SPECTRAL ENERGY DISTRIBUTION (119 - 685 nm) IN 16 SHELL STARS AND A TENTATIVE MODEL FOR ACCRETING Be STARS

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ABSTRACT I.U.E. low-dispersion spectra and spectral scans made with the Lick Observatory IDS scanners have been combined for 16 shell stars. Eleven objects can be represented by Kurucz model atmospheres, although some of them display strong shell-type line spectra. Five among them are known binaries. The six remaining objects (all interacting binaries) display complex spectra. A model involving continuum and line radiation from a hydrogen cloud surrounding the accreting component is proposed. A generalization of this model with optically thick segments of the cloud promises to explain even more exotic objects such as β Lyrae, W Serpentis and possibly ε Aurigae.

This paper will ultimately contain the claim that the exotic eclipsing binary system W Serpentis contains a Be star, and should therefore be represented at the Be Stars Symposium. The chain of arguments leading to this conclusion will start with a survey of 16 shell stars. Spectral energy distributions of these shell stars were obtained by combining low-dispersion I.U.E. spectra with scans made with the Image Dissector Scanners attached to the 120-inch and 24-inch telescopes of the Lick Observatory. With the gratings used, the resolving power of the scanners has been very nearly the same as that of the I.U.E. spectra. In favorable cases, the entire spectral interval 119 through 685 nm was covered. More often, there exists a gap between about 320 and 365 nm, since the I.U.E. calibration is not reliable beyond 320 nm and the red-sensitive tube of the 24-inch scanner does not give good response shortward of 365 nm. A complete spectral scan consists of two I.U.E. spectra (short camera, SWP, between 119 - 196 nm, and long camera, LWR, between 190 - 320 nm), and of two grating settings of the Lick Scanner.

The complete spectral scans were compared with Kurucz (1979) model atmospheres with normal chemical composition. (We tested Kurucz models against normal stars and found very good overall agreement. Several local discrepancies will be discussed elsewhere.) Monochromatic fluxes were extracted from the observed continuous energy distributions at up to 191 wavelengths corresponding to those used by Kurucz. A least-squares fit was then made in an effort to solve simultaneously for the

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color excess E(B-V), the effective temperature of the star, T_{eff}, and its surface gravity (log g). Using two quite different acquisition systems may lead to systematic displacements on both sides of the Balmer jump, the more so because it was impossible to obtain I.U.E. and optical data simultaneously. For that reason, separate solutions were first made for the two parts of the spectrum. Surprisingly, for all the "simple" shell stars, the mutual agreement was perfect. The only deviating case, HD 206773, required only a vertical displacement of the optical spectrum, most likely because of an incorrectly recorded scanning time.

SIMPLE SHELL STARS

Eleven shell stars could be fitted by the Kurucz atmospheres over the whole scanned spectral interval (in two the coverage is incomplete, though). No additional source of radiation is required, except that in five of them, a later-type companion is to be expected, since they are known binary systems. In such cases, we at first fitted only the blue optical scans (shortward of about 500 nm) and included longer wavelengths only if they were consistent. In practice, only in 17 Leporis is the companion clearly present in our scans. A list of the most important parameters for the 11 "simple" shell stars is in Table 1. Please note that the spectral types and luminosity classes were assigned from the directly determined values of T_{eff} and log g. This inverse calibration is based on the recent tables by Flower (1977) and Hayes (1978), while the luminosity classes were derived from the log g calibration given by Schmidt-Kaler (1965).

Our values agree in general very well with spectral types derived by various authors from the photospheric line spectra. It is rather surprising to see that the circumstellar shells seem to have little influence on the continuous energy distribution, although they affect the line spectra quite conspicuously.

Perhaps the most surprising result is the low effective temperature found for 17 Leporis. Cowley (1967) and others saw or suspected spectral features characteristic of a B9 spectrum. Yet, the I.U.E. spectra of 17 Lep led quite unmistakably to the low temperature listed, and no other source of radiation appears to be present -- at least not at the observed phase.

COMPLEX SHELL STARS

Five objects cannot be fitted by normal Kurucz atmospheres; they require inclusion of an additional source of radiation, different from the companion which is either clearly visible in our scans (as in AX Mon and HD 51480) or known to exist from various other observations. Surprisingly, the simplest of these complex systems appears to be ϕ Persei. The optically thin free-free radiation of circumstellar hydrogen observed, e.g., by Gehrz, Hackwell and Jones (1974), combined with bound-free radiation, can be traced on both sides of the Balmer jump, but contributes relatively little, so that the whole spectrum can be fitted by a Kurucz model with T_{eff} = 20750°K, log g = 3.75 with very good accuracy, except longwards of about 600 nm where the hydrogen radiation becomes more prominent. Also, the surprisingly low color excess E(B-V) = 0.04 appears to be well-established.

The systems KX And, AX Mon, HD 51480 and HD 72754 seem to be rather similar to each other, and all of them bear a good deal of resemblance to the Serpentids as defined and described by Plavec (1980). The first three stars have been more completely observed (the fourth one is invisible from Lick) and have these peculiar properties: i) The optical continuous spectra resemble those of A stars, in agreement with the shell lines, but in sharp disagreement with the presence of the He I lines. For example, KX And can be formally fitted by a T_{eff} = 9000°K atmosphere in the optical region, although its photospheric line spectrum has been classified as B3; ii) The far ultraviolet spectrum disagrees with the nominal A-type optical spectrum, and is much more indicative of the B-type spectrum suggested by the optical photospheric lines. However, it shows unusually deep absorption lines, or rather clusters of lines, not observed in any of our comparison standard B spectra obtained with I.U.E. by Plavec and Koch; iii) There tends to be an excess flux, over even the B-type spectrum, between about 240 - 320 nm (and possibly further to the Balmer jump). Another such excess flux is observed between about 190 - 210 nm, except that HD 72754 shows anomalously low flux there.

These characteristics can be in principle explained by two alternative models: A) The stars are indeed A stars as their optical, continuous and shell spectra indicate. Since they are the accreting components of interacting binaries, one can anticipate the existence of an accretion disk. The hottest part of the disk would be the transition layer between the disk and the star (Pringle 1977). It would produce a B-type spectrum in the FUV, but owing to its small surface area, it cannot dominate in the optical region. This model was discussed by Plavec (1980); B) The stars are B stars as their FUV spectra and optical photospheric lines suggest. The B star is heavily obscured by a disk. Outside the star, the disk itself radiates, usually as an optically thin hydrogen cloud. This continuous radiation of the disk becomes relatively stronger as we proceed toward longer wavelengths in the optical region, and the combined continuous spectrum appears to have a much less steep slope of the Paschen continuum, thereby simulating a cooler star.

We are more and more convinced that model B) represents the typical case. This is confirmed by our observations of the primary component of β Lyrae. This star is usually classified as B8 II. Actually, its spectral energy distribution resembles that of a B8 II star only in the optical region, between about 380 - 600 nm. Continuous radiation of hydrogen is quite prominent longward of 600 nm and between about the Balmer jump down to about 240 nm. The above-mentioned excess flux near 190 - 210 nm is also present in β Lyrae, and is probably due to a superposition of numerous emissions of Fe III, as already suggested by several authors before. In HD 72754, Fe III lines are in equally conspicuous absorption.

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The disk we envisage here is not the optically thick but geometrically quite thin (with respect to a non-degenerate star) disk obtained by simply scaling up the classical alpha-disks used to interpret the cataclysmic variables. Rather, we anticipate a disk that is quite thick geometrically, even perpendicular to the orbital plane, but often optically thin for continuous radiation in the spectral region considered here. Such disks have been advocated by Hall (1969), Wilson (1974), Polidan (thesis, 1979) and Kříž (preprint, 1980). Rapid variability seems to be their common property and we detected such variability, e.g., in KX And.

EVEN WILDER MODELS FOR THE WEIRDEST SYSTEMS

W Serpentis, although classified as F5 II (with probably a cooler invisible companion) displays emission lines of hydrogen in the optical region, and we (Plavec, Polidan and Peters) discovered even emission lines of He I. The far UV spectrum resembles that of a B star, and we claim that the accreting component most likely indeed is a B star, but largely obscured by that portion of the circumstellar disk that is projected against it (Plavec and Sakimoto 1978).

How do we explain the observed F-type continuum in the optical region? Assume that the density of absorbing hydrogen atoms decreases with some power of distance from the accreting star. If so, then as our line of sight approaches the star, the optical thickness of the disk must increase steeply and will at some point make the disk optically thick. We are viewing this eclipsing system essentially edge-on, so that the edge of the disk will appear to us as a spurious photosphere, largely hiding the B star inside. What kind of radiation will be emitted by the edge of the disk? Stellar radiation will hardly reach it; most of it will be either absorbed inside the disk or scattered perpendicularly to the orbital plane. The source of the energy of the disk edge will more likely be the dissipated kinetic energy of an impacting stream. Madej and Paczynski (1977) suggested for a similar case of U Gem that the edge will mimic a photosphere of approximately solar type.

In the 1940's, Otto Struve led us to realize that some absorption lines in interacting binaries need not come from stellar surfaces. Today, we have to take one step further and realize that continuous and whole absorption spectra do not have to come from stellar photospheres. If we accept this principle, we may hope to resolve other puzzling systems. The Serpentids (Plavec 1980) are among them; similarly, RZ Ophiuchi may actually very well be an earlier-type star inside a thick disk. Perhaps the most audacious idea is to re-examine ε Aurigae once more. The puzzling quasi-total eclipse does not seem to be fully explained yet, in spite of several ingenious theories (Huang 1965; Hack 1962; Hack and Selvelli 1978). It would be explained rather naturally as an eclipse of a large disk (seen edge-on) by a smaller, cooler object. However, the large luminosity of the alleged F2 Ia supergiant is not easy to explain by this model, and there are other difficulties. Nevertheless, further explorations of the complex nature of accreting stars are promising.

Table 1

Parameters of Simple Shell Stars

Star	HD	T_{eff}	log g	Spectral type	E(B-V)	Date I.U.E.	Observed Lick
Cas	698	12,000	3.0	B8.5 III	0.25	5 Feb 79	
Cas	220300	16,000	4.0	B4.5 V	0.15	10 Feb 79	
Cep	206773	30,000	4.0	B0 V	0.50	18 Aug 79	18 Jul 79
CX Dra	174237	19,000	4.0	B3 V	0.05	6 Feb 79	13 Sep 79
4 Her	142926	12,000	4.0	B8 V	0.03	6 Feb 79	28 Apr 79
88 Her	162732	13,000	4.0	B7 V	0.03	6 Feb 79	28 Apr 79
EW Lac	217050	19,500	4.0	B2.5 V	0.12	6 Feb 79	13 Sep 79
17 Lep	41511	8,000	3.0	A6 III	0.05	5 Feb 79	13 Sep 79
FX Lib	142983	15,250	4.0	B5 V	0.06	8 Feb 79	28 Apr 79
HR 716	15253	9,400	3.5	A1 III	0.04	8 Feb 79	12 Sep 79
28 Tau	23862	10,750	3.0	B9 III	0.07	9 Feb 79	12 Sep 79

Remarks: HD 698: alternative fit: T_{eff} = 14,000°K, log g = 3.0, SP B6 III, E(B-V) = 0.33. HD 220300 and 28 Tau: LWR spectrum only.

Table 2

Tentative Stellar Parameters of Complex Shell Stars

Star	HD	T_{eff}	log g	Spectral type	E(B-V)	Date I.U.E.	Observed Lick
KX And	218393	13,000	3.0	B7 III	0.15	14 Nov 78	Many
AX Mon	45910	17,000	4.0	B4 V	0.18	9 Feb 79	12 Sep 79
Mon	51480	14,000	4.0	B6.5 V	0.15	9 Feb 79	12 Sep 79
ϕ Per	10516	20,750	3.7	B1.5 III	0.04	8 Feb 79	12 Sep 79
FY Vel	72754	22,500	3.0	B1 III	0.45	14 Nov 78	

We have passed rather smoothly from the "classical" shell stars to interacting binaries. It is hard to draw a line between them, even for shell stars listed as "simple" in our Table 1.

In dealing with these complex and often variable objects, one realizes that coordinated, nearly simultaneous I.U.E. optical and infrared (spectroscopic as well as photometric) observations are essential. We wish therefore to emphasize the importance of the coordinated campaigns initiated by Harmanec and Kříž from the Ondřejov Observatory.

A more complete article on these observations and problems will be published elsewhere. Our thanks are due to the I.U.E. Observatory staff, to N.S.F. and NASA for supporting grants, to C.D. Keyes, M.P. Lesser and Z. Plavcová for considerable programming assistance, and to R.L. O'Daniel for typing the manuscript.

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DISCUSSION

Slettebak: With regard to the spectral type of 17 Lep, my recent spectrograms show no trace of helium. I would classify the star as A-type rather than late B.