GAMMA CASSIOPEIAE AND BE STARS

BY M. L. WHITEHORNE
R.A.S.C. Halifax Centre
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ABSTRACT

A brief review of recent literature is presented regarding the complex nature of Be stars. These objects have been studied extensively and as yet no satisfactory model exists that can explain their unusual behaviour. Be stars may represent an extreme example of processes occurring to a much lesser degree in several types of normal stars. I have attempted to demonstrate the three major spectral phase changes observed in Be stars.

RÉSUMÉ

Je présente une brève analyse de la littérature récente concernant la nature complexe des étoiles Be. Ces objets ont été étudiés en profondeur, et pourtant jusqu'à présent il n'existe aucun modèle satisfaisant qui puisse expliquer leur comportement peu commun. Les étoiles Be pourraient représenter un exemple extrême de processus se produisant à un degré beaucoup moins élevé dans plusieurs sortes d'étoiles normales. J'ai essayé de démontrer les trois changements principaux observés dans les étoiles Be.

I. Introduction. Professional astronomers are being challenged by the intriguing Be stars. These bright stars' strange behaviour has been reluctantly yielding to the efforts of many researchers, but the picture is far from complete.

I encountered these curious objects quite by accident. An interested amateur, I was enrolled in an observational astronomy course at Saint Mary's University and working on an assignment of taking stellar spectra and classifying them. I stumbled across γ Cassiopeiae with its emission line spectrum. The R.A.S.C. OBSERVER'S HANDBOOK (Bishop 1988) listed the star as "B0 IV npe (shell)", just enough information to arouse one's curiosity. *The Bright Star Catalogue* (Hoffleit and Jaschek 1982) was more informative. γ Cas is a variable star and its spectrum demonstrates complex variations.

After completing the astronomy course, I applied for and obtained time on the telescope to acquire some spectra of γ Cas and demonstrate some changes therein. Further research as to what results I might have expected revealed a disappointment. The star's cycle of variability occurred over a period of decades, and short term changes required a high dispersion spectrograph (10–12 Å/mm) (Doazan 1982). The two spectrographs I would be using had lower dispersions (123 Å/mm and 84 Å/mm).

The work up to this point served to increase my interest, and I decided to pursue these unusual Be stars further. Since the available equipment would not demonstrate short term spectral changes, perhaps it would be possible to demonstrate the three major phases seen in Be stellar spectra with three different stars. This paper is the result. γ Cas will serve as a focal point of this paper. The paper is divided into three sections.

The first section deals with the history of this unique star as well as two other well-known Be stars. These other two stars serve to illustate how Be stars differ in their individual behaviour. The second section examines Be stars in general; what we think we know and what the trends are in current research. The third section contains a discussion of the pros and cons of the various proposed models and their attempts to explain the observations.

II.1 A Brief History of γ Cassiopeiae, 59 Cygni, and EW Lacertae. γ Cas was the first emission line star to be discovered. In 1866, Angelo Secchi observed Hβ in emission (Hoffleit and Jaschek 1982, Kitchin 1982). This first Be star as well as Be stars in general have continued to interest astronomers ever since.

According to *The Bright Star Catalogue*, γ Cas is a variable star; its colour and spectrum exhibit changes and its visual magnitude varies from 3 to 1.6. The star is multiple. One companion is some 6.3 magnitudes fainter and 2.3 seconds of arc away. The other may be a neutron star (Marlborough *et al.* 1978). The projected rotational velocity is 300 km/s and the system's radial velocity is −7 km/s (approaching the sun) (Bishop 1988, Hoffleit and Jaschek 1982). This star has a rapidly expanding circumstellar shell and a variable rate of mass loss. A high dispersion spectrogram reveals many variable features with periods ranging from a few hours to several decades (Doazan 1982). These features will be discussed later in this paper.

γ Cas is a member of the Cas-Tau OB I association and is the source of excitation for the H II region S185, as well as the illuminator for the reflection nebulae IC 59 and IC 63 (Hoffleit and Jaschek 1982). The star has been extensively studied since its discovery and its activity can be divided into two periods (Doazan 1982). From 1866 to 1942 there was a long Be phase followed by a ten year period of spectacular variations, dispersion of its envelope, and a conversion to a quasi-normal B phase.

During the ten years between 1932 and 1942, γ Cas showed many unpredictable changes with increasing and decreasing Balmer emission, appearance and disappearance of a shell spectrum and luminosity changes. By 1942 the shell spectrum and emission lines had disappeared and γ Cas presented a normal B spectrum. For γ Cas, the emission phases are when the star is at its most luminous; it is less so during the shell phase. Other Be stars behave similarly although not all of them do (Barylak and Doazan 1986, Doazan 1982).

From 1942 to 1981 the star went from a quasi-normal B to an irregular Be phase with only small variations in the spectra. After the dispersal of its shell and a return

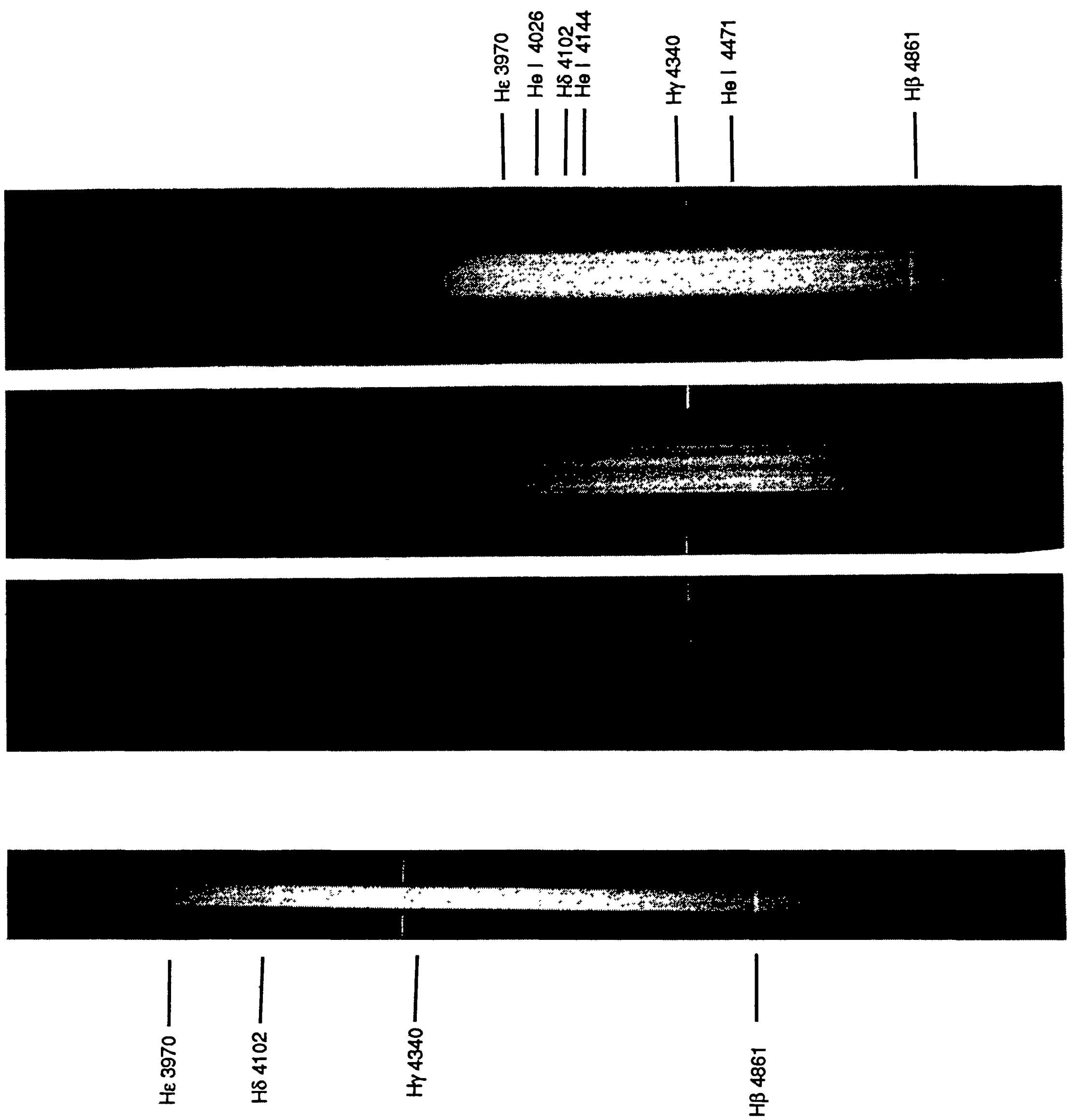

FIG. 1—Low-dispersion (123 Å/mm) spectrograms of γ Cas (Be phase) taken over a four week period that show an apparent change in the emission strength of Hγ. Figure 1a (Jan. 29/88): Hγ is hardly visible. Figure 1b (Feb. 14/88): Hγ shows increasing emission strength. Figure 1c: (Feb. 27/88) Hγ shows a decrease in emission strength. Note the broadened Balmer absorption lines in the blue end of the spectrum due to rapid stellar rotation and the Stark effect. Figure 1d: γ Cas Be phase. Spectral type B0 IVnpe. Low-dispersion spectrogram (84 Å/mm) of γ Cas taken on May 13th, 1988 showing a nearly featureless Be spectrum except for Hβ and Hγ in emission.

to a normal B phase, γ Cas began a new Be phase. Until 1980 the emission increased slowly and irregularly with only small variations. In 1969 V/R variations (see section III) began to be observed. Intensity of emission underwent some variations and the luminosity of the star increased from a visual magnitude of 3.0 to 2.35 in 1980. According to the 1989 OBSERVER'S HANDBOOK the current magnitude of γ Cas is 2.5. It is interesting to note that γ Cas displays a considerable range in visual magnitude. This is unusual because most Be stars have a variation in visual magnitude on the order of only tenths of a magnitude, see Kitchin (1982). γ Cas is of spectral type B0 IV e, has a mass ≈ 17 $M_\odot$, a radius of ≈10 $R_\odot$ and a temperature in the range of 25,000 K; see for instance, Kitchin (1982).

The usual spectrum of γ Cas shows nearly a complete absence of sharp features as evidenced by the spectra that I acquired. See figure 1. A close inspection of the four spectra of γ Cas revealed an unexpected surprise. Hγ is extremely faint on January 29 (figure 1a), shows an increase in emission on February 14 (figure 1b), a decrease in emission on February 27 (figure 1c) and another increase in emission on May 13 (figure 1d). It is very subtle but it is there! Absorption lines are broadened rotationally and the rotational velocity is estimated to be between 230 km/s and 570 km/s (de Jager 1980). Ultraviolet studies show a mass loss of 7 $\times$ 10^{-9} $M_\odot$/year (Kitchin 1982, Doazan 1982). A P Cygni feature in the C IV doublet (in the ultraviolet) indicates outstreaming motions in the circumstellar envelope. See for instance de Jager (1980), Kitchen (1982), Doazan (1982).

One proposed model for γ Cas is that of gas being ejected from a star rotating at or near the critical velocity and accelerated radially (stellar wind), forming a gaseous ring that is densest near the equator and more corona-like at higher stellar latitudes. Observed variable X-ray emission is believed to be generated in the circumstellar shell. The envelope extends outwards from 50 R_* to 250 R_*. γ Cas exhibits an infrared excess of about one magnitude and the mechanism for this is still in question. Studies of polarization in the spectrum suggest a disk-like envelope, inclined at 47° to our line of sight, which rotates clockwise as seen from Earth.

Variations in the continuum polarization in γ Cas on a scale of just a few hours are attributed to inhomogeneities in the rotating circumstellar envelope. Turbulence caused by an outstreaming stellar wind might lead to corona formation; see, for instance de Jager (1980).

II.2 59 Cygni. This star has not been observed as well as γ Cas but nevertheless its behaviour has been recorded since 1904 (Doazan 1982). At that time 59 Cyg was in a Be phase which by 1916 had decreased to a normal B phase. Then from 1917 to 1977, the star underwent a complete cycle variation: from normal to B to a new, long Be phase with strong variations and finally a five year period of spectacular phase changes. It then settled into a "normal" B phase. Starting in 1978, 59 Cyg began another Be phase with an increasing degree of Balmer line emission. During this weak, slowly and irregularly increasing Be phase, the strongest mass ejection activity ever observed in this star was detected in its ultraviolet spectrum. 59 Cyg, at present, has a "normal" B-type spectrum with no evidence of emission in the visual range on low-dispersion (84 Å/mm) spectrograms. See figure 2. It is interesting to note that over the years, this star has been variously classified as O9 V,

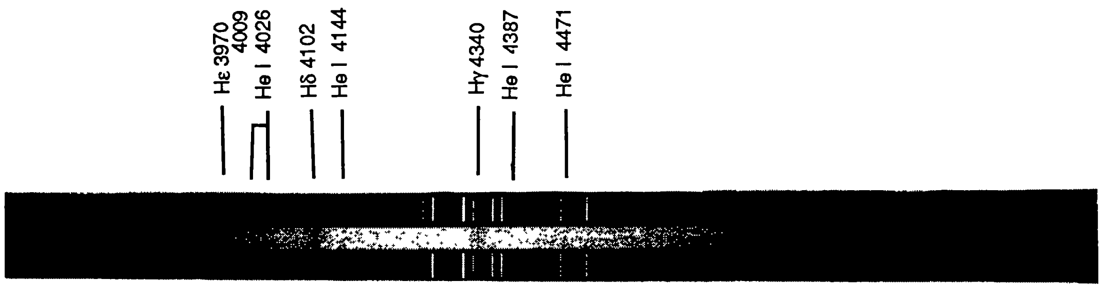

FIG. 2—59 Cyg "normal" B phase. Spectral type B1 IV-Vne. Low-dispersion (84 Å/mm) spectrogram of 59 Cyg taken on May 13th, 1988 showing a normal B-type series of hydrogen and helium absorption lines. Note the rotationally broadened and diffuse appearance of the Balmer lines.

B0p, B1 IVe and B1.5 Venn. It is currently classified as B1 ne with a visual magnitude of 4.74. This star is rapidly rotating with $v \sin i = 374 \text{ km s}^{-1}$ (Hoffleit and Jaschek 1982).

II.3 EW Lacertae. Here is another well-documented Be star which also has its own unique pattern of changes. It is listed in the *The Bright Star Catalogue* as spectral class B4 IIIpe with a visual magnitude of 5.43 and $v \sin i = 350 \text{ km s}^{-1}$. It has also been classified as B2 Ve. EW Lac showed (Doazan 1982) strong variations until 1920 with several appearances and disappearances of its shell spectrum. This was followed by a very quiet period during which the shell spectrum underwent very few changes (1926 to 1977). During this period of spectral quiescence, there was a five year period (1972 to 1977) of rapid variations in visual magnitude. In 1978 the star began a new phase of activity with strong variations in colour and in the Balmer series spectral lines. Figure 3 shows a low-dispersion (84 Å/mm) spectrogram of EW Lac, apparently in a shell phase.

III.1 Some General Characteristics of Be Stars. Be stars are main sequence stars with emission lines in their spectra. There has been some confusion between Be stars and shell stars, but current theories suggest the two types are different phases of the same object (Underhill 1960, Doazan 1982, Kitchin 1982, Dachs *et al.* 1986).

There are a few types of related objects; the Wolf-Rayet stars, the Oe stars and Ae stars (Type O and A which also show emission) (de Jager 1980, Doazan 1982). There are also the Bep, B(e) and Be(q) type stars. These types show forbidden nebular emission in addition to the Balmer emission (Dachs *et al.* 1986).

The main spectral characteristics present in Be stars are: an absorption and continuum spectrum like a normal B star except that the absorption lines are diffuse and broadened (Doppler broadening due to rapid rotation) and the widths of the lines are wavelength dependent. Emission lines are present which may be

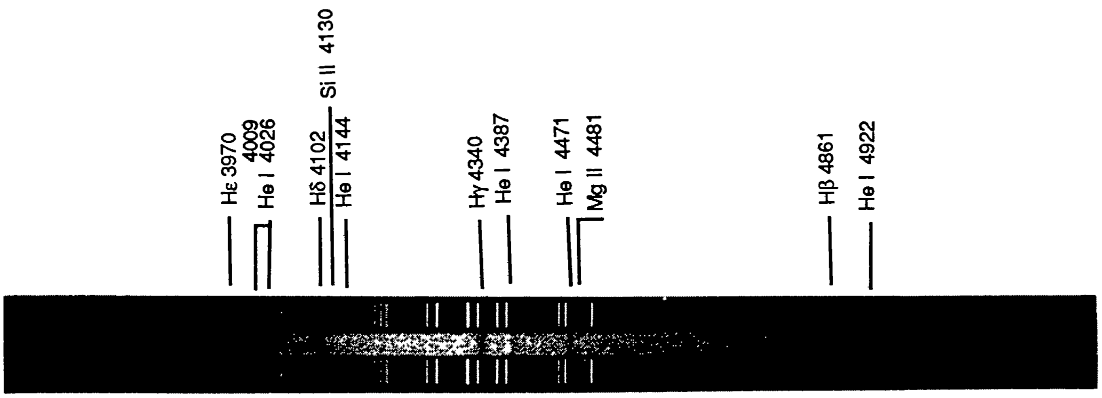

FIG. 3—EW Lac shell phase. Spectral B4 IIIep. Low-dispersion (84 Å/mm) spectrogram of EW Lac taken on May 13th, 1988 showing shell features. Note the sharp absorption cores over the broadened, diffuse Balmer lines; the very narrow absorption core superimposed over the faint Hβ emission line; and the presence of Mg II (4481 Å) and Si II (4130 Å).

superimposed on the broad absorption lines. Emission lines may be single or double peaked. Some other features may or may not be seen. These include abnormally narrow absorption lines, V/R variations, E/C variations and P Cygni features.

III.2 Explanation of Terms. V/R Variations: V/R is the ratio of the intensity of the violet to red emission peaks on either side of a central absorption core which is superimposed over a single emission feature. See figure 4.

E/C Variations: This quantity exists for all emission lines and is the ratio of the intensity of the emission lines to the intensity of the continuum. Variations of this E/C ratio represent variations in the strength of the Be phenomenon itself. The time interval for E/C variations from star to star is very individual – months, years or decades.

P Cygni Characteristic: This is a spectral line having a redward displaced emission component with one or more blueward displaced absorption components. This feature is due to one or more expanding envelopes around the star and is named for the first star observed to display this particular line structure. The intensity of the P Cygni characteristic varies inversely with the rate of mass flow from the star. See figure 5.

These properties are described in more detail in several review articles. See, for instance, Kaler (1987), Kitchin (1982), Doazan (1982) and de Jager (1980).

There are several layers that make up the outer regions of a star. These include the photosphere (the so-called surface of the star), the chromosphere, the corona and the post-corona or exo-photospheric region. The atmospheres of the Be stars differ from those of normal B type stars in the existence of a cool post-coronal

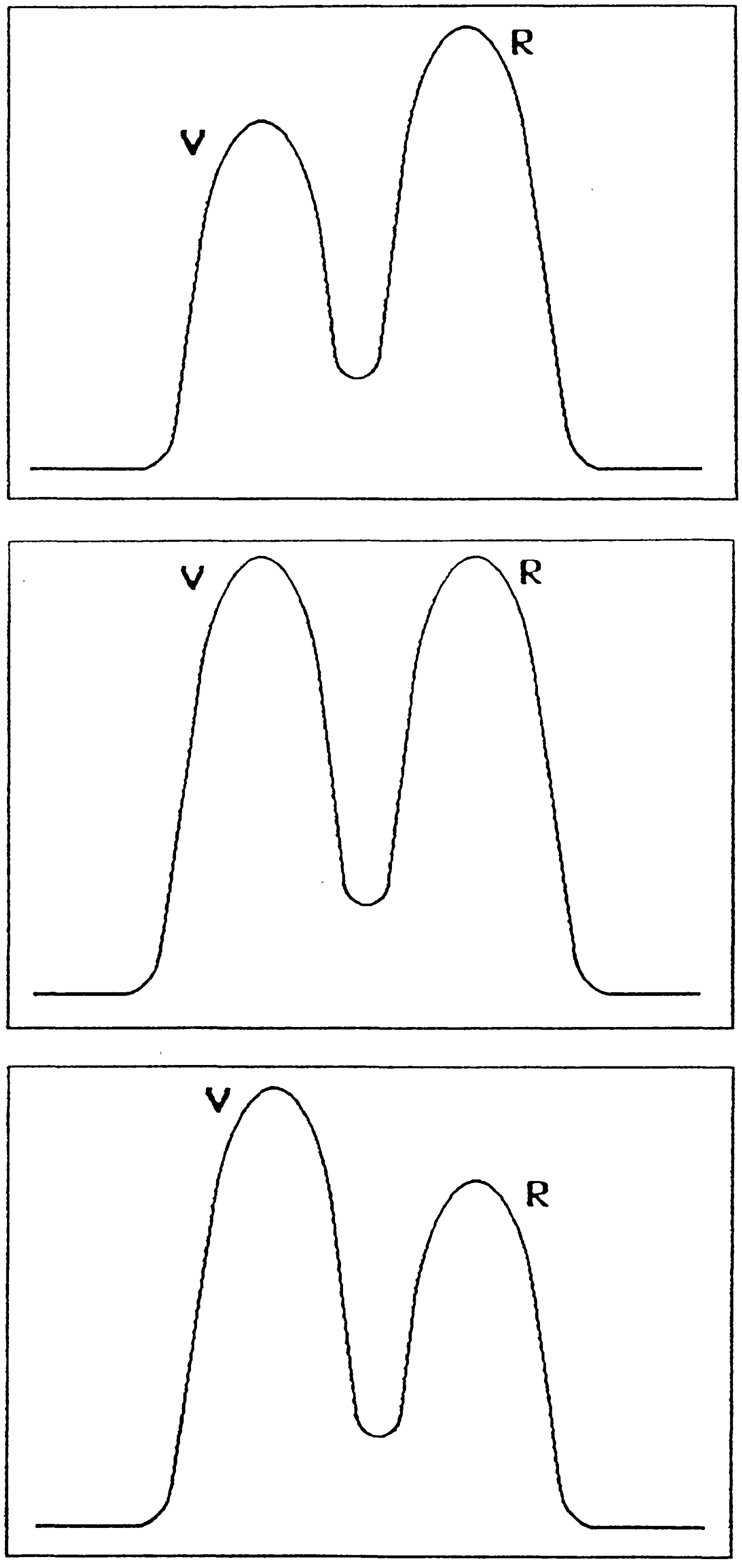

FIG. 4—Schematic line profile showing changing V/R ratio.

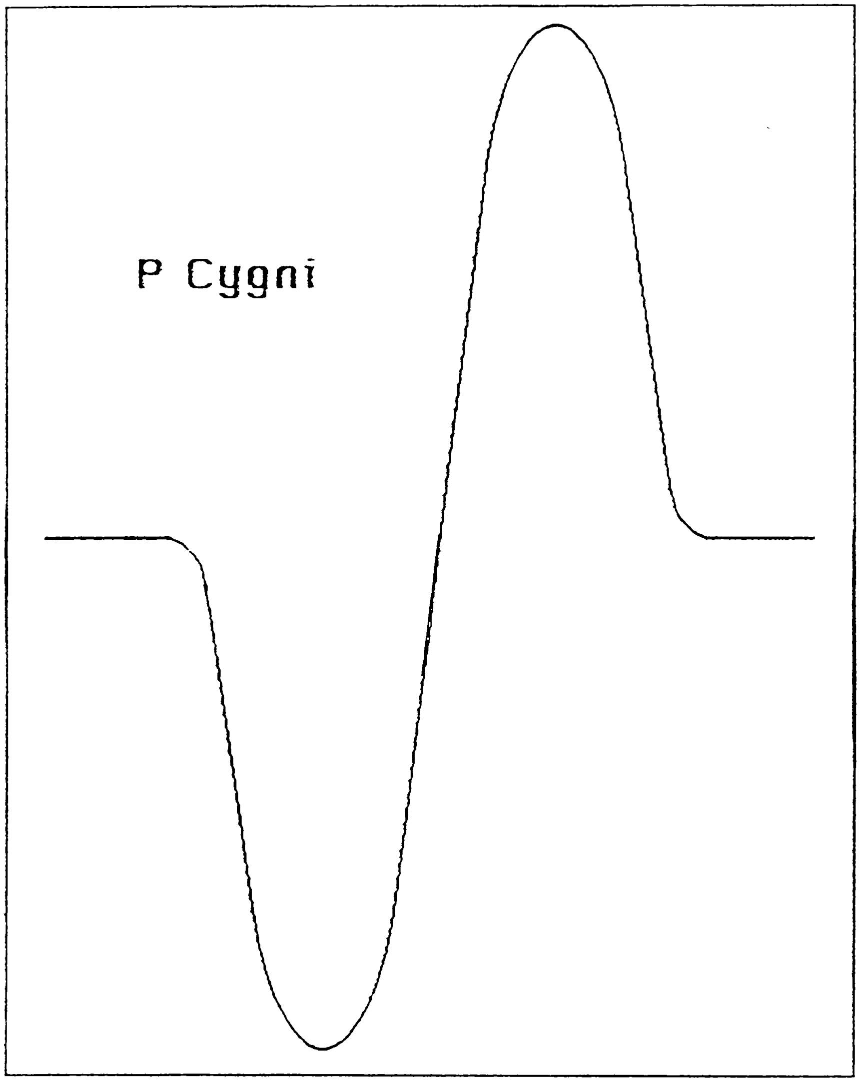

FIG. 5—A schematic P Cygni type line profile showing a blueward displaced component and a redward displaced emission component.

region also called the envelope. This envelope is not observed in normal B stars; it must be relatively extensive for the formation of strong emission lines to occur. Be stars account for approximately 20 per cent of all the B stars with a maximum frequency at spectral types B2 and B3 (Underhill 1960, Doazan 1982).

Be stars can exhibit three types of spectra: (1) a normal B spectrum like 59 Cyg in figure 2, (2) a Be spectrum which contains emission lines which may or may not have a central absorption core like γ Cas, figure 1, and (3) a Be shell spectrum as in EW Lac, figure 3, where the Balmer lines and singly ionized metal lines exhibit deep, narrow absorption lines (or central reversals) which may or may not have emission wings. There are also three important properties of the Be/shell spectra: (1) all Be/shell stars are variable, the variability pertaining to all the spectral features accompanying the Be phenomena, (2) there is a gradual transition from B to Be/shell phases with no clean break between types and (3) Be/shell stars show many individual differences at the same spectral type. The Be stars also show variability in the radio, infrared and ultraviolet regions of the spectrum, not just in the visual region. See, for instance, Doazan (1982).

There is still dispute as to the origin and geometry of the Be stellar envelope. The line emitting envelope is believed to consist of at least two separate components; a cool Balmer line emitting region rotating around the central star and a higher temperature stellar wind component (which produces changes in the UV spectrum), considered to be separate from the cooler component of the envelope. Models for the cool component range from a rotating equatorial disk around the central star, to an accretion disk in a mass exchanging binary system, to a spherical onion-skin envelope arrangement, see, for instance, Underhill (1960), de Jager (1980), Doazan (1982) or Kitchin (1982).

Be stars can occur singly, in clusters or as components of binary systems. Thus the instability that produces the Be phenomenon must be a property of the star itself and not related to the star's position in space relative to other surrounding stars. In close binary stars the spectroscopic features may be affected by the neighbouring star's atmosphere (Underhill 1960).

In general the continuous spectrum of the Be stars differs from that of the normal B stars; they have a higher luminosity and a redder colour (they look more yellow instead of blue-white as would be expected in a type B star). However, there are also a few cases of bluer than normal Be stars (Barylak and Doazan 1986).

It is a characteristic feature of Be stars that emission line intensities change from time to time, like the Hγ line in figure 1, as do the line profiles (i.e. changes in the V/R ratio). Small amplitude changes also occur over very short time scales but these cannot be detected without very high dispersion spectrograms (Underhill 1968, Doazan 1982).

Nearly all Be stars show an ultraviolet excess and a few have been identified with X-ray sources (Van den Heuvel and Rappaport 1987).

Ultraviolet studies show that Be stars have a greater degree of mass loss and a greater variability in their stellar wind than do normal B stars. Phase variations and E/C variations indicate variable mass flux (Doazan 1982).

It is impossible to predict the behaviour of Be stars. Their spectra can change from normal to Be to shell phases several times and these transitions can occur in any order. Within a single phase the intensities and the profiles of the spectral lines are also irregularly variable. Time scales also vary and range from fractions of a day to months, years or decades. See, for instance, Doazan (1982). Small wonder that these stars are interesting to many professionals!

There is no nice, neat interpretation of observed luminosity and colour changes of Be stars in terms of atmospheric structure. No currently proposed model fits all of the observed data. So far, there have not been sufficient observations in a wide enough range of spectral regions (X-ray, UV, visual and IR) over long enough time scales to establish a pattern of behaviour in Be stars.

Some researchers assume that the Be stars' envelopes are all basically similar in property and structure and that individual differences in spectral line strengths and shapes are due to varying aspect angles of the envelope system or to different envelope sizes and/or mean gas density (Dachs *et al.* 1986).

IV. Be Star Models. Be stars are rapidly rotating objects with equatorial velocities in the range of 400 – 450 km/s. This rotation is close to the critical velocity but not quite high enough to be the only cause of mass ejection. The rapid rotation does cause a reduced effective gravity but it is very likely that other processes such as radiation pressure, surface activity and binary interactions are active in causing mass outflow. In Be stars associated with X-ray sources, mass loss from the Be star may be the mechanism leading to accretion onto the companion star, thus producing the X-rays (Van den Heuvel and Rappaport 1987).

Just a few years ago the origin of the circumstellar shell was considered to be the rapid rotation of the star causing an ejection of material around the star's equator. The presence of a shell was therefore related to mass loss. The amount of loss is not very great, on the order of 10^{-9} $M_{\odot}$ per year. It would therefore take 10^9 years for an average Be star to lose one solar mass (Hammerschlag-Hensberge *et al.* 1979, Underhill 1968). Rapid rotation contributes to but is not the only mechanism responsible for mass loss (Marlborough 1987, Baade 1987, Poe and Friend 1987, Plavec 1987a, Smith 1987).

The main body of the shell is thought to be concentrated around the star's equator. Different parts of the shell may be in relative motion; some researchers believe that changes in apparent wavelengths (and therefore radial velocity) indicate an inward and outward motion of the shell relative to the star.

Some Be stars exhibit periodic light variations that coincide with their rotational periods. Their light curves have a double wave pattern with unequal maxima and minima. One likely explanation is that of a "spotted star" with the observed variations being attributed to two diametrically placed spots whose positions may change and where one spot is likely to be dominant. These spots may be similar to sunspots or they may be caused by gas streams (Balona and Engelbrecht 1986).

Another explanation may be that of "non-radial oscillations" where the star jiggles like a ball of jello. This theory is gaining favour among researchers and a number of different types of stars are now known to be non-radial pulsators. The underlying mechanisms that cause the pulsations are not understood (Balona and Engelbrecht 1986, Kaler 1987, Baade 1987).

V. Conclusion. There has been a tremendous volume of research undertaken in recent years on the topic of Be stars. It has become evident that the Be phenomenon is more complicated than previously thought. There are now five competing models and much remains to be done before an understanding of the underlying mechanisms driving these complex objects can be reached.

Plavec in *Physics of Be Stars* (1987b) lists the five models now in contention to explain the Be phenomenon:

(1) the stellar wind model, enhanced by rapid rotation,

(2) a binary system with mass transfer from an unstable component,

(3) a non-radially pulsating star where a surface wave travels around the star in the opposite direction to that of its rotation,

(4) a complex outer structure in the Be star with a chromosphere and corona; mass flux from inside plus non-radiative energy flux, plus radiation,

(5) the magnetic loop model where there is a low density wind and disk generated by magnetohydrodynamic interactions.

The idea of mass ejection as a result of rapid rotation without any other supporting mechanism has now fallen out of favour. Astronomers recognize that there may be, in fact, several models required to explain observations of Be stars fully.

More and more, Be stars are recognized as being not an isolated group of objects but are only a specialized case of a more wide-spread phenomenon.

As a result of curiosity about one star, I have learned quite a bit about the Be stars but I still do not know what makes γ Cas "tick". What new models will be proposed next year? Will we ever discover all of the secrets of the Be stars? I hope so!

I would like to thank Dr Gary Welch for allowing me observatory privileges. Also, Dr Randall Brooks for his invaluable assistance in teaching me how to overcome the quirks of the telescope as well as some of the "black art" of darkroom techniques. I am also grateful to Mr Douglas Pitcairn and Mr Patrick Kelly for their word processing talents in the final preparation of this essay. I would also like to thank Dr J. Norman Scrimger for his reading of (and helpful comments on) this paper.

Mary Lou Whitehorne,
53 Zinck Avenue,
Lower Sackville, Nova Scotia,
B4C 1V9

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