PROPOSED THREE-PHASE MODELING OF Be STARS FROM COMBINED UV AND VISUAL OBSERVATIONS

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ABSTRACT : FarUV observations of the behavior of (wind-velocity, superionization) values as a function of the phase of the (Be, B-shell, B-normal) pattern established by visual observations for γ Cas and 59 Cyg are translated into a crude atmospheric model for the Be phase and several kinds of mass-flux variability across the three phases.

I. INTRODUCTION :

In the visual spectral region, one finds it possible to establish quite homogeneous classes of normal stars, based on their continuum, the overall strengths of some lines, and the wings of most lines. Such features characterize a photosphere, defined as an atmospheric region which can be modeled from values of (gravity, total radiative-flux $\equiv$ effective temperature) under those thermodynamic constraints accompanying the condition that the star be a closed, thermal system. Those anomalous features, and those stars in which such anomalous features are strong, which cannot be modeled under the preceeding two-dimensional, (closed, thermal) description are labeled peculiar ; and their origins are attributed to the existence of atmospheric regions lying above the photosphere, within which the thermodynamic constraints accompanying the (closed, thermal) description are not imposed. Prior to observations made in the farUV, x-ray, farIR, and radio spectral regions, our knowledge of such outer atmospheric regions came almost wholly from such peculiar stars, including the Sun because of its peculiarly-close location, which enables detection of anomalous features with only small amplitudes. Indeed, there has been strong confusion as to whether many normal stars do not have such outer atmospheric regions, or whether they are simply too small to be detected under present observational techniques in such stars.

In the farUV and x-ray spectral regions, such homogeneity within visually-defined (luminosity, spectrum) class is very often replaced, among both normal and peculiar stars, by strong individuality and variability in the observed spectral features ; which implies that such two-dimensional specification of a star is insufficient, observationally and thermodynamically. These same features of individuality and variability are shown in the visual spectral regions of most peculiar stars, as is the additional feature of gradualness, or the existence of all degrees of peculiarity between very large and very small. Such gradualness should be contrasted to any belief that peculiarity is an abruptly-occuring characteristic. All this suggests that peculiar stars differ from normal stars only in having larger amplitudes of those parameters which must be adjoined to the "normal", two-dimensional, set in order to describe the "anomalous" phenomena in the visual, and the "normal" phenomena in the farUV, x-ray, farIR, and radio regions, and to model those outer atmospheric regions where such phenomena arise. This suggests that a combination of visual spectral features of peculiar stars and pan-spectral features of both peculiar and normal stars can be used, empirically : first, to map out the structure of those exo-photospheric regions ; then, to identify those additional, independent parameters and modified thermodynamic constraints that are necessary and sufficient to model such structure.

The present paper summarizes such a combination of recent farUV observations with visual observations extending over almost a century for one type of peculiar star : the Be/shell. We find that the apparently different "objects" --- Be, B-shell, B-normal --- are actually just three different temporal phases of one kind of object, with passage between phases occuring in time incomparably shorter than evolutionary. By linking such phase-changes, and implied atmospheric structure, to different levels of mass-flux occuring at different times in a given star, while noting that the maximum superionization level in the farUV region does not appear to change, we identify both additional parameters and modified thermodynamic restraints and character. We note that 30 % of main-sequence B stars show, at a given epoch, either the Be or B-shell phase spectra. Some portion of the remaining B-normal stars must correspond to the third, B-normal, phase, with temporarily-low mass-flux amplitudes, even though some B-normal stars may have too small potential-amplitudes to ever show such phase-changes. Thus, peculiarity and variability seem essential aspects of main-sequence B stars ; and their existence is evidently important in understanding stellar structure and evolution. We suggest the same situation holds throughout the HR diagram, for other ("peculiar", "normal") pairs; and that such investigations as the present should be extended to them.

II. OBSERVATIONS :

1. Visual evidence for 3-phase representation :

Many astronomers regard Be and B-shell spectra as characterizing similar, but not identical, objects ; it is not always accepted that they may well be only different time-phases of the same kind of object, corresponding to different phase-values of those thermodynamic parameters needed to describe exo-photospheric structure. However, there are sufficient examples in the literature of stars passing variously between Be, B-shell, and B-normal spectra in all directions (Ref. 1). In the stars 59 Cyg (B1.5Ve) and γ Cas (B0.5IVe), each of which has been studied over almost a century, we find a remarkable similarity in pattern of such change,over the last 70 years,differing only in epoch. Each has been characterized by long,relatively-quiet periods, with relatively-short periods of spectacular change (about 7 years, for each). During these latter, each star showed two short B-shell phases, which occur between two strong Be phases, with the whole episode ending in a phase which would be B-normal under low resolution, and is at most a very weak Be phase under high resolution,with any emission limited very feebly to Hα. Fig. 1 exhibits this history.

Thus the visual spectrum shows in each of two stars : (1) Balmer emission lines that can be produced only by atmospheres extended several radii,with displacements of emission lines, or of absorption cores, corresponding to less than 100 kms^{-1}.Conclusions from line-widths are uncertain because of difficulty in separating electron-scattering, rotation, expansion effects ; (2) Sub-ionized FeII, etc lines, in both emission and absorption, again showing velocities $\lesssim 100$ kms^{-1} ; (3)Both these features appearing and disappearing in times ranging from weeks to years. We have collected other examples of such behavior, some similar, some different, in passage between different phases (Ref. 1). The important point is that this behavior of 59 Cyg and γ Cas is not exceptional.

2. FarUV characteristics in various phases of Fig. 1 :

a) 59 Cyg (B1.5Ve) : Snow and Marlborough (Ref. 2) made farUV observations with Copernicus in 1972, apparently just at the end of a long Be phase or just before a shell-phase ; and in 1975, just after a shell-phase and the beginning of a rise to a strong emission phase. In 1972, the strongest NV absorption component is violet displaced $\lesssim 50$ kms^{-1}, with a faint component at about -300 kms^{-1}. In 1975, they report only one component, at about -180 kms^{-1}. SiIV echoes this behavior ; and the lines are highly asymmetric.

We (Ref. 3) obtained IUE results in December 1978 and June 1979, during a feeble, but rising Be phase ; Rogerson, Snow, Marlborough and ourselves obtained Copernicus observations monthly between July and October 1979. In December 1978, the deepest portion of the NV resonance line is shifted by -750 kms^{-1} ; in June, it is shifted by -400 kms^{-1}. The following monthly observations show shifts varying with no pattern, but always in the range -400 to -800 kms^{-1}. Fig. 2 shows all these data for NV. In December 1978 and June 1979, the CIV resonance lines follow the velocity shifts of NV ; while the SiIV resonance lines show no shifts larger than -100 kms^{-1} and are quasi-symmetric. The striking thing is the absence, for NV and CIV, of the small velocity shifts; and for SiIV, of the large, during 1978-79 ; by contrast to the 1972 behavior.

b) γ Cas (B0.5IVe) : Hammershlag-Hensberge (Ref. 4), on the basis of IUE observations showing narrow, violet-displaced, additional (to an almost undisplaced component) components in the NV, CIV, SiIV lines in March 1979, as contrasted to April-May 1978, alerted that γ Cas might be entering a new shell phase. It is clear, from Fig. 1, that when these stars enter a "shell-phase", events happen quickly.

We obtained IUE observations at VILSPA-Madrid in October 1979, as well as visual spectra in October, November, December 1979 and February and April 1980, at the Haute-Provence Observatory. A comparison of these visual spectra with those taken regularly over the last 20 years shows no change, other than the well-known V/R variation of the Hα and Hβ emission peaks, and small changes in the emission intensity. Thus we conclude that the narrow absorption components observed in the farUV by Hammerschlag-Hensberge do not correspond to a new shell phase at this moment ; they correspond simply to the double-component mass-flow pattern in a well-defined Be-phase (Ref. 5).

Our IUE observations confirm the existence of the narrow, violet-displaced components observed in NV, CIV, SiIV by Hammerschlag-Hensberge (Ref.9) In conjunction with the 59 Cyg results, these data are very interesting, as regards conditions on the long-term variability cycle. These γ Cas data, taken at "quiet and moderately strong" Be phase, show two velocity components (Fig. 3) -- or two concentrations of absorbing atoms -- for each of SiIV, CIV, NV : one, the largest, at about -100, -200 kms^{-1} ; the smaller, at about -1400 kms^{-1}. By contrast to 59 Cyg, observed at increasing emission phase, we observe no ionization-velocity correlation : just this apparent ionization-height gradient. These results should be compared with the cited 1972 observations of 59 Cyg, at the end of a long emission phase or at the beginning of the second shell phase. There, also, no ionization-velocity correlation was noted ; but there, also, one observed a faint, high velocity component in the NV and SiIV lines at about -300 kms^{-1} ; while the strong absorption component lay at about -50 kms^{-1} or less.

III. CONCLUSIONS :

. We suggest the following tentative model :

1. From γ Cas in 1978-79 and 59 Cyg in 1972 : reasonably strong Be emission phases : The two absorption components in all highly-ionized lines refer to chromosphere-coronal transition, and postcoronal, atmospheric regions. The lack of such ions at intermediate velocities corresponds to the presence of a corona sufficiently-hot to suppress such ions. The coronal-level x-ray emission from γ Cas substantiates this picture.

Thus, in the well developed Be phase, we have evidence for an atmospheric structure in which : (i) a radiative flux under quasi-thermal conditions provides a photosphere ; (ii) a nonradiative flux provides a heating supplemental to radiative, resulting in an outward increase, then decrease, of T_e ; (iii) a matter-flux provides a flow accelerating outward through sub-thermal, trans-thermal, and superthermal ranges, and an associated density decrease much flatter than photospheric. These are the characteristics of the atmosphere of an (open, non-thermal) system (Ref. 6). The T_e, flow-velocity, and density distributions are given in Fig. 4 : adopting the Mihalas photospheric model (Ref. 7) of a B0.5IVe star as starting point for T_e, density ; a mass-flux of 10^{-8} $M_{\odot}y^{-1}$ to locate starting point for trans-thermal flow, and maximum beginning height of chromosphere ; an x-ray indication of 10^6 K corona ; and the observed (V, ionization) values of γ Cas for pre- and post-corona. We have only relative locations in height, no absolute scales. Note that a mass-flux range from 10^{-7} to 10^{-9} corresponds to 3.10^{11} - 3.10^{9} range in particle concentrations at beginning of trans-thermic flow.

2. From the Balmer and metal-shell observations : From the T_e values in Fig. 4, we see that Balmer emission can be produced in the photosphere-chromosphere, and in those postcoronal regions cooler than where the farUV lines arise. The sub-ionized metals, such as FeII, can arise only in the latter retion. The velocities associated with the Balmer and sub-ionized emission require, then, a deceleration in the far post-coronal regions ; these are indicated by dotted lines in Fig. 4. Such deceleration must come from interaction with the ISM, apparently closer than the ~ 0.1psc distances associated with such interactions in the usual literature (Ref. 8) ; but the problem is open.

3. Variability in mass-flux : IF we associate variability in mass-flux velocities with that in mass-flux itself, we identify three kinds of such variability ; (a) That corresponding to small fluctuations in the developed Be phase, where the velocity of the two maximum concentrations of absorbing superionized species does not change significantly, only the size of the concentration (ie density of the wind) ; (b) That corresponding to variations in the phase of

increasing from small to large Be emission, where both velocity of maximum superionization concentration and its size change significantly ; (c) That corresponding to different phases, where the velocity changes very strongly ; for example, between the 1972 and 1978-79 phases of 59 Cyg. These aspects of variability are evidently critical in understanding the variability of atmospheric structure between the B-normal, Be, and B-shell phases. The size of the mass-flux evidently plays a crucial role ; but the interactions between mass-flux size, the ability of the nonradiative flux to heat a particular atmospheric region, and of the radiative flux to provide further acceleration to whatever maximum velocity is reached are equally important. To clarify these problems, empirically, we clearly need observations in farUV, x-ray, farIR and radio, very frequently during such rapidly-changing epochs as the 7-year ones shown by γ Cas and 59 Cyg.

4. The densities in Fig. 4 are too small to produce the observed Hα emission during a strong Be phase. Since densities increase as F_M : either we increase $F_M \geq 10^{-6}$ in the strong Be phase ; or we abandon a density fixed by a continuous flow in the postcoronal regions, substituting for part of that region a reservoir, with boundaries fixed by interaction with the ISM, filled by a variable mass-flux, enhanced during the beginning and increasing Be phases.

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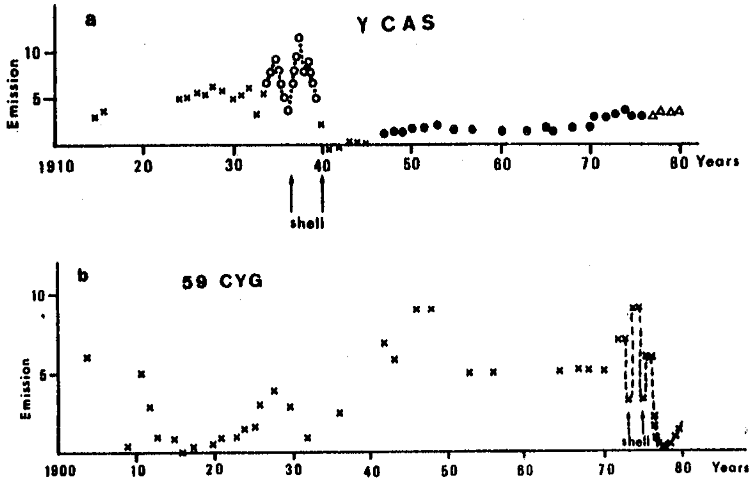
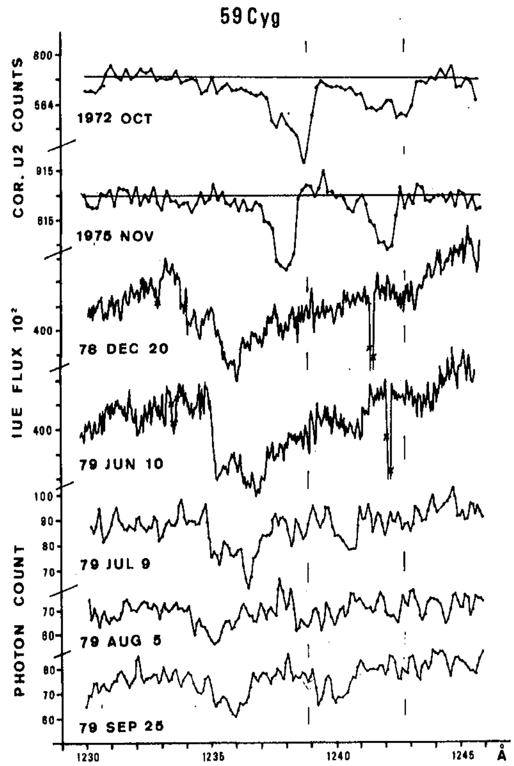


<u>FIG. 1</u> : Long-term variations of γ Cas (1a) and 59 Cyg (1b) in the visual, Ref. 5. Ordinates : arbitrary-scaled Balmer line emission.



<u>FIG. 2</u> : NV resonance lines in 59 Cyg : 1972, 1975, Copernicus, Ref. 2 ; December'78, June'79, IUE, Ref. 3 and this paper ; July-September'79, Copernicus. Solid lines are laboratory λ ; crosses are reseau.

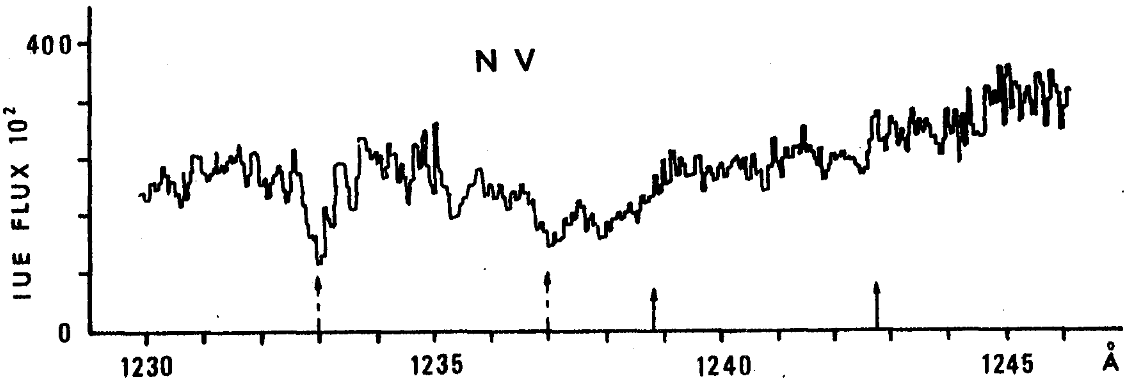


FIG. 3 : NV resonance lines in γ Cas, Ref. 5. Solid arrows are laboratory λ, crosses are reseau marks. Ordinates : 10^2 IUE flux counts.

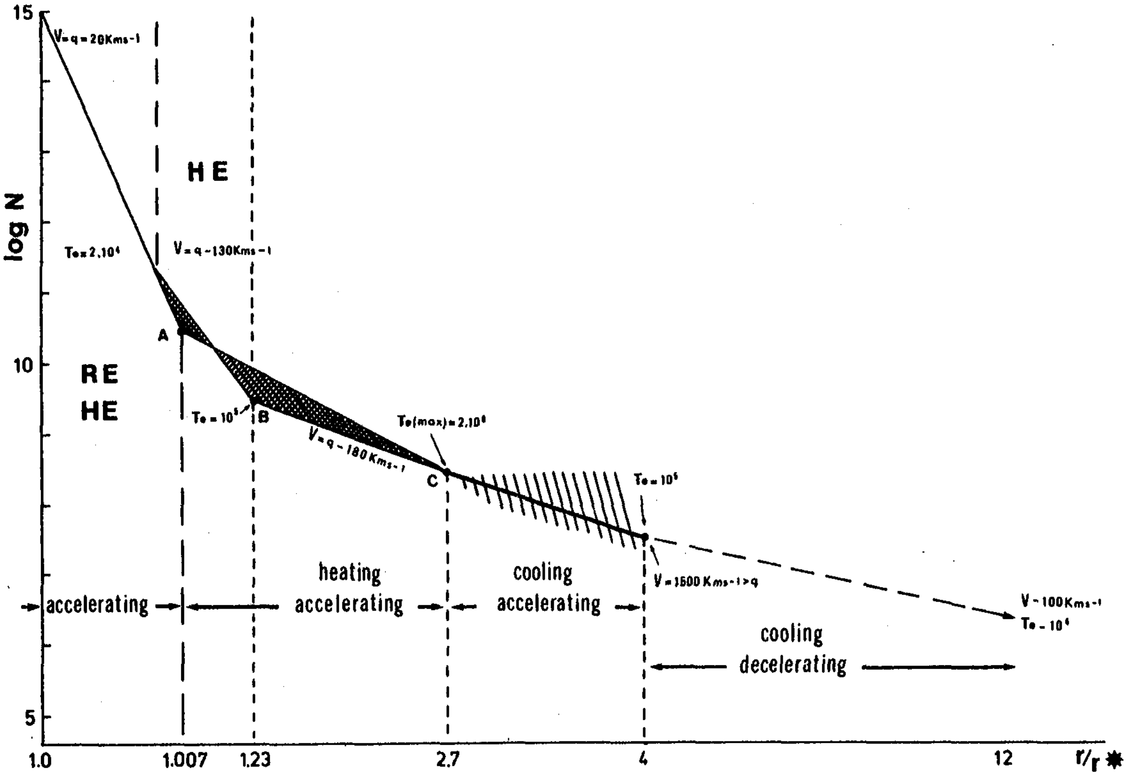


FIG. 4 : Schematic γ Cas atmosphere for $F_M = 10^{-8} M_\odot y^{-1}$. Flow becomes transsonic at thermal points : A, if no preheating ; B, if preheating ; cross-hatched area shows uncertainty in preheating : and supersonic in region of T_e(max), beginning at C. Single-hatched area shows uncertainty on cooling and acceleration/deceleration.