PERIODIC VARIABILITY OF Be STARS: NONRADIAL PULSATION OR ROTATIONAL MODULATION?

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Abstract. A large fraction of Be stars show periodic light and line profile variations with a timescale of about one day. The mechanism which causes these periodic variations has been attributed to nonradial pulsation (NRP) or rotational modulation (RM). The authors present arguments supporting the two opposing points of view with the purpose of stimulating subsequent discussion by the Symposium participants.

1. The Case for Nonradial Pulsation (D. Baade)

1.1. Weaknesses of the Rotational Modulation Hypothesis

The primary reason, which has enabled the RM hypothesis to become a contender for the explanation of the periodic variability of Be stars, is that the observed periods are *statistically* indistinguishable from the best currently possible guesses for the rotation periods. This is certainly suggestive, but it must be kept in mind that presently rotation periods of *individual* stars cannot nearly be determined with the required accuracy. Increasing the sample further does *not* help because the *systematic* uncertainties are much larger.

More important is another objection. Recall that (i) only single-channel photometry has been performed, (ii) periods have been derived which broadly overlap with the expected rotation periods, and (iii) only these periods are interpreted: Is it, then, possible to draw any other conclusion than that the observed variability is due to some surface inhomogeneity which is carried around the star by rotation? The answer can only be a clear no. However, such a hypothesis is *observing strategy-limited* and should, therefore, be received with utmost skepticism so long as it has not been demonstrated that the RM hypothesis can accommodate more observational facts.

Many such facts (mainly supplied by spectroscopy) exist already (for a more complete description see the reviews by Gies IAU162*, Gies 1991, and Baade 1987):

* References which in the text are marked 'IAU162' concern papers included in these Proceedings.

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- The line profile variability (*lpv*) extends virtually always over the full width of the lines: Why would putative corotating *surface* structures in virtually all stars be concentrated on the equator? In known magnetic stars there does not seem to be a preferred latitude for spots (except, perhaps, polar caps).
- *Circumstellar* structures are difficult to reconcile with both of the following two pairs of observations:
  1. Line profile variability is seen also in pole-on stars whereas ordinary shell spectra are confined to equator-on stars.
  2. The amplitude of the *lpv* is quite similar for many photospheric lines of very different strengths. This would require an amazingly precise tuning of the circumstellar physics including abundances. By contrast, conventional shell spectra are not nearly as exotic.
- If corotating inhomogeneities do not have a pronounced vector-like component, they cannot explain the increase in amplitude of the profile variability from the line centre to the wings (cf. Gies IAU162).
- Kambe *et al.* (1993) report that in ζ Oph the range in radial velocity, over which moving bumps can be observed, is different during different phases of mass loss episodes. The authors attribute the additional mass loss to accelerated rotation at the equator and the latter to the NRP-supported transfer of angular momentum from the stellar core. However, at the same time the observed periods do not change. Such a behavior would imply that the surface inhomogeneities assumed by the RM hypothesis would have to be rooted in very deep layers. It appears, therefore, very important to obtain an independent confirmation of this observational result.
- The periodic component of the light variability often only accounts for the lesser part of the total power in the statistics used for the time series analysis (e.g., Cuypers, Balona & Marang 1989). The explanatory power of a purely rotational model is accordingly reduced.
- What would cause the multi-pole symmetry which is required to explain the high-order line profile variability which is periodic (but probably only with limited phase coherence so) in both space and time?

Finally, it is disturbing that qualitatively indistinguishable phenomena, especially the high-order variability, should require different explanations in Be and δ Scuti stars (cf. Kennelly *et al.* IAU162). This is all the more so since advocates of the RM hypothesis have carefully avoided elaborating on a physical model of the inhomogeneities invoked by them. A reminder that weak magnetic fields cannot easily be sustained in a radiative atmosphere has been provided by Saio (IAU162).

My personal expectation is that spectroscopic observations will in the not too distant future prove beyond doubt that the line profile variability of some Be star is multi-periodic, i.e., Be stars *do* pulsate.

1.2. Ways to Further Consolidate the NRP Model

1.2.1. Observations

In spite of what I just said, it appears essential not to get obsessed with the hunt for multi-periodicity even though a positive result would be extremely important. However, I suspect that it will still not terminate the dispute because some people will argue that of n periods found in some star only $n-1$ are due to pulsation and the nth one is caused by rotational modulation.

Therefore, it is essential to devise observational experiments which can give conclusive results. This includes covering as large an observational parameter space as possible and requires that *all* information is exploited in a synoptic way:

- One high-priority goal must be to study the atmospheric response to the variability. This is especially important since in the corotating frame periods are very long so that non-adiabaticity will be prominent:
  - From the work on β Cephei and δ Scuti stars it is well known (cf. Jerzykiewicz IAU162; Cugier *et al.* IAU162 [two papers]) how much information is contained in color variations. Furthermore, the periods of Be stars are much longer than in the other stars named, and the amplitudes are conveniently large (Štefl *et al.* IAU162 [two papers]). Since virtually every reasonable photometer has a filter wheel or equivalent device, it should simply be used.
  - Technically more difficult to satisfy is the equivalent spectroscopic demand to observe more than one line simultaneously. Work by, e.g., Fullerton *et al.* (IAU162), Smith (IAU162), and Reid (IAU162) convincingly shows the value of studying lines which are formed at different atmospheric depths or stellar latitudes.
- Long-period g-modes are characterized by large horizontal-to-vertical amplitude ratios of the pulsation amplitude. This provides a prime discriminant between a pulsation velocity field and most scalar models:
  - The change of the *lpv* between line wings and centre should be studied more systematically (cf. Gies IAU162), especially for low-order variations. The high-order variability presently gives a rather confusing picture: the phase coherence is low (Gies IAU162); temporary differences between the two halves of a spectral line have been reported (Štefl *et al.* IAU162); and the velocity range over which traveling bumps are seen may vary with phase of the mass loss cycle but the periods are maintained (Kambe *et al.* 1993).
  - Observations of low-$v \sin i$, i.e. pole-on, stars can reveal the vector character of the variability in a second dimension. Particularly attractive is the possibility to discriminate between sectorial ($\ell = m$) and tesseral ($\ell \neq m$) modes. Because of cancellation across the stellar disk, the difference between the two categories of modes is quite sub-

tle for equator-on situations so that observers generally still *assume* sectorial modes. In pole-on stars this should not be necessary.

- Since the κ-mechanism is sensitive to metallicity, it is desirable to:
  - observe Be stars in low-metallicity environments such as the Magellanic Clouds (e.g., Mazzali *et al.* IAU162; Kjeldsen and Baade IAU162).
  - determine chemical abundances of Be stars, especially in comparison with Bn stars (cf. Kolb and Baade IAU162).
- Be, Bn, and 53 Per stars should be compared with respect to their line profile variability (e.g., Fieldus and Bolton IAU162). Bn stars with low-order *lpv* are interesting because it is thought that the incidence of such variations in Bn stars is much lower than in Be stars. Since this appears to be supported by photometry, photometric follow-up of such stars is important.
- Attempts to verify suggestions that changes of the pulsation amplitude and mass loss events in Be stars may be correlated (Penrod 1986) have yielded negative results (Smith 1989; Bolton and Štefl 1990). However, the underlying speculation may be revived, if it is confirmed that the range in velocity, over which traveling bumps are seen, changes with phase of mass loss episodes. If $v \sin i$ varies while a low-order mode is excited, one may not notice this but rather diagnose a change in the pulsation amplitude. Within the picture sketched by Kambe *et al.* (1993), the primary role of the pulsation would be a cyclic increase of the equatorial rotation velocity by transfer of angular momentum from the stellar core. The effect of the pulsation on circumstellar emission and absorption lines is also worthwhile studying (cf. Gies IAU162).
- Observed series of line profiles should always be presented also as gray-scale coded, so-called dynamical spectra (e.g., Gies IAU162).
- Interferometric resolution of the central stars of Be systems will answer many of the questions that we have today. However, these answers may not come very soon as baselines of the order of a kilometer are required even for relatively nearby stars.

Of course, any of the above observational approaches can be combined into even more powerful strategies. Especially simultaneous spectroscopy and photometry bear many promises (cf. Štefl *et al.* IAU162).

1.2.2. Theory

It is encouraging that now two driving mechanisms, namely the κ-mechanism (Dziembowski IAU162) and the core convection (cf. Saio IAU162), are 'competing' for the explanation of the pulsations of Be stars. Current observations, that may help to discriminate between the two and in any case require some guidance by theory for their analysis and the definition of future work, include:

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- the existence of pulsating Oe- and other O-stars (where, however, the concept of luminosity classes and related evolutionary stages gets increasingly blurred towards higher T_{eff}),
- the high proportions of Be stars in metal poor environments (cf. Balona 1992, see also Kjeldsen and Baade IAU162),
- the dominance of very few modes although at long periods the g-mode spectrum should be dense,
- the preference for very low frequencies in the co-rotating frame,
- the pronounced amplitude variability (cf. Dziembowski IAU162),
- the constancy of pulsation periods during phases of apparently accelerated surface rotation (Kambe *et al.* 1993).

It might be that some of these points are presently more readily accommodated by the overstable core convection model. But the rôle of rapid rotation in many of these areas probably is very important and may easily invalidate premature conclusions.

For the modeling of observations, two domains appear particularly important:

- the atmospheric response to the pulsation (Cugier *et al.* IAU162; Lee *et al.* 1991); this should also include model atmospheres for extremely rapidly rotating stars,
- eigenfunctions of rapidly rotating stars (Clement IAU162, see also discussion thereafter; Aerts IAU162; Lee and Saio 1990).

1.2.3. Observations and Theory

Although I have discussed observational and theoretical efforts separately, it is obvious that, for maximum efficiency, problems should be tackled jointly.

2. The Case for Rotational Modulation (L.A. Balona)

2.1. The Distinguishing Characteristics of Be Stars

For many decades the only distinguishing characteristic of Be stars, apart from the emission lines, is that as a group they rotate more rapidly than non-emission B stars of the same temperature and luminosity class. The discovery that more than half of the Be stars show periodic light variations (λ Eri variables), and that this characteristic is unique to Be stars, has added another distinguishing feature. Clearly, these are two powerful clues to the mechanism which causes enhanced mass loss in Be stars. It is important to bear in mind that only *low degree* spherical harmonic variations can lead to observable light variations. Several instances are known of non-Be stars in which line-profile variations of high degree ("moving bumps") are found, but rapidly-rotating stars with variations of low-degree and periods between 0.5 and 2 d are invariably Be stars. It follows that the enhanced mass loss in Be stars is directly connected in some unknown way with rapid rotation and low-degree light and line profile variations. High-degree line profile variation cannot be directly responsible for the Be phenomenon because it is found in non-Be stars. It is therefore possible that different mechanisms are responsible for the low-degree and high-degree variations.

2.2. Why Rotational Modulation is expected in Be Stars

It is evident that if the photosphere of a rotating star does not have a cylindrically-symmetric brightness distribution, light and line-profile variations with the period of rotation must occur to some degree. We know that Be stars are very complex objects and it is clear that there is considerable activity at or near the photosphere (Smith IAU162). It is therefore difficult to understand how the photosphere of a Be star can at all times maintain a cylindrically-symmetric brightness distribution. It follows that some kind of light variability due to rotational modulation (RM) is not only plausible, but expected at some level. The question is not so much as to whether RM exists in Be stars, but whether it is at such a level that it can cause the observed low-degree periodic variations in the λ Eri stars.

The answer to the question depends on whether RM can be clearly and unambiguously identified in some stars. The strongest case for RM is that of κ CMa. The reader is referred to Fig. 5 of Balona (1990) which shows the light curve of κ CMa over a four-week period during 1987 January. The onset of periodic variations coincides with a sudden increase in brightness. The periodic variations cease when the star reaches its maximum brightness. This particular observation can be understood if we suppose that a sudden localized brightening of the photosphere (hot spot) occurred. This would cause periodic variations in brightness as the hot spot is carried round the star by rotation. After a few days the hot spot disperses or is veiled and the periodic variations cease. It is difficult to conceive of an acceptable alternative explanation. Advocates of NRP would presumably claim a sudden excitation of pulsations coinciding with a brightening of unknown origin followed subsequently by the abrupt cessation of NRP. This model is unacceptable because it demands a mechanism which can switch on and switch off excitation of pulsations of large amplitude in a very short time. Our current understanding of pulsation in B stars cannot account for such behaviour. This is certainly a case in which RM can accommodate observations but where NRP fails. Although this example is the most dramatic, there are many other examples of rapid changes in light amplitude among λ Eri stars. During all these changes the period is extremely stable.

2.3. The Periods of Be Stars

To show that periodic variations can be identified with RM one needs to first demonstrate that the photometric and line-profile variations have a period which is the same as the period of rotation of the star. One also needs to show that the variations are singly-periodic. Now it stands to reason that one can never prove beyond all shadow of doubt that the two periods are precisely equal because of observational uncertainties. The only way that this can be done at present is to estimate the rotational period from its projected equatorial rotational velocity, $v \sin i$, and its radius (using the spectral classification). The result, however, is merely a lower limit of the period of rotation because the angle of inclination is unknown. It is evident that no satisfactory estimate of the rotational period is possible for any single star.

However, we do know the mean equatorial velocity, $< v_e >$, for early Be stars *as a group* rather accurately. By statistical deconvolution of a large number of O9–B5 stars, Balona (1975) finds $< v_e >= 265 \pm 5$ km s^{-1}. If we observe many λ Eri stars and determine the mean equatorial velocity of this group using estimates of their radii and their photometric periods (assuming of course that the variations are due to RM), we obtain $< v_e >= 272 \pm 18$ km s^{-1} from 34 stars (Balona 1990). The good agreement between these numbers is obviously encouraging for the RM hypothesis. A simple statistical test shows that there is only a very small probability that these two estimates of $< v_e >$ differ by more than 20 per cent. The analysis by Balona (1990) was made using the radius calibration of Underhill & Doazan (1982). Other calibrations may give somewhat different results, but the fact remains that *within the errors* the hypothesis that the photometric period is precisely equal to the rotational period is fully justified.

From time to time it is claimed that multiperiodicity has been found in one or another Be star. Of course, if multiperiodicity is ever shown to occur in Be stars, then RM will need to be abandoned. It is clear that the light curves of λ Eri stars cannot be adequately represented by a single periodic component. Rapid changes in the amplitudes and shapes of the light curves are quite common. In this sense one could claim multiperiodicity of a kind, but true multiperiodicity demands the detection of periods which are *coherent* (i.e. maintain phase) at least for a few cycles. Up till now, no case of multiperiodicity in this sense has been found. (The photometric data for λ Eri stars have been published in full and are therefore available to anyone who still suspects multiperiodicity.) Indeed, the single period that is found remains remarkably constant over many seasons.

Having shown that the period is indistinguishable from the rotation period, we propose that the observed period *is* precisely equal to the rotation period. The observed light and line profile variations are simply a manifestation of the activity which we *know* is present at or close to the photosphere of Be stars (Smith IAU162). However, it is not possible at this stage to determine the form of this large-scale disturbance arising from the active sites. As we mentioned above, it may be widespread flaring or obscurations or both. The rapid fluctuations so characteristic of λ Eri stars, in combination with an extremely constant period, is unknown in any pulsating star; certainly our current understanding of pulsation theory is unable to accommodate these facts.

2.4. Physical Limitations of NRP

If it is accepted that the photometric periods of Be stars are precisely equal to the periods of rotation, it follows that the period of NRP in the corotating frame is infinite. This is equivalent to a stationary geometrical distortion of the star (the pulsation velocity is zero) and a stationary temperature distribution of the photosphere. This is nothing more than a special case of RM. The greater the difference between the photometric and rotation period, the shorter the pulsation period in the corotating frame and the larger the pulsational velocity for the same displacement amplitude. Proponents of NRP wish to claim that there is a difference between the two periods. As we have seen, observational uncertainties allow a difference of about 20 per cent between these two periods at the most. If we assume a typical pulsation amplitude of about 10 per cent, it is a simple matter to show that the horizontal pulsational velocity amplitude cannot exceed 15 km s^{-1} in these stars. Radial velocity amplitudes of many Be stars, such as λ Eri, η Cen and others, are often much larger than this. This can only be accommodated in the NRP hypothesis if it is assumed that the line profile variations are dominated by temperature perturbations.

For *g*-mode pulsations the radial displacement is very small. The geometric distortion is negligible and cannot account for light amplitudes of 0.1 mag. or more seen in some λ Eri stars. In any case, for $l = 1$ sectorial modes seen equator-on the amplitude due to the geometrical effect should be zero. In the NRP hypothesis, it is very clear that practically all the light and line profile variation must be caused by the temperature perturbation. The periodic variation of temperature across the photosphere, in combination with rapid rotation, leads to periodic line profile variations. Additional observational evidence to show that the temperature effect dominates in λ Eri stars comes from multicolour observations (Cuypers *et al.* 1989): the $u - b$ colour is bluest when the star is brightest. The far-UV light amplitudes are greater at shorter wavelengths as would be expected if the variations were due to temperature perturbations (Percy & Peters 1990).

From these simple and rather general deductions, we are forced to conclude that the NRP model is in reality practically identical to the starspot model. The "starspot" in this case consists of a spatial distribution of temperature described by the spherical harmonic degree of the pulsation. Because the period of pulsation in the corotating frame is very long, this "starspot" is almost stationary. In spite of this quite general conclusion, the line profile variations are still being interpreted in terms of a pure velocity field and not an almost scalar temperature field as demanded by the above arguments.

The fact that low-degree NRP in λ Eri stars is observationaly indistinguishable from a smooth, stationary temperature distribution over the photosphere is inconsistent with the detailed light curves which clearly imply the presence of many small-scale variable features. It is probably inconsistent with the line profiles. Indeed, NRP advocates have always argued against such a model themselves (failing to realize that their representation of the profile variations by a pure velocity field is physically impossible). They also fail to grasp the difference between the low-order and the high-order *lpv*, mistakenly attributing both to the same cause. This, in particular, has led to much confusion.

2.5. Concluding Remarks

The mechanism which is responsible for the enhanced mass loss in Be stars is, of course, crucial to our understanding of these stars. It is well established that the majority of Be stars rotate with an equatorial velocity which is not much larger than half of the critical rotation speed. A velocity component of several hundred km s^{-1} is required to accelerate the equatorial layers to escape velocity. As we have seen, the largest pulsational amplitude that can be accommodated is no more than 10–20 km s^{-1}. Under the circumstances, it is difficult to see how NRP can play any role in the process.

I feel that the mechanism must be sought elsewhere. There are indirect but rather persuasive observations that suggest the presence of magnetic fields in these stars (Smith IAU162). Even a weak magnetic field can play a role in enhancing the mass loss by forcing material into corotation. At this stage this is mere speculation, but the idea would certainly gain strength if observations of corotating material could be found. Indeed, Peters (1991) shows that the C IV wind lines are modulated with the phase of the light curve, indicating corotation above the photosphere. I believe that the evidence has been there all along, but we have been blinded by trying to force every unknown periodic phenomenon into the NRP mould. Be stars are very complex objects and there is no reason why they should fit into this mould.

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Discussion

Le Contel: Maybe comparison with other groups of stars could enlighten the discussion:

- β Cep stars: short periods and fundamental mode.
- 53 Per stars: slowly rotating stars (1–3 day periods).

In between there are a few stars where the two time scales are present. As an example that the two phenomena (RM and NRP) could be present in a single star, I would like to emphasize the case of ET And (see Kuschnig *et al.* IAU162) which is a Bp star where the rotational period is well known and a slow pulsation is also present.

Balona: Yes, it is important to place λ Eri stars within the context of the pulsating B stars. We can distinguish several kinds of intrinsic variables based on their observed characteristics:

- The β Cep stars: periods characteristic of p-modes.
- The 53 Per stars: slowly-rotating stars with periods in the g-mode range.
- ζ Oph stars: generally rapid rotators showing line profile variations of high degree. In the corotating frame these have very long periods (g-modes).

According to current thinking, the λ Eri stars may be the rapidly-rotating counterparts of the 53 Per stars. The discovery of λ Eri stars in a metal-poor system (Balona 1992) is a problem since pulsational driving is not expected in stars with low metal abundance. Moreover, it seems that rapid rotation will inhibit pulsation as there are no 53 Per stars in NGC 3293 and NGC 4755 — two young open clusters containing rapidly-rotating stars (Balona 1994, Balona & Koen 1994). These observations do not favour the NRP interpretation for λ Eri stars. However, I do believe that NRP might be the correct explanation for the high-degree *lpv* in Be stars, so I think RM and NRP can indeed co-exist in these stars. The interesting case of ET And needs further study: perhaps it is a late-type 53 Per star.

Percy: In other (though different) stars, e.g., ρ Cas and HR 8752, pulsation *seems* to be able to trigger a brightening of the star followed by a slow decline (Percy & Zsoldos 1992, Zsoldos & Percy 1991). Why can pulsation *not* trigger an outburst in κ CMa and ϵ Cap and *how* can the rotational modulation theory explain it?

Balona: According to the references you quote, the light curves of these hypergiants are complicated by episodes of shell ejection. This is hardly a case of pure pulsation and cannot be taken as an example of how pulsation can lead to rapid fluctuations. We know that there *is* photospheric activity in Be stars. All that I am suggesting to account for observations in κ CMa and ϵ Cap is a sudden localized outburst of one of these active regions. Rotational modulation is a direct result of such an outburst. What causes the outburst is not known, though one may speculate on flaring or other magnetically-related mechanism.

Le Contel: How can you be sure you do not have shorter periods in your observations? In fact, the sharp changes in the light curve of stars such as κ CMa may mask the presence of other periods.

Balona: The observations certainly cannot be represented by a single sinusoidal period. On the other hand, there is only one *coherent* period. You show this by calculating a periodogram of the data. You then find only one significant peak in the periodogram. The Fourier decomposition of the light curves require very many frequency components to describe them, but only one component is coherent.

Gies: J-P. Zahn argues that the differential rotation rate of the core differs from the surface rate by no more than 20 per cent. If NRP is driven by convective motions in the core, then the superperiods would be similar to the surface rotation periods.

Balona: If NRP at the surface is driven by the rotating core and if, as you say, the period that would be observed differs from the rotational period by no more than 20 per cent, it would be consistent with observations in this one respect. However, the core is very small indeed for giants at the end of core hydrogen burning and for late B-type stars. I cannot see how the near-absence of a convective core could drive pulsations, but it would be important to predict the instability strip for such a mechanism. The Be stars do not appear to be confined to early main sequence dwarfs. I therefore think that this is not the explanation for the λ Eri stars. Besides, how can one explain sudden increases and decreases in amplitude in such a model?

Harmanec: I think that what is important to the whole problem is the observed co-existence of slow light and line-profile variations and travelling sub-features which often move with the *same* acceleration across the line profile. Free NRP should not have such commensurable periods. Possible explanations can perhaps be found in the theoretical work of Dr Aerts who showed us that travelling bumps can be produced by *low-order* nonradial pulsation.

Baade: It should be kept in mind, though, that genuine commensurability has not been demonstrated in any star with any certainty. Often, the phase coherence of the high-order variability is not very pronounced. My intensive search for one common superperiod in 2 weeks worth of high-quality spectra of the Be star μ Cen firmly excludes any superperiod between one and a few days.

Gies: In Balona's talk he mentions that the expected velocity amplitudes for periodic Be stars do not exceed 20 km s^{-1}. Model NRP profiles show shape changes that are very significant! Velocity changes in the line centroid can be large. I will measure the velocity variations in these model profiles and send him my results.

Baade: We must also remember the effect of rotation which strongly amplify any "real" radial velocity amplitude.

Balona: The point I want to make is that if the photometric period and the rotational period differ by no more than 20 per cent, as the observations indicate, then the contribution of the pulsational velocity to the radial velocity is very low. The changes in the line profile are dominated by temperature variations which in a rotating star produces a shift in the line centroid (radial velocity), as Dietrich has just mentioned. If the dominating effect of NRP is to produce a variation of temperature in the photosphere, this is in reality equivalent to a washed-out star spot which the NRP proponents assure me does not fit the line profiles. I do not believe in such a spot model: the rotational modulation must be due to a more complex phenomenon such as a corotating obscuration or localized hot spot at or close to the photosphere.

Smith: Actually, I believe there are two separate mechanisms on the surfaces of many Be stars, but that is not the question. The question concerns the *periodic* variations. I would like to make the following points in defense of NRP as opposed to RM:

(1) As Gies and I have both been attempting to show over a few years, *both* the footprints (and their associated wings) move back and forth in agreement with the line profile variations, radial velocity and photometric periods of several Be stars. I can't see how anything other than a velocity field can cause this!

(2) I have done the disk-wind modelling of the *lpv* variations in λ Eri (e.g., Smith 1989) and only small velocity amplitudes are necessary to fit them, values that do not violate any fluid flow conservation conditions.

(3) I think we should establish a picture of these RM entities and call them "spots". Thanks to Holberg *et al.* IAU162, we now have a colorimetric paradigm of what one of these double-wave photometric variables, α Eri, is doing and we see from the UV-optical color that the star is blue when it is bright. Therefore $T_{spot} < T_{eff}$ and we can say that the immaculate phase of the star's light curve should also be its maximum. If this is true, then we expect light curves from several stars, statistically, to show a flat light maximum for 50–60 per cent of the period during the time that the spot is occulted behind the visible disk. I've looked for this simple signature among λ Eri light curves and I'm not sure that I can find an extended light maximum even once! Therefore, I conclude there could be a fundamental problem with the RM-spot hypothesis.

Balona: (1) I do not think that the variation of the footprints is explicable only if there is a velocity field. The radiation flux which causes the extreme ends of the line profiles originates at the equatorial limbs of the star. As one limb darkens and the opposite limb brightens (by a large-scale obscuration, say), the intensities of the footprints and wings will change accordingly and give rise to the effect you mention. Also, we know that moving bumps are present in some Be stars on many occasions. The nature of these high-degree line profile variations is not understood but is probably NRP. The footprints can be severly distorted by these features, but this is not relevant to the present discussion which is confined to the *low-degree* line profile variations unique to Be stars.

(2) In the first place, it is not really correct to model the line profiles using the eigenfunction of a non-rotating star for the Be stars which are very rapid rotators. Even worse, the temperature perturbation is ignored. The periodic Be stars do, of course, change amplitude quite markedly from time to time. Over the last few years λ Eri has had a very low amplitude, so I can quite believe that you can model the line profiles with small pulsational amplitudes and no temperature perturbation as there are many free parameters. Bear in mind however, that many years ago the situation was quite different. When λ Eri was at high amplitude, Bolton (1981) obtained a radial velocity amplitude of 60 km s^{-1}. As I point out, this can only be understood if the temperature variation dominates the line profile.

(3) I agree that the simple picture of a starspot is not adequate to explain all the complex line profile and light variations in the λ Eri stars. Note, however, that the spot model is almost indistinguishable from the NRP model (because temperature is so dominant) and in arguing against the spot model you argue against NRP. I cannot pretend to have a full picture

of what is causing the rotational modulation, but I suspect it is probably a corotating obscuration or hot area rather than a star spot as in the Sun.

Saio: Balona, Sterken & Manfroid (1991) show that the light curves of the λ Eri stars are not correlated with the Hα emission line intensity variations. It seems to me that this observational fact is inconsistent with the rotational modulation model.

Balona: The Hα emission strength is determined by the envelope, not by what is happening in the photosphere. What these authors show is that the intensity of Hα emission does not seem to depend on the amplitude of the periodic light variations. This seems to rule out a direct connection between the mass-loss rate and the amplitude of the periodic variations, but it has no bearing on what is causing the periodic variations itself. One can use the same argument against NRP of course.

Peters: To Petr Harmanec: Have you attempted to reconcile your conclusions on η Cen (see Štefl *et al.* IAU162) with the wind variability that we observed during our campaign?

Harmanec: The seemingly periodic RV variation of η Cen is a real phenomenon which affects the whole line. The centroid, bisector and outer wings move in phase and should be taken into account by any model attempting an interpretation. My feeling is that the periodic variations are very complex and that both RM and NRP might be occurring. In η Cen large bumps reappear exactly at the phase of light minimum which seems to speak in favour of some projection effect.

Peters: To Luis Balona: (1) How can you explain the observed wind behaviour with the spot model?

(2) Comment on periods: For all the stars we studied in the campaigns (except ϕ Per), the observed FUV/optical photometric and spectroscopic periods are systematically smaller than those expected from rotation, assuming that the objects are not precisely all zero-age main sequence stars.

Balona: (1) Without an understanding of what is the actual cause of the enhanced mass loss (which not even proponents of NRP claim to know), it is impossible to answer your question.

(2) Calibrations of the radii of B stars differ and it is not surprising that systematic errors exist. You have to look at the statistics. *Within the errors of these calibrations*, the photometric and spectroscopic periods are the same.