THE WINDS OF THE HOT, CONTACT BINARY TU MUSCAE (HD100213)

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Abstract

A model of the TU Muscae binary system has been developed by a study of the wind-line profiles in 23 *SWP* spectrophotometric images obtained with *IUE*. The images are well distributed in Keplerian orbital phase thereby permitting a simultaneous fitting of the CIV wind-line profile by the SEI method and the light curve for the same bandpass by means of a program similar to that of Wilson and Devinney. The result is a set of parameters characterizing the physical and geometric properties of the wind envelopes surrounding the stars. Surprisingly, there is no evidence for a shock front in the system as has been found for similar investigations of EM Carinae and HD159176. This is probably a result of the contact nature of the binary.

1. Introduction

A series of 4 previous papers published elsewhere has developed models of the wind structure and activity for four massive, close binaries. Three of these concerned the "well-separated" pairs Y Cyg, CW Cep, and EM Car, while the remaining one studied a much tighter but not a contact system, HD 159176. The current contribution looks at TU Mus, a true contact (or double contact in some notation) object in a similar way. A priori, one cannot tell if the contact nature of the object will change the winds from the character known for the 4 binaries already studied.

A brief history for TU Mus has been summarized by Stickland *et al*. (1995) and more recently by Terrell et al. (2003), who note the importance of this very hot star. Both studies conclude with the confounding result that a high-weight, UV radial velocity curve from *IUE* images yields a mass ratio which apparently disagrees significantly with the mass ratio from an adequate "blue" radial velocity curve (Anderson et al., 1989) supplemented with 2 normal points from Terrell et al. This matter has been discussed in detail by Terrell et al. and it appears the source of the disagreement is an enigma. However, the seeming difference between the mass ratios from the two latter observational sets is not significant when realistic errors are imposed on the parameters.

The IUE archives hold 23 high quality SWP images for the contact binary system TU Muscae. The aim of the present paper is to model the winds and their interactions in this binary by means of the same *IUE* images used by Stickland et al. (1995) for their velocity analysis. The latter study established precise orbital dimensions ($a\sin i = 15.41 R_\odot$) and masses $M_1 \sin^3 i = 15.70 M_\odot$ and $M_2 \sin^3 i = 9.85 M_\odot$, yielding a mass ratio q=0.627. A light curve analysis by Anderson, *et al*. (1975) yielded $i = 76^o$. However, the more recent study by Terrell *et al*. (2003)

determined a value of i= 77.8° and a mass ratio of 0.651, which, as mentioned above, is the same number obtained by Anderson, et al within 2σ.

For this binary, the Si IV and N V doublets within the *SWP* bandpass are too weak to provide useful information. Hence, this paper is limited to an analysis of the C IV feature near 1550Å . This profile has been fitted with an *SEI* program developed by Lamers et al. (1987}, which has been adapted for use with binary stars by Pfeiffer, et al. (1994) and is referred to as *BSE*I. For this study, substantial changes have been made to the methodology for fitting the UV light curves that were employed in the previous studies.

2. The Mass Ratio

The situation may be summarized in this way. The visible-band photometry and spectroscopy essentially converge on q = 0.70 while the UV continuum light curve is most consistent with the UV radial velocities leading to q = 0.63. At least formally, these two values do not overlap at 3σ. There is, however, a way to understand and resolve this difference. Choose the two photospheric temperatures given by Wilson and Rafert. (Their procedure cannot really determine these temperatures with high accuracy but the ratio of the temperatures is significant.) These temperatures lead to theoretical flux levels in the model atmospheres of Kurucz at any tabulated wavelength. For the UV continuum the ratio of the flux levels for the two temperatures is 1.58 while the same ratio is 1.31 in the visible. With the component stars in contact, the absorption and re-radiation of one star's flux by another and the differential between the two processes (distilled into the astronomical colloquialism of "the reflection effect") is very important. It displaces the light centers of the stars away from the positions of their projected mass centers toward the systemic mass center. The effect on the cooler, fainter star is the more important because it causes that star to seem to move in a smaller orbit in the UV than in the visible. The process does logically affect both the UV continuum and the UV line centroids and accounts for the consistency of the UV spectroscopy and light curve. The recognition of the effect is quite old: Kuiper first presented precepts for correcting it in 1938. However, the message here is somewhat different than the classical understanding. The results may be interpreted to mean that the visible-band mass ratio is more reliable than the UV one, even though the latter is derived by a procedure which possesses the highest internal weight. This conclusion also negates some of the force of the dictum that the UV, where most of hot star radiation is emitted, is the proper electromagnetic domain to study hot stars. However, a recent reanalysis of the UV radial velocities by Geis *et al*. (Ref.) has concluded that this is not the case. There results strongly indicate that mass ratio given by the UV analysis is the correct one.

3. Fitting the UV Light Curves

For HD 159176, Pachoulakis showed that the UV Spectrophotometry in the SWP bandpass yields good light curves, even if the flux modulation is only that of an ellipsoidal binary and that even these modest light curves can be modeled usefully. The UV light curves for Y Cyg and CW Cep had previously been found to resemble the visible-band ones if the resonance wind lines were avoided in selecting the bandpasses. Consequently, two light curves for TU Mus were extracted from the *IUE* spectra by integrating the observed flux over two bandpasses. The first is a continuum bandpass from 1450 to 1490 Å and the second encompasses all of the C IV profile from 1530 to 1560 Å.   A 200Å bandpass between 1620 and 1800Å was also investigated to see if an improvement in the noise in the continuum light curve could be obtained. It could not.

A study of these light curves shows that the UV radiation of TU Mus is intrinsically variable aside from the usually binary induced causes: the first 4 images lead to continuum flux levels which are consistently brighter by 10% than the levels for all later images. The earlier and later sets of images are separated by more than 2,400 days or 1,700 cycles. The flux difference seems to have no effect on the Doppler displacements of the photospheric lines in the study by Stickland *et al*. (1995) and it has no known cause at present.

The UV continuum light curve may be faced against the visible-band ones already analyzed by Anderson, et al. (1989) and Terrell, et al. (2003). This has merit even though the IUE light curve is populated by only 19 data points (the four earlier *IUE* images having been excluded). The resemblance between the three data sets is generally quite strong.

The light curve for C IV feature has very little information in it. Although morphologically the same as the continuum one, it suffers from shot noise in the spectrum because the line is so strong.

A reasonably good fit to the UV continuum light curve and u bandpass of Terrell et al. has been obtained using a program developed by employing techniques similar to that utilized by Wilson and Divinney (1971) and Wilson (1976). See Fig. 1.

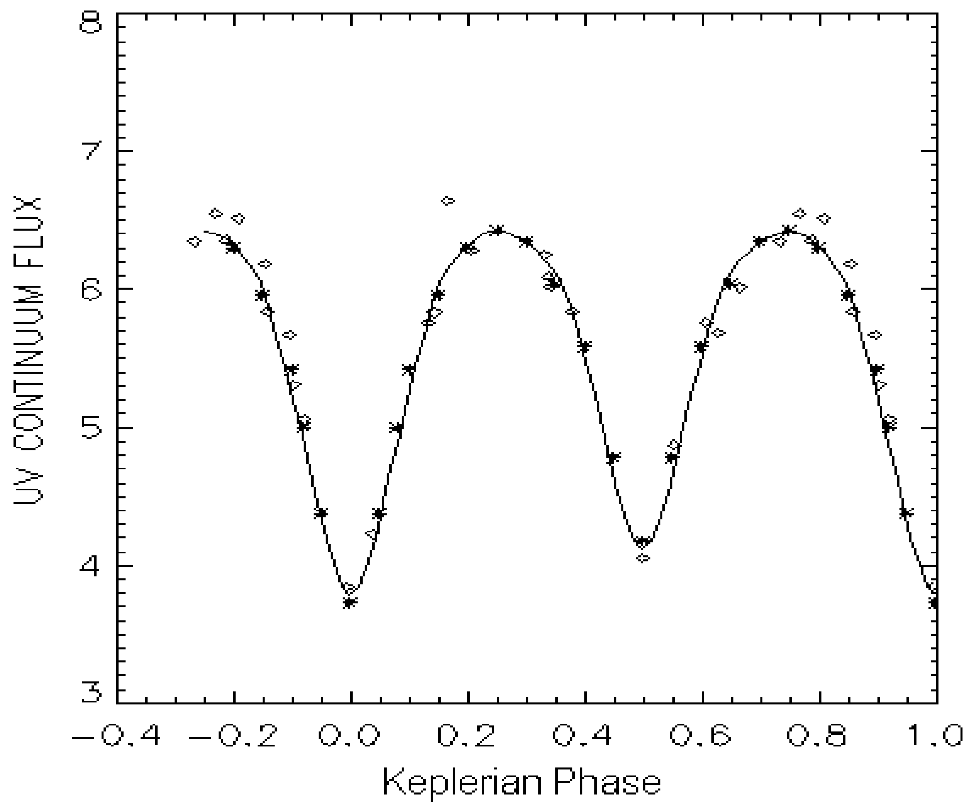

Fig. 1 displays three continuum light curves for TU MUS. The diamonds represent observations derived from the *IUE* blanketed continuum (1450 - 1490 Å) outside the C IV line profile. The stars are data points taken from Terrell et al's published light curve in the u bandpass, renormalized to the IUE flux levels, and the solid curve is a fit using a program developed by the author following a methodology similar to that published by Wilson and Devinney (1971).

The primary purpose of achieving such a fit is to test the algorithms so developed that, when they are integrated into the binary interaction program BSWI (Pfeiffer and Stickland, 2004), the latter may be confidently brought to bear upon fitting the light curve of the C IV wind-line profile. The binary, as represented by these algorithms is depicted in Fig. 2.

In this new program, the light assigned to each star is in accord with the light ratio known from photometric solutions (Ref.). The out-of-eclipse, fiducial flux level of the system was determined from the image taken at phase 0.735 for each bandpass. This flux was then partitioned among the stars, wind envelopes, and a possible shock. The partitioning parameters are input parameters for the BSWI program and are varied to achieve a good fit. For a given set of input parameters, a light curve is generated taking into account all binary interaction effects: (1) all ellipsoidal variations contributing to the systemic light, (2) photosphere-photosphere eclipses, (3) photosphere-wind envelope eclipses, (4) photosphere-shock eclipses, (5) wind attenuation of the photospheres, shock, and other wind, and (6) shock attenuation of the photospheres and wind envelopes.

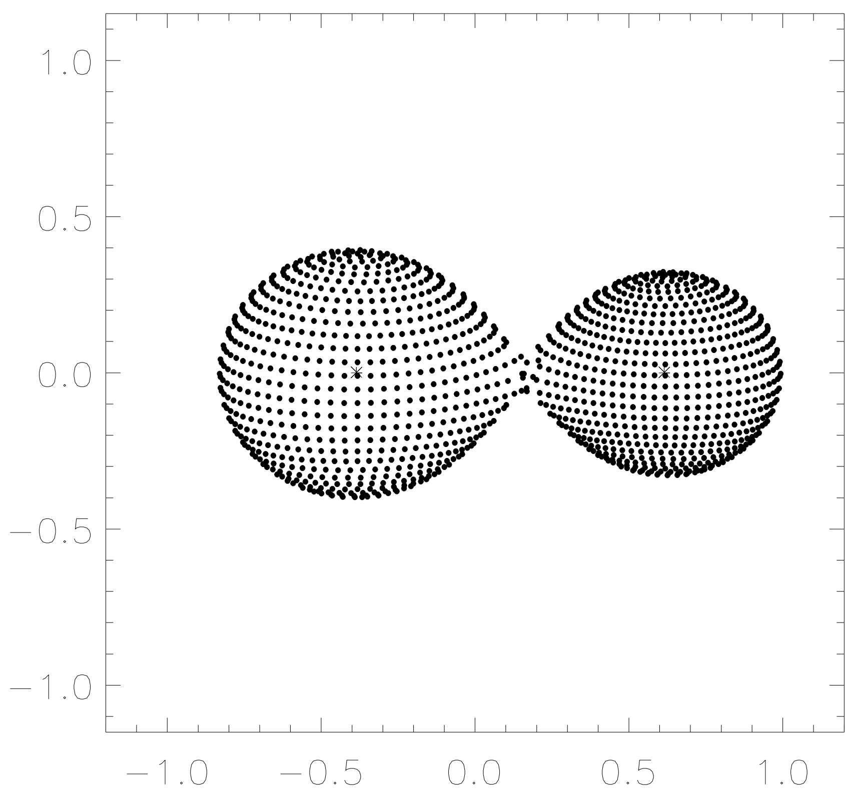

Fig. 2 The TU Mus system as represented by the algorithms that produced the light curve fit shown in Fig. 1. A value of q=.651 was used. The other binary parameters are taken from Terrell et al.

Only an optically- and geometrically-thin shock has been assumed. Hence, a ray from any grid point passing through the model shock is attenuated by the same factor. However, the effective value of this factor is varied with phase to account for the changing aspect of the shock relative to the line of sight. The ions of the shock are assumed to be Rayleigh scatterers and therefore, the absorption coefficient per volume element of a shock is related to the Rayleigh scattering cross-section in the usual way. The amount of photospheric and wind emission scattered by the shock towards the observer is computed according to classical Rayleigh scattering theory. A fraction of this emission undergoes a cos (2ϕ) variation to account for a greater optical depth through the shock for some volume elements at the quadrature phases.

To be continued

4. The BSEI Fitting of the C IV Profile

The concern about the mass ratio is not an inconsequential one, for it determines the stellar dimensions in this contact system and thus locates the bases of the stellar winds. From the argument just concluded, it was decided to use q = 0.651, although it isn't clear that this choice has to lead to the best wind geometry.

The winds can be modeled by fitting the profiles of the wind-sensitive lines. For TU Mus the N V doublet near 1240Å is so severely convolved with the very broad interstellar L_α line that there was no confidence in trying to isolate the stellar line. Also, the Si IV lines near 1400A are rather weak and give little indication of a wind. They appear to be dominated by photospheric absorptions. Consequently, all information about the systemic wind comes from the C IV feature at 1550Å. In addition, it was found that all 23 images can be used for the wind profile fitting, which is to say, that in observed flux units, the 4 earliest images give line strengths and profiles which are indistinguishable from those of the later images. There is no current explanation why the continuum and line fluxes should be uncoupled in this way.

To begin, a *BSEI* fit to the C IV profile was made for the image at Keplerian phase 0.735. This seemed to be the most readily obtained fit, since the wind interaction effects would be at a minimum at this phase. The fit had to match the mean level of the metallic blanketing and noise both within the line profile and in the adjacent continuum between 1500 and 1600 Å. Determining what the mean continuum level is, is not critical as long as one allows for the same amount of blanketing inside the profile as outside, but keeping in mind that the CIV ion provides the strongest absorption component of the blanketing.

It was decided to incorporate interstellar lines into the fits by using Gaussian profiles, which was not done in the previous papers in this series, In this way, one avoids making optical depths that are too strong for the C IV ion. The two interstellar C IV lines are easily recognized and fitted. These have total widths of about 1 Å. In addition, there appear to be several other narrow lines (< 2.0 Å in total width) within the bandpass, which cannot be of photospheric origin. The dictum is that a photospheric line must be rotationally broadened (about 2.5 Å in total width as judged from the HeII feature at 1640.5Å which agrees with the rotational velocities determined by Stickland et al) and such lines cannot conspire to produce narrow lines. However, several close interstellar lines can conspire to produce a broadened feature. The question is, which of these features are real lines in the spectrum and which are noise. The answer to this was decided by comparing all the images to see which narrow features were consistently present. In some cases, an interstellar line may be obliterated by the Doppler walking of unknown photospheric lines. On the other hand, these features may be the infamous DACs mentioned by others, such as Howarth, et al. It was decided that if a narrow feature appeared to be at the same wavelength with the same approximate strength in three or more images, it is a real interstellar line. If the feature seemed to indicate an increasing blue Doppler shift with Keplerian phase, the probability is that the feature was a DAC.

The fitting procedure uses normalized fluxes in the sense that the average noise and blanketing of the continuum results in an observed continuum flux level that is defined to be 1.0 over the above wavelength interval. However, as with EM Car, it was decided not to normalize the IUE fluxes, but instead, transform the normalized BSEI fluxes to the absolute flux levels of the IUE data. This was accomplished, by using the IUE average blanketed fluxes at 1500 and 1600, found from the dereddened fiducial IUE image, to define the slope of a linear interpolation over this wavelength interval.

Next, the absolute integrated flux for the BSEI profile was found and divided by the profile bandwidth to yield an average monochromatic flux for that bandpass. The result is the same for each image, since the equivalent width of the profile remains the same for each fit. Table 1 presents the BSEI parameters determined for the TU Mus system. The definitions of these parameters may be found in Paper 1. The determination of the *BSEI* denormalization constants can be a source of error at this stage. In addition, other errors may be introduced by the assumption that the fluxes between 1500 and 1600 may be fitted by simply a linear interpolation.

Table 1
BSEI Parameters for CIV

Parameter	Primary	Secondary
w_o	0.01	0.01
bw	1.0	1.0
wg	0.37	0.37
bet	1.0	1.0
alfao	0.01	0.01
alfat	2.9	2.9

Parameter	Primary	Secondary
aphotB	0.20	0.22
aphotR	0.10	0.11
TtotB	3.8	3.6
TtotR	1.9	1.8
Delta\lambda	7.5	6.05

To be continued

5. The Binary Wind Interactions

The *BSWI* program used to fit the light curve of the C IV profile is the same one simultaneously employed to fit the continuum light curves. This imposes constraints on the input parameters of the program, thereby resulting in a self-consistent method of analyzing both data sets. This assumes the *BSEI* fit is a good one and the denormalizing constants have been properly determined. If there are interaction affects among the stars and their wind envelopes, these effects should be zero or at least a minimum at the quadrature phases. This is why the fiducial fit was done at phase 0.735. Even if interaction effects exist at this phase, these effects would have been effectively included in the profile fit.

Now as the stars approach a conjunction the binary interactions increase in the sense that the depth of the wind-line changes relative to the fiducial, blanketed, continuum level. One of the most significant of these effects will be a reduction in the absolute value of the metallic line blanketing, z. This occurs because of: (1) an ellipsoidal variation in the stellar fluxes, and (2) photospheric eclipses. At phase 0.735 (SWP54407), the dereddened continuum flux extrapolated to the center of the C IV profile is about 6.05e-10 cgs units. This is very nearly the maximum value for such flux, as a result of the photospheric ellipsoidal variation. Now at this same phase, the metallic line blanketing is also a maximum because of the ellipsoidal variation in the stellar fluxes: From an inspection of SWP37879 at phase=0.552, z appears to have a minimum value of 0.22 as evidenced by the maximum excursion of the variations in the blanketed continuum. But this value is already diminished by the ellipsoidal variation of stellar fluxes. This means z_{max} is about 0.30.

To be continued

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