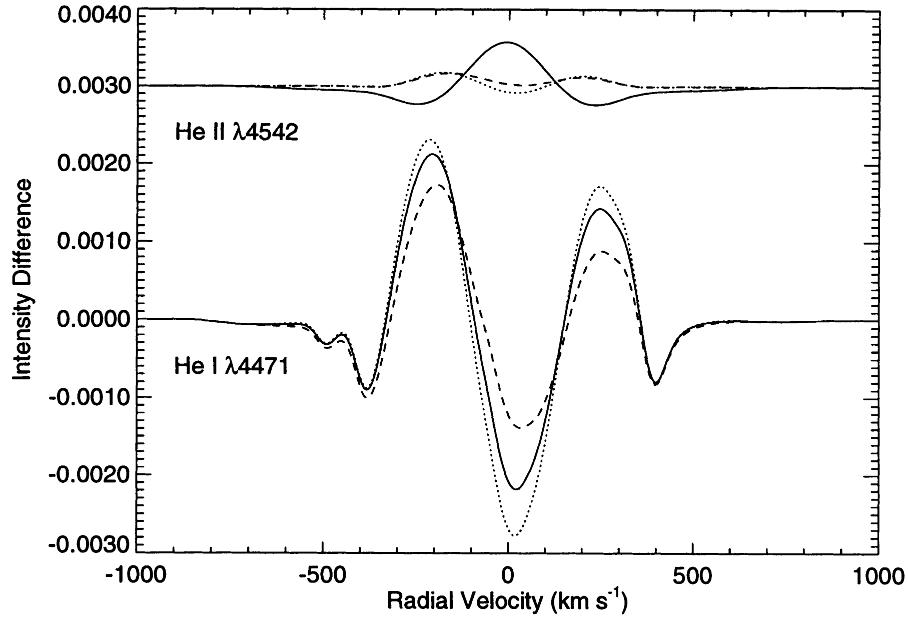

Figure 2. Difference profiles for He lines at NRP phase 0.25. The plots show the cumulative influence of NRP velocity fields (*dotted lines*) plus continuum flux variations (*dashed lines*) plus equivalent width variations due to NRP (*solid*).

amplitude associated with each of the 4 modes described by Reid et al. (1993) (10, 10, 9, and 6 km s^{-1} for $|m| = 4, 5, 8$, and 10, respectively). I then made a simulated time series of *lpv* that corresponds approximately to that shown in the upper panel of Figure 3 of Reid et al. This sequence appears in Figure 3. The stellar images at left show the 4500 Å flux maps of the star for times marked by large tick marks (NRP patterns move from left to right with time). These images show the cumulative effects of limb darkening, gravity darkening, and NRP induced flux variations. The He II *lpv* are subtle (5 times smaller and opposite in phase to those of He I).

4. Summary

The profile variations observed in the spectra of OB stars provide strong circumstantial evidence that their photospheres are modulated by the effects of nonradial pulsations. Future high S/N observations that record *lpv* in a variety of lines (with differing temperature sensitivities) offer the promise of determining the spatial distribution of the NRP modes and the actual stellar rotation speeds (especially in very rapid rotators like ζ Oph). Such

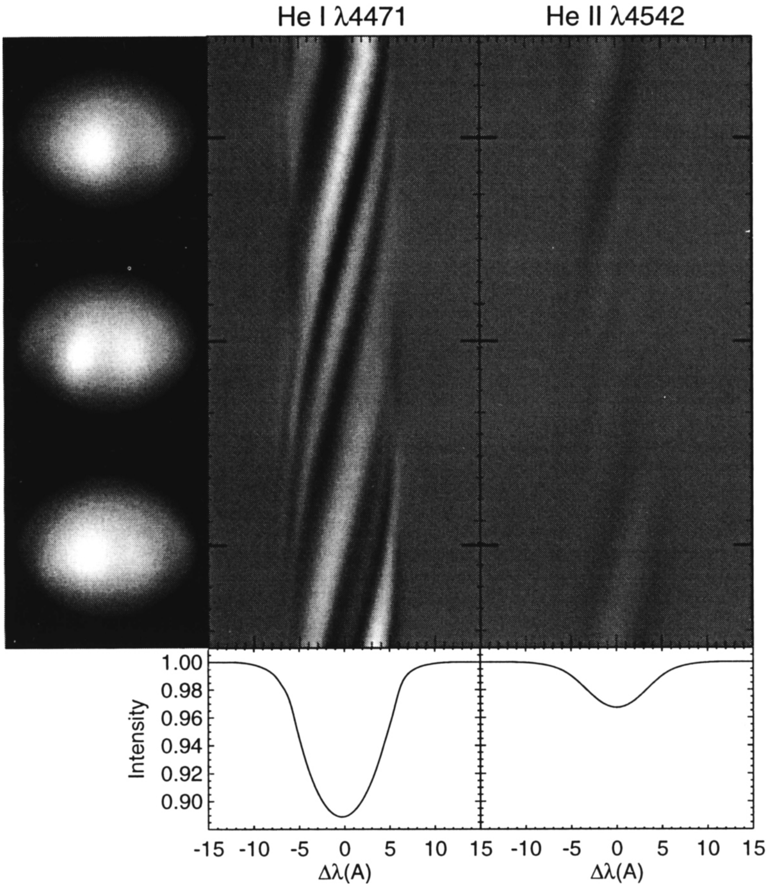

Figure 3. A simulated sequence of spectral variations including all 4 modes described by Reid et al. (1993) for the approximate time span given in their Fig. 3 (upper panel). Time progresses upwards in the gray scale representations of the difference spectra; each tick corresponds to 0.01 d. The stellar images at left show the flux distributions at the times indicated by large tick marks.

observations will give us a first glimpse of what the surfaces of hot stars will look like when observed directly through long baseline interferometry. In addition, such observations will provide new understanding about the role of NRP for episodic mass loss in hot stars and will expand the field of asteroseismology into the hot star regime.

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