A RADIAL VELOCITY ANALYSIS OF THE BINARY STAR TU MUSCAE

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ABSTRACT

Several papers provide conflicting results for the radial velocities and mass ratios of the binary star TU Muscae; this paper intends to shed light on this issue. A radial velocity analysis was done by fitting Gaussian curves to the absorption lines of helium II (He II) and silicon IV (Si IV). The corresponding red and blue Doppler shifts of these absorption lines were measured and the radial velocities of the stars at each orbital phase were then computed. The radial velocity diagram for the system was then constructed and best fits to the data were obtained by the method of least squares to minimize the standard deviation. The best fits to the data yielded the gamma velocity (γ-velocity) of the system as well as the orbital velocities of the two stars. This then led to the calculation of the mass ratio for the system. The results for He II gave a mass ratio equal to 0.65±0.07 and a γ-velocity equal to -16±7 km/s, while for Si IV the mass ratio is 0.61±0.02 and a γ-velocity equal to -18±5 km/s. These results for both the mass ratio and the γ-velocity agree with those found in an earlier paper written by Stickland et al. (1995, hereafter S95).

INTRODUCTION

TU Muscae is an over-contact binary star with an orbital plane inclined by 78 degrees to Earth's line of sight. Therefore, this system is a good case study for a radial velocity analysis because the Doppler shifts are very pronounced. Twenty-four ultraviolet spectrophotometric images of the binary star were taken with the International Ultraviolet Explorer (*IUE*) and used in this study to determine the Doppler shifts of the absorption lines belonging to both the primary and secondary stars in the system. By fitting the absorption profiles of the lines using Gaussian curves, the Doppler shifts were determined and from these the corresponding radial velocities for each star were calculated. This was done using the He II absorption line and the Si IV absorption line doublet. These radial velocities were then used to construct a radial velocity diagram. By determining the best fits to the data in this diagram the mass ratio and the radial velocity of the center of mass of the system relative to the Sun (γ- velocity) were determined.

Radial velocity analyses of this system have been published by several others but using a variety of different techniques. The mass ratios so obtained have been a matter of contention. The first radial velocity study was done by Anderson and Groenbech (1975, hereafter A75) using a few optical spectra made near the quadrature orbital phases. Terrell *et al*. (2003, hereafter T03) used the same method employed in this paper but also used several spectral lines in the visible bandpass including the Balmer line, H-beta. S95 used the same images obtained by the IUE but employed a cross correlation method to determine the radial velocities. These three papers are in disagreement over the mass ratio and γ-velocity of TU Muscae; this research tries to address the issue.

THE DATA

The International Ultraviolet Explorer was a space observatory jointly operated by NASA, ESA and the UK Science Research Council. The spacecraft was launched into a geosynchronous orbit in 1978 and functioned until 1996. The spectrophotometric images taken are in the ultraviolet bandpass from 1200 to 2000 Å. These images were downloaded from the NASA data archives for use in this study. The spectra suffer from severe line blanketing mainly because of the many ionized elements in the atmospheres of the component stars. Figure 1 illustrates the stark difference between the blanketing in the ultraviolet and the visible. This heavy blanketing makes finding individual absorption lines very difficult in the ultraviolet, a complication not shared in T03 and A75 when studying the visible bandpass.

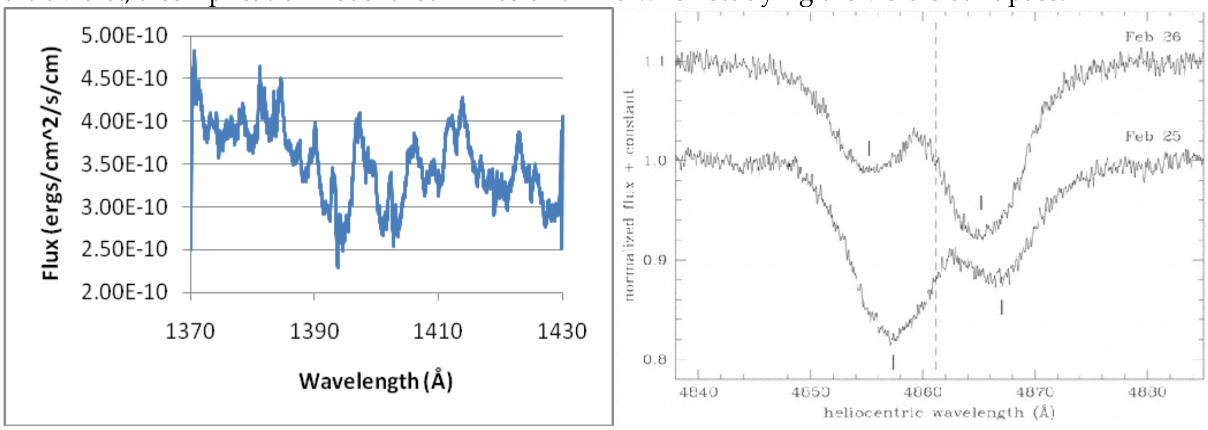

Figure 1 – Images of the Si IV doublet (left) and Balmer (right) absorption lines.

LIGHT CURVE

To calculate an appropriate flux level for use as a continuum in fitting the line profiles with Gaussian curves, the light curve of the binary star was calculated. Two methods were used to generate such a light curve and the median of these methods became the source of the continuum. The first method calculated the area under the curve in the bandpass 1620 Å to 1660 Å by numerically integrating to find the corresponding strength at each phase of the orbit. The areas were then normalized by dividing each area by a factor equal to 0.86 ergs/cm^2/s/Å. An average flux value was used to generate the second light curve. Fluxes at each wavelength were summed and then divided by the bandpass. These average fluxes were then also normalized by dividing all values by the maximum average flux of 6.4E-11 ergs/cm^2/s/Å.

The midpoint of the normalized strength and the normalized average flux was then utilized in finding the value of the continuum flux to be used in fitting Gaussian curves. All three curves are displayed in Figure 2 where the normalized flux is shown at each phase. To get an appropriate flux from the normalized values for use as the continuum, the midpoints were multiplied by the previously used normalizing factor of 6.4E-11 ergs/cm^2/s/Å.

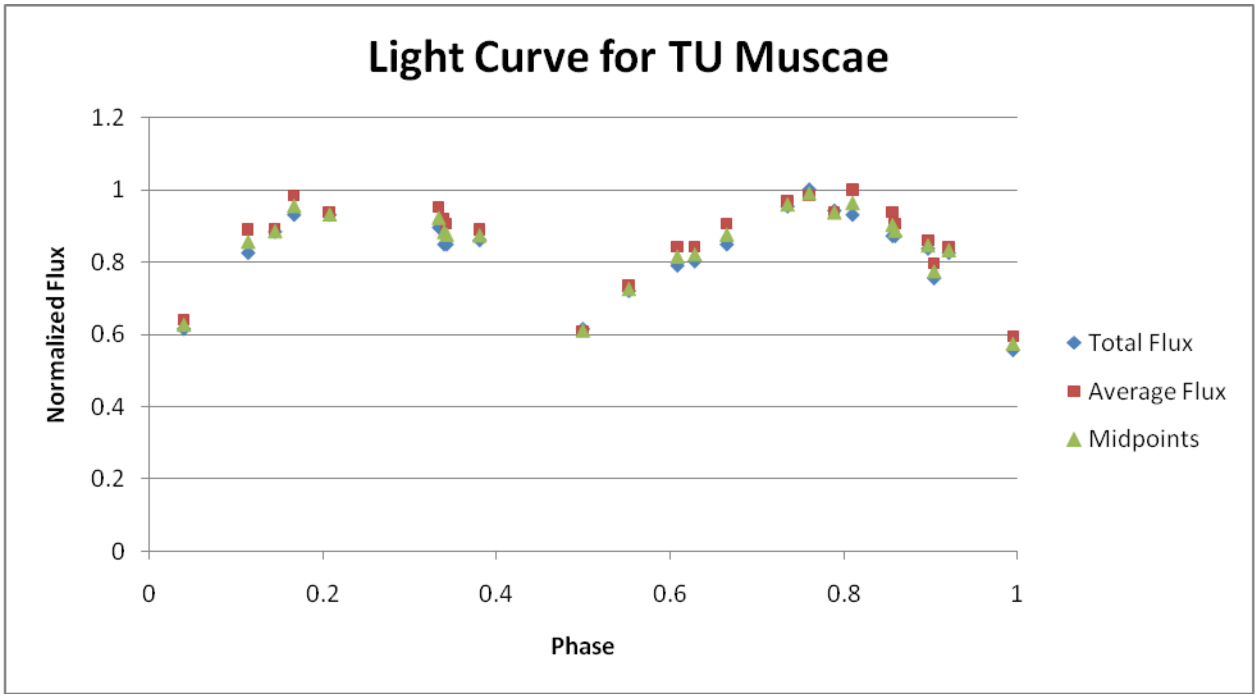

Figure 2 – Normalized plots of the two methods using to generate a light curve.

PROFILE FITTING

Gaussian curves fitting the absorption lines of TU Muscae were generated using the programs PROFIT01 and SYNSPEC6 developed by R. J. Pfeiffer (2011). These programs take user inputs to create a Gaussian curve with the desired features. The features are changed manually and enable the user to change the radial velocity, line depth, and line width. The input also includes a continuum flux, which is the flux that would be observed if no stellar blanketing were to take place. A Gaussian curve with these features that fits the absorption spectrum would be of the form:

$F = F_o – De^{-(\lambda-\lambda_o)/W}$.

F_o is the continuum flux and D is the line depth both in ergs/cm²/s/Å; λ is the wavelength; λ_o is the central wavelength; and W is the width in angstroms. Using the laboratory calculated central wavelengths we can calculate the Doppler shift corresponding to the radial velocities of each star in the binary system. By changing these radial velocities until the Doppler shifted Gaussian lines match that seen in the absorption spectra we can determine the radial velocities of the stars in each of the IUE images. Changing the line depth and width also gives an indication of the strength of the absorption lines.

RADIAL VELOCITY CURVE

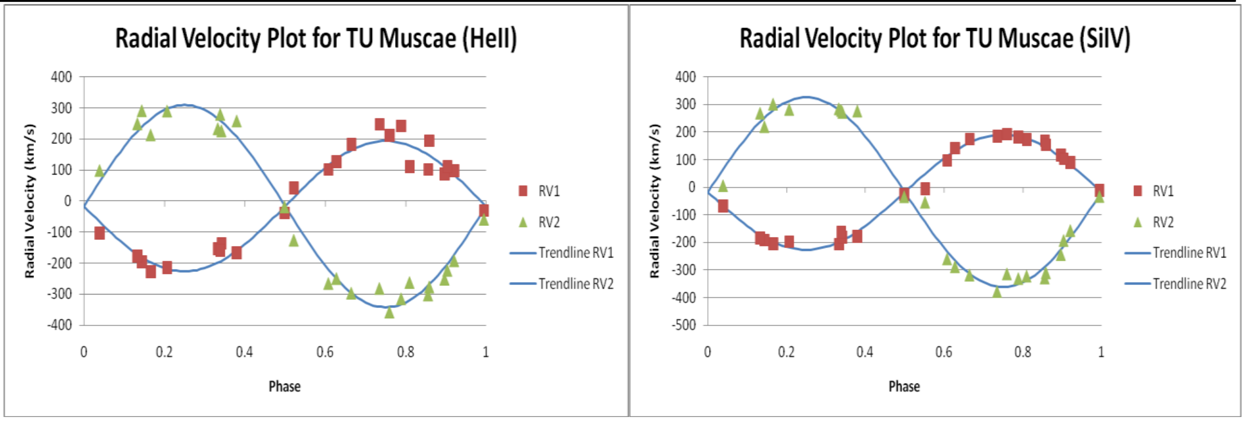

Figure 3 – Radial velocity plots for He II (left) and Si IV (right).

Plotting the radial velocities of each star with respect to the orbital phase then shows the changing orbital velocities of the binary star components during one orbital cycle. A fit is then used to determine the trend that best describes the data. Curves resulting from this fit can be seen in Figure 3 and form the sinusoidal curves expected in an orbital motion. The velocities used in the fits are given by the function: $RV = K[e\cos(\omega)+\cos(\omega+\nu)]+\gamma$.

K is the amplitude, e is the eccentricity, ω is the orientation of the orbital major axis, ν is the orbital phase in degrees, and γ is the radial velocity of the binary system (γ-velocity). To find the best fit for the data the amplitude and γ velocity were changed until the standard deviation of the data points from the fit was minimized. The standard deviation is given by $\sigma = [\Sigma(RV_o\text{-}RF_f)/N(N\text{-}1)]^{1/2}$.

RV_o is the observed radial velocity and RV_f is the radial velocity fit both in km/s; N is the number of data points. Minimizing the standard deviation was done by using the “Solver” method available in Microsoft Excel. This method adjusts an input value until a separate desired value is minimized. This was then used to minimize the standard deviation by adjusting the amplitudes for the radial velocity of each star. The “Solver” was also used to calculate the γ-velocity that would minimize this standard deviation.

The ratio of the amplitudes is proportional to the mass ratio of the binary star system and hence the mass ratio can be calculated by comparing the K factors determined in the radial velocity plot. The results for these computations are shown below in Table 1.

Table 1

Results for stellar parameters.

	He II	Si IV
K1 (km/s)	210±7	209±4
K2 (km/s)	326±7	344±7
M1/M2 (K1/K2)	0.65±0.07	0.61±0.02
γ (km/s)	-16±7	-18±5

ABSORPTION LINE STRENGTH

An attempt was made to look for a correlation between the orbital phase and the strength of the absorption lines. This was done by multiplying the depth of a line by its width for He II and for each Si IV absorption line in the Si IV doublet. This parameter gave an approximate value for the strength of the absorption line. The results indicate that there is no correlation between the strength of the line and the orbital phase of the binary star.

CONCLUSION

The results show that the mass ratio of the two stars differs marginally between that calculated using the He II absorption line and that using the Si IV absorption line. In fact, when including the error bars the mass ratios agree. The large error bar for He II is due to the heavy blanketing which makes accurate measurements extremely difficult. Both He II and Si IV have mass ratios that correspond to those found in S95 which calculated 0.627±0.009 as the mass ratio. T03 measured a mass ratio of 0.651±0.001, this is similar to that determined using He II, but is nowhere near that found using Si IV.

The γ-velocities have a rather large error bar, but once included, the velocities correspond for both He II and Si IV. These γ-velocities agree with that calculated by S95 which put the velocity at -12.7±2.1 km/s. Even when including the large error bar, these results differ from the γ-velocity of -4±4 km/s calculated in T03.

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