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NEW PHOTOMETRIC STUDY OF THE INTERACTING BINARY STAR SYSTEM Y PISCIUM

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ABSTRACT

We present a new photometric study of Y Piscium (Y Psc), which includes *BVI* light curves and a period analysis. With an orbital period of 3.77 days, this neglected system undergoes period changes described by an overall quadratic ephemeris with oscillating variability superimposed. Variations in the light curve and ephemeris curve, possibly resulting from changes in the accretion structure and mass transfer rate, suggest that Y Psc may be a direct-impact system like U Coronae Borealis and U Sagittae, which are known to exhibit variable accretion states. The 0.46 m modified Cassegrain telescope at the Kutztown University Observatory (Kutztown, PA) was used to obtain the new CCD photometry over 18 nights of observation between 2011 October 5 and 2012 January 15. We present a new photometric model that was determined using the computer program PHOEBE and suggest a reclassification of the spectral type of the primary star. An analysis of previously recorded times of minimum, in conjunction with our observations, was used to suggest possible physical mechanisms intrinsic to the system. These include magnetic activity (Applegate mechanism) and angular momentum transfer, while the possibility of a third body is ruled out. The results presented here demonstrate that Y Psc is an excellent candidate for a high-resolution spectroscopic study.

Key words: binaries: close – binaries: eclipsing – stars: individual (Y Psc) – stars: magnetic field

Online-only material: color figures

1. INTRODUCTION

Y Piscium (Y Psc; HIP 116339, HD 221700) was observed spectroscopically by Struve (1946) and photometrically by Walter (1973b). Struve noted a spectral classification of A3 outside of eclipse and that of K0 during the primary eclipse. He measured a maximum radial velocity $K = 37$ km s^{-1} and a mass function $f(m) = 0.019$. Struve's radial velocity (RV) plot also suggested a rather eccentric orbit ($e = 0.12$). Walter's light curve, however, demonstrated a circular orbit, as should be expected in such a close binary system. Walter noted a primary eclipse that was total for 63 minutes, as well as unexplained variations following the secondary minimum.

Both Struve's spectroscopic data and Walter's photometric data were later reanalyzed by Mezzetti et al. (1980). The RV curve was recapitulated with the presupposition of a circular orbit, resulting with the revised parameters of $K = 41.5$ km s^{-1} and $f(m) = 0.028$. Wood's model (Wood 1972) was used for the light curve reanalysis and gave similar results as Walter's original rectification method. It should be noted that these spectral classifications of A3 (main-sequence) and K0 (subgiant) rely on spectrographic plates from the 1940s and no known modern spectroscopic studies have yet been performed.

Qian (2000) performed a detailed period study of Y Psc, using published times of minimum light ranging from 1965 through 1998. Qian noted an overall decreasing orbital period, which would indicate a non-conservative case for an Algol-type system, with several sudden period jumps superimposed.

Y Psc is a member of the short-period Algol-type binaries that is in dire need of further study. It is important because it has an orbital period of 3.77 days, similar to that of the direct-impact alternating Algols (e.g., U Coronae Borealis (U CrB) and U Sagittae (U Sge)), which display changes in accretion structure from a disklike state to a streamlike state (Richards & Albright 1999). The photometry described in this paper provides system properties that are needed before a more detailed spectroscopic study of this binary can be accomplished. The current photometric study and proposed spectroscopic studies of this binary will provide us with additional clues regarding the evolutionary changes during the first phase of Roche lobe overflow (RLOF).

In this work, we report new *BVI* photometric observations of Y Psc (Section 2) that extend its baseline of photometry to 45 years; used the PHOEBE code to model the light curve to solve for system parameters (Section 3); and examined the variability of the ephemeris for primary minimum (Section 4). The results are discussed in Section 5.

2. OBSERVATIONS

New CCD photometric observations of Y Psc in *BVI* bands were collected at the Kutztown University Observatory (KUO). A total of 7849 data images were taken over 18 different nights between 2011 October 5 and 2012 January 15. The 0.46 m modified Cassegrain optical telescope (Tinsley Instruments, 1968) at KUO is equipped with a thermoelectric- and water-cooled CCD camera with 3072 × 2048 (9 μm) pixels and an internal filter wheel.

The exposure times for *B*, *V*, and *I* were 15 s, 8 s, and 6.5 s, respectively, and the CCD chip was cooled to −15°C. The comparison stars were 2MASSJ23340965+0758310, 2MASSJ23340773+0749362, and GSC0116900413. The typical error in the resulting apparent magnitudes ranged from 0.003 to 0.005 mag. Orbital phase values were obtained using the following ephemeris:

$$\mathrm{HJD}_{\mathrm{PrMin}} = 2455870.5851 + 3.765767 \times E.$$

The observed *B*-, *V*-, and *I*-band light curves are shown in Figure 1. There are clear variations following secondary eclipse, similar to those observed by Walter (1973a). In fact, the *B* light curve shows a post-secondary dip that appears to be deeper than the secondary eclipse itself. Also of note is the depth of the secondary eclipse in the *I* light curve, illustrating the importance of the *I* band in providing much needed information about the

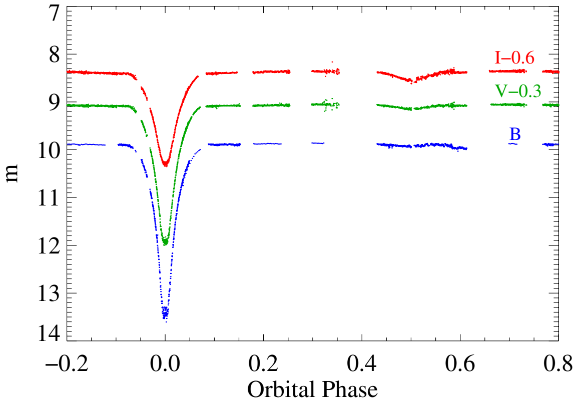

Figure 1. Observed *BVI* light curves of Y Psc.

(A color version of this figure is available in the online journal.)

Table 1
The Light Curve Parameters, as Determined Using PHOEBE

	System	
Parameter	Primary	Secondary
Orbital period	$3^{\mathrm{d}}\!.765767$*	
Inclination	$87^{\circ}\!.8$ (±1.0)	
Mass ratio	0.264 (±0.069)	
Surface temp.	7880 (±420) K	4200* K
Radius (back)	0.200 (±0.015)	0.295 (±0.022)
Radius (side)	0.199 (±0.015)	0.262 (±0.036)
Radius (pole)	0.198 (±0.017)	0.252 (±0.015)
Surface potential (Ω)	5.298 (±0.270)	2.385 (±0.153)

Note. Those marked with * are assumed values.

secondary eclipse. This increased depth reflects the increased contribution of the secondary to the total light of the binary in the *I* band.

3. PHOTOMETRIC MODEL

We computed an orbital solution using the PHOEBE program (Prša & Zwitter 2005), which is based on the Wilson–Devinney code (Wilson & Devinney 1971). During the total primary eclipse, the color index ($B - V$) was observed to be 1.2, which indicates a surface temperature of 4200 K for the secondary star. So, we fixed the temperature of the secondary star and allowed PHOEBE to fit the primary's temperature, which was found to be 7880 K (±420). A summary of the other orbital parameters can be found in Table 1. The *BVI* light curves are replotted in Figure 2, in terms of relative flux, along with the synthetic model obtained from PHOEBE.

The PHOEBE analysis showed that the binary has an orbital period of about 3.77 days, with a mass ratio of 0.264 (±0.069) and an orbital inclination of $87^{\circ}\!.8$ (±1.0). As a result, the eclipse is (just) total, as shown with the line-of-sight view of the system at phase 0.5 (Figure 3). The configuration of the PHOEBE model is that of a semi-detached system with the secondary star filling its Roche lobe, which is also shown in Figure 3.

Based on the shape of the light curve and the combination of previously reported spectral types (A3+K0), Y Psc is a classical Algol-type binary. However, since our model requires the primary star's surface temperature to be 7880 K, which is somewhat cooler than that of an A3 spectral class (as determined by Struve 1946), the primary might actually be a much later A-type star. Our mass ratio of $q = 0.264$, combined with Struve's spectroscopically derived mass function of $f(m) = 0.019$, yields masses of $M_{\mathrm{primary}} = 1.65\,M_{\odot}$ and $M_{\mathrm{secondary}} = 0.44\,M_{\odot}$. In this case, the mass of the primary also coincides with that of a late A-type main-sequence star. If we apply the Mezzetti et al. (1980) reformulated mass function of $f(m) = 0.028$, the masses of Y Psc's components would be $M_{\mathrm{primary}} = 2.44\,M_{\odot}$ and $M_{\mathrm{secondary}} = 0.64\,M_{\odot}$, and the primary's mass would seem to be more like that of a much earlier, hotter main-sequence star and is not consistent with our photometric model.

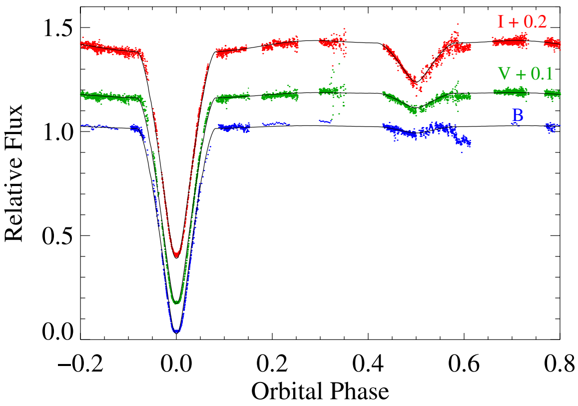

Figure 2. *BVI* light curves of Y Psc in terms of relative flux. The solid lines represent the synthetic models based on the PHOEBE code.

(A color version of this figure is available in the online journal.)

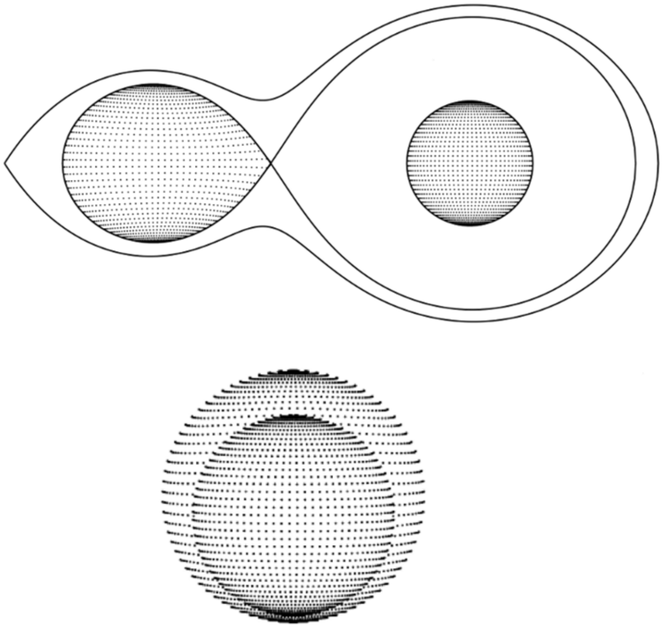

Figure 3. Top: an overhead view of Y Psc showing the geometry of the PHOEBE model, including two equipotential surfaces. The inner surface is the critical Roche lobe containing the first Lagrange point. The secondary star fills its Roche lobe. Bottom: the modeled line-of-sight view of Y Psc during secondary eclipse (at phase 0.5). These images were created using Binary Maker 3 (Bradstreet & Steelman 2002) with our PHOEBE parameters.

The dips in the light curve just past secondary eclipse are interesting and probably real, especially since the dip is deeper in *B* than in *V* and *I*, similar to the variations noted by Walter (1973a) in his early light curves. Since Algol-type binaries are interacting binaries, then this unusual dip may be caused by the gas stream itself or a cooler accretion structure passing in front of the primary star. A similar effect was seen in the ultraviolet light curve of R Arae (Reed et al. 2010), which is an Algol-type system with an orbital period of 4.4 days.

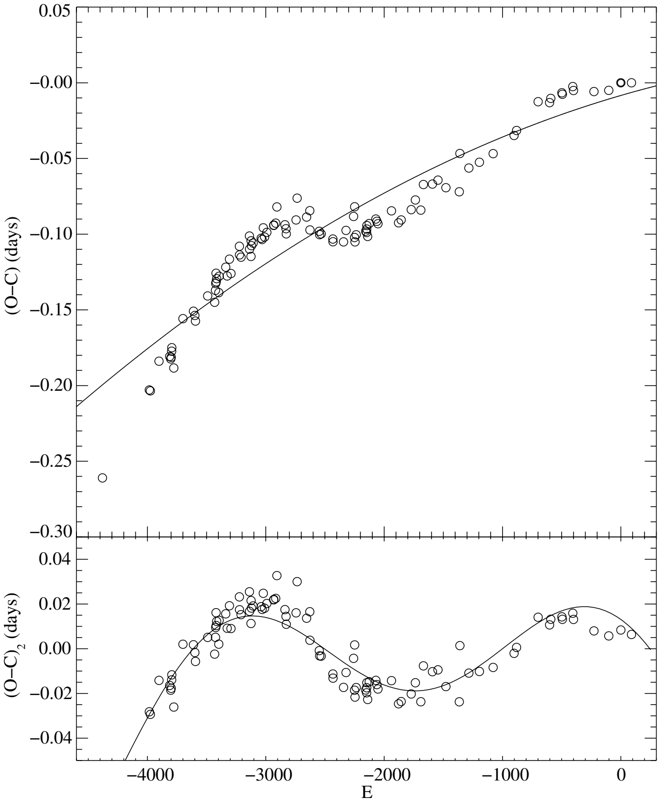

Figure 4. Top: the ephemeris curve for Y Psc. The solid line is the best-fit quadratic curve. Bottom: the residuals of the quadratic fit. The solid line represents the best-fit form of Equation (1).

4. EPHEMERIS ANALYSIS

In addition to the times of minimum light considered by Qian (2000), we have added an additional 12 years of more recent data to our ephemeris curve (Figure 4), which spans over 45 years. These additional observations are listed in Table 2. Four new times of minimum light were determined during this study; the data for two of which (2008 July 29 and 2009 November 12) were retrieved from the archives of the American Association of Variable Star Observers (AAVSO). The eclipse on 2010 December 1 was observed using the remote-controlled 0.41 m telescope at the Tzec Maun Observatory, located near Cloudcroft, NM, and the latest eclipse of 2011 November 5 was observed at KUO. The light curves for all four of the new eclipses are plotted in Figure 5.

We used the ephemeris of $\mathrm{HJD}_{\mathrm{PrMin}} = 2455531.6692 + 3.765767 \times E$ when calculating times of minimum light. The solid line in the upper plot of Figure 4 is the best-fit quadratic function of the following form $(O - C) = (-8.38 \times 10^{-3}) + (2.27 \times 10^{-5})E - (4.78 \times 10^{-9})E^2$, which corresponds to a rate of orbital period change of $\dot{P} = -9.28 \times 10^{-7}\ \mathrm{s\,yr}^{-1}$.

The parameters of a quadratic ephemeris could normally be used to determine a (conservative) rate of mass transfer presenting itself as a steady period change, but for this Algol-type system, it cannot be the case. Since the more evolved and less massive secondary star is presumably donating material to the more massive but less evolved primary, the period should be increasing rather than decreasing. The observed ephemeris curve is indicative of some other non-conservative orbital angular momentum loss.

Table 2
Recent Observed Times of Primary Minimum of Y Psc

Observed Time of Pr. Min. HJD − 2400000	Date	Epoch	Observer/Reference
51468.3976	1999 Oct 16	−1079	Agerer et al. (2001)
52134.9441	2001 Aug 13	−902	Nelson (2002)
52214.0278	2001 Oct 31	−881	Nagai (2002)
52899.4100	2003 Sep 16	−699	Diethelm (2004)
53264.6854	2004 Sep 16	−602	Ogloza et al. (2008)
53302.3456	2004 Oct 23	−592	Diethelm (2005)
53656.3281	2005 Oct 12	−498	Zejda et al. (2006)
53671.3900	2005 Oct 27	−494	Zejda et al. (2006)
54002.7795	2006 Sep 24	−406	Ogloza et al. (2008)
54025.3713	2006 Oct 16	−400	Hübscher & Walter (2007)
54676.8422	2008 Jul 29	−227	AAVSO*
55147.5595	2009 Nov 12	−102	AAVSO*
55531.6692	2010 Dec 1	0	Reed (this paper)*
55870.5851	2011 Nov 5	90	Yuhas (this paper)*

Note. The times marked with * were determined in this study.

The bottom panel of Figure 4 plots the residuals of the ephemeris curve after subtracting the quadratic fit. The period variations appear to be somewhat cyclic, with a cycle lasting approximately 27.8 years. In order to determine whether or not the cyclic variation is due to the light travel time effect (LTTE) of an orbit about an unseen third object, we followed the procedure presented by Kopal (1978) and Borkovits & Hegedüs (1996). This requires fitting a function of the following form to the $(O - C)$ residuals:

$$O - C(E) = \frac{a_0}{2} + \sum_{k=1}^{2} [a_k \sin(2\pi k E/P') + b_k \cos(2\pi k E/P')]. \tag{1}$$

The third-body orbital parameters are calculated from the Fourier coefficients as follows:

$$e' = 2\sqrt{\frac{a_2^2 + b_2^2}{a_1^2 + b_1^2}}, \tag{2}$$

$$a' \sin i' = c\sqrt{a_1^2 + b_1^2}, \tag{3}$$

and

$$f(m_3) = \frac{4\pi^2 a'^3 \sin^3 i}{G P'^2}, \tag{4}$$

where e' is the orbital eccentricity, c is the speed of light, $f(m_3)$ is the mass function, G is the gravitational constant, and P' is the orbital period of the third body's orbit.

The best-fit form of Equation (1) is plotted in the bottom of Figure 4. The coefficients of this function yield an eccentricity of $e' = 1.47$ and a mass function of $f(m_3) = 1.88 \times 10^{-7}\ M_\odot$. The mass of a third body would range from 0.012 $M_\odot$ (for $i' = 90°$) to 0.035 $M_\odot$ (for $i' = 20°$), depending on the inclination of the orbit. It is clear that the presence of a third body cannot account for the fluctuations in the $(O - C)$ curve via LTTE, primarily because the eccentricity implies an open orbit. Again, these period variations are probably resulting from some other mechanisms that will be suggested in the next section.

5. DISCUSSION

This *BVI* photometric study clearly puts Y Psc at an interacting stage in its life as the secondary star in this close binary

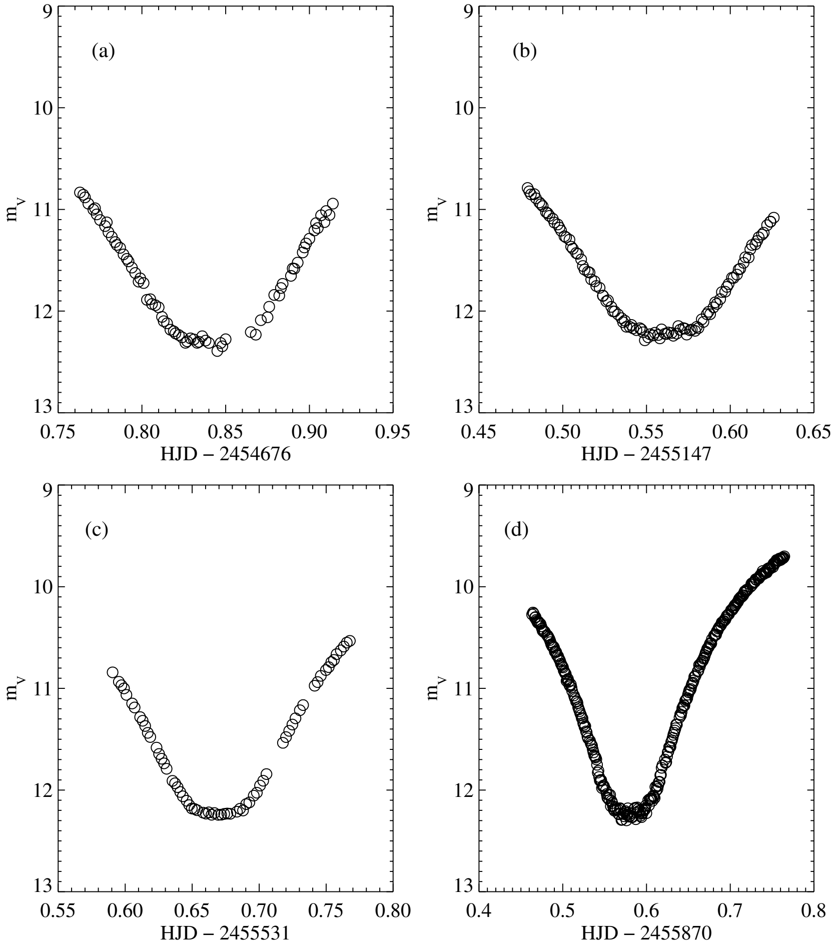

Figure 5. Light curves showing the new times of primary eclipse. The data for (a) and (b) were collected from the AAVSO archive. The data for (c) were collected using the Tzec Maun Observatory and those for (d) were obtained at the Kutztown University Observatory.

system is undergoing RLOF. We also provide evidence that its spectral classification is later than A3, although a new spectroscopic analysis is needed to provide an accurate spectral type. The observed variations in its light curve and ephemeris curve make Y Psc an important system for studying non-conservative mass transfer and other processes that affect the evolution of close binaries.

The roughly cyclic nature of Y Psc's period variations might be explained through an Applegate mechanism (Applegate 1992). If the secondary star is convective and generates magnetic fields of sufficient strength, we might be seeing the effects of a 28 yr magnetic activity cycle on the angular momentum of the system. Having a spectral classification of K0, the secondary star in Y Psc is certainly capable of being convective and producing suitable magnetic fields. Applegate (1992) states that magnetic activity may influence the orbital angular momentum of a binary system if the orbital period modulations are of amplitude $\Delta P/P \sim 10^{-5}$ over timescales of decades or longer. The period modulations we observe for Y Psc have an amplitude of $\Delta P/P = 2\pi(O - C/P_{\rm mod}) = 2.57 \times 10^{-5}$ and appear to be cyclic but not strictly periodic (as was shown in the third-body analysis of Section 4). In addition, Y Psc is similar to many of the Algols studied by Zavala et al. (2002), which undergo similar $O - C$ fluctuations that cannot be explained by LTTE and contain convective secondary stars.

The other peculiarity with Y Psc's $O - C$ curve is the overall negative quadratic form that indicates a significant rate of period decrease. Again, this cannot be due to conservative mass transfer because that would cause the orbital period to increase. There seems to be a loss of orbital angular momentum, which might be explained by the interaction of the mass transfer stream with the primary star. Y Psc's orbital period of 3.77 days is not long enough for the mass transfer stream to miss the primary and form a stable accretion disk; instead direct impact of the stream onto the primary star is expected. The mass transfer stream is likely striking the primary star at an angle, allowing it to spin-up the accretor. Evidence that this is taking place can be found in Struve's original RV plot (Figure 6). Recall that Struve noted an (spurious) orbital eccentricity, as can easily be seen in his RV plot. A spun-up primary star would cause the observed RVs to appear exaggerated just before and after primary eclipse. If it is the case that the mass transfer stream is interacting in such a way with the primary star, this could be a mechanism transferring orbital angular momentum of the system into spin angular momentum of the primary star.

Tidal interactions would work to slow a spun-up primary star back down to a synchronous rate and would transfer angular momentum back to the system's orbit. Therefore, a combined effect of mass transfer interactions and tidal interactions might also contribute to the cyclic nature of the $O - C$ variations. While it is true that a combination of effects due to magnetic activity (Applegate mechanism, magnetic braking, etc.) alone could produce the observed $O - C$ variability, they would not account for the distorted RV plot.

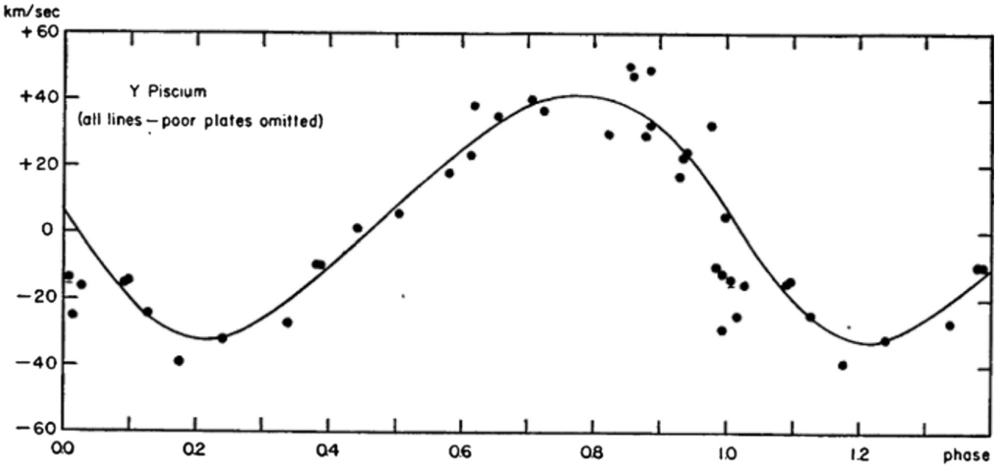

Figure 6. Radial velocity curve of Y Psc, as observed by Struve (1946). This is reprinted from Struve, O. (1946, ApJ, 104, 253, Figure 15). The solid line is Struve's model, which requires an orbital eccentricity of $e = 0.12$. Of course, this close binary actually has a circular orbit, so the apparently distorted RV curve is due to some other mechanism such as a spun-up primary star and/or surrounding accretion disk.

It is worth noting that if the mass transfer interaction is indeed spinning the primary star to a super-synchronous state, an interesting result is that the system's dynamics will deviate from the basic Roche model assumption that the spin and orbital motions of the stars are synchronized (e.g., Szebehely 1967). As the primary (which is also the accretor) spins up, its effective critical equipotential surface will contract (e.g., Avni & Schiller 1982) and could affect the rate of accretion and cause mass loss from the system. Whether magnetic fields, interaction-induced angular momentum transfer, or a combination thereof are causing the variations, the processes at work surely influence the conditions for variability in the accretion states of the binary.

Y Psc has been severely neglected spectroscopically. A much needed high-resolution spectroscopic study would provide answers to many of the questions still surrounding this interesting system. Such a study would detect non-orbital motions due to mass transfer streams, rotational broadening due to a spun-up accretor, and P Cygni features caused by a mass-loss wind. It would also help to verify the true spectral classification of the primary star. Doppler tomography would be ideal for observing the state, and any changes therein, of Y Psc's accretion structure, as has been done for U Coronae Borealis (Albright & Richards 1996; Agafonov et al. 2009), U Sagittae (Albright & Richards 1996), and TT Hydrae (Albright & Richards 1996; Miller et al. 2007).

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