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INFRARED SPECTROSCOPY OF SYMBIOTIC STARS. V. FIRST ORBITS FOR THREE S-TYPE SYSTEMS: HENIZE 2-173, CL SCORPII, AND AS 270

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ABSTRACT

Infrared radial velocities have been used to compute first orbits of the M giants in three southern S-type symbiotic systems. Of the three, Hen 2-173 has the longest orbital period, 911 days, and also has a noncircular orbit with an eccentricity of 0.21. The large value of its mass function suggests that Hen 2-173 may be an eclipsing system. For CL Sco our spectroscopic orbital period of 626 days is essentially identical to the previously determined light variability period of 625 days, and we have adopted the latter. AS 270 has an orbital period of similar length, 671 days, and both CL Sco and AS 270 have circular orbits. Only CL Sco has been extensively investigated previously, and we compare our results with the conclusions of Kenyon & Webbink. We also have examined the period-eccentricity relation for 30 S-type symbiotics. Circular orbits are found for 81% of the systems with orbital periods up to 800 days, while they occur for only 22% with periods greater than 800 days. This distribution is quite unlike that for G and K giants; rather, it is similar to that for barium stars, another type of mass-transfer binary, which also consists of a late-type giant and a white dwarf companion.

Key words: binaries: symbiotic — infrared: stars — stars: individual (AS 270, CL Scorpii, Henize 2-173) — stars: late-type

1. INTRODUCTION

Berman (1932) and Hogg (1934) suggested that the peculiar combination spectra of the stars now given the appellation "symbiotics" could be explained by a binary star. After decades of uncertainty, visual and ultraviolet spectroscopy finally showed conclusively that symbiotic stars are mass-transfer binaries, consisting of a cool giant and a hot star (Kenyon & Webbink 1984; Garcia 1986; Mürset et al. 1991). Usually, the companion of the giant appears to be a compact object, either a white dwarf or, at least in one case (Hinkle et al. 2006), a neutron star, but in a few systems it may be a low-mass, main-sequence star. From their characteristics at infrared wavelengths Webster & Allen (1975) separated the symbiotics into two subclasses, D for dusty-type and S for stellar-type systems. The S-type symbiotics have typical orbital periods of 2–3 yr, while those of the D-type systems are at least an order of magnitude longer (Schmid & Schild 2002). Fekel et al. (2000b) and Mikolajewska (2003) provide a detailed introduction to the orbital analysis for this group of stars.

Orbital elements are a major starting point for understanding symbiotic systems. Unfortunately, the veiling and emission-line complexity of their blue spectra and the long orbital periods, which result in low velocity amplitudes, make well-determined orbital elements difficult to obtain. Of the nearly 200 symbiotic systems listed in the recent catalog of Belczyński et al. (2000), less than 30 have had orbital elements determined for the cool giant component (Mikolajewska 2003). In previous papers in this series (Fekel et al. 2000a, 2000b, 2001; Hinkle et al. 2006), we have determined the orbital elements of the late-type component in 15 systems, 4 of which are first orbits. In this paper we present first orbits for the M giants in three more S-type symbiotics, Hen 2-173, CL Sco, and AS 270. Of the three systems only CL Sco has been extensively investigated (Kenyon & Webbink 1984). Basic information on the three program stars is provided in Table 1.

2. OBSERVATIONS AND REDUCTIONS

From 2001 March to 2006 June we obtained 18 spectroscopic observations of Hen 2-173. The first eight were acquired with the 1.88 m telescope and coudé spectrograph system at the Mount Stromlo Observatory (MSO), Canberra, Australia. The detector was an infrared camera, NICMASS, developed at the University of Massachusetts. We obtained a 2 pixel resolving power of 44,000 at a wavelength of 1.623 μm. A more complete description of the experimental setup may be found in Joyce et al. (1998), as well as in Fekel et al. (2000b). The detector and electronics were previously used for our survey of northern symbiotics, carried out with the coudé feed telescope at Kitt Peak National Observatory (KPNO).

The devastating bush fire of 2003 January destroyed both the 1.88 m telescope at MSO and our infrared NICMASS camera. On four dates between 2003 February and 2004 April we were

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TABLE 1
BASIC PROPERTIES OF PROGRAM STARS

Name	V^a (mag)	K (mag)	$H-K$ (mag)	Primary Spectral Class[b]	Orbital Period (days)	$\dot{M}^c$ ($M_\odot$ yr^{-1})
Hen 2-173	13.83	6.78[d]	0.32[c]	M4.5	911	...
CL Sco	13.25	7.86[a]	0.28[a]	M5	625	1.1×10^{-7}
AS 270	13.71	5.65[a]	0.42[a]	M5.5	671	2.7×10^{-8}

[a] Munari et al. (1992).
[b] Mürset & Schmid (1999).
[c] Seaquist et al. (1993).
[d] Allen & Glass (1974).

able to continue observations using the Phoenix cryogenic echelle spectrograph, mounted on the 8 m Gemini South telescope at Cerro Pachon, Chile. A complete description of the spectrograph can be found in Hinkle et al. (1998). Two Gemini South observations that were centered at 2.223 μm, a region containing several atomic lines, have a resolving power of $\sim$70,000. The wavelength and resolution were selected to allow detailed analysis of line profiles. The other two spectrograms were centered at either 1.563 or 2.223 μm and have a lower resolving power of $\sim$50,000. These data were taken for a separate program on symbiotic abundances, as well as the current radial velocity work.

The six most recent observations were acquired from 2004 May to 2006 June at KPNO with the 0.9 m coudé feed telescope, coudé spectrograph, and a CCD, designated LB1A. This 1980 $\times$ 800 pixel CCD was manufactured by Lawrence Berkeley National Laboratory and is 300 μm thick. Although this thickness results in increased pixel contamination by cosmic-ray and background radiation events, the chip was used because of its high quantum efficiency at far-red wavelengths. Our spectrograms, centered near 1.005 μm, have a wavelength range of 420 Å and a resolving power of $\sim$21,500.

The observing histories for CL Sco and AS 270 are similar to that of Hen 2-173. Over a 5 yr period we acquired 15 spectroscopic observations of CL Sco. From 2001 March through 2002 June we obtained six spectrograms at MSO with the same telescope, spectrograph, and infrared camera that were used for Hen 2-173. After the loss of the MSO facility and our NICMASS camera, from 2003 February through 2004 April we made four observations with the 8 m Gemini South telescope and the Phoenix spectrograph. We completed our observations at KPNO with six more spectrograms, obtained from 2004 May to 2006 June. For those observations we used the coudé feed telescope, coudé spectrograph, and LB1A CCD detector.

From 2000 July to 2006 June we acquired 19 spectrograms of AS 270 with several telescope and detector combinations. The two initial observations were made at KPNO in 2000. The first was obtained with the 2.1 m telescope and Phoenix spectrograph, while the second was acquired with the coudé feed telescope, coudé spectrograph, and NICMASS detector. From 2001 March through 2002 August we obtained nine spectrograms at MSO with the same telescope, spectrograph, and infrared detector that were used for Hen 2-173 and CL Sco. Following the destruction of the MSO facility and our detector, we obtained two spectrograms between 2003 February and 2004 April with the Gemini South telescope and Phoenix spectrograph. Our final six observations cover the period 2004 May through 2006 June. Similar to those for Hen 2-173 and CL Sco, they were acquired with the KPNO coudé feed telescope, coudé spectrograph, and LB1A CCD.

Standard observing and reduction techniques were used (Joyce 1992). Wavelength calibration at the infrared wavelengths of 1.563 and 2.223 μm posed a challenge, because the spectral coverage was far too small to include a sufficient number of ThAr emission lines for a dispersion solution. Our approach was to use absorption lines in a K III star to obtain a dispersion solution. Several sets of lines were tried, including CO, Fe I, and Ti I. These groups all gave consistent results. For the spectrograms acquired with the LB1A CCD at 1.005 μm, we were able to used ThAr spectra for wavelength calibration. Telluric lines are present in the 1.005 and 2.223 μm wavelength regions. These lines were removed from our observations by ratioing the spectra to a hot star spectrum observed on the same night.

Representative spectra of the three program stars at wavelengths of 1.005, 1.563, and 2.223 μm are shown in Figures 1, 2, and 3, respectively. All three regions are dominated by absorption

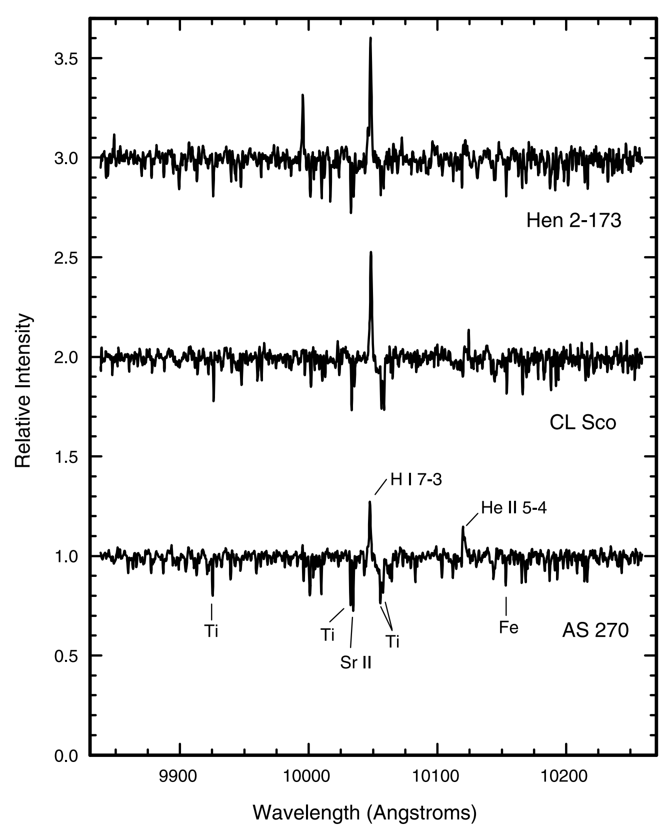

FIG. 1.—Spectra of the three program stars at 1.005 μm observed with the KPNO coudé feed telescope, spectrograph, and LB1A CCD. The relative intensity scales for CL Sco and Hen 2-173 have been offset by 1.0 and 2.0, respectively. A few of the stronger representative absorption and emission lines are identified. The entire observed spectral region is shown. The telluric spectrum has been ratioed out by referencing a hot star spectrum acquired on the same night.

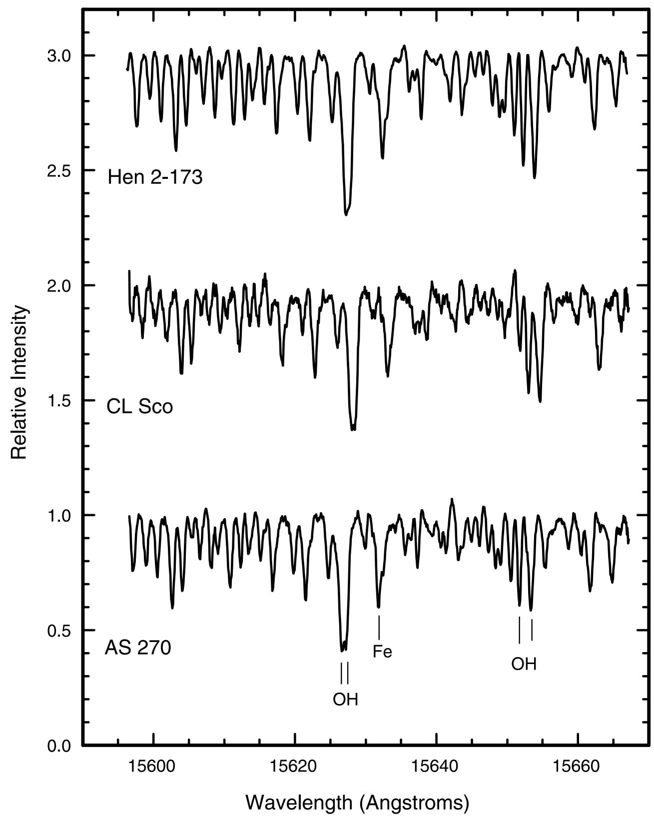

FIG. 2.—Spectra of the three program stars at 1.563 μm observed with Gemini South and the Phoenix spectrograph. The relative intensity scales have been offset as in Fig. 1. This spectral region is not contaminated by telluric lines.

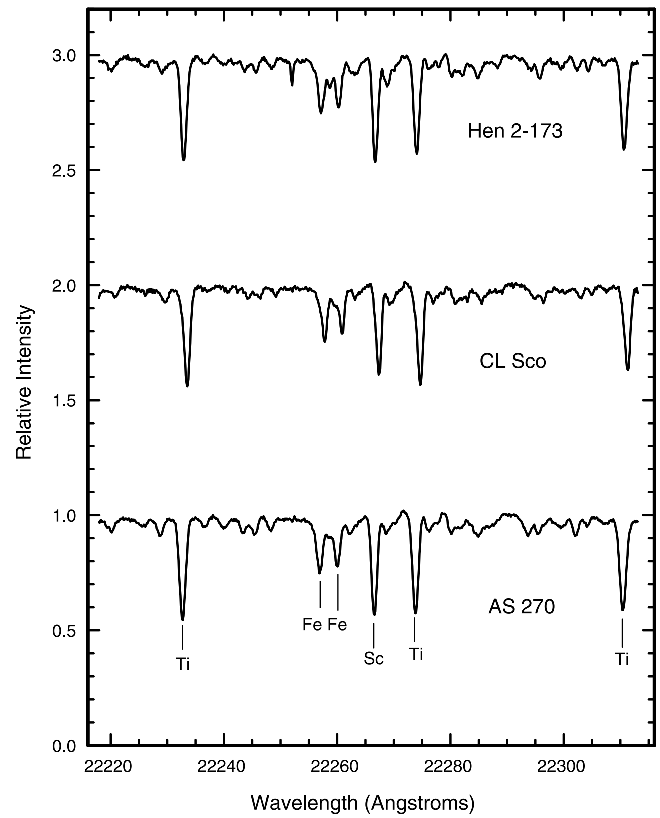

FIG. 3.—Spectra of the three program stars at 2.223 μm observed with Gemini South and the Phoenix spectrograph. The relative intensity scales have been offset as in Fig. 1. The telluric spectrum has been ratioed out by referencing a hot star spectrum acquired on the same night.

lines arising in the photosphere of the red giant. The 1.005 μm region has a number of neutral atomic lines present, especially from Ti and Fe. There are also many weak to moderate-strength lines from bands of the $\Delta v = -1$ CN red system. Unlike the two spectral regions farther to the red, the one centered on 1.005 μm also contains some emission features associated with the symbiotic mass transfer. The 1.563 μm region is dominated by OH first-overtone lines and a selection of neutral atomic lines and also has weak CN red-system $\Delta v = -1$ lines and CO vibration-rotation second-overtone lines. The 2.223 μm region contains moderately strong Ti I lines, as well as a few other neutral atomic lines, especially from Fe I and Sc I. The CN red-system $\Delta v = -2$ transition provides a background of weak lines.

Radial velocities of the program stars were determined with the IRAF cross-correlation program FXCOR (Fitzpatrick 1993). The vast majority of the velocities were determined relative to the M giant International Astronomical Union (IAU) velocity standard, δ Oph, which was obtained multiple times during the course of each night. Its radial velocity of -19.1 km s^{-1} was adopted from the work of Scarfe et al. (1990). For one or two spectra of Hen 2-173, CL Sco, and AS 270, observations of δ Oph were unavailable, so the M giant HR 7900 was used as a velocity reference star. This secondary standard was observed on numerous nights, and we determined a velocity of -9.6 km s^{-1} for it relative to the IAU standard δ Oph. Spectrograms of all three program stars, obtained in the 1 μm region, show two or three emission lines (Fig. 1), which were excluded from the cross-correlation velocity analyses.

Orbital elements of the three systems were determined with various computer programs. First, a preliminary period was identified with a program named PGRAM (PeriodoGRAM). An extensive range of periods was searched by computing the phases of the observed velocities for each trial period and comparing those phased velocities to a sine curve fit. The sum of the squared velocity residuals from the sine curve fit was computed, and the period having the smallest value of that sum was adopted as the preliminary period. The period was used with BISP, a computer program that implements a slightly modified version of the Wilsing-Russell method (Wolfe et al. 1967), to determine initial orbital elements. A differential corrections program, called SB1, of Barker et al. (1967) was used to refine the eccentric orbits of the single-lined systems. For each system the orbital eccentricity is small enough that a circular-orbit solution may be appropriate. Such orbits were computed with SB1C (D. Barlow 1998, private communication), which also uses differential corrections to determine the orbital elements.

3. HEN 2-173 = WRAY 15-1518 = SS 73-61

3.1. *Short History*

Henize (1967) obtained objective-prism spectra of the sky south of declination $-25°$ to identify Hα emission-line objects. Examining the medium-exposure plates from that extensive survey, Henize (1967) published a catalog of planetary nebula, which included the object that became known as Hen 2-173. From the long-exposure plates of that same survey Wray (1966) also identified the same star as having Hα emission, and it received the designation Wray 15-1518. Sanduleak & Stephenson (1973) carried out another extensive objective-prism survey of the southern sky but with plates that covered a more extensive wavelength range, from 3300 to 6800 Å, than those of Henize (1967). With its appearance in their list (Sanduleak & Stephenson

TABLE 2
RADIAL VELOCITIES OF HEN 2-173

HJD 2,400,000 +	Phase	Velocity (km s^{-1})	$O - C$ (km s^{-1})	Observatory
51,995.157	0.267	−48.3	0.1	MSO
52,046.145	0.323	−49.7	0.8	MSO
52,095.129	0.377	−52.6	−0.1	MSO
52,132.069	0.417	−55.6	−1.6	MSO
52,353.232	0.660	−60.9	0.2	MSO
52,399.148	0.711	−63.0	−1.2	MSO
52,445.005	0.761	−61.9	0.1	MSO
52,503.936	0.826	−61.0	0.1	MSO
52,686.900	0.027	−47.4	1.1	Gemini S
52,749.751	0.096	−46.6	−1.0	Gemini S
52,866.502	0.224	−45.6	1.4	Gemini S
53,098.705	0.479	−55.2	1.0	Gemini S
53,129.851	0.513	−56.0	1.3	KPNO
53,178.730	0.567	−58.5	0.4	KPNO
53,493.880	0.913	−56.1	1.0	KPNO
53,537.782	0.961	−54.7	−1.3	KPNO
53,861.852	0.317	−51.0	−0.7	KPNO
53,899.766	0.359	−53.2	−1.4	KPNO

1973) the star also became known as SS 73-61. Because they were unable to find any definite emission features in the blue-green region of its spectrum, Sanduleak & Stephenson (1973) placed the star in a group of objects of unknown nature. However, they noted that since that group of objects was concentrated toward the Galactic center, most were likely highly reddened Be or symbiotic stars. Allen (1973) observed nearly 250 early-type emission-line stars at infrared wavelengths and concluded that the continuum of Hen 2-173 at such wavelengths resembled the continuum of a late-type star. In a follow-up photometric paper, Allen & Glass (1974) listed Hen 2-173 in a group of objects that were likely symbiotic stars. Allen (1984) presented a low-dispersion slit spectrum that showed weak TiO bands and a variety of weak and strong emission features, confirming Hen 2-173 as a symbiotic star. From red or near-infrared absorption features Mendina Tanco & Steiner (1995) classified Hen 2-173 as M7, while Mikolajewska et al. (1997) found M3, and Mürset & Schmid (1999) adopted a classification of M4.5. The system was included in the symbiotic star catalog of Allen (1984), as well as the more recent catalog of Belczyński et al. (2000).

3.2. *Orbital Elements*

Our 18 radial velocities of Hen 2-173 (Table 2) cover 2.1 orbital cycles. An analysis of the velocities with PGRAM resulted in a preliminary period of 917 days. Adopting this value and assigning a unit weight to each velocity, we obtained preliminary orbital elements with BISP that were refined with SB1. Because of the relatively low orbital eccentricity of 0.21 ± 0.05, we used SB1C to determine a circular-orbit solution. However, the tests of Lucy & Sweeney (1971) indicated that the eccentric solution is to be preferred, so it is given in Table 3. The standard error of an individual velocity is 1.2 km s^{-1}. Orbital phases for the observations and velocity residuals to the final solution are given in Table 2. In Figure 4 the velocities and computed velocity curve are compared, and zero phase is a time of periastron passage.

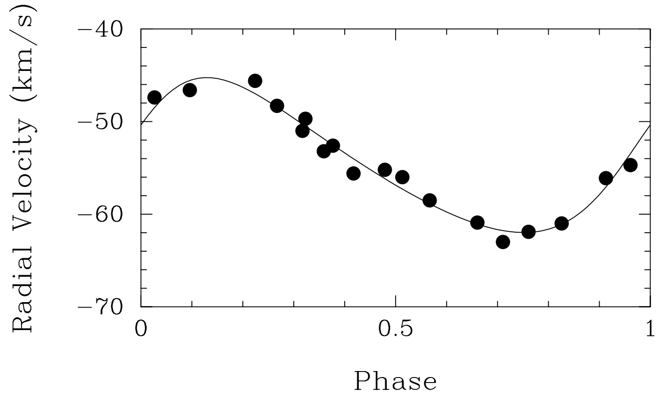

FIG. 4.—Radial velocities of Hen 2-173 (*filled circles*) compared with the computed orbital fit (*solid line*). Zero phase is a time of periastron passage.

3.3. *Discussion*

Hen 2-173 has been part of several photometric and spectrophotometric surveys. Allen & Glass (1974) provided *JHK* photometric magnitudes, while Munari et al. (1992) determined $UBVR_CI_C$ magnitudes. As noted in § 3.1 several groups have determined the spectral class of the late-type component, which has ranged from M3 to M7. Mürset & Schmid (1999) presented the most comprehensive list of spectral classes, deriving results for about 100 systems and including classifications of an additional 70 or so symbiotics from the literature. The low-resolution spectra of Mürset & Schmid (1999) covered the near-infrared region, where the spectrum of the late-type giant is less affected by veiling than in the visual region. They stated an uncertainty of one spectral subclass for their results, so we have adopted their classification of M4.5 (Table 1). From a low-resolution spectrogram Mikolajewska et al. (1997) provided a limited analysis of Hen 2-173. They estimated a system distance of 2.8 kpc and a hot component temperature between 54,000 and 100,000 K, plus a luminosity of 700 $L_\odot$.

TABLE 3
ORBITAL ELEMENTS AND RELATED PARAMETERS OF HEN 2-173

Parameter	Value
P (days)	910.6 ± 10.6
T (HJD)	2,452,662.5 ± 36.2
γ (km s^{-1})	−54.29 ± 0.30
K (km s^{-1})	8.36 ± 0.48
e	0.210 ± 0.051
ω (deg)	292.9 ± 14.8
$a \sin i$ (10^6 km)	102.4 ± 6.1
$f(m)$ ($M_\odot$)	0.0517 ± 0.0091
Standard error of an observation of unit weight (km s^{-1})	1.2

Based on the theoretical work of Zahn (1977), Schmutz et al. (1994) and Mürset et al. (2000) have argued that in most S-type symbiotics the giant star is synchronously rotating. They then derived the radius of the giant in various symbiotic binaries. However, the orbit of Hen 2-173 is not circular but has a modest eccentricity of 0.21. Thus, the rotational angular velocity of the M giant will tend to synchronize with that of the orbital motion at periastron, a condition called ‘‘pseudosynchronous rotation’’ (Hut 1981). With equation (42) of Hut (1981) we calculated a pseudosynchronous period of 719 days.

If, as suggested by theory, the M giant is pseudosynchronously rotating, its projected rotational velocity can be used to estimate its minimum radius. To determine the $v \sin i$ of the M giant, we measured the full width at half-maximum of a few atomic features observed on the Phoenix 2.223 μm spectra. We also measured the same lines in several late-type giants with known $v \sin i$ values. With the latter set of stars, we produced an empirical broadening calibration similar to that of Fekel (1997). Using the calibration and an adopted macroturbulence of 3 km s^{-1}, we determined $v \sin i = 8 \pm 1$ km s^{-1} from two observations. The pseudosynchronous period and the $v \sin i$ value result in a *minimum* radius (i.e., $\sin 90^\circ = 1$) of 114 ± 14 $R_\odot$. If, as is generally assumed, the orbital inclinations of binaries are randomly oriented in space, then half of the inclinations are greater than 60° and half are less than this value (Russell et al. 1938, p. 701). In addition, if, as expected, the orbital and rotational axes of the binaries are parallel, then the same distribution of inclinations holds for the rotational inclinations. Reducing the rotational inclination from 90°, an angle making the rotational axis perpendicular to the viewing direction, to 60° increases the radius to 132 $R_\odot$.

The effective Roche lobe radius of the giant depends on the separation of the stars and their mass ratio. We adopted typical masses of 1.5 and 0.5 $M_\odot$ (Mikolajewska 2003) for the M giant and its companion, respectively. We then used Kepler's third law to determine the semimajor axis of the orbit. However, since the distance between the two components varies in an eccentric orbit, we adopted the smaller periastron separation rather than the semimajor axis. With equation (2) of Eggleton (1983) we estimated a Roche lobe radius of 187 $R_\odot$ for the M giant. A rotational inclination of about 38° is needed for the radius to fill such a Roche lobe. Of course, the Roche lobe radius will be larger when the distance between the components is greater than the periastron separation.

For a single-lined orbit a quantity known as the ‘‘mass function,’’ which is computed from the orbital elements, relates the primary and secondary masses and the orbital inclination (Batten et al. 1989). The mass function for the orbit of Hen 2-173 has a value of 0.052 $M_\odot$ (Table 3), which is rather large for a symbiotic binary. However, the symbiotic binary V1329 Cyg has a similar mass function of 0.048 $M_\odot$ (Fekel et al. 2001), and that system is an eclipsing binary with an orbital inclination of 86° (Schild & Schmid 1997). This comparison suggests that the orbital inclination of Hen 2-173 is also close to 90°, so the system may be eclipsing. Thus, a search for such eclipses should be made.

From our orbital elements the ephemeris for conjunctions with the M III in front, which corresponds to times of mideclipse if the binary has a high enough inclination, is

$$T_{\rm conj}({\rm HJD}) = 2,452,625(\pm 36) + 911(\pm 11)E,$$

where E is an integer number of cycles.

4. CL SCO = HV 4035 = AS 213 = SS 73-69 = HEN 3-1286

4.1. *Short History*

Interest in CL Sco began when Luyten (1927) listed it as Harvard Variable 4035 and noted the unusual character of its light variation. It showed changes of up to 3 mag over a timescale of more than a decade. Swope (1941) measured the brightness of CL Sco on about 650 Harvard plates that covered 50 yr and displayed the light variations. Payne-Gaposchkin (1957, p. 217) included CL Sco in her discussion of symbiotic novae, noting that the light curve presented by Swope (1941) is similar to that of Z And. She also estimated a variability period of about 600 days. In their major work on the nature of symbiotic stars, Kenyon & Webbink (1984) determined a binary period of 625 days from an analysis of the well-observed optical light minima of CL Sco.

Spectroscopically, Elvey & Babcock (1943) obtained two observations of CL Sco that showed a continuous spectrum plus strong hydrogen emission features and at least two helium emission lines. On their objective-prism plates Merrill & Burwell (1950) found the star to have very strong Hα emission. As a result of the work of Elvey & Babcock (1943) and Merrill & Burwell (1950), Bidelman (1954) placed CL Sco in his list of stars with combination spectra, which included many symbiotic stars. CL Sco was also identified as an emission-line object in the southern-sky surveys of Sanduleak & Stephenson (1973) and Henize (1976). Sanduleak & Stephenson (1973) noted the presence of the He II line at 4686 Å and suspected TiO bands, which are indicative of a late-type star of M spectral class. They suggested that CL Sco was likely a symbiotic star. Following up on the results of Sanduleak & Stephenson (1973), Allen (1978) acquired a low-dispersion slit spectrum of CL Sco. He confirmed that it was a symbiotic star, noting its weak TiO absorption and lines of He I, He II, [O III], and [Ne III] in emission. Spectrophotometry at optical wavelengths was also carried out by Blair et al. (1983). Their spectrum clearly showed weak TiO bands and a red continuum, as well as an emission-line spectrum dominated by Balmer and He I lines. Blair et al. (1983) also noted that strong ultraviolet emission lines of C III], C IV, O III], and N III] were found in an *IUE* spectrum (Michalitsianos et al. 1982) obtained within a month of their optical observations. As a result of these various detections, Allen (1984) listed CL Sco in his catalog of symbiotic stars, in which he also presented a low-dispersion spectrum of it that showed emission lines similar to those found by Blair et al. (1983).

A moderate range of spectral classes has been found for CL Sco. Allen (1980) first classified it as K5 from a spectrum at 2 μm. Mendina Tanco & Steiner (1995) determined a spectral class of M2 from a visual comparison of its red wavelength region with standard star spectra, while Mürset & Schmid (1999) estimated an even later class of M5, which we have adopted (Table 1), from an analysis of the strength of several near-infrared wavelength TiO band heads. Comparing synthetic-spectrum models with low-resolution *IUE* spectra, Kenyon & Webbink (1984) concluded that CL Sco also contains a low-mass, main-sequence star rather than a white dwarf companion. Additional information for CL Sco is summarized in the symbiotic star catalog of Belczyński et al. (2000).

4.2. *Orbital Elements*

From 2001 May to 2006 June we obtained 15 radial velocities of CL Sco (Table 4) that cover nearly three orbital cycles. An analysis of these velocities with PGRAM produced an initial

TABLE 4
Radial Velocities of CL Sco

HJD 2,400,000 +	Phase	Velocity (km s^{-1})	$O - C$ (km s^{-1})	Observatory
52,049.051	0.800	−35.6	0.2	MSO
52,099.952	0.881	−32.8	0.0	MSO
52,354.260	0.288	−38.4	1.1	MSO
52,401.066	0.363	−41.6	0.7	MSO
52,449.912	0.441	−43.1	1.2	MSO
52,687.835	0.821	−33.3	1.6	Gemini S
52,749.780	0.921	−30.7	1.1	Gemini S
52,866.538	0.108	−32.6	−0.1	Gemini S
53,098.784	0.479	−45.9	−1.2	Gemini S
53,130.897	0.531	−46.3	−1.7	KPNO
53,178.812	0.607	−41.5	1.7	KPNO
53,494.932	0.113	−34.8	−2.1	KPNO
53,539.826	0.185	−35.2	−0.0	KPNO
53,861.976	0.700	−41.0	−1.0	KPNO
53,900.817	0.763	−38.8	−1.5	KPNO

period of 627 days. Adopting this value and assigning a unit weight to each velocity, we obtained preliminary orbital elements with BISP that were refined with SB1. This latter solution had a rather low and uncertain orbital eccentricity of 0.09 ± 0.08. Thus, we used SB1C to determine a circular-orbit solution. The tests of Lucy & Sweeney (1971) indicated that the circular orbit is to be preferred. The period of this circular-orbit solution is 625.7 ± 7.3 days, which is just 1 day longer than the light variability period of 624.7 ± 1.5 days (Kenyon & Webbink 1984). Given the agreement of the two periods and the uncertainties in the two determinations, we adopted a period of 625 days for our final circular-orbit solution, which is listed in Table 5. As recommended by Batten et al. (1989), for circular orbits we have identified T_0 as a time of maximum velocity. The standard error of an individual velocity is 1.4 km s^{-1}. Orbital phases for the observations and velocity residuals to the final solution are given in Table 4. In Figure 5 the velocities and computed velocity curve are compared.

4.3. *Discussion*

Michalitsianos et al. (1982) obtained an ultraviolet spectrum of CL Sco with *IUE*. That spectrum showed no N v emission at 1239 and 1242 Å and only a very weak He ii emission feature at 1640 Å. Thus, they concluded that this symbiotic has a low-excitation nebular region.

Kenyon & Webbink (1984) have provided the most extensive analysis of the system to date. Their best fit to the *IUE* ultraviolet spectra of Michalitsianos et al. (1982) was with a main-sequence

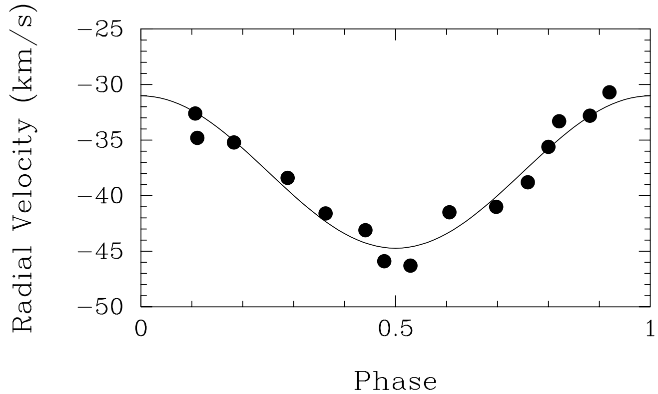

Fig. 5.—Radial velocities of CL Sco (*filled circles*) compared with the circular-orbit fit (*solid line*). Zero phase is a time of maximum velocity.

star. From well-observed optical minima they determined a light variability period (Kenyon & Webbink 1984) of 624.7 ± 1.5 days but did not show a phase diagram. They suggested that the radius of the late-type giant is about 140 $R_\odot$, assuming that it fills its Roche lobe. This led them to adopt a bright giant luminosity class for the late-type star and to estimate a distance of 8 kpc for the system, placing CL Sco in the Galactic bulge over 1 kpc above the Galactic plane. From these results, combined with a spectral class of K5 (Allen 1980), Kenyon & Webbink (1984) were led to conclude that CL Sco, similar to AG Dra and V443 Her, was a member of the halo stellar population. They noted that measuring the binary center-of-mass velocity would be important in determining the validity of their model.

In fact, Kenyon & Webbink (1984) favored a binary model consisting of a Roche lobe–filling M giant and a low-mass, main-sequence companion for 5 of the 16 symbiotics they examined, including CL Sco. More recently, Mürset & Schmid (1999) noted that the number of systems associated with this binary model has been decreasing as the result of new observations. For example, while Mikolajewska & Kenyon (1992) found that the outburst activity of CI Cyg and AX Per is best explained with a low-mass, main-sequence accretor, Mikolajewska (2003) stated that the quiescent characteristics of the two components place the stars in the same region of the H-R diagram as hot compact objects in other symbiotics.

Mürset & Schmid (1999) examined 30 symbiotic systems with known orbital periods. With estimated values of masses and radii, they determined that the radii of the late-type giants were much smaller than the corresponding distances to the inner Lagrangian points in the systems for all but one of the systems. Thus, they concluded that nearly all symbiotics are well-detached binary systems and argued against the main-sequence accretor model,

TABLE 5
Orbital Elements and Related Parameters of CL Sco

Parameter	Value
P (days)	625.0 (adopted)
T_0 (HJD)	2,452,174.2 ± 7.0
γ (km s^{-1})	−37.87 ± 0.35
K (km s^{-1})	6.86 ± 0.52
e	0.0 (adopted)
$a \sin i$ (10^6 km)	58.9 ± 4.4
$f(m)$ ($M_\odot$)	0.0209 ± 0.0047
Standard error of an observation of unit weight (km s^{-1})	1.4

which requires a very high mass transfer rate associated with a Roche lobe–filling radius to produce the high luminosity of the hot source.

With the same procedure that we used for Hen 2-173, from two spectra we determine $v \sin i = 7 \pm 1$ km s^{-1} for the M giant component of CL Sco. Following Schmutz et al. (1994) and Mürset et al. (2000), if we assume that the giant is synchronously rotating, the minimum radius of CL Sco is $87 \pm 12\ R_{\odot}$. Such a value is identical to the mean radius of five low-mass, M5 III stars with well-determined *Hipparcos* parallaxes that was determined from the data of Dumm & Schild (1998). If the rotational inclination of the M giant is reduced from 90° to 60°, the radius increases to 100 $R_{\odot}$.

The effective radius of the Roche lobe depends on the mass ratio and separation of the components. We adopted typical masses of 1.5 and 0.5 $M_{\odot}$ (Mikolajewska 2003) for the M giant and its companion, respectively, and used Kepler's third law to determine the semimajor axis of the orbit. Equation (2) of Eggleton (1983) then produced an effective Roche lobe radius of 184 $R_{\odot}$ for the M giant. Thus, if the giant is rotating synchronously, its rotational inclination must be reduced to about 28° for it to fill its Roche lobe.

The luminosity of the system that Kenyon & Webbink (1984) estimated resulted from an adopted spectral class of K5 and a radius that filled its Roche lobe. The revised M5 spectral class of Mürset & Schmid (1999) corresponds to an effective temperature of 3470 K (Dyck et al. 1996). Combined with a radius of 100 $R_{\odot}$ ($i = 60°$), we obtain a luminosity of 1300 $L_{\odot}$ for the M giant. Ignoring a contribution from the second star, this suggests a distance of perhaps 3000 pc, compared to the 8000 pc estimated by Kenyon & Webbink (1984). Such a decrease results in a distance of 420 pc above the Galactic plane, reducing the need to identify CL Sco as a halo population star. Also, the line strengths seen in our spectra of CL Sco (Figs. 1–3) appear quite similar to those of the other two program stars, which suggests that CL Sco is not metal-weak. Finally, our systemic radial velocity of -38 km s^{-1} does not provide strong support for halo population membership. Thus, a number of results and arguments suggest that the model that Kenyon & Webbink (1984) advocated for CL Sco, a Roche lobe–filling giant and a low-mass main-sequence star, is not correct.

Kenyon & Webbink (1984) found a light variability period for CL Sco and determined an ephemeris for minimum light,

$$T_{\rm min}({\rm JD}) = 2,427,020(\pm 21) + 624.7(\pm 1.5)E,$$

where E is an integer number of cycles. In addition to CL Sco Kenyon & Webbink (1984) noted periodic light variations in a number of other symbiotics. In many cases light minimum occurs at inferior conjunction, when the M giant is in front of the hot component. This suggests that the cause of this variability is the reflection effect (e.g., Formiggini & Leibowitz 1990). However, Skopal (2001) has argued that the light changes occur because nebular emission produces the phase-dependent variability. From the results in Table 5 our spectroscopic ephemeris for inferior conjunction is

$$T_{\rm conj}({\rm HJD}) = 2,452,018(\pm 7) + 625E.$$

The adopted period of 625 days results in 39.997 cycles between the recent conjunction epoch and the older minimum light epoch. This outstanding agreement convincingly supports a geometric cause for the light variations.

TABLE 6

Radial Velocities of AS 270

HJD 2,400,000 +	Phase	Velocity (km s^{-1})	$O-C$ (km s^{-1})	Observatory
51,738.752	0.907	−52.9	0.5	KPNO
51,832.580	0.047	−52.6	0.0	KPNO
51,993.263	0.286	−60.7	−0.4	MSO
52,047.209	0.367	−62.5	0.6	MSO
52,094.244	0.437	−66.3	−1.5	MSO
52,131.128	0.492	−66.1	−0.9	MSO
52,152.058	0.523	−65.6	−0.4	MSO
52,354.299	0.824	−55.9	0.0	MSO
52,400.271	0.893	−54.6	−0.9	MSO
52,448.177	0.964	−53.3	−0.8	MSO
52,504.019	0.047	−51.5	1.1	MSO
52,687.892	0.321	−61.1	0.5	Gemini S
53,098.870	0.934	−53.9	−1.0	Gemini S
53,129.950	0.980	−51.7	0.7	KPNO
53,179.882	0.054	−52.2	0.5	KPNO
53,494.977	0.524	−63.7	1.5	KPNO
53,537.892	0.588	−63.5	0.8	KPNO
53,859.957	0.068	−52.2	0.7	KPNO
53,901.831	0.130	−55.3	−0.9	KPNO

5. AS 270 = SS 73-126 = HEN 3-1581

5.1. *Short History*

Merrill & Burwell (1950) listed this star as one of 519 additional stars with Hα in emission that was found on Mount Wilson objective-prism plates, so it became known as AS 270. In the notes to their Table 1, they reported that R. Minkowski had found the star to have TiO absorption bands, indicative of an M spectral class, as well as strong hydrogen emission lines. This led Bidelman (1954) to place it in a list of stars with combination spectra, which included many symbiotic stars. Later, AS 270 was detected in the objective-prism southern-sky surveys of Sanduleak & Stephenson (1973) and Henize (1976). Sanduleak & Stephenson (1973) placed it in a group of peculiar M-type emission-line stars that have strong hydrogen emission but no evident He II emission at 4868 Å. They noted that some stars in this group had been classified elsewhere as symbiotic stars. Allen (1978) obtained a low-dispersion slit spectrum of AS 270, which showed strong TiO bands of a late-M star, as well as emission lines of He I, He II, and [O III]. He concluded conservatively that it was a possible symbiotic star. However, he included the star in his catalog of symbiotic stars (Allen 1984) and presented a spectrum of AS 270 with features quite comparable to those of other symbiotic stars.

Allen (1980) and Gutiérrez-Moreno et al. (1999) classified the star as M1, while Mendina Tanco & Steiner (1995) determined a spectral class of M2. However, Mürset & Schmid (1999) found a somewhat later spectral class of M5.5, which we have adopted (Table 1). Additional information on the properties of AS 270 is given in the symbiotic star catalog of Belczyński et al. (2000).

5.2. *Orbital Elements*

Our 19 radial velocities of AS 270 (Table 6), obtained from 2000 July to 2006 June, span 3.2 orbital cycles. An analysis of these velocities with PGRAM produced a preliminary period of 668 days. Adopting this value and assigning a unit weight to each velocity, we obtained orbital elements with BISP that were refined with SB1. The SB1 solution produced a low orbital

TABLE 7
ORBITAL ELEMENTS AND RELATED PARAMETERS OF AS 270

Parameter	Value
P (days)	671.2 ± 7.4
T_0 (HJD)	2,451,801.1 ± 11.2
γ (km s^{-1})	−58.79 ± 0.22
K (km s^{-1})	6.47 ± 0.29
e	0.0 (adopted)
$a \sin i$ (10^6 km)	59.7 ± 2.8
$f(m)$ ($M_\odot$)	0.0189 ± 0.0025
Standard error of an observation of unit weight (km s^{-1})	0.9

eccentricity with a relatively large uncertainty, 0.09 ± 0.06. Thus, we used SB1C to determine a circular-orbit solution. The tests of Lucy & Sweeney (1971) indicated that the circular orbit is to be preferred, so it is given in Table 7. As recommended by Batten et al. (1989), for circular orbits we have identified T_0 as a time of maximum velocity. The standard error of an individual velocity is 0.9 km s^{-1}. Orbital phases and velocity residuals for the circular-orbit solution are given in Table 6. In Figure 6 the velocities and computed velocity curve are compared.

5.3. *Discussion*

Like Hen 2-173, AS 270 has been part of several photometric and spectrophotometric surveys, but there is very little additional information on the system. Kenyon (1988) provided *JHK* photometric magnitudes, while Munari et al. (1992) determined both $UBVR_CI_C$ and infrared *JHKL* magnitudes. As noted in § 5.1 several groups have determined the spectral class of the late-type component, which has ranged from M1 to M5.5.

With the same procedure that we used for Hen 2-173 and CL Sco, from a single spectrum we determine $v \sin i = 10 \pm 1$ km s^{-1} for the M giant component of AS 270. Following Schmutz et al. (1994), if we assume that the giant is synchronously rotating, the minimum radius is 133 ± 14 $R_\odot$. If the rotational inclination is reduced from 90° to 60°, the radius increases to 154 $R_\odot$.

As mentioned previously, the effective radius of the Roche lobe depends on the mass ratio and separation of the components. Because there is so little information on this system, we again adopted typical masses of 1.5 and 0.5 $M_\odot$ (Mikolajewska 2003) for the M giant and its companion, respectively, and used Kepler's third law to determine the semimajor axis of the orbit. With equation (2) of Eggleton (1983) we then estimated an effective Roche lobe radius of 193 $R_\odot$ for the M giant. Thus, if the giant is rotating synchronously, its rotational inclination must be reduced to about 43° for it to fill its Roche lobe.

From our orbital elements the ephemeris for conjunctions with the M III in front, which corresponds to times of mideclipse if the binary has a high enough inclination, is

$$T_{\rm conj}({\rm HJD}) = 2,451,633(\pm 11) + 671(\pm 7)E.$$

The symbol E represents an integer number of cycles.

6. PERIOD-ECCENTRICITY DISTRIBUTION

Zahn (1977) has shown that tidal forces in binaries cause rotational synchronization and orbital circularization and that the timescale for synchronization is shorter than that for circularization. Both the synchronization and circularization times are principally dependent on the ratio of the semimajor axis of the relative orbit, a, to the radius, R. The synchronization time scales as $(a/R)^6$, while the circularization time scales as $(a/R)^8$.

The distribution of binaries in the period-eccentricity plane provides information about binary star evolution (Jorissen et al. 1998). Figure 7 is the period-eccentricity distribution for the 30 symbiotic binaries that currently have spectroscopically determined orbits. The vast majority, 27 systems, are tabulated by Mikolajewska (2003). We have excluded one of those systems, CH Cyg, because it is uncertain whether it is a triple system with periods of 756 and 5292 days (Hinkle et al. 1993) or whether the shorter period results from pulsation (Schmidt et al. 2006). To the 26 remaining systems we have added the results for V2116 Oph (Hinkle et al. 2006) and the three binaries of the current work. Of the 30 systems, 21 have periods less than or equal to 800 days, of which 17, or 81%, have circular orbits. For periods greater than 800 days, only two of nine systems, or 22%,

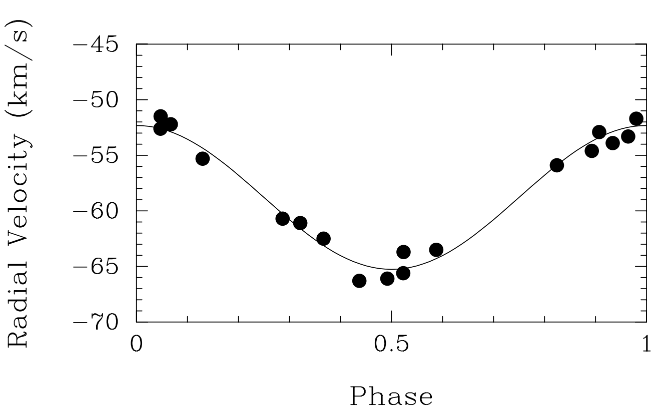

FIG. 6.—Radial velocities of AS 270 (*filled circles*) compared with the circular-orbit fit (*solid line*). Zero phase is a time of maximum velocity.

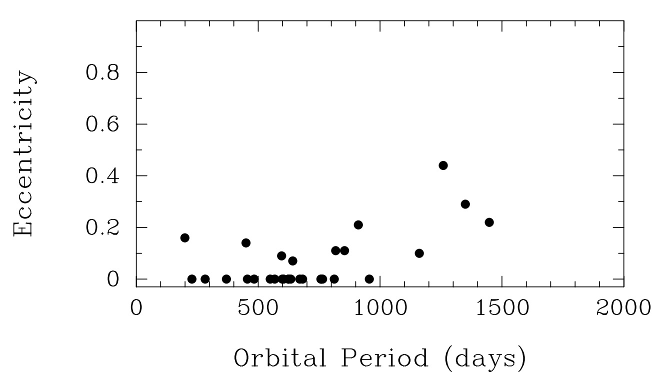

FIG. 7.—Orbital period vs. eccentricity for 30 symbiotic systems with spectroscopic orbital elements. Over 80% of the systems with periods less than 800 days have circular orbits. Only 22% of the systems with periods greater than 800 days have circular orbits.

have orbits that are circular. For comparison, the circular-orbit cutoff for G and K giants, which have much smaller radii, is about 70 days (Boffin et al. 1993), at least a factor of 10 smaller than that for our sample of symbiotics, and the range of eccentricities for the G and K giant sample is much greater. The current period-eccentricity distribution for symbiotics appears to approximate that for barium stars (see Fig. 4 of Jorissen et al. 1998).

Barium stars are binaries that contain a G or K giant with enhanced abundances of *s*-process elements and a white dwarf companion that has previously transferred mass to the current giant component. Boffin et al. (1993) and Jorissen et al. (1998) concluded that at a given orbital period, the maximum eccentricity for barium stars is much smaller than for normal G and K giant binaries. Verbunt & Phinney (1995) have shown that when the more massive star in a binary fills its Roche lobe, tidal interactions will very rapidly circularize the orbit. Even if the Roche lobe is not completely filled, the eccentricity of the system will be reduced when the more massive star increases in size as it evolves toward its end state of a compact object. Since the vast majority of symbiotics are believed to consist of a white dwarf and a late-type giant, it is not too surprising that the period-eccentricity distributions of symbiotics and barium stars resemble each other.

Four symbiotic binaries with periods less than 800 days have eccentric orbits. They are BD Cam ($e = 0.09$), V1261 Ori ($e = 0.07$), TX CVn ($e = 0.16$), and V343 Ser ($e = 0.14$). While all four eccentricities are relatively low, less than 0.2, the value of the eccentricity for TX CVn is perhaps the most problematic, since that binary has the shortest known orbital period, 199 days, of any symbiotic system. However, Kenyon & Garcia (1989) concluded that the eccentricity of 0.16, obtained from the solution of their velocities for TX CVn, is only marginally significant. They urged that higher quality velocities be obtained to confirm the reality of that eccentricity.

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