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The β Lyrae Puzzle

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Abstract. Accurate simulation of optical wavelength CCD spectra is possible by adopting a black-body representation for the radiation characteristics of the β Lyrae accretion disk rim. Application of this model to *IUE* spectra shows that the anomalous system light curves, in the satellite UV, arise from a source of radiation, not included in the current model, which is visible during the phase 0.0 eclipse.

1. Introduction

β Lyrae long set the standard for stars that are difficult to interpret. Peculiarities include six different systems of spectral lines (Harmanec 2002), eclipse light curves that are anomalous in both the IR and satellite UV (Linnell 2000), cessation of light variation shortward of 1100 Å (Kondo et al. 1994), continuum fluxes of the two components, from decomposition of spectral scans, that "cannot be satisfactorily matched by any standard star or model atmosphere" (Plavec 1987), an orbital period that is increasing by 19 sec/yr, and a spectacular set of emission lines with a confluence of emission lines in the wavelength range 1800 Å to 2500 Å described as the "emission bump" (Hack et al. 1976).

Recognition that β Lyrae is a mass transfer system with an accretion disk began with an important paper by Huang (1963). Balachandran et al. (1986) determined a $T_{\rm eff}$ for the donor. Harmanec & Scholz (1993) determined the presently-accepted masses of the system components. The known parameters permit an attempt at simulation of the system.

2. Initial simulation results

The BINSYN program package (Linnell & Hubeny 1996) permits simulation of an accretion disk system with an optically-thick accretion disk. An initial study (Linnell, Hubeny, & Harmanec 1998, hereafter LHH) was successful in representing the optical and UV light curves in terms of an accretion disk system in which the thick accretion disk hides the massive gainer from the observer. An important result of that study is that only the accretion disk rim and the mass loser contribute detectably to the observed system light.

One of the system anomalies occurs in the satellite UV, for OAO2 light curves. At 2400 Å, the OAO2 light curve is "normal," in the sense that the phase 0.0 eclipse, when the relatively cool accretion disk rim eclipses the hotter mass loser, is deeper than the phase 0.5 eclipse. For OAO2 light curves at successively

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shorter wavelengths, the relative depth of the phase 0.0 eclipse becomes smaller, and at 1430 Å the depth of the phase 0.5 eclipse equals or slightly exceeds the phase 0.0 eclipse.

A separate feature of the light curves is that they show substantial epoch-to-epoch variation. There also is a well-known 275-day variation with an amplitude of a few hundredths of a magnitude in the visible (Guinan 1989) and of unknown origin. The light curve anomaly has been a persistent feature that appears unrelated to the intrinsic system variability. The present objective is to identify a cause for the light curve anomaly as an isolated phenomenon.

The OAO2 light filters define band passes that include β Lyrae emission lines. Hack et al. (1977) and Kondo et al. (1994) measured flux levels on spectroscopic data, in the same wavelength region as the anomalous OAO2 light curves, but in wavelength intervals that were uncontaminated by emission lines and appeared to be pure continuum. They found the same light curve anomaly. The important implication is that the anomaly is a property of the continuum, unrelated to the existence of emission lines. This feature justifies calculation of synthetic spectra, intended to investigate the anomaly, which include only the continua of the components, without any model of the emission lines.

LHH adopted a two-temperature accretion disk rim in calculating synthetic light curves. The BINSYN model adopts an axisymmetric accretion disk as a first approximation to an accurate physical model. Bisikalo et al. (2000) have done a hydrodynamics simulation of β Lyrae, using the currently-accepted mass transfer rate (Harmanec & Scholz 1993). The Bisikalo et al. results agree reasonably well with the axisymmetric assumption. In addition, Bisikalo et al. find that there is no "bright spot" on the accretion disk rim, in agreement with observation. The mass transfer stream dissipates its mechanical energy well within the accretion disk. The LHH model provided the first representation of the full set of OAO2 and *UBV* light curves with a consistent, single set of model parameters.

3. Spectrum synthesis: optical wavelength results

In addition to *IUE* spectra, two sets of ground-based spectra have become available recently. These include a set of 11 photometrically-calibrated spectral scans by Burnashev & Skulskij (1978), kindly forwarded by P. Harmanec, and a larger se,t of uncalibrated CCD spectra, taken at the University of Wisconsin Pine Bluff Observatory and kindly forwarded by Ms. J. L. Hoffman.

The temperature calibration by Balachandran et al. (1986) and the Roche lobe-filling geometry of the mass loser provide a basis to calculate synthetic spectra of that component. Although the geometry of the accretion disk rim is definite in the BINSYN model, the way to treat the radiation characteristics of the rim is not straightforward.

The physical conditions in the rim differ from the hydrostatic equilibrium prevailing in stellar model atmospheres. A gas parcel in the rim and on the orbital plane will be in equilibrium, with zero net force (and zero gas pressure), if it moves slower than Keplerian by an amount just to balance the outward radiation pressure. Clearly, some fictitious $\log g$ must be adopted if a model atmosphere in hydrostatic equilibrium is to represent the physical conditions

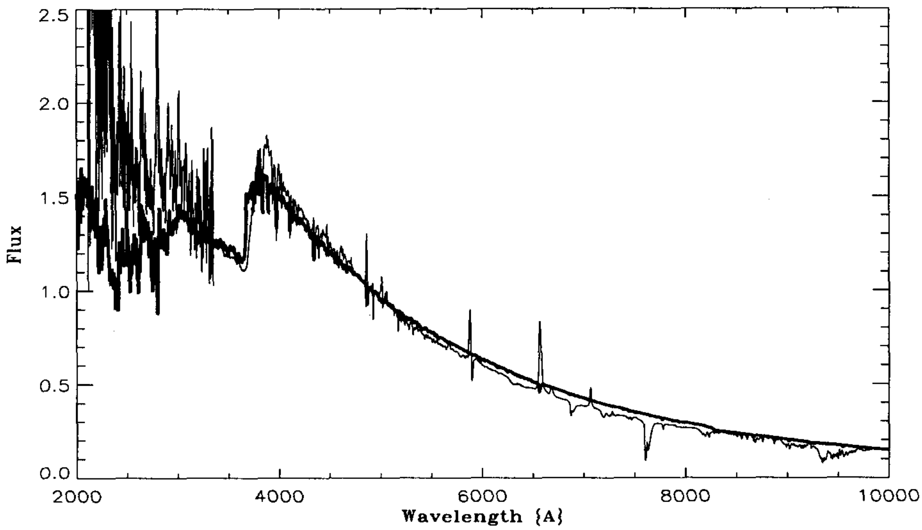

Figure 1. Combined *IUE* and CCD spectrum (the light line) compared with system synthetic spectrum (the heavy line) at orbital phase 0.0154. Note the good fit longward of 4000 Å and the good fit to the Balmer jump.

in the accretion disk rim. At a given T_{eff}, model atmosphere synthetic spectra are relatively insensitive to $\log g$. Consequently, initial tests adopted a synthetic spectrum for a Kurucz solar composition model atmosphere of $T_{\text{eff}} = 9000$ K and $\log g = 2.5$ to represent the accretion disk rim. Based on this representation, comparison of the system synthetic spectrum with scan data (Linnell 2000) found two discrepancies: (1) the synthetic spectrum displayed a much larger Balmer jump, and, (2) the synthetic spectrum had smaller long-wavelength flux than in the scan spectrum.

Further experimentation showed that representing the rim with a 9000 K black-body spectrum produces a remarkably good system synthetic spectrum fit to both the scan spectra and the CCD spectra. The fit includes the height of the accretion disk rim as an assignable parameter. The adopted optimum choice assigns a rim height equal to the projected polar diameter of the mass loser (Linnell 2002a). Theoretically, the rim of a thin accretion disk is a half toroid (Hubeny & Plavec 1991). Tests with both a half-toroidal rim and a cylindrical rim show that the latter structure provides a better representation of the observational data. The half-toroidal rim produces a primary eclipse that is too narrow. This effect arises from the gradual ingress and egress for a very tall curved rim. The accretion disk radius already slightly exceeds the theoretical tidal cutoff radius. The cylindrical rim is in agreement, by visual inspection, with the hydrodynamics simulation by Bisikalo et al. (2000).

This isothermal rim model eliminates both of the discrepancies present in the earlier simulation, which used a $\log g = 2.5$ synthetic spectrum to represent

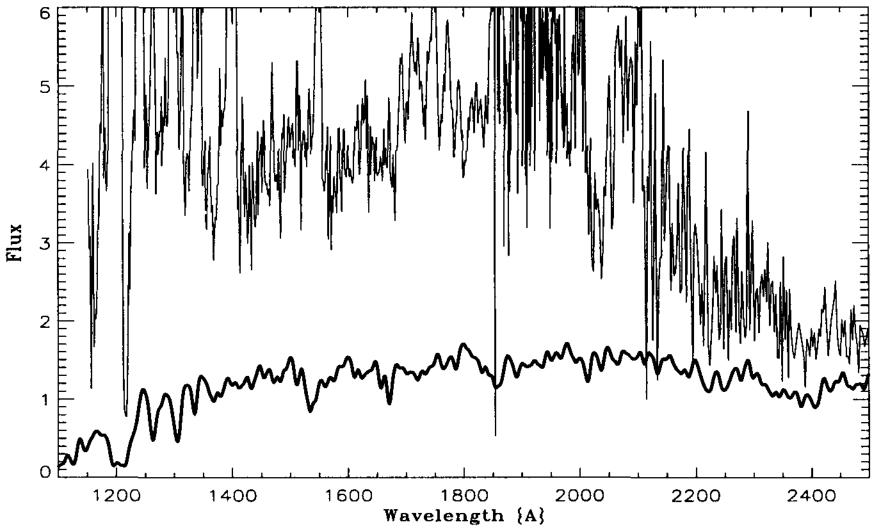

Figure 2. *IUE* spectrum (the light line) compared with system synthetic spectrum (the heavy line) at orbital phase 0.0154. Note the large discrepancy.

the accretion disk rim. The new model produces a good representation of the flux variation of the calibrated scan spectra with orbital phase. However, the Balmer jump, in the synthetic spectrum, is too small during the phase 0.0 eclipse. This defect arises because there is no Balmer jump in the black body spectrum representing the rim, and the contribution of the mass loser is small during the phase 0.0 eclipse.

Using the Hubeny program TLUSTY (Hubeny 1988), it is possible to calculate a zero-order, LTE, grey body model atmosphere for a limiting log g=0.7. (Smaller $\log g$ values are Eddington unstable.) Substitution of the corresponding grey body synthetic spectrum for the black-body spectrum produces a good system synthetic spectrum fit to both scan spectra and CCD spectra at all orbital phases, including the phase 0.0 eclipse (Linnell 2002a). Simulation of the mass loser uses synthetic spectra calculated from a grid of non-LTE model atmospheres on the Balachandran et al. (1986) abundances. Fig. 1 illustrates the fit at orbital phase 0.0154.

Superposition of the synthetic spectra on the scan spectra uses a single normalizing divisor. There are some discrepancies in individual fits; β Lyrae shows non-repeating spectrum variation and the simplest explanation of the discrepancies is intrinsic source variability. The available data set does not permit investigation of this aspect of the system.

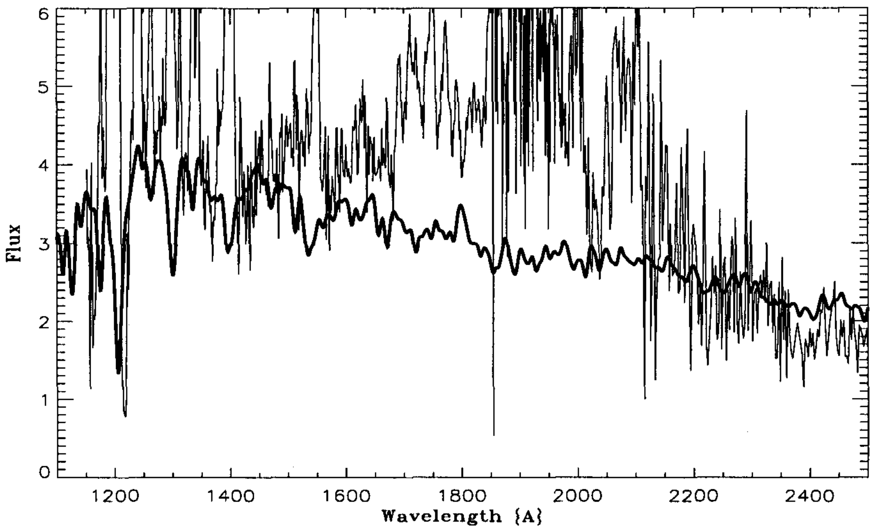

Figure 3. Fit of two-temperature rim model to *IUE* spectrum. Note the improved fit compared with Fig. 2.

4. Spectrum synthesis results in the satellite UV

Twelve pairs of SWP+LWP spectra of β Lyrae are available that are free of overexposure flags or other defects (Linnell 2002b). These spectra have been recalibrated with the Massa & Fitzpatrick (2000) software. A CCD spectrum of the proper orbital phase has been combined with each SWP+LWP pair to produce individual calibrated spectra extending from 1100 Å to 10,000 Å. The spectra are well distributed in orbital phase.

The isothermal rim model fits the *IUE* spectra well except within the phase 0.0 eclipse, and omitting emission lines. In particular, the model fits the *IUE* spectra in the vicinity of 1500 Å, where the light curve anomaly occurs. This feature supports the earlier conclusion that the light curve anomaly is a property of the continuum and is independent of emission lines. The emission lines may associate with the jet-like structures found by Harmanec et al. (1996) and by Hoffman et al. (1998). These structures extend far above the accretion disk proper. As such, they do not affect the light curves except to require third light in the representation of OAO2 light curves (LHH).

The isothermal rim model fails to fit the SWP *IUE* spectrum within the phase 0.0 eclipse by a large factor. Fig. 2 illustrates the comparison. A synthetic light curve, based on synthetic photometry (Linnell 2002b), also is very discrepant from the OAO2 1430 Å light curve. (The OAO2 light curve is a proxy for a continuum light curve.)

A synthetic system spectrum, based on the two-temperature rim discussed earlier, also fits the optical spectrum well, at orbital phase 0.0154, except at the Balmer jump. This good fit demonstrates that a range of representations for the rim can provide a good fit to optical spectra. The fit to the SWP spectrum is in Fig. 3. The fit is much improved over Fig. 2. However, a synthetic light curve, via synthetic photometry, still has a phase 0.0 eclipse that is deeper than the phase 0.5 eclipse.

The synthetic spectrum simulation of the *IUE* spectra shows that the light curve anomaly arises from extra radiation in the system, not included in the present model, which is visible during the phase 0.0 eclipse. The key question is: What is the source of extra radiation? Linnell (2002b) discusses alternatives for possible sources.

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