LINE PROFILE VARIATIONS IN Be STARS

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Abstract. The periodic variations in the photospheric lines of Be stars could result from rotation or nonradial pulsations (NRP). Here I review the spectroscopic results on ten Be stars which have been targeted in recent multiwavelength campaigns. Most of the 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 is strongest in the line wings which only agrees with the NRP prediction that horizontal motions should exceed vertical motions for g-mode pulsations. High frequency, non-periodic variations are also observed, but I argue that these are of circumstellar origin and do not represent high-order NRP. The NRP periods are also found in variations of the Hβ emission line but these probably result from photospheric and not disk variations. However, the same periods occur in the C IV λ1550 P Cygni line, which strongly suggests that NRP modulates the local stellar wind.

1. Introduction

Ten years have past since Vogt & Penrod (1983) showed how nonradial pulsations (NRP) could explain the blue-to-red moving absorption bumps observed in the spectral lines of the O9.5 V*enn* star ζ Oph. Penrod (1986) found similar line profile variations (*lpv*) in a high S/N spectral survey of some 20 Be stars, and he speculated that NRP could be the missing factor leading to formation of Be envelopes. There has been substantial progress over the past decade in studies of *lpv* in selected targets (see the reviews of Baade 1987, 1992; Fullerton 1991; Smith 1986; Walker 1991), and several recent studies are particularly noteworthy (cf. Yang *et al.* 1990 [ζ Tau]; Floquet *et al.* 1992 [EW Lac]; Bossi *et al.* 1993 [28 Cyg]; Reid *et al.* 1993 [ζ Oph]; Kambe *et al.* 1993 [ζ Oph]). This substantial effort has demonstrated the widespread occurrence of *lpv* among Be and other early-type stars, but the specific periodic content, amplitudes, duration, and origin remain controversial. Here I describe new results from a series of multiwavelength campaigns on Be stars designed to study rapid variability and mass loss.

2. Be Star Observing Campaigns

The close agreement between time scales of variation observed in *lpv*, photometry, and UV wind lines provided the motivation for a series of coordinated observing campaigns to search for a connection between *lpv* and mass loss in Be stars. Here I shall highlight the preliminary results of the campaigns with special emphasis on the spectroscopy. Other contributions in

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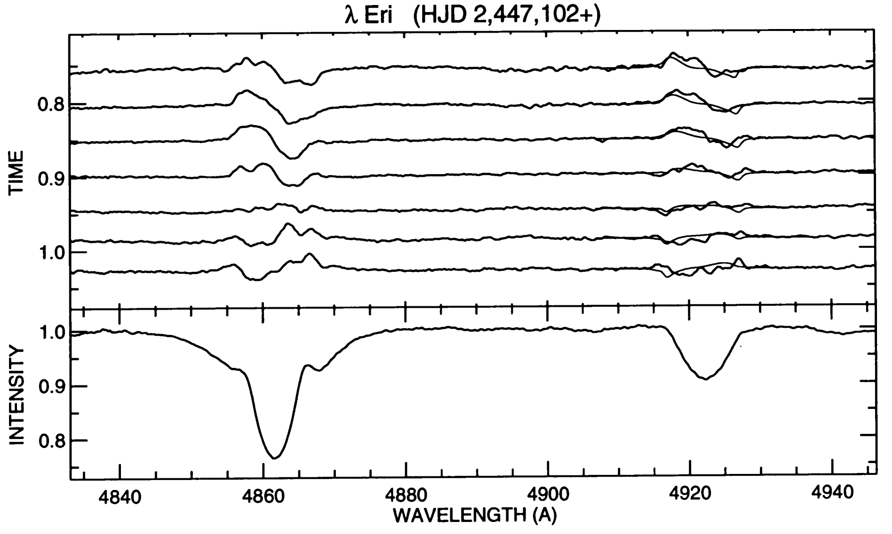

Fig. 1. The time evolution of the spectrum of λ Eri during the night of 1987 November 3. The lower panel shows the average spectrum from the run, and the upper panel illustrates individual difference spectra aligned with the time of observation (intensity scaled to the same units as the time axis). The thin line superimposed on the He I λ4921 difference profiles shows the predictions of the NRP model for a single $l = -m = 2$ mode.

these Proceedings describe in more depth IUE high and low dispersion spectroscopy (Peters *et al.*), optical photometry (Percy), polarimetry (McDavid *et al.*), and high S/N spectroscopy (Hahula & Gies). The line profile data were obtained in six campaigns on a total of ten targets, and some 1200 individual spectra have been recorded. Whenever possible we observed a large portion of the optical spectrum, but in all cases the spectral range included the Hβ and He I λ4921 lines.

An example of the observations is illustrated in Figure 1 which shows the time evolution of the spectrum of λ Eri over one night. This example shows two kinds of variability that we found in virtually every Be star. First, there is an overall change in the broad shape of the difference profile which is seen in both Hβ and He I λ4921. This type of low-order variation generally shows up as a periodic signal in time series analyses (see below). Second, there are narrower sub-features that often display blue-to-red motion but which generally are irregular in appearance and time evolution. These narrow features are not noise artifacts, since they have an amplitude much greater than the measurement errors and display similar patterns in both Hβ and He I λ4921. In the following sections, I will describe the characteristics and possible origins of both kinds of variability.

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TABLE I
Periodic Signals in He I λ4921 and UV Fluxes

Object	P (d)	$-m$	T_0(NRP)	R	P_{UV} (d)	ϕ_{min}	Δm_{UV}
o And	1.48±0.33	0	7011.6018	0.056	1.57	0.36	0.10
λ Eri	0.71±0.12	2	7104.5320	0.173	0.70	0.01	0.20
ω Ori	...	...	...	...	1.40	...	0.05
28 Cyg	0.64±0.06	2	7790.3188	0.088	0.69	0.73	0.20
η Cen	0.61±0.04	2	8347.2906	0.082	0.61	0.75	0.16
48 Lib	...	...	...	...	0.40	...	0.07
ζ Tau	0.80±0.06	2	8538.5296	0.066	0.81	0.36	0.17
ψ Per	...	...	...	...	1.04	...	0.05
2 Vul	1.27±0.15	2	8879.8170	0.086	0.64	0.23	0.07
KY And	0.79±0.60	2	8879.8975	0.070	...	...	...

3. Low-Order Variations

The profile data were analyzed using the time series methods described in Gies & Kullavanijaya (1988). This involves the Fourier transformation of the line intensity data for time series defined at each wavelength position across the profile. The resulting periodograms can be used to find the periodic signals, power distribution, and and number of cycles of variation across the profile (Fig. 2). The last quantity leads to the modal order m in the context of the NRP model (based on the assumptions that $l = |m|$, since these modes are least prone to cancellation effects from competing surface elements, and that there is a correspondence between radial velocity and stellar longitude, i.e., the Doppler imaging approximation which is valid for inclinations near $i \approx 90°$). We formed a ratio R of the integrated semi-amplitude to the equivalent width to provide a simple estimate of how much of the profile is modulated by the periodic signal.

The time series results are summarized in Table 1 (details in Hahula & Gies, these Proceedings). We find evidence of periodic variability in 7 of the 10 stars, and the periods we obtain correspond in most cases to those determined from UV and optical photometry. None of these seven stars show any evidence of multiple periodicities. This is a surprising result since other workers have found additional signals (usually with shorter periods) and since high-order variations are clearly visible in the profiles (Fig. 1). Evidently, such high-order variability is not periodic in the stars of our sample. The seven periodic variables all have $m = -2$ except for o And which has $m = 0$. Finally, the strength of the periodic *lpv* (as measured by the ratio R) appears to be correlated with photometric amplitude, Δm_{UV}.

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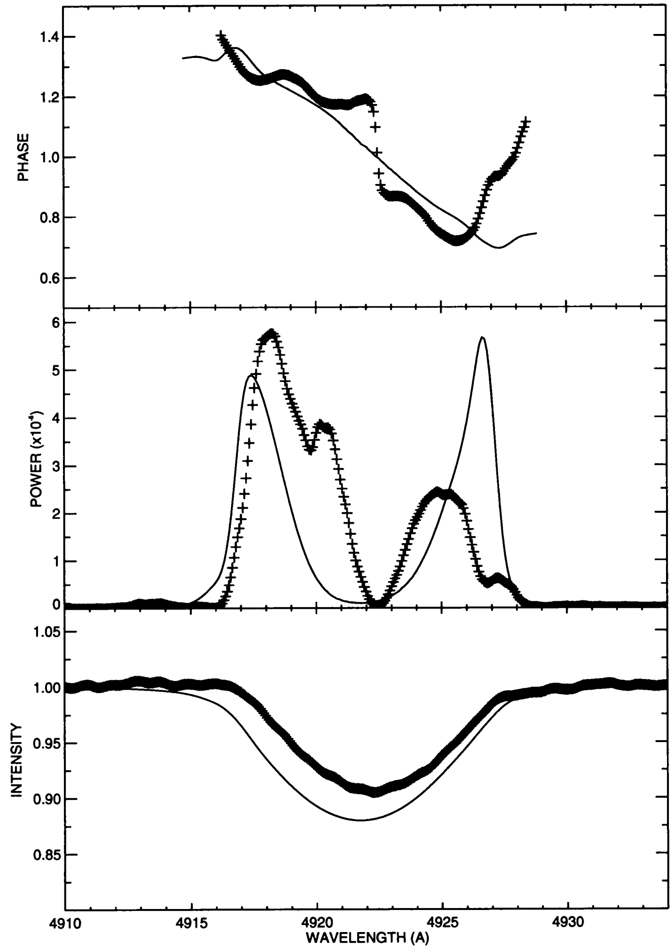

Fig. 2. Periodic signals in the observations (*plus signs*) and NRP model (*solid lines*) for the He I λ4921 profile in λ Eri. *Lower panel:* average profile. *Middle panel:* power distribution across the profile at the signal frequency of 1.4 d^{-1}. *Upper panel:* complex phase of the periodogram across the profile at the signal frequency. Phase becomes indeterminate where the power vanishes (in the line core and wings).

4. NRP Model

Two basic "clocks" could lead to these periodic signals, pulsation or rotation. The key difference between the models is that there are velocity fields associated with NRP that are absent in the rotation model. Thus an analysis of *lpv*, which is particularly sensitive to velocity fields through the Doppler effect, can play a critical role in distinguishing between acceptable models. Here I will explore what predictions about *lpv* and photometric variability

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follow from the NRP model using a light curve and profile synthesis program I have written based on the NRP formulation of Buta & Smith (1979). This code is a surface integration scheme that represents the pulsations as Legendre polynomials. This is strictly only applicable to nonrotating stars, and additional terms are needed in rotating stars (Lee & Saio 1990; Aerts & Waelkens 1993). Nevertheless, the models should give a first-order approximation of the expected *lpv*. The code includes the geometric Roche distortion of a rapidly rotating star and the temperature variations that result from gravity darkening and NRP (Lee *et al.* 1992).

I have applied the code to the case of λ Eri to present a representative example of NRP variability (I plan to make detailed models for each target). The stellar parameters for λ Eri are taken from Smith *et al.* (1991): $R_e = 7\ R_\odot$, $M = 12\ M_\odot$, $i = 90°$, and $v \sin i = 310$ km s^{-1}. For spheroidal modes, the ratio of horizontal to vertical velocity amplitude k follows from the assumed mass, radius, and corotation frequency, and from the adopted NRP mode $l = -m = 2$ and period $P = 16.84$ hours, I obtain $k = 24.6$ (essentially all horizontal motion). If the oscillations are adiabatic, then the temperature variation follows from k (Buta & Smith 1979): $dT/T = 58\ dR/R$. The only free parameter in the model is the vertical velocity semi-amplitude A_r which I set at $A_r = 0.65$ km s^{-1} based on a rough fit of the observed *lpv*. This leads to a horizontal velocity semi-amplitude $A_h = 16.0$ km s^{-1}, fractional radius semi-amplitude $dR/R = 0.13$ per cent, and a fractional temperature semi-amplitude $dT/T = 7.4$ per cent. The model calculations of surface fluxes, velocity fields, and profiles are illustrated for several NRP phases in Figure 3.

The predictions of the NRP model can now be compared directly with the observed *lpv* in λ Eri. Synthetic difference profiles are superimposed on the observed He I λ4921 profiles in Figure 1. The models do a reasonable job of reproducing the low-order variations, but as noted above there is still an additional high-order (non-periodic) component of variability. I made a time series analysis of the model profiles in the same way as the observations (results in Fig. 2). This exercise verifies that the assumed period and mode used in the model are successfully identified in the periodogram. The chosen velocity amplitude for the NRP mode yields *lpv* with an amplitude similar to that observed: $R(\text{model}) = 0.11$ vs. $R(\text{obs}) = 0.17$.

A key test of the NRP model lies in the power distribution of the periodogram across the profile. The model predicts that there will be more power in the line wings because of the dominance of horizontal motions for the large k value associated with the $m = -2$ mode, and this trend is indeed found in the power distributions (middle panel of Fig. 2). The power distributions observed in the periodograms of most of the targets appear to be double-peaked or flat. In the rotational modulation picture, "spots" act to change the flux distribution in a rotationally broadened profile. Clearly, such

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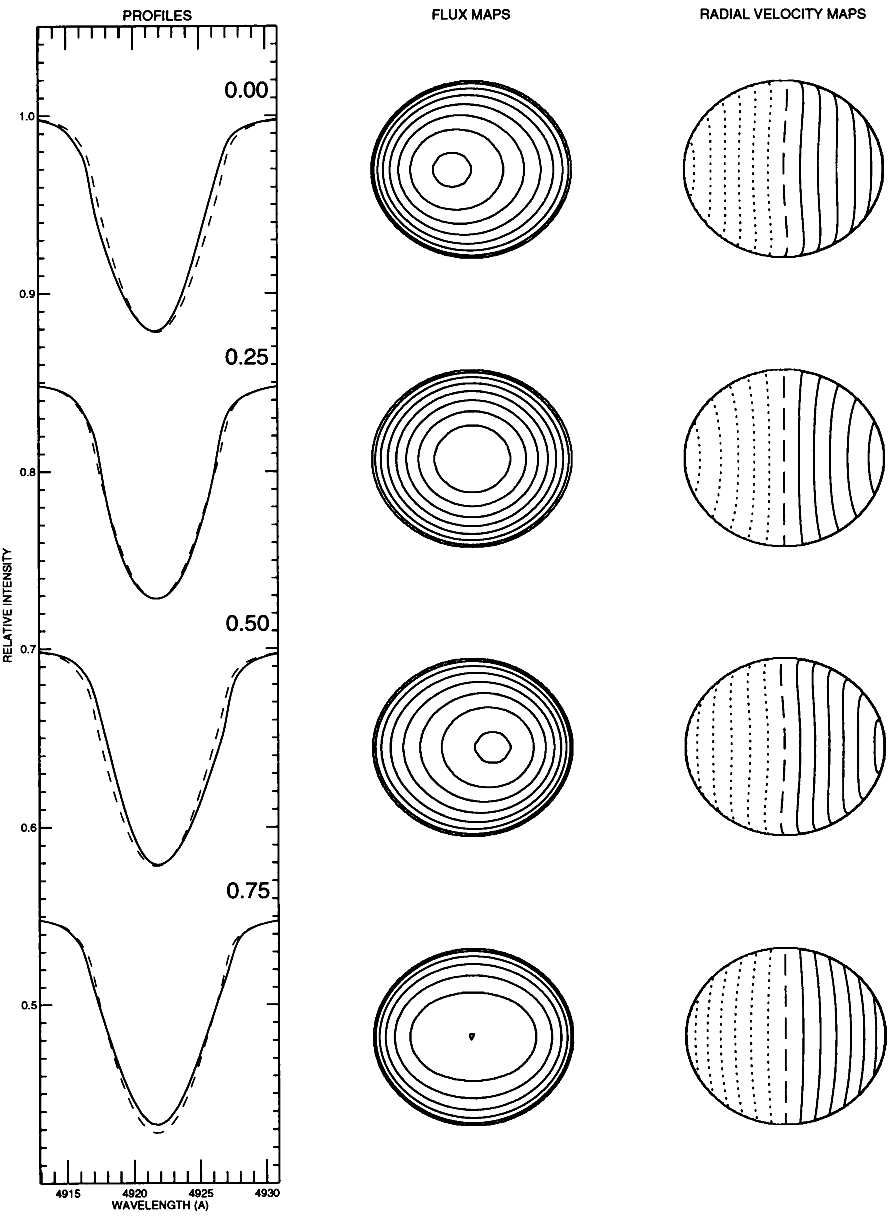

Fig. 3. NRP profiles, flux distributions, and velocity fields for the λ Eri model. The left column illustrates the calculated He I λ4921 profiles (*solid lines*) relative to a model with no pulsation (*dashed lines*) for four NRP phases. The central column gives the UV flux distributions across the visible hemisphere of the star for the same NRP phases (as isophotal contours in equal steps equivalent to 1/8 maximum intensity). The star is brightest at phase 0.25. The right column shows radial velocity maps for the same NRP phases (in contour steps of 50 km s^{-1}; dotted lines for $V_r < 0$, dashed lines for $V_r = 0$, and solid lines for $V_r > 0$).

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a "spot" would have its maximum influence on the profile when it crosses the central meridian since the star is brightest near the center of the disk due to limb darkening. Thus the rotation model predicts that the signal power should attain a maximum at line center. This is a definitive test, and the observations clearly support the NRP model and appear to rule out a "spot" origin in most cases.

The NRP model also succeeds in reproducing the photometric variations. The full amplitude of the light curve at 1450 Å is $\Delta m_{1450}(\text{model}) = 0.21$ (close to the observed value, $\Delta m_{1450}(\text{obs}) = 0.20$), and this declines in the B-band to $\Delta m_B(\text{model}) = 0.09$ (slightly larger than the value $\Delta m_b(\text{obs}) = 0.05$ found by Balona *et al.* 1992 during the time of the campaign). Minimum light occurs at NRP phase 0.75 when a cool sector crosses the meridian. The observed phase of minimum light ϕ_{min} (based on the spectroscopic ephemeris) is 0.01 from the UV light curve (which covers only 2 cycles), but the more extensive b-band photometry from Balona *et al.* (1992) yields $\phi_{\text{min}} = 0.77$ as expected in the NRP model. The other targets with well defined UV light curves also have $\phi_{min} \approx 0.75$. The observed sense of the phase relation between the profile and photometric variations indicates that the adiabatic dT/T relation of Buta & Smith (1979) is probably valid for low-order NRP in Be stars (Lee *et al.* 1992).

5. Hβ Variability with Similar Periods

If NRP is the source of the photospheric *lpv*, then it is important to search for the occurrence of these periods in other phenomena associated with mass loss. I have made a preliminary time series analysis of the Hβ emission lines in the campaign targets, and in most cases, the derived periods are the same as found in the photospheric lines. However, the properties of these periodograms suggest that the source of the variability lies in the photospheric variations and not in the emission components. The Hβ periodograms of the non-shell stars (λ Eri, 28 Cyg, 2 Vul, and KY And) are very similar to the corresponding He I λ4921 periodograms. This indicates that the two lines vary in unison, and, consequently, the Hβ *lpv* are probably entirely due to NRP effects on the underlying photospheric line. In the shell stars (η Cen, 48 Lib, and ζ Tau), the power distribution is concentrated at the central shell component, and the complex phase undergoes an abrupt 0.5 cycle change through line center. The shell lines are presumably formed at some distance from the star where the gas motions are mainly orbital (nearly tangential to the line of sight). The blue (red) portion of the shell feature corresponds to gas projected on the approaching (receding) semi-circle of the rotating star. Thus as a hot, bright sector crosses the disk of the star, the blue half of the shell feature would first absorb more flux until the wave crosses the meridian when the red half would absorb more. Consequently, the apparent

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lpv in the shell features probably arises in the changing illumination by the stellar photosphere and not by variations in circumstellar gas.

6. UV Wind Line Variations

The periodicities we have detected also appear in variations of the stellar wind lines. The C IV λ1550 doublet is a weak P Cygni feature in many Be stars which indicates the presence of a radiatively driven, supersonic wind. The IUE spectra obtained during the campaigns indicate that in most targets the blue-edge of the P Cygni profile is modulated with the NRP period, so that the absorption equivalent width is positively correlated with the FUV flux level (Peters 1991; Peters *et al.*, these Proceedings). This indicates that the local wind velocity (and probably the mass loss rate) increases above regions through which a hot, bright, NRP wave is passing.

7. Nature of the Narrow Moving Features

I described earlier a non-periodic type of variability that appears as narrow features in difference spectra (see Fig. 1). The patterns are irregular, and they do not appear as signals in the periodograms. However, the narrow features do appear to be related to the $-m = 2$ NRP variations: (1) the profile crossing times are similar (where they can be measured), and (2) the rate of occurrence appears to be correlated with the NRP pulsation amplitude. Perhaps the most important clue is that the narrow features are also seen in Hβ as sharp features. Since the linear Stark broadening of Hβ in the photosphere will significantly broaden any spectral structure, this property suggests that the narrow features probably have an origin in lower density gas above the photosphere. As a working hypothesis, I suggest that the narrow features form in the inner disk in localized regions of relatively high density. Since the narrow features move approximately with the NRP pattern and since they are more numerous when the NRP amplitude is high, the observations suggest that NRP induces some type of turbulence in the inner disk. Such a relation is plausible since hot sectors will locally increase both the radiatively driven wind and the azimuthal velocity (so that the surface element is moving faster than rotation). Both effects could lead to increased photosphere and disk interaction over hot regions.

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Discussion

Balona: If you feel that the NRP model is the correct interpretation for the low-order line profile variations, it should be possible to model them. I believe the NRP model will not account for the radial velocity amplitude of ≈ 60 km s^{-1} discovered by Bolton for λ Eri.

Gies: It is important to model the profile variations with an NRP code, and the model profiles I have presented here for λ Eri do resemble the observed ones (Fig. 1). I plan to present NRP model profiles for all the targets in the near future. The NRP synthetic profiles for λ Eri show the largest variations in the wings, and I imagine that this will lead to large changes in the measured radial velocity. [Note: After the meeting, I measured the radial velocities of the synthetic profiles in Fig. 3 by calculating the first moment of the profile; the first moment changes by 46 km s^{-1} between NRP phases 0.0 and 0.5.]

Harmanec: Your interesting presentation convinced me even more that most of the line profile changes we observe are due to structured material moving at some distance (perhaps only a fraction of the stellar radius) above

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the stellar surface, no matter what is the origin of this material. I agree that the data exclude simple spheroidal models. You should also check for radial velocity changes; if you forget about them, your Doppler imaging is fooled. Note that Štefl *et al.* (these Proceedings) found radial velocity variations of the whole line of full amplitude 70 km s^{-1} (for η Cen).

Gies: I agree that the narrow feature *lpv* may have an origin in circumstellar material, but that is only part of the story. The broad, low-order *lpv* can be explained successfully with the NRP model using amplitudes that produce photometric variations that are consistent with those observed. Thus I think it would be a mistake to try to explain all the observed *lpv* on variations in the circumstellar gas. You are right to promote the measurement of radial velocities, since some Be stars are members of binary systems and it is important to remove Keplerian motion before attempting any time series analysis. None of our targets are known short-period binaries. However, it is also important to realize that low-order NRP will produce lines that have large apparent radial velocity variations (see my reply above to Balona).

Waelkens: Coming back to Luis Balona's statement, I want to point out that the ratio k of horizontal to vertical displacement is fixed by theory and is not a free parameter. For a 0.7 day pulsation period, k should be order unity, and then the vertical displacement would be large, causing larger photometric variations. A larger k would correspond to a much longer pulsation period in the corotating frame, and then the ratio of pulsation to rotation period is much too large to use the usual expressions for nonradial modes.

Gies: Yes, k is fixed by theory and is given by

$$k = \frac{GM/R^3}{\sigma_{\rm cr}^2}$$

where $\sigma_{\rm cr}$ is the corotating frequency. For the λ Eri parameters I have used, the corotation period is 74 hours and thus $k = 24.6$. The corotation pulsation period is larger than the rotation period (27.4 hours), so clearly expressing the NRP waves as simple spheroidal functions is only an approximation. I plan to revise my NRP code in the near future to better account for the influence of rotation on the eigenfunctions.

Smith: I have three comments for you.

(1) Erratic bumps in line profiles have indeed been noticed almost as soon as *lpv* were discovered in various Bn and Be stars; for example, in ϵ Per and in λ Eri. I think there are a variety of possible explanations for them, such as nonlinearities in the NRP (e.g. in ϵ Per) and non-LTE effects associated with possible localized heating on the star's surface as the wave sweeps by. But who knows?

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(2) I am very surprised that you get such good agreement with adiabatic NRP theory as prescribed by Buta & Smith (1979). Actually, that paper was written in the context of 53 Per itself, a slow rotator but with a corotating period rather similar to that of λ Eri. Ironically, even new optical/UV photometry do not remove the now-famous discrepancy between the light and *lpv* amplitudes, and probably Dziembowski's non-adiabatic correction is needed!

(3) For clarity I would suggest that you find a way of normalizing the power functions in wavelength that you compute to remove the effects of "phase clustering" in your observing window.

Gies: (1) I agree that there may be many sources for the erratic bumps that appear in profiles. My suggestion that the narrow features originate in clumps in the inner disk was motivated by the sharp appearance of these features in Hβ, but other possibilities need to be explored.

(2) The Buta & Smith prescription for NRP is successful in matching model and observed *lpv* and photometric amplitudes and their phase relationship in the best studied targets.

(3) Unfortunately, with a limited duration of observations, there is usually a non-uniform coverage of the NRP cycle, and the power distribution may partially reflect the NRP phase distribution of the observations. The best solution is to obtain long observing runs covering many cycles of variability.

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