DOPPLER IMAGING OF VARIABLE EARLY-TYPE STARS*

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ABSTRACT. Line profile-variability (LPV) is very wide-spread among early-type stars. With the exception of inhomogeneous surface abundance distributions associated with magnetic fields, the LPV of ***bona fide*** non-magnetic stars is consistent with (often only with) nonradial pulsation (NRP). Peculiar surface chemistry and NRP may even be mutually exclusive, and there are other indications that in spite of the ubiquity of NRPs the distribution of their characterizing parameters in the HRD is far from being uniform. This may be important for uncovering the driving mechanism of NRPs in early-type stars.

1. INTRODUCTION

In ideal stars the rotational Doppler effect only broadens the spectral lines whereas on many real line profiles the fingerprints of surface inhomogeneities are imposed as various irregularities and distortions. From a single observation one may only conclude that there are variations with stellar longitude. A series of spectra not only complements the information to the full stellar circumference but may also reveal dependences on latitude. However, extracting this information and reconstructing a stellar image requires an inversion of the observations, and it is a matter of definition if this favour to the observer is called Doppler imaging or whether that term is reserved for the solution of the inversion problem.

If the inhomogeneities are merely of a radiometric nature the correspondance between the location of a feature on the rotating star and its propagation in the observed spectra is relatively unique, and the inversion reduces largely to a geometrical-mathematical problem (see the papers by Vogt and by Hatzes in these proceedings). However, if the inhomogeneities are kinematic ones due to an atmospheric velocity field, the position of a feature in the line profile depends on the location of the absorbing (or emitting) gas on the stellar surface *and* its velocity. The solution of the inversion problem is, then, so little constrained by the observations alone that the usage of a physical model is indispensible. Intermediate between these two extremes are Zeeman broadened lines of strongly magnetic stars.

2. DOPPLER MAPPING THE HERTZSPRUNG-RUSSEL DIAGRAM

The spatial resolution of Doppler images is the higher, the faster the star rotates, so that

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this technique is especially applicable to early-type stars. However, with increasing broadening spectral lines become shallower. With regard to the subject of this symposium it is therefore interesting to note that the first detections of line profile variability (LPV) were made in narrow-lined early-type stars several decades ago whereas efficient low-noise detectors permitted a systematic exploration of the upper left corner of the HRD only rather recently. Additions of major groups of early-type stars to the LPV domain have been:

- β Cephei stars (Henroteau 1918),
- narrow-lined B stars (Petrie and Pearce 1962, Smith 1977),
- Be stars (Baade 1979, Walker *et al.* 1979, Vogt and Penrod 1983),
- medium- (Petrie 1958, Smith 1985) and broad-lined (Smith and Penrod 1984) B stars,
- broad-lined ($\geq$ 100 km/s) OB supergiants (Baade and Ferlet 1984, Baade 1987),
- helium-variable stars (Bolton *et al.* 1987; Bohlender and Landstreet, these proc.),
- δ Scuti stars (Yang and Walker 1987),
- Ap stars (Hatzes, these procedings; Landstreet, these proceedings)
- Herbig Ae stars (Baade and Stahl 1988, in preparation).

LPV has been detected in spectral types as early as O4 (Baade 1987b), and for the normal members of any of the groups listed exceptions from LPV have not so far been reported. The emerging ubiquity of LPV may, therefore, eventually make non-detections not less significant results and give them their own diagnostic value. Known LPV voids or very low amplitude regions in the HRD include:

- the zone between about B7 and the blue edge ($\sim$ A2) of the δ Scuti instability strip (Smith and Penrod 1984, Baade 1986) with the possibly important exception of the Herbig A0e star HD 163296 (Baade and Stahl 1988, in preparation).
- narrow-lined (v sin $i \leq$ 100 km/s) OB supergiants (Baade 1987b).
- some chemically peculiar stars (Smith and Stern 1979; Baade unpublished).

Occasionally, also Be stars may display no detectable LPV; but as they are then probably merely in a 'dormant' phase (see Baade, these proceedings), the phenomenon is different.

3. CLASSIFYING THE PHENOMENA

The necessary pre-classification (see Introduction) of the LPV is the easiest for stars with measured magnetic fields because the solution of the inversion problem is more constrained. Unless the star is also pulsating, there is just one period which along with information about the geometry of the magnetic field is usually known from photometry or polarimetry. Lines with the least magnetic sensitivity can then be used to infer the abundance geometry of various ions. From the analysis of lines with different Landè g factors and the comparison with the magnetic field measurements, further refinements are possible as detailed by Bohlender and Landstreet, by Hatzes, and by Landstreet in these proceedings.

Without magnetic field, the distinction between radiometric and kinematic inhomogeneities can only be based on line profiles and hopefully also on simultaneous photometry (for a clearer separation of velocity and temperature effects on the line profiles). The criteria for the discrimination between corotating surface inhomogeneities and nonradial pulsation have been summarized many times in recent years (Vogt and Penrod 1983, Smith 1986, 1987; Percy 1987; Baade 1986, 1987a). Most compelling in favour of NRPs are multiperiodicity and phase velocities that differ drastically from the equatorial rotation velocity. In fact, spectroscopy has not so far detected any non-magnetic early-type star with spots.

However, the interpretation in terms of NRPs requires a model (see Introduction), and there is always the danger that the analysis merely 'confirms' the assumptions it is based upon. This is all the more so since in principle the eigenfunctions of rotating nonradially pulsating stars are the superposition of an infinite number of spherical harmonics which form a complete set and therefore can reproduce any observation if only the amplitudes can

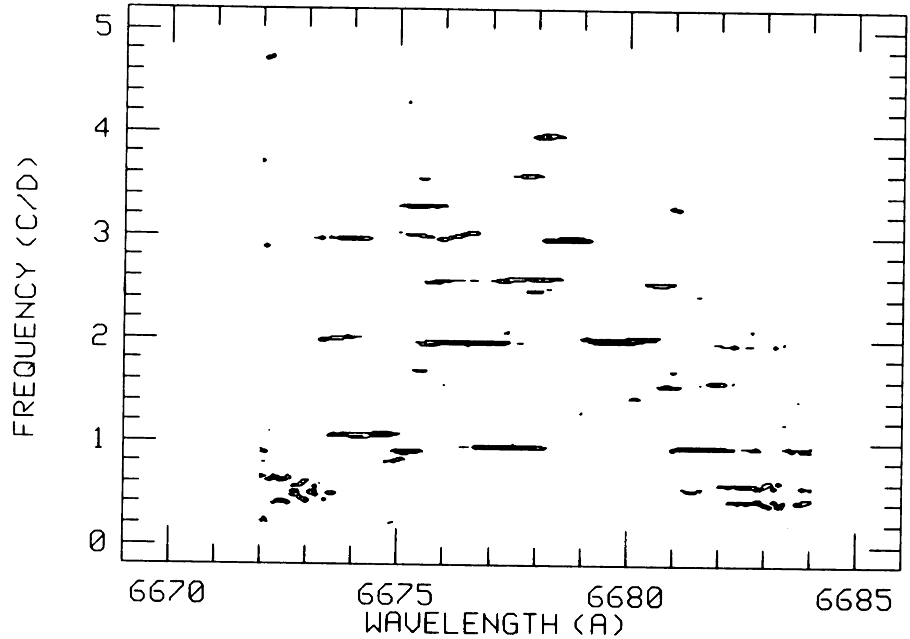

Figure 1: Composite power spectrum for 122 He I λ 6678 Å profiles obtained of μ Cen (B2 IV–Ve) over 9 nights in 1987 April (Baade, these proceedings). Individual power spectra have been calculated for time series of 0.1 Å wide bins, deconvolved with the window spectrum and the CLEAN algorithm, and combined according to wavelength. Power contours are shown for 0.1, 0.2, 0.3, 0.4, and 0.5 in arbitrary units; step size in frequency is 0.02 c/d.

be suitably chosen. Fortunately, recent work by Lee and Saio (1986) suggests considerable constraints on the number of terms with significant amplitudes. But to minimize the unavoidable model dependence, any possibility to determine free parameters beforehand should be exploited. This notably concerns the number of modes and their periods.

Unfortunately, photometry with its conveniently Fourier–analyzable scalar data in practice finds it difficult to detect multiple periods because the amplitudes are so low (see, *e.g.*, Smith *et al.* 1987). Spectroscopy appears in a better position because a fit of a single line profile would even fix the *phase*. However, with multiply periodic stars this turns into a shortcoming when, after the gross LPV has been accounted for, profile fitting has to decide whether to add more pulsation modes or whether to adjust the ephemeris of the modes identified already. The former alternative will in practice be difficult to choose because errors in the periods, phases, or amplitudes of the modes included may render any additional modes undeterminable from the residuals. The second one may imply curious results such as that the observer 'knows' the pulsation ephemeris better than the star does.

Balona (1986) has proposed to use the first four moments of the line profiles to obtain model–independent periods. However, sacrificing the high spectral resolution appears a doubtful strategy. A method that without a model uses all observations simultaneously at all wavelengths has recently been applied by Gies and Kullavanijaya (1987) to ϵ Per (B0.7 III) and by Baade (these proceedings) to μ Cen (B2 IV–Ve). For each resolution element in wavelength of a given spectral line, time series are constructed from the flux measurements in all spectra. Each time series can then be independently analysed for periodicities by conventional techniques. An example where the individual power spectra obtained have been joined together according to their respective wavelengths is shown in Fig. 1. Not unexpectedly, this technique finds more periods than other analyses of the same stars had before. But the confirmation, within the errors, of the previously determined periods also gives credit to the earlier results. Gies and Kullavanijaya additionally offer independent evidence that the mode orders, m, had been correctly identified by Smith *et al.* (1987). It remains to be seen if inclusion of the additional modes can alleviate some of the former oddities such as rapidly varying O–C residuals of the pulsation phase.

4. DOPPLER IMAGING CIRCUMSTELLAR MATTER

Doppler imaging is also possible of moving circumstellar structures. In σ Ori E, corotating matter above the intersection of magnetic and rotational equator produces complex variations of emission and absorption components in Hα (Bolton *et al.* 1987). In Be stars, double-peaked emission lines arise from a rotating envelope and their V/R ratio often varies with the period of the stellar low-order NRP mode. (Baade 1979, Smith and Penrod 1984, Baade 1987a). The pulsation therefore locally leads to either an enhancement of the circumstellar matter density or a change of the ionization balance caused by the variable radiation field associated particularly with a vertical component of the NRP velocity field. Similar V/R variations are also seen in broad-lined OB supergiants (Baade 1987b).

Non-saturated lines formed in the extremely fast winds of early-type stars also provide maps which, however, so far have proven to be difficult to read. Especially the narrow components (Henrichs 1987) are not understood because they are often nearly stationary for many wind flow times. But others have also been observed to drift red-to-blue across the wind profiles so that they could be due to density enhancements being accelerated in the ambient wind. Similar, complex variability has recently been detected in optical absorption lines of several WNL+abs stars (Stahl, Vreux, Magain and Baade 1988, in preparation).

5. SUMMARY AND CONCLUSIONS

While early-type stars do not find it easy to escape NRP, the contrary is true of theoretical models. Covering a factor of ~4 in T_{eff}, any surface driving mechanism would be little constrained by the observations. Not at last for that reason, Osaki (1987) and Lee and Saio (1987) consider the coupling between oscillatory convection of the *core* and a gravity mode of the *envelope*. In fact, the periods of low-order modes are often too long for p-modes (Smith 1986). The range of super-periods, *i.e.* the time needed for one complete revolution (in the observer's frame) of the pulsation pattern about the star, is smaller than expected on the basis of the range of probable surface rotation periods (Smith and Penrod 1984, Baade 1986). This may provide additional circumstantial evidence of the core dominating over the envelope and/or the rotation acting as an active mode filter.

The distribution in the HRD of the most prominent pulsation modes is clearly non-uniform. For instance, low-order modes seem to be the distinguishing characteristic of Be stars *vs.* Bn stars. A more detailed mapping of the HRD may therefore eventually provide some insight into the structure and evolutionary state of various early-type stars. Particularly interesting are deviations from the general pattern. *E.g.*, the ^{3}He rich star 3 Cen A (Smith and Stern 1979) and the mild OBN star θ Car (B0 Vp; Baade, unpublished) show no indication of NRP related LPV. An exclusion mechanism between unusual surface abundances and NRP is therefore possible (but θ Car is also a close binary) and should be investigated in more detail. The Herbig A0e star HD 163296 shows LPV with all the symptoms known of nonradially pulsating stars. If this preliminary classification is borne out by a more detailed study (Baade and Stahl, in preparation), not only the first nonradial pulsator among pre–main sequence stars would have been discovered, but also the first one in the apparent NRP void between B7 and A2 (Smith and Penrod 1984, Baade 1986). This combination triggers the speculation if the core of this star has already reached the evolutionary stage where pulsation à la Osaki (1987) and Lee and Saio (1987) is sustained while the surface temperature is still lagging behind.

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DISCUSSION

PRADERIE I wonder how you identify the order and degree of the non-radial oscillations, in the case of the stars you study ? What is the systematics ?

BAADE If you continuously observe a single line in a single star over about 10 days, you'll find many similar (if not nearly identical) single profiles, however hardly ever identical sequences. This almost certainly means multiperiodicity. So, the first step to bring some system into this apparent chaos is to establish reliable periods without imposing a model early on. This has been done by Gies and Kullavanijaya (1987) for ϵ Per (B0.7 III), and in my next paper I'll show the same type of analysis for μ Cen (B2 IVe). In either case, multiple periods were found. To what extent mode identifications can be obtained depends not at last on whether the eigenfunctions of non-rotating stars are acceptable approximations for the rapidly rotating stars observed whose eigenfunctions are the superposition of in principle infinitely many spherical harmonics. If you believe in such an approximation, the modes can be identified by line profile fitting, analysis of the observed acceleration of the line profile bumps (cf. the work by Gies and Kullavanijaya), etc. The radial overtone, n, can only be derived from the comparison with suitable stellar models.

BOHANNAN Do you get a consistent period of the absorption line features in ζPuppis from observing session to observing session ?

BAADE For 2 consecutive observing seasons this seems to be the case if my preliminary analysis is correct. However, with a one year gap in the data it most probably won't be posssible to check the phase coherence.