NON-RADIAL PULSATION IN Be STARS

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1. INTRODUCTION

Be stars are B stars in which emission has been observed in at least one hydrogen line on at least one occasion. Some Be stars are pre-main-sequence stars, mass-transfer binaries, or supergiant stars with extended atmospheres. The majority, however, are classical Be stars: single stars on or near the main sequence. An important characteristic of these stars seems to be their rapid rotation - close to but not at the "critical" velocity at which the effective gravity vanishes at the equator.

Be stars are photometrically and spectroscopically variable on time scales ranging from hours to decades. The long-term variability seems to depend on the amount of emitting material around the star, and on the geometry of this material relative to the star and to the observer. The short-term variability has been ascribed to non-radial pulsation, and it is possible that this pulsation contributes in a fundamental way to the Be phenomenon. The study of non-radial pulsation, and its relation to the nature, origin and variability of the Be phenomenon, is a rapidly-developing field. It was discussed in detail at a recent Workshop on the Relation between Non-radial Pulsation and Mass Loss in Hot Stars (held in April 1985 at the University of Colorado), the proceedings of which are to be published in the Publications of the Astronomical Society of the Pacific.

2. SHORT-TERM PHOTOMETRIC VARIABILITY

Historically, this was the first evidence that non-radial pulsation might be present in Be stars (though it was initially ascribed to the effects of rotation or orbital motion). Several observers in the 1940's and 1950's found photometric variations in Be stars on time scales of about a day. Conspicuous examples were o And, V923 Aql, EM Cep, EW Lac and 2 Vul. An excellent review of this and other aspects of the photometric variability of Be stars is by Harmanec (1983). Early studies of short-term spectroscopic variability were hampered by the complexity of the spectra, and the limitations of the available detectors.

J.-P. Swings (ed.), Highlights of Astronomy, 265–272.

The lack of progress in understanding the short-term photometric variability was in part due to observational problems: the time scales near one day (different cycles were sampled on different nights), the rapid changes in amplitude and in the mean light of the star, and the generally inadequate numbers of observations - all of which complicate the power spectrum analysis. A solution to these problems is to organize "campaigns" on selected stars, involving not only photometry but also spectroscopy and other techniques as well. Long-term photometric campaigns on Be stars have been organized by astronomers at the Ondrejov Observatory (Czechoslovakia) and at the European Southern Observatory.

Two Recent Studies

Within the framework of the former campaign, a very successful "mini-campaign" was carried out in 1983 to study the short-term photometric variability of the Be stars o And, KX And, KY And, LQ And and EW Lac. With observations from several longitudes (Yugoslavia, China and North America), alias peaks in the power spectra were much reduced. Periods of 1.57, 0.47. 1.51, 0.30 and 0.72 day were found in the five stars respectively, according to a preliminary analysis by Stagg (1986). Similar periods were present in 1984, but the amplitudes in o And and EW Lac were much reduced. Three of the stars had light curves which were non-sinusoidal, or which had alternating deep and shallow minima.

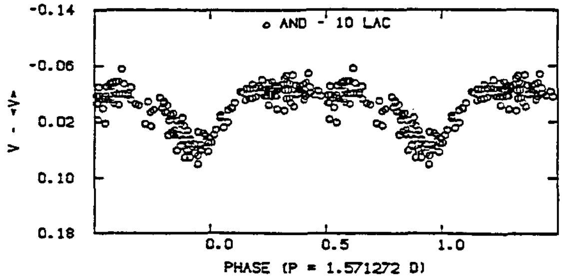

Figure 1: The V Light Curve of o And in Early Autumn 1983 (Stagg, 1986).

Balona and Engelbrecht (1986) have carried out a five-week photometric study of the seven Be stars in NGC 3766. Four show strictly periodic variations on a time scale of about a day. Two others are certainly variable, but the amplitudes are too small for reliable periods to be found. The light curves are in most cases non-sinusoidal, and (having been made by careful observers using a single telescope) show very little scatter. As discussed later, Balona and Engelbrecht attribute the variability to rotation rather than pulsation.

The Incidence of Short-Term Photometric Variability

The high incidence of short-term variability in Be stars has been confirmed by two other studies. Stagg (1986) surveyed 85 bright Be stars south of declination -20°, and found that about 50 per cent seem to vary at a low (0.01 to 0.02) level. A few specific stars showed larger variations. Percy (unpublished) searched the archive of UBV photometry of bright Be stars at the Ondrejov Observatory and found that, of the several dozen stars for which observations were made on several consecutive nights, about 25 per cent showed large night to night scatter corresponding to short-term amplitudes greater than 0.03. Both Stagg (1986) and Percy found that early to mid-B stars were more likely to be short-term variables than late B stars.

3. SHORT-TERM SPECTROSCOPIC VARIABILITY

The recent growth of interest in the short-term variability of Be stars, and the belief that it is due to non-radial pulsation, are both due to spectroscopic developments: the availability of high signal-to-noise detectors, and the realization that, because of the concept of "Doppler imaging" (Vogt and Penrod, 1983), the visibility of certain kinds of pulsation would be enhanced rather than hidden by rapid rotation. Walker et al. (1979) observed moving "bumps" in the line profiles in ζ Oph. Baade (1982) reported an unusually short and stable spectroscopic period (1.365 days) in 28 CMa, and has since observed similar phenomena in other southern Be stars. Bolton (1981) using photographic spectroscopy, reported radial velocity variability in λ Eri; the period (0.702 day) and variable amplitude suggested that it was due to non-radial pulsation. Vogt and Penrod (1983), in a key paper in this field, carried out a detailed study of the short-term variability (primarily spectroscopic) of ζ Oph, modelled it in various ways, and concluded that it was due to non-radial pulsation.

The largest survey of short-term spectroscopic variability in Be stars is by Penrod (1985), who obtained about 1500 high-resolution, high signal-to-noise spectra of about 25 rapidly-rotating B and Be stars from 1983 to 1985. He found that all of the Be stars show absorption line profile variations, which were interpreted as due to low-order ($l = 2$) non-radial pulsation in g-modes. Non-Be stars do not show such low-order modes. The spectroscopic periods of the Be stars are about a day, and agree with photometric periods where both are known. Both the B and Be stars were (probably) pulsating in one or two higher-order ($l = 4$ to 10) modes. All of the modes were (probably) sectorial modes, and travelled from blue to red across the absorption line profile though, in some cases, the actual wave motion is retrograde, and the apparent prograde motion is due to the star's rapid rotation. The amplitudes of the pulsations ranged from a few km/s up to the sound speed. The amplitude was in some cases variable. Many of the stars were perfectly periodic, but a few appear to alternate between two or three sets of modes.

4. EVIDENCE FOR NON-RADIAL PULSATION

The strongest evidence for non-radial pulsation in Be stars is the short-term spectroscopic variability - absorption line profile variations caused by the velocity fields in the photosphere. At low resolution, these may appear as radial velocity variations. Light and colour variations, due to changes in temperature and radius, are also to be expected, and these are seen as short-term photometric variability. The observed periods are consistent with those to be expected for low-order g-modes in a rapidly-rotating star. They are also consistent with those expected for rotation, as discussed in detail below. Although the rotation of photospheric spots or circumstellar spokes might conspire to produce the symmetry changes in the line profile (ascribed to low-order g-modes), the "ripples" in the line profile (ascribed to higher-order modes) would be much more difficult to mimic. They would require many spots or spokes, distributed around the star in a symmetric way.

The procedure for modelling the line profile variations by non-radial pulsation is as follows. The intrinsic profile of the line (determined from a model atmosphere or a standard star) is subjected to the velocity field of an assumed mode. This velocity field is described in terms of spherical harmonics. The following parameters must be chosen: the inclination, equatorial rotation velocity, the mode (l,m), its velocity amplitude, the ratio of vertical to horizontal velocity, and the pulsation phase. In principle, there is enough information in a single observed line profile to determine all six parameters. In practice, a long series of profiles is used.

5. EVIDENCE AGAINST NON-RADIAL PULSATION

Those who maintain that short-term variability in Be stars is due to rotational effects, rather than non-radial pulsation, list the following reasons (e.g. Balona and Engelbrecht, preprint). (i) The periods are consistent with the rotation periods. (ii) The light curves often show double-wave variation, which is difficult to explain by non-radial pulsation unless some type of resonance is active. (iii) The light amplitude can sometimes be as large as $0^{m}.2$, which may be too large to be produced by non-radial pulsation. (iv) Variability is seen in stars with spectral types from B0 to B8, which seems difficult to reconcile with any pulsation mechanism. (v) There is little or no evidence for multiple periodicities characteristic of non-radial pulsation. One may dispute these reasons by pointing out that:
(i) although no explanation for the double-wave light curves has been proposed within the framework of the non-radial pulsation hypothesis, there is no reason to believe that no such explanation exists
(ii) predictions of light and colour variations in non-radial pulsation are still rather crude; large amplitudes are not excluded and (iii) short-term variability is more common in Be stars of early spectral type - the same spectral types in which non-radial pulsation is found in the 53 Per and β Cep stars.

There are several weaknesses, both real and apparent, in the procedures used to observe the line profile variations, and to model them with non-radial pulsation. (i) relatively few astronomers have access to the specialized facilities needed to observe line profile variations, so there has been little opportunity to verify interpretations.

(ii) The modelling procedures are still something of an art, carried out by relatively few practitioners. Since there are several free parameters in the modelling, it is not always clear whether the derived parameters - and the interpretation - are unique. (iii) Much of the work (e.g. Penrod, 1985)) is still unpublished. Some presentations of preliminary data have emphasized oddities and deviations from regular behaviour. Penrod (1985) finds, however, that virtually all of the Be stars which he has modelled are well-behaved. (iv) Modelling is done in the framework of spherical harmonics, which may not be a good assumption in the case of rapidly-rotating stars. There are additional uncertainties in the prediction of light and colour variations due to non-radial pulsation in rapidly-rotating stars. (v) Vogt and Penrod (1983) discarded rotation of spots or spokes as an explanation of the short-term variability of ζ Oph partly because of the lack of observed photometric variability, even though such variability had not been looked for in detail.

These criticisms have some merit, and it is certainly important to verify and improve the modelling procedures. The strength of the non-radial pulsation hypothesis is that it is physically plausible and complete, and can explain or accommodate the large number of observations of line profile, light and colour variations, as well as the long-term and short-term changes in the variability.

6. CORRELATION BETWEEN SHORT-TERM VARIABILITY AND EMISSION EPISODES

The outstanding problem of the Be stars is that of the origin of the emission and its variability. Rotation and radiation pressure are important in driving steady mass loss, but they are not necessarily sufficient, and they do not explain how a star can change from B to Be and back again. For this reason, the following observations of a correlation between short-term variability (non-radial pulsation) and emission episodes are important.

Baade (1983) proposed, on the basis of observations of η Cen, that short-term spectroscopic microvariability might be a precursor of shell episodes in Be stars. Vogt and Penrod (1983) presented strong (but not definitive) evidence for a correlation between line profile variability and emission in ζ Oph. Harmanec (1984) pointed out that there was a correlation between the amplitude of the short-term variability of o And and its mean brightness, which is believed to depend on the amount of emitting material in its circumstellar disc. Penrod (1985) has found that the amplitude of the line profile variability in λ Eri decreased from 20 km/s to nearly zero within a few days of the beginning of an emission episode in this star. Bolton (1981) had earlier suggested a correlation between short-term variability and emission in this star.

Further progress in this area will require regular monitoring of selected Be stars, both photometrically and spectroscopically. Both aspects of this project could be carried out with a relatively small telescope, as long as it was available on a continuous, long-term basis.

7. THE IMPLICATIONS OF NON-RADIAL PULSATION IN Be STARS

Willson and Bowen (1984) have discussed the general role which pulsation might play in driving mass loss in stars. Willson (1985) has discussed qualitatively the application of this work to Be stars. Long pulsation periods and moderately large vertical pulsation motions are conducive to driving mass loss by shock waves. Both of these appear to be present in Be stars, though the relative amount of vertical motion in the non-radial pulsations in Be stars is still open to question. Willson notes that, because the pulsations are strongly concentrated to the equatorial regions, the character of the mass loss may be different in the equatorial and polar regions, and in the former regions they will depend on the pulsation amplitude. In this way, it is possible to explain transitions from B to Be to B by invoking changes in the pulsation amplitude. To some extent, this scenario can be tested by examining the geometry of mass loss in Be stars, and how it changes with time.

Penrod (1985) has also suggested that the long-period (l = 2) non-radial modes serve to "puff up" the outer atmosphere of the star with shock waves, until rotation and radiation pressure act to throw the material into orbit. The pulsation is not the sole cause of the mass loss. Rapid rotation and radiation pressure must be present as well. Slowly-rotating B stars, even if pulsating, do not become Be stars. Rapidly-rotating B stars may become Be stars if and when they excite a long-period non-radial mode. An extended atmosphere may form around the star but, once it does, wave energy may leak out, so that eventually the pulsation amplitude becomes too small to support the extended atmosphere, and the mass loss ceases. This may provide a mechanism for varying the pulsation amplitude (and the mass loss) in a quasi-random way. It is interesting that, according to Penrod, the energy in a pulsation mode is approximately equal to the energy needed to eject an envelope in a Be star.

The ultimate cause of the pulsation is not known. Some possible mechanisms for causing pulsation in B stars are discussed by Osaki elsewhere in this volume. The cause of the variability of the pulsation amplitude is also not known, though one possibility was discussed above. It has been observed that the amplitude of a low order mode can change within a few days. This places some limits on the amount of energy in such a mode.

8. FUTURE RESEARCH

The problem of the pulsation mechanism in Be stars (and all other B stars) remains unsolved; indeed, it is one of the major remaining problems in stellar pulsation theory. The nature of non-radial modes in rapidly-rotating stars must also be investigated, and better predictions of light and colour variations made. Realistic models must be constructed to verify that pulsation and shock waves can actually drive mass loss in Be stars, especially in the equatorial regions.

Those who have proposed that the short-term variability in Be stars is due to rotational effects (either spots on the photosphere or blobs or spokes anchored to the star by magnetic fields or freely orbiting in a disc) must construct realistic and plausible models, to verify that these effects can produce the observed line profile variations, and can accommodate the large and often-changing light and colour variations.

Coordinated multi-site spectroscopic and photometric observations of a few selected Be stars should be made, because simultaneous observations of line profile, light and colour variations can confirm mode identifications, and distinguish between modes (sectorial and Rossby, for instance) which can produce similar line profile variations but quite different photometric variations. Long-term monitoring of such stars would be useful in exploring possible correlations between short-term variations and emission episodes.

9. Be STARS SHOWING SHORT-TERM VARIABILITY

The Appendix contains a list of Be stars in which short-term photometric or spectroscopic variability has been observed, or is strongly suspected.

ACKNOWLEDGEMENTS

I am grateful to D. Baade, L.A. Balona, C.T. Bolton, C. Engelbrecht, A.W. Fullerton, D.R. Gies, P. Harmanec, P. Koubsky, Y. Osaki, G.D. Penrod, M.A. Smith, C.R. Stagg, C. Waelkins and L.A. Willson for useful comments and/or sharing their unpublished data. I also thank the Natural Sciences and Engineering Research Council of Canada for research support.

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APPENDIX: Be STARS IN WHICH SHORT-TERM VARIABILITY HAS BEEN OBSERVED

This list is based upon ones compiled by Balona and Engelbrecht (private communication), Stagg (1986) and the author. Many of the periods are in need of confirmation. Most of the amplitudes are variable. In the remarks column, DW refers to a double-wave or non-sinusoidal light curve, and 2K is the total velocity amplitude in km/s if the variable line profiles are measured for radial velocity.

HD	HR	Name	Spectrum	Δm	P(d)	Remarks
10144	472	α Eri	B3Vpe	0.03	1.46	DW
33328	1679	λ Eri	B2IVe	0.03var	0.70	DW:, 2K=30var
37490	1934	ω Ori				
41335	2142		B2Ve	0.03:	0.3::	81^d binary
56014	2745	27 CMa	B3IIIe			
56139	2749	28 CMa	B2.5IVe	0.02var	1.37	2K=10
120324	5193	μ Cen	B2IV-Ve		0.51	
127972	5440	η Cen	B1.5Vne		hours	
138749	5778	θ CrB	B7e	large?		not variable?
149757	6175	ζ Oph	O9.5Vne	0.02:	1.::	
157042	6451	ι Ara	B2IIIne	0.05	0.51	DW
158427	6510	α Ara	B2.5Ve	0.02	0.66	DW?
172256			B5e	0.12	0.5::	
180968	7318	2 Vul	B0.5IVe	0.06	0.61	DW, 2K=7
183656	7415	V923 Aql	B5Ve	0.10	0.85	
189687	7647	25 Cyg	B3Ve	0.03	0.21:	
191610	7708	28 Cyg	B3Ve	0.06var	0.7	
200120	8047	59 Cyg	B1IVe	small	0.26:	
205637	8260	ε Cap	B3Ve	0.02	0.22	
208392		EM Cep	B1IIIe	0.15	0.4	DW?
209014	8386	12 PsA	B8Ve	0.02	0.40	DW?
209409	8402	o Aqr	B8Vpe	0.02	0.72	
217050	8731	EW Lac	B4IIIe	0.06var	0.72	DW, 2K=7?
217675	8762	o And	B6IIIe	0.05var	1.57	DW, 2K=16var
218393		KX And	Bpe	0.10:	0.47:	39^d binary
218674		KY And	B3IVe	0.10:	1.51	DW?
224559	9070	LQ And	B3IVe	0.03	0.31	
		NGC3766-01	B2IVp(e)		1.74	
		NGC3766-15	B2IIIe		0.96	
		NGC3766-63	B1.5Vn		0.84	
		NGC3766-88	B3npe		0.95	

This list is not necessarily complete; there are many other Be stars suspected of short-term variability.