Astron. Astrophys. 317, L17–L20 (1997)

ASTRONOMY AND ASTROPHYSICS

LETTER

Letter to the Editor

Shell phases of some Be stars: equatorially concentrated, LBV-like eruptions?

J.M. Marlborough

Department of Physics and Astronomy, The University of Western Ontario, London, Ontario N6A 3K7, Canada

Received 30 May 1996 / Accepted 29 October 1996

Abstract. The apparent similarity between the variations of γ Cas in the period 1933$-$1942 and the variations of $1-2^m$ which occur in the luminous blue variables on time scales of tens of years is described. Some consequences of such a connection are briefly considered.

1. Introduction

There exists a remarkable similarity between the light curves of some luminous blue variables (LBVs) and that of the Be star, γ Cas, during its phase of variability in the period 1933$-$1942. Is this similarity simply fortuitous or does it indicate some unexpected connection between the two types of star and/or between the circumstellar environment of each? In the following I discuss evidence for this apparent similarity and consider some consequences.

2. Shell Stars

According to Merrill (1953), Otto Struve first introduced the term shell star to describe a star with an extended atmosphere. Now the term is generally interpreted to mean a late O, B or A star of luminosity class III$-$V with the following properties. Usually emission is seen in one or more of the Balmer lines; the star is thus a Be star. As a group Be stars rotate rapidly and are surrounded by circumstellar material which is not expected to be distributed with spherical symmetry. Recently the circumstellar matter around γ Cas (Quirrenbach et al. 1993, Stee et al. 1995) and several other Be stars has been resolved, directly confirming this expectation.

In addition the hydrogen lines also have narrow, deep absorption cores; in one star absorption lines up to H42 have been seen. Frequently these lines have zero central depth, implying that the matter in which these lines arise, referred to as a shell, covers the star in the line of sight. The spectrum at optical wavelengths also contains a large number of narrow, deep absorption lines of singly ionized metals such as Fe, Ti, Ca, Sc, Cr, etc. For these lines the lower level of the particular transition is either the ground state of the ion or is metastable. The gas producing these lines has a lower degree of ionization than the photosphere, with the result that the overall spectrum resembles an early A supergiant, except that lines whose lower level is neither the ground state nor metastable are much weaker in the spectrum of the shell star than they are in the spectrum of the supergiant. In the ultraviolet the spectrum is also greatly affected by the presence of large amounts of circumstellar matter. This is well illustrated by the comparison of the absolute energy distribution of the Be star 59 Cyg before and during a shell phase (Beeckmans 1976).

There are a small number of shell stars whose spectra have not changed over long periods of time (Gulliver 1981, and references therein). In general, however, variability predominates with the shell features appearing and later disappearing completely. Well known examples are γ Cas and 59 Cyg (Underhill and Doazan 1982 and references therein).

It has frequently been proposed that Be stars are interacting binaries (Harmanec 1987 and references therein). According to one version of this suggestion the Be star is the mass gaining star in an interacting binary system in which the companion fills its Roche lobe. However, despite extensive study of some systems thought to be prime candidates, no such cool giant companion has yet been detected (Hubert 1994). Based upon a consideration of numerous cases, Hubert (1994) concluded that ".... it is clear that the circumstellar envelope of the majority of Be stars in binary systems is produced by ejection from the star itself". Some Be stars are known to be members of binary systems, specifically the Be/X-ray binaries (van den Heuvel and Rappaport 1987). In these systems, however, the Be star is the mass losing star. γ Cas has long been suspected as being a member of a binary system of this type due to its hard X-ray emission (Haberl 1995 and references therein). The hypothetical companion might therefore be either a neutron star or a white dwarf.

Send offprint requests to: J.M. Marlborough

Neither possibility, however, seems to be a likely candidate for the source of the circumstellar material responsible for the variability which occurred in 1933-1942.

3. The Shell Phase of γ Cas

Be stars were discovered when Secchi (1867) noted visually that Hβ was in emission in the spectrum of γ Cas (B0IVe). Astronomers have observed γ Cas regularly since that time, initially with the unaided eye and then later with both photometric and spectroscopic instruments.

Edwards (1944) assembled observations of γ Cas obtained over a time interval of about 100 years. He concluded that any magnitude changes between 1830 and 1930 were generally small, probably less than 0.3^m. His claim that these variations were periodic, however, does not seem to be very convincing. Photoelectric measures of the brightness of γ Cas between 1931 and 1939, which include the period when it brightened to magnitude $\sim$ 1.5, are given by Huffer (1939). Following this variation in the 1930s, there was little change in magnitude until the late 1950s; a slow increase of about 0.3^m has occurred between that time and 1970 (Cowley *et al.* 1976). In summary, the magnitude of γ Cas was approximately constant, varying only by a small amount from 1830 to about 1931. There followed a short period when it brightened by about 1^m, faded back to its preoutburst level, brightened again by a few tenths of a magnitude, then decreased somewhat and has not varied significantly since that time.

Greaves and Martin (1938) determined temperatures from the optical continuum of 16,100 K in 1926.7, 10,500 K in 1936.9 and 9200 K in 1937.7. Edwards (1956) discussed spectral changes between 1929 and 1942, and noted in particular that the colour temperature, obtained from the slope of the Paschen continuum, had decreased to 8500 K in 1937. Cowley and Marlborough (1968) showed changes in the spectrum over the period 1911 to 1966. Specifically their spectra show the two distinct shell phases of γ Cas, between October 1935 and August 1936, and between June 1939 and October 1940, as indicated by the presence of He I λ 3889. All the variations between 1933 and 1942 are described in greater detail in Underhill and Doazan (1982). This phase of variability certainly appears to be rare. Only one example of it has occurred in the 165 years of recorded observations of γ Cas.

4. Luminous Blue Variables

Humphreys and Davidson (1994) have published recently a comprehensive review of the properties of LBVs. The LBVs are stars of large bolometric luminosity, $L/L_\odot \sim 10^5 - 10^6$, and large mass loss rate $\gtrsim 10^{-6}$ $M_\odot$ y^{-1}. They are thought to be massive stars, $40 \lesssim M/M_\odot \lesssim 100$, in a post main sequence phase of evolution. Their spectra show broad emission lines of H I, He I, He II, Fe II, Fe [II], ..., with P Cyg profiles sometimes. At minimum the spectrum resembles that of a late O or B star, characteristic of a temperature in the range $1.6 - 3 \times 10^4$ K; at maximum the spectrum resembles an A star with a temperature of about 8000 K.

One of their most distinctive characteristics is variability over a wide range of time scales. On time scales of months to years, variability at a level of $\lesssim 0.1^m$ is common. On time scales of tens of years, variations of $1 - 2^m$ occur, with the time from minimum to maximum of order a few months. For both of these levels of variability, L $\sim$ constant. On times of $\geq 10^2 - 10^3$(?) y, eruptions or violent ejections occur. During such eruptions, $\Delta m > 2^m$, and L may increase. The overall behaviour is reminiscent of terrestrial volcanoes: long periods of quiescence interrupted from time to time by minor activity, with violent ejections at much more widely spaced times. For some LBVs ejected material is directly observed around the star. For others excess infrared emission provides evidence for the presence of circumstellar material.

Until recently there have been many suggestions but no agreement as to what is the physical cause or causes of the LBV eruptions. Nevertheless, because LBVs have luminosities, L, close to their Eddington limits, L_{Ed} (Appenzeller 1989), where $L_{Ed} = 4\pi cGM/ < \kappa >$ and $< \kappa >$ is some appropriate flux averaged opacity, it has generally been suspected that some physical process occurring in layers close to the photosphere, where $L/L_{Ed} \sim 0.8 - 0.9$, may lead to an instability which is responsible for the subsequent variability observed. Recently, Stothers and Chin (1993, 1994, 1995) have discovered a specific destabilizing mechanism, which seems capable of explaining the $1 - 2^m$ variations that occur on time scales of decades. In brief Stothers and Chin found that the outer layers of the envelope of a post main sequence supergiant can become almost detached from the remainder of the star due to the large iron opacity at a temperature of 2×10^5 K, and that a dynamical instability will arise in these layers due to the effects of a high radiation force in combination with partial ionization of hydrogen and helium. They predicted that a massive star can undergo this type of dynamical instability at two evolutionary phases: just after the end of central hydrogen burning and again before the end of central helium burning. Only stars with initial masses > 60 $M_\odot$ enter this first phase of instability. Stars with masses > 30 $M_\odot$ are expected to pass through the second phase of instability. In each case the instability phase is one of enhanced mass loss. During this phase the stellar model remains essentially in the same place in the theoretical HR diagram. The large colour and temperature variations that are observed arise from the enhanced, optically thick wind. Stothers and Chin also note that such behaviour may actually be cyclical, with the mean interval between these variations decreasing with increasing luminosity of the star.

5. The γ Cas shell episode: a small scale LBV eruption?

In their review article Humphreys and Davidson (1994) give some examples to illustrate the wide variety of LBV light curves. Of particular interest here are the light curves of the Hubble-Sandage variables, Var C and Var 2, in M33. Their light curves are shown in Figure 3 of Humphreys and Davidson (1994). Var

C varied irregularly by several tenths of a magnitude from the early 1920s to about 1937. It then increased by about 2^m to a maximum in 1947-48. It resembles, qualitatively, the variation of γ Cas from 1830 to its maximum in mid 1937, although γ Cas brightened by perhaps only half as much. Hubble and Sandage (1953) note that at maximum Var C had a spectral type somewhat later than F0, whereas at minimum the star had a colour index characteristic of a much hotter star. A recent eruption of Var C is described by Humphreys et al. (1988). They report that its spectrum at maximum suggested a temperature of about 7500 K. Var 2 was at maximum near 1925 and then declined by about 2^m to a minimum in the 1930s; it subsequently varied irregularly by a few tenths of a magnitude. Taken together, the light curves of Var C and Var 2 are strikingly similar to the variation of γ Cas, although the range from maximum to minimum for the LBVs is larger.

At maximum the LBVs are considerably cooler than at minimum. Presumably this is due to enhanced mass loss producing an optically thick, large shell, which radiates more energy at longer wavelengths. The variations of γ Cas are qualitatively similar. Either the rate of mass loss increased significantly or some matter was ejected from the star into the line of sight. In either case the resultant continuum energy distribution at optical wavelengths indicated a significantly lower temperature. The presence of He I λ 3889 implies this matter had a lower density than that of the atmosphere before the outburst. Thus there are sufficient similarities between the shell episode of γ Cas and the variability of LBVs to suggest that a similar physical process might be responsible in both cases.

Nevertheless, despite these apparent similarities, the shell phase of γ Cas cannot have arisen by the Stothers-Chin mechanism. Stothers (1996) investigated the dynamical stability of two 15 $M_\odot$ models, one not rotating and the other rotating uniformly at the Keplerian speed in the equatorial plane. In neither model was there any tendency for the outer envelope to become quasi-detached from the remainder of the star. Therefore, some physical process other than the Stothers-Chin mechanism is required, if the matter responsible for the shell phase of γ Cas was ejected from γ Cas itself.

6. Discussion

Prior to Stothers and Chin (1993, 1994, 1995), LBV eruptions were thought to be irregular (Humphreys and Davidson 1994). Hence proposed explanations were constructed around this aspect of the behaviour of LBVs. Since the shell phase of γ Cas seems to be a rare event, perhaps the process responsible either is rare itself, or is a rare occurrence in an otherwise ongoing process. As an example of the latter in the context of LBVs, Hummer (1989) suggested that fluctations at the base of the photosphere due to non-radial pulsations may account for eruptions in the LBV P Cyg. Although many non-radial modes may be excited regularly at some location at or near the surface, these modes may normally interfere destructively so that nothing significant happens. However, if they interfere constructively at irregular intervals so that some critical amplitude is exceeded, then a major change in the structure of the atmosphere could occur, perhaps leading to ejection of some matter by the radiation force. Small scale fluctuations of order $\lesssim 0.1^m$ do occur in LBVs. For example Percy *et al.* (1988) detected irregular variations of $\lesssim 0.2^m$ in P Cyg on time scales from a few days to a few months. Perhaps these are manifestations of non-radial pulsations. Non-radial pulsations are strongly suspected to occur in main sequence stars having the same range of spectral type as those of the LBVs at minimum (Baade, 1988; Gies, 1991). Even more appropriate may be the photospheric activity detected over a wide range of wavelengths in the Be star μ Cen (Peters 1986) and the variations observed in the Be stars γ Cas and λ Eri (Smith 1991, 1994).

Lastly, the B[e] stars have properties which seem to suggest some connection between the LBVs and Be stars. The B[e] stars occupy the same area of the HR diagram as do the LBVs and are surrounded by circumstellar matter which has a more disc-like than a spherically symmetric structure (Zickgraf 1989, 1992).

Stothers and Chin (1994) initially suggested that the luminous B[e] stars might be the evolutionary descendents of the LBVs. However, Stothers and Chin (1996) now suspect that the majority of B[e] stars are more likely to be in a late main sequence phase. More interestingly Gummersbach et al. (1995) have discovered 4 B[e] stars in the LMC, whose luminosities suggest they evolved from main sequence stars with masses between 10 and 15 $M_\odot$, the same mass range of many Be stars. Perhaps these B[e] stars are Be stars in a shell phase more extensive than that of γ Cas during 1933-1942?

7. Conclusion

I have outlined the evidence which points to the possibility of a connection between the LBV variations of $1-2^m$ on time scales of tens of years and the shell phase of γ Cas in the period 1933 - 1942. A recent mechanism proposed by Stothers and Chin (1993, 1994, 1995) seems to be capable of explaining these variations in the LBVs. However it will not work for the shell phase of γ Cas.

Photospheric variability is common in many Be stars. Perhaps very infrequently a non-linear amplification occurs, resulting in the ejection of a significant amount of matter into the line of sight, a super, μ Cen-like process, possibly? If the matter is sufficiently optically thick, it may behave as a false photosphere simulating a cooler, less dense atmosphere. Superficially such variations in γ Cas may appear similar to those in LBVs, although they have arisen from different physical causes.

8. Acknowledgements

I thank both R. B. Stothers, the referee, and L. B. F. M. Waters for their comments and I acknowledge financial support from the Natural Sciences and Engineering Research Council of Canada.

References

Appenzeller, I., 1989, The Role of Radiation Pressure in LBV Atmospheres. in: Davidson, K., Moffat A., Lamers H. (eds.) IAU Coll.

113, Physics of Luminous Blue Variables. Kluwer, Dordrecht, p. 195

Baade, D., 1988, Ground-Based Observations of Intrinsic Variations in O, Of, and Wolf-Rayet Stars. in: Conti, P. S., Underhill, A. B. (eds.) O Stars and Wolf-Rayet Stars. N.A.S.A., Washington, SP-497, p. 137

Beeckmans, F., 1976, A&A 52, 465

Cowley, A. P., Marlborough, J. M., 1968, PASP 80, 42

Cowley, A. P., Rogers, L., Hutchings, J. B., 1976, PASP 88, 911

Edwards, D. L., 1944, MNRAS 104, 283

Edwards, D. L., 1956, Vistas in Astronomy 2, 1470

Gies, D. R., 1991, Nonradial Pulsation and Line Profile Variability in Early Type Stars. in: Baade, D. (ed) Rapid Variability of OB-Stars: Nature and Diagnostic Value. ESO, Garching, p. 229

Greaves, W. M. H., Martin, E., 1938, MNRAS 98, 434

Gulliver, A. F., 1981, ApJ 248, 222

Gummersbach, C. A., Zickgraf, F.-J., Wolf, B., 1995, A&A 302, 409

Haberl, F., 1995, A&A 296, 685

Harmanec, P., 1987, Emission-Line Stars As Interacting Binaries. in: Slettebak, A., Snow, T.P. (eds.) IAU Coll. 92, Physics of Be Stars. Cambridge, Cambridge University Press, p. 339

Hubble, E., Sandage, A., 1953, ApJ 118, 353

Hubert, A. M., 1994, Variability in the Circumstellar Envelope of Be Stars. in: Balona, L. A., Henrichs, H. F., LeContel, J. M. (eds.) IAU Symp. 162, Pulsation, Rotation and Mass Loss In Early-Type Stars. Kluwer, Dordrecht, p. 341

Huffer, C. M., 1939, ApJ 89, 139

Hummer, D. G., 1989. in: Davidson, K., Moffat A., Lamers H. (eds.) IAU Coll. 113, Physics of Luminous Blue Variables. Kluwer, Dordrecht, p. 242

Humphreys, R. M., Davidson, K., 1994, PASP 106, 1025

Humphreys, R. M., Leitherer, C., Stahl, O., Wolf, B., Zickgraf, F.-J., 1988, A&A 203, 306

Merrill, P. W., 1953, PASP 65, 113

Percy, J. R. et al., 1988, A&A 191, 248

Peters, G. J., 1986, ApJ 301, L61

Quirrenbach, A., Hummel. C. A., Buscher, D. F., Armstrong, J. T., Mozurkewich, C., Elias II, N. M., 1993, ApJ 416, L25

Secchi, A., 1867, AN 68, 63

Smith, M. A., 1991, Spectral Line Transients in λ Eri and Related Be Stars, in: Baade, D. (ed) Rapid Variability of OB-Stars: Nature and Diagnostic Value. ESO, Garching, p. 59

Smith, M. A., 1994, Photospheric Activity in Selected Be Stars: λ Eri and γ Cas, in: Balona, L. A., Henrichs, H. F., LeContel, J. M. (eds.) IAU Symp. 162, Pulsation, Rotation and Mass Loss In Early-Type Stars. Kluwer, Dordrecht, p. 241

Stee, Ph., de Araujo, F. X., Vakili, F., Mourard, D., Arnold, L., Bonneau, D., Morand, F., Tallon-Bosc, I., 1995, A&A 300, 219

Stothers, R. B., Chin, C. W., 1993, ApJ 408, L85

Stothers, R. B., Chin, C. W., 1994, ApJ 426, L43

Stothers, R. B., Chin, C. W., 1995, ApJ 451, L61

Stothers, R. B., Chin, C. W., 1996, ApJ 468, 842

Stothers, R. B., 1996, private communication

Underhill, A. B., Doazan, V., 1982, Be Stars With and Without Emission Lines. N.A.S.A., Washington, SP-465, p. 325

van den Heuvel, E. P. J., Rappaport, S., 1987. X-Ray Observations of B-Emission Stars. in: Slettebak, A., Snow, T.P. (eds.). IAU Coll. 92, Physics of Be Stars. Cambridge, Cambridge University Press, p. 291

Zickgraf, F.-J., 1989, The B[e] Stars, in: Davidson, K., Moffat A., Lamers H. (eds.). IAU Coll. 113, Physics of Luminous Blue Variables. Kluwer, Dordrecht, p. 117

Zickgraf, F.-J., 1992, Observations of B[e] Stars, in: Drissen, L., Leitherer, C., Nota, A. (eds.). Nonisotropic and Variable Outflows from Stars. PASPC No. 22, p. 75

This article was processed by the author using Springer-Verlag LaTeX A&A style file *L-AA* version 3.