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THE TRIPLE SYMBIOTIC SYSTEM CH CYGNI

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ABSTRACT

A 13 yr time series of high-resolution 2 μm infrared spectra of CH Cygni has been analyzed. While confirming the previously suggested orbit of 15–16 yr, our observations show that CH Cyg is a triple system with a short-period orbit of just over 2 yr. The period ratio of 7 for CH Cyg is the smallest known for a triple system. The symbiotic pair is the short-period system. Thus, previous identification of the symbiotic system as the pair of stars in the long-period orbit as well as the interpretation of an eclipse of the hot companion in the long-period orbit are incorrect. With the addition of velocities from other sources we have determined both an eccentric and a circular orbit solution for the short-period pair. Circularization time scales and line asymmetries lead us to conclude that the circular-orbit solution is more appropriate. The observed eccentricity appears to be caused by phase-dependent line asymmetries resulting from the irradiation of the M giant by the white dwarf. Observations of the Brackett γ line show that the system does not eclipse. The long-period orbit has a period of 5294 ± 117 days or 14.5 ± 0.3 yr, an eccentricity of 0.058 ± 0.035, and a semiamplitude of 4.8 ± 0.2 km s^{-1}. The short-period orbit has a period of 756 ± 4 days, an assumed eccentricity of 0.0, and a semiamplitude of 2.6 ± 0.1 km s^{-1}. The most consistent model of the system results in a short-period pair consisting of a M6 giant of 2 $\mathscr{M}_\odot$ that is within a factor of 2 of filling its Roche lobe and a white dwarf of 0.2 $\mathscr{M}_\odot$. With this information and the assumption that the previously observed jet is collimated by the accretion disk, the orbital inclination must be $\sim 70°$. The unseen third star in the CH Cyg system is probably a G-K dwarf.

1. INTRODUCTION

CH Cyg=HD 182917 is the brightest symbiotic star ($m_v = 7$) at visual wavelengths and the second brightest symbiotic ($m_K = -1$) in the 2 μm infrared. The large northern declination ($\delta = +50°$) of this star makes it a choice monitoring target for northern hemisphere observers. As might be expected, CH Cyg has been observed both photometrically and spectroscopically from radio through x-ray wavelengths. Interestingly, while many of the well-studied symbiotics are now known to be binaries with periods of about 2 yr, CH Cyg has been especially reluctant to reveal its binary nature. In fact CH Cyg was at one time held up as the prime example of a single-star symbiotic, with the high-excitation lines hypothesized as arising from an active chromosphere (Hack & Selvelli 1982) or a strong magnetic field (Wdowiak 1977).

Equally interesting is the relatively recent classification of CH Cyg as a symbiotic. The outbursts that have taken place over the last few decades were preceded by a prolonged period of exceptional inactivity. CH Cyg was classified as an ordinary Mb star at Harvard. Wilson (1942) and Joy (1942) used this star as a typical M star in surveys and it was used as a M6 spectral standard (Keenan 1963, Yamashita 1967). In 1963 September Deutsch (1964) noted that the spectrum had become composite, with a hot blue continuum and emission lines of H, He I, [Fe II], and Ca II combined with a late-type spectrum. No trace of the hot star could be seen in spectra taken in 1961 even though a review of photometric data indicates that stellar activity increased around 1960 (Gusev 1976). Deutsch (1964) noted that the CH Cyg spectrum of 1963 closely resembled that of the recurrent nova T Coronae Borealis a few months after its outburst of 1946. Deutsch stated "no doubt there is a nova-like variable star in the CH Cyg

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system, too." However, radial velocity measurements taken by Deutsch showed no evidence of the expected orbital motion.

Mikolajewski *et al.* (1990) reviewed the photometric variability of CH Cyg over the last century. In accord with spectroscopic evidence, they found no evidence of an "outburst" before 1963. Periods of ~ 100, ~770, and ~1300 days were derived from the *V* through *K* broadband colors. The ~100 day period has been recognized since 1924 (Graff 1924a,b) and is generally ascribed to semiregular variations of the M giant. Skopal (1989) noted that reanalysis of visual photometry supplied by Luud *et al.* (1977) gives a period of 758 days. Muciek and Mikolajewski (1989) found a 780 day period. A period of 4 yr, which is approximately twice 750 days, was claimed by Gusev (1976). This is similar to the 1300 day period noted by Mikolajewski *et al.* (1990). Bode *et al.* (1991) noted that *U* band flares in 1972 and 1974 are correlated with the 758 day period. This period was not seen until after the onset of activity in 1963. The 758 day variability increased in amplitude, to >1 mag in the visual, in the 1970's (Mikolajewski *et al.* 1990).

In the last decade considerable evidence has been amassed indicating a binary nature for CH Cyg. Wallerstein (1968) and Cester (1968) first noted rapid variability in the blue continuum of CH Cyg. Kaler *et al.* (1983) established the connection between the hot accreting object and the emission line spectrum by observing that variations of the hydrogen emission lines are correlated with variations of the blue continuum. These variations are not related to variations of the red star. The variations in the blue continuum were shown by Slovak and Africano (1978) to have ~5–20 min time scale. This "flickering" was not found in the red continuum. Kenyon and Webbink (1984) listed *o* Cet B and T CrB as similar systems. Although flickering is not a phenomenon common to all symbiotic stars, it is commonly seen in cataclysmic variables. In these stars it is associated with accretion processes. In the symbiotics flickering seems limited to the systems within a factor of 2 of filling their Roche lobes (Garcia 1986).

Perhaps the most powerful previous evidence concerning the binary nature of CH Cyg comes from radio observations. Taylor *et al.* (1986) discovered a multiple component radio jet in CH Cyg. A number of other symbiotic systems are detectable at radio wavelengths (Seaquist & Taylor 1990) but have shell-like geometries (Kwok *et al.* 1984). The CH Cyg jet appeared at a time when the visual brightness fell dramatically. Measurements by Taylor *et al.* (1986) and by Taylor *et al.* (1988) indicate an expansion rate, projected on the plane of the sky, of 1.1 arcsec yr^{-1}. Solf (1987) has observed the jet visually in [O III] 5007 Å and Hα. Solf's observations suggest an expansion velocity on the order of 800 km s^{-1} (based on an assumed distance of 330 pc) with a collimated flow and inclination axis nearly perpendicular to the line of sight. Solf argued that the jet arises in an accretion disk that is seen nearly edge on ($i \sim 88°$). Bode *et al.* (1991) presented further [O III] observations, which combined with the radio expansion rate and the assumption that the optical and radio jets are formed in the same region, set the jet inclination for an assumed distance. Bode *et al.* find $i \geqslant 84°$ again based on a distance of 330 pc.

From radial velocities of visual spectra, Yamashita and Maehara (1979) first proposed an orbit with a possible period of about 16 yr for the M giant of CH Cyg. Batten *et al.* (1989) have given this orbit a quality rating of "d," indicating that the orbital elements are poorly determined. During the 1980's additional data were added and the orbital elements were recomputed (e.g., Skopal *et al.* 1989). However, the scatter of the radial velocities (e.g., Fig. 1 of Mikolajewski *et al.* 1988) is similar to the derived orbital amplitude (~9 km s^{-1}), leaving the reality of this orbit in question. Further, such a long-period orbit seems disturbingly out of accord with what would be expected from the properties of the CH Cyg symbiotic system (Kenyon 1986).

In 1984 a large drop in the blue magnitude of CH Cyg accompanied the development of the radio jet (Mikolajewski & Tomov 1986). At the same time changes were seen in the UV line spectrum (Selvelli & Hack 1985). Nearly simultaneously the x-ray flux in the 0.1–2.5 keV range increased by a factor of ≥85 (Leahy & Taylor 1987). This event has been interpreted as an eclipse of the hot object by the M giant (e.g., Mikolajewski & Tomov). Mikolajewski *et al.* (1990) have used the 16 yr orbit to identify a similarly shaped event in the light curve as a probable historic eclipse. On the basis of this evidence Mikolajewski *et al.* provided an eclipse ephemeris.

In addition to the 16 yr period, other periods have been suggested from the radial velocities. Skopal (1989) noted that a statistical analysis of the velocities shows a period in the 650–855 day range. Mikolajewski *et al.* (1990) found periods of 100, 760, and 1350 days in residuals of velocities measured in the visual. Mikolajewski *et al.* ascribe the ~770 and ~1300 day periods to "changes in the M giant's photosphere" possibly related to pulsation overtones. These periodicities also have been linked to rather subtle changes in the M giant spectral type between M6.5 and M7.2 III (Andrillat 1988; Mikolajewski *et al.* 1990).

In 1979 we began taking high resolution 1.5–2.5 μm spectra of CH Cyg. The original goal was to examine the spectra for possible peculiarities. In the early 1980's we became interested in monitoring stellar pulsations in the 2 μm infrared. Since CH Cyg had a well-known 100 day period and is bright, this star was included in a monitoring program to define the nature of the 100 day period. By 1985 we had detected a long-period trend in the velocities (Hinkle *et al.* 1985). In this paper we report the results of monitoring CH Cyg for 13 yr.

2. OBSERVATIONS

High resolution 2 μm region spectra of CH Cyg were obtained on 70 occasions between 1979 and 1992. The majority of the observations were taken with either a *K* filter (2.0–2.5 μm) or a broadband 1.5–2.5 μm filter covering both the *K* and *H* bands. Two spectra were taken with a *H* filter (1.5–1.8 μm). From 1983 to 1986 CH Cyg was ob-

TABLE 1. Infrared spectra of CH Cygni.

Date	JD (2,440,000+)	Wavenumber Region	Integration Time (minutes)	Resolution (Theoretical FWHM)	S/N	CO Δv=2 Hel. Cen. RV	CO Δv=2 Number of Lines	CO Δv=3 Hel. Cen. RV	CO Δv=3 Number of Lines
1979 Feb 8	3913.138	3950-6600	64	0.08	133	-59.14±0.13	42	-59.16±0.09	183
1979 Feb 12	3917.267	3950-6600	85	0.06	82	-59.25±0.12	22	-59.19±0.04	181
1980 Jan 24	4263.275	3950-6600	44	0.07	80	-64.70±0.21	39	-66.19±0.15	107
1980 Feb 27	4297.144	3950-6600	67	0.07	129	-65.97±0.26	39	-66.48±0.07	117
1980 Sep 25	4507.607	4150-5000	53	0.14	138	-60.47±0.29	24	--	--
1981 Jan 17	4622.194	4150-5000	28	0.06	123	-63.86±0.11	23	--	--
1981 Feb 24	4660.378	3950-6600	58	0.07	38	-62.50±0.13	42	-63.36±0.14	104
1981 Mar 28	4692.110	3950-4600	47	0.10	171	-63.59±0.34	41	--	--
1982 Jan 4	4974.297	4150-4600	11	0.10	70	-68.03±0.23	21	--	--
1982 Nov 6	5279.640	3950-6600	59	0.07	139	-63.36±0.09	42	-64.06±0.06	122
1983 Jan 25	5360.478	4150-4600	25	0.07	133	-63.61±0.14	21	--	--
1983 Feb 26	5392.184	4150-4600	66	0.07	138	-61.21±0.13	22	--	--
1983 May 20	5475.199	3950-6600	25	0.07	68	-64.59±0.10	43	-65.21±0.16	52
1983 Jun 4	5490.162	4150-5000	18	0.14	81	-64.36±0.21	23	--	--
1983 Jun 4	5490.162	5700-6600	18	0.14	61	--	--	-64.79±0.12	78
1983 Jun 21	5507.001	4150-4600	16	0.07	118	-64.20±0.21	23	--	--
1983 Sep 27	5604.862	3950-6600	12	0.10	77	-66.30±0.32	23	-65.79±0.23	60
1983 Nov 8	5647.498	3950-6600	34	0.07	82	-65.75±0.19	41	-65.24±0.10	87
1983 Dec 14	5683.282	4150-4600	31	0.10	201	-67.71±0.26	18	--	--
1984 Jan 21	5721.218	4150-4600	13	0.07	119	-67.20±0.23	21	--	--
1984 Feb 21	5752.156	3950-6600	34	0.07	100	-65.89±0.37	38	-67.52±0.17	66
1984 Mar 16	5776.080	3950-6600	25	0.07	73	-66.15±0.31	34	-67.06±0.14	86
1984 Mar 22	5782.082	3950-6600	42	0.07	58	-65.92±0.25	39	-66.92±0.15	81
1984 Apr 8	5799.055	3950-6600	34	0.07	37	-65.32±0.30	39	-66.54±0.20	65
1984 Apr 21	5812.076	3950-6600	67	0.07	93	-64.41±0.16	38	-65.39±0.07	107
1984 May 16	5837.034	3950-6600	33	0.07	90	-63.36±0.20	41	-64.94±0.09	72
1984 Sep 5	5948.828	3950-6600	33	0.07	90	-59.21±0.11	38	-61.24±0.10	95
1984 Oct 12	5986.495	3950-6600	34	0.07	118	-61.57±0.10	43	-61.52±0.07	104
1984 Oct 31	6005.414	3950-6600	33	0.07	82	-60.19±0.09	40	-60.49±0.08	106
1984 Nov 13	6018.341	3950-6600	34	0.07	77	-59.49±0.09	41	-60.29±0.05	121
1984 Dec 9	6044.386	3950-6600	34	0.07	55	-60.26±0.16	23	-60.38±0.12	180
1984 Dec 30	6064.855	3950-6600	14	0.07	105	-60.26±0.10	42	-60.66±0.08	76
1985 Feb 11	6107.908	3950-6600	18	0.07	83	-60.61±0.08	40	-60.43±0.09	78
1985 Mar 1	6125.872	3950-6600	15	0.07	53	-60.32±0.11	38	-60.76±0.14	73
1985 Apr 2	6157.791	3950-6600	13	0.07	83	-60.68±0.12	38	-61.25±0.09	77
1985 May 1	6186.830	3950-6600	20	0.07	60	-60.82±0.10	41	-61.23±0.13	77
1985 Jun 7	6223.774	3950-6600	18	0.07	64	-59.85±0.10	41	-60.14±0.12	78
1985 Sep 2	6310.529	3950-6600	14	0.07	98	-61.64±0.08	42	-61.69±0.09	76
1985 Oct 6	6344.562	3950-6600	32	0.07	72	-61.55±0.12	43	-61.10±0.14	74
1985 Dec 27	6426.835	3950-6600	18	0.07	50	-63.44±0.13	39	-63.06±0.18	73
1986 Jan 22	6452.877	3950-6600	20	0.07	55	-62.88±0.12	40	-63.51±0.20	73
1986 Feb 17	6478.799	3950-6600	25	0.07	110	-63.33±0.12	39	-63.60±0.10	76
1986 Mar 3	6492.844	4150-5000	23	0.07	41	-63.02±0.21	39	--	--
1986 Mar 20	6509.786	3950-6600	18	0.07	40	-61.69±0.21	39	-62.52±0.19	76
1986 May 19	6569.772	3950-6600	25	0.07	55	-60.02±0.18	39	-60.43±0.15	76
1986 Sep 23	6696.608	3950-6600	14	0.07	100	-56.18±0.08	40	-56.63±0.10	79
1986 Oct 17	6721.501	3950-6600	19	0.07	40	-55.05±0.09	42	-55.98±0.09	77
1986 Nov 14	6748.537	3950-6600	18	0.07	50	-54.11±0.10	41	-55.22±0.12	76
1987 Jan 22	6818.466	4150-5000	12	0.07	61	-56.15±0.10	38	--	--
1987 Jan 22	6818.466	5800-6800	12	0.07	46	--	--	-56.36±0.09	78
1987 Feb 12	6838.810	3950-6600	19	0.07	50	-55.32±0.07	39	-56.10±0.10	80
1987 Mar 14	6869.183	4150-5000	17	0.07	95	-56.89±0.13	42	--	--
1987 May 15	6931.016	4150-5000	56	0.07	176	-56.06±0.10	41	--	--
1987 Jun 3	6949.766	4150-5000	8	0.07	44	-55.39±0.18	41	--	--
1987 Sep 15	7053.636	4150-5000	18	0.07	90	-56.26±0.15	40	--	--
1987 Oct 1	7069.749	4150-5000	61	0.07	115	-58.14±0.20	40	--	--
1987 Nov 13	7113.295	3950-6600	97	0.07	73	-58.86±0.19	37	-58.48±0.15	71
1987 Dec 30	7159.503	3950-6600	13	0.07	57	-60.13±0.21	40	-59.24±0.11	73
1988 Feb 9	7201.195	4150-5000	18	0.07	96	-59.67±0.17	40	--	--
1988 Mar 8	7229.269	4150-5000	18	0.07	60	-59.57±0.20	37	--	--
1988 May 4	7286.152	4150-5000	35	0.07	68	-58.56±0.27	38	--	--
1988 May 25	7307.126	4150-5000	18	0.07	56	-58.86±0.26	36	--	--
1988 Jul 1	7344.045	3950-6600	18	0.07	85	-56.65±0.14	42	-57.19±0.10	77
1988 Nov 22	7488.413	4150-5000	18	0.07	102	-53.63±0.28	21	--	--
1989 Jan 13	7540.384	4150-5000	36	0.07	81	-54.50±0.13	42	--	--
1989 Sep 14	7783.636	4150-5000	66	0.07	64	-55.30±0.24	22	--	--
1990 Apr 3	7985.231	4150-5000	55	0.07	26	-59.95±0.35	21	--	--
1991 Apr 5	8352.289	4150-5000	35	0.07	53	-55.54±0.19	22	--	--
1991 Apr 6	8353.143	4150-5000	35	0.07	119	-55.33±0.10	22	--	--
1991 Apr 30	8377.043	4150-5000	35	0.07	121	-54.89±0.10	21	--	--
1991 Jul 2	8440.068	4150-4400	18	0.07	107	-56.20±0.23	23	--	--
1991 Nov 25	8586.221	4150-5000	27	0.07	100	-58.59±0.22	22	--	--
1992 Jan 22	8644.104	4150-5000	20	0.07	106	-58.79±0.19	22	--	--

served intensively. Over the remaining years observations were obtained a few times per year. A log of the observations is presented in Table 1. The signal-to-noise (S/N) ratios reported in Table 1 are for the peak signal. In the broadband spectra the peak signal occurs near 4600 cm^{-1} with the S/N ratio in the 1.5–1.8 μm region less by as much as a factor of 2. The resolution since 1984 has been fixed at 0.07 cm^{-1} ($\lambda/\Delta\lambda \sim 60\,000$). Prior to that the resolution (see Table 1) was never lower than ~30 000.

All the spectra were observed with the Fourier transform spectrometer (FTS) at the Coudé focus of the Kitt Peak 4 m telescope (Hall *et al.* 1978). Adequate discussion of the instrumentation and general characteristics of the data may be found in Hall *et al.* and Hinkle *et al.* (1982). We will reemphasize that the photometric accuracy and frequency calibration of spectra obtained with the FTS are limited by noise rather than instrumental characteristics. Frequencies are referenced to the spectrometer's laser frequency and after correction for the index of refraction of air, the spectral frequencies require only the addition of a small zero-point correction (<1 km s^{-1}) due to collimation differences between the reference and signal beams.

All spectra discussed in this paper have been apodized by function I2 of Norton and Beer (1976). Apodizing decreases the amplitude of the side lobes of the intrinsic sinc-function FTS instrumental profile and creates an instrumental profile similar to that of a grating spectrograph. In this process the apodizing function lowers the resolution but increases the S/N ratio. The resolutions and S/N ratios reported in Table 1 are apodized values.

Nearly all the spectra were observed in the daytime. The FTS has dual entrance beams that provide sky subtraction of about a factor of 100. Additional sky subtraction is provided by aperture switching. CH Cyg is easily observed in daytime in the 2 μm infrared since it is much brighter than the daytime 2 μm sky in the 4–7 arcsec input apertures.

For a sample of about a dozen spectra, CO $\Delta v=2$ and $\Delta v=3$ lines were selected and measured with the technique described in Hinkle *et al.* (1982) and Hinkle *et al.* (1984). Measurements of CO $\Delta v=2$ lines were restricted to the 4150–4360 cm^{-1} region of the *K* band and of CO $\Delta v=3$ lines to the 5550–6400 cm^{-1} region of the *H* band by telluric lines and filter responses. To summarize the measurement procedure, lines with unblended cores were identified from the known behavior of line strength with rotational quantum number for each vibration transition. Typically $\gtrsim 50$ relatively unblended lines can be found in each CO overtone. These lines then had velocities measured from the line core. Since the infrared CH Cyg spectra are all very similar in appearance, we formed a line list of unblended lines from a detailed study of about a dozen spectra. These lines were used to measure the velocities of the other spectra. This procedure avoids the highly labor-intensive step of selecting for each spectrum the least blended lines on the basis of central depths. The heliocentric velocities for the CO lines are presented in Table 1. Note that for spectra containing both CO overtones no systematic differences exist between the velocities from the two overtones. The entire time series has been plotted as a function of Julian day number in Fig. 1.

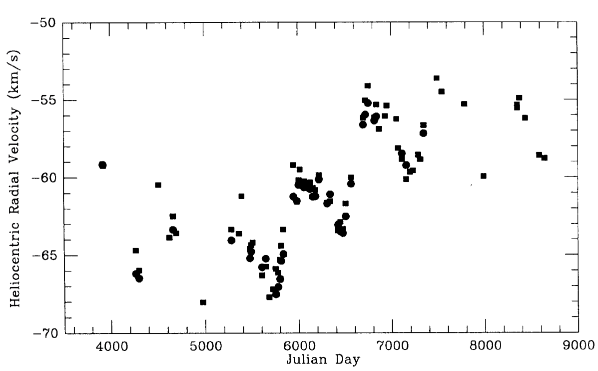

FIG. 1. Heliocentric radial velocities of the M6 giant measured from the 2.3 μm CO $\Delta v=2$ (squares) and from the 1.6 μm CO $\Delta v=3$ (circles) as a function of Julian day number (-2440000).

The only feature of the infrared spectra that differs from a typical M giant is the occasional presence of the hydrogen Brackett γ line very weakly in emission. Brackett γ emission is not an obvious spectral feature and would not be noted in a cursory examination of the spectrum. We detected the emission as a high point in the continuum of the highest S/N spectra in the early 1980's. The emission was not detected in spectra observed before or after this period. Our best Brackett γ detection is on 1982 November 6 when the equivalent width was ~8 mk [i.e., $\log(W_\lambda/\lambda) = -5.8$]. The infrared CO spectrum is clearly formed entirely in the M giant, thus the velocities in Table 1 reflect only the velocity of the M giant. The observation that the infrared spectrum contains only features of the M star is confirmed by broadband photometry (Ipatov *et al.* 1984), which shows that the M giant dominates the colors longward of 1 μm. This is quite important because during active phases the visual spectrum is heavily contaminated by line and continuum emission from a high excitation source, which interferes with visual velocity measurements of the M giant.

The velocity precision apparent in Table 1 results from the precise internal frequency calibration in a FTS. Velocities are limited in accuracy by the resolution and the S/N ratio. The mean S/N ratio of the observations reported in Table 1 is 85. Hall and Hinkle (1981) related these quantities to the expected velocity precision. For a typical spectrum, the velocity uncertainty per line is expected to be 0.2 km s^{-1}. In practice we find that the velocity derived from line cores is within a factor of 2 of this, with a typical internal uncertainty of ~0.06 km s^{-1} for a set of ~50 lines. The frequency zero-point correction is measured from telluric lines and this introduces the major uncertainty of ~0.1 km s^{-1}. A typical total uncertainty of ~0.12 km s^{-1} is more than an order of magnitude less than the uncertainties for CH Cyg velocities reported in the literature.

3. NATURE OF THE VELOCITY VARIATIONS

The velocities plotted in Fig. 1 clearly show two periods, one of about 2 yr and a second of about 15 yr. The short-period velocities have an amplitude of 5.7 km s^{-1} while those of the long period have an amplitude of 9.4 km s^{-1}. These accelerations must result from either stellar pulsation or orbital motion.

Recent work on pulsations in late-type stars allows tight constrains to be placed on the amplitude of stellar pulsations possible in CH Cyg. A limit on the absolute bolometric magnitude is required and this depends on knowledge of the distance. A good limit can be set on the distance to CH Cyg by comparing interstellar lines in the CH Cyg spectrum and those in the spectrum of a B8 V star which lies close (12′ away) to CH Cyg on the sky (Deutsch *et al.* 1974). The B8 V star has weak interstellar Na D lines and a distance of 200 pc. CH Cyg has no such interstellar lines and, therefore, must be closer. This estimate of the distance is supported by the work of Ivison *et al.* (1991), who determined a distance of 170 pc to CH Cyg from the ultraviolet color excess and by Kenyon *et al.* (1988) who found 100 pc from infrared colors and the Barnes–Evans relation.

Ipatov *et al.* (1984) derive the apparent bolometric flux of the M giant in the CH Cyg system from infrared photometry. With a distance limit of 200 pc, the absolute bolometric magnitude must be > -4.6. Hughes and Wood (1990) provide ($M_{\rm bol}$,log P) diagrams for Mira and SRa variables in the LMC. While these stars have a lower metallicity than expected for LPV's in the Galaxy, the LMC results demonstrate that Miras and SRa variables form a sequence on the ($M_{\rm bol}$,log P) plane. The Galactic ($M_{\rm bol}$, log P) relation is expected to be similar. The absolute magnitude limit for CH Cyg corresponds to periods of $\lesssim 300$ days. The long periods seen in CH Cyg, i.e., $P > 700$ days, are pulsation periods of stars much more luminous than CH Cyg could possibly be and are in strong disagreement with any reasonable distance to CH Cyg. Therefore, it seems extremely improbable that for CH Cyg these long periods have their origins in a Mira-type stellar pulsation. The 100 day period of CH Cyg and the classification of CH Cyg as a SRa variable are in accord with the above limit on the bolometric magnitude. In the LMC the 100 day period would imply a bolometric magnitude of -3.5.

We also note that the short- and long-period infrared velocity variations shown in Fig. 1 do not look like those of any Mira or SRa variable previously observed (Hinkle *et al.* 1984, Hinkle *et al.* 1993). The combination of the above results drives us to conclude that the observed velocity variations are the result of orbital motion.

4. ORBITAL SOLUTION

To solve a simultaneous orbital solution for the short- and long-period velocity variations a general least squares program (Daniels 1966) was employed. As a starting point for the long-period elements, the values of Mikolajewski *et al.* (1988) were assumed. Visual inspection of a plot of our velocities vs time suggests that the short period is about 770 days. This period is bracketed by the 760–780 day periods suggested from photometry and visual radial-velocity residuals. Although our phase coverage of the long-period orbit is not quite complete, both the maximum and minimum of the velocity curve have been covered. Thus, both periods are well determined from our data along with $P_L = 5483 \pm 278$ days and $P_s = 749 \pm 4$ days. Given the rather large uncertainties of previous velocities, the original long-period orbital solution proposed by Yamashita and Maehara (1979) was relatively accurate, while revisions of that orbit have resulted in much too large an eccentricity (see Mikolajewski *et al.* 1988).

To see if our orbital elements could be improved, the extensive datasets of Deutsch *et al.* (1974), Hack and collaborators (Hack *et al.* 1982, Hack *et al.* 1986), and Yamashita and collaborators (Yamashita & Maehara 1979, Yoo & Yamashita 1991) were compared separately with our orbital elements. Despite their large scatter, many of these velocities agree quite well with our long-period orbit, except for velocities obtained during many of the increased activity phases. The velocities agree less well with our short-period orbit, presumably because the semiamplitude of the short-period orbit is similar to the uncertainties of these velocities. Numerous velocities of Hack *et al.* (1982,1986) were obtained during the times of significantly increased activity. For certain Julian date ranges many of these velocities had residuals of 8–14 km s^{-1}. Overall our solution was not improved by the inclusion of the Hack data so those velocities have not been used. Many of the velocities of Deutsch *et al.* obtained from late 1971 to 1973 had large velocity residuals and so all of their velocities in this period were given zero weight. These velocities are listed in Table 2 but are not plotted in the figures. In the final orbital solution the rest of the velocities of Deutsch *et al.* and all those of Yamashita and collaborators were assigned weights of 0.05 relative to those of our velocities (Table 2). When the weights of these velocities were changed to 0.1, the resulting elements were not changed significantly. Determinations of the center-of-mass velocities for each of the three datasets indicate that relative to our velocities, no velocity shift is necessary for the observations of Deutsch *et al.* (1974) but -2 km s^{-1} must be added to those of Yamashita and collaborators.

An orbital solution for the M6 III was obtained with velocities of these two sets of data, appropriately weighted, and our velocities. Table 3 compares the orbital elements from our data alone with the results from a combined solution with all elements varied. The combined solution further reduces the uncertainties, especially in the long-period orbit, by increasing the time base to nearly 31 yr. For plotting purposes each observed velocity has been separated into a long-period velocity, V_L, and a short-period velocity, V_s. Each of these computed velocities, V_L and V_s, consists of its predicted velocity plus one-half of the observed velocity residual. Figure 2 compares these long-period velocities with their predicted velocity curve while Fig. 3 similarly compares the short-period velocities with their velocity curve. All the individual observations and fitted values are given in Table 2. Column 1 is the heliocentric Julian date for our observations or the Julian date for the observations of others. Column 2 lists the measured total velocity. Columns 3–7 present the results of the first orbital solution given in Table 3, that of the best fit to the combined visual and infrared data. Column 3 lists the total velocity residual to the short- and long-period orbits. Columns 4 and 5 give the phase in the long-period orbit and the computed long-period velocity, respectively. Columns 6 and 7 list the short-period phase and computed short-period velocity.

TABLE 2. Orbital fit.

JD (2,400,000+)	Observed RV	Eccentric Fit					Short Period Circular Fit				
		O-C	ϕ_L	V_L	ϕ_S	V_S	O-C	ϕ_L	V_L	ϕ_S	V_S
37385.0[a]	-55.4	2.83	0.465	-54.61	0.804	-0.79	3.51	0.450	-54.54	0.503	-0.86
38276.0[a]	-61.2	0.28	0.633	-58.79	0.990	-2.41	-0.67	0.618	-59.77	0.681	-1.43
38335.0[a]	-59.8	-0.59	0.644	-59.51	0.068	-0.29	-0.22	0.629	-59.84	0.759	0.04
38458.0[a]	-56.3	1.25	0.668	-59.21	0.232	2.91	1.76	0.652	-59.49	0.922	3.19
38601.0[a]	-56.8	2.08	0.695	-59.54	0.422	2.74	2.33	0.679	-59.96	0.111	3.16
38604.0[a]	-60.0	-1.08	0.695	-61.13	0.426	1.13	-0.82	0.680	-61.55	0.115	1.55
38991.0[a]	-64.5	1.47	0.768	-61.88	0.941	-2.62	0.49	0.753	-62.92	0.627	-1.58
39193.0[a]	-57.5	3.86	0.806	-61.64	0.210	4.14	4.54	0.791	-61.83	0.894	4.33
39395.0[a]	-59.3	3.75	0.844	-62.49	0.479	3.19	4.17	0.829	-62.77	0.161	3.47
39657.0[a]	-66.4	1.17	0.894	-64.46	0.827	-1.94	1.68	0.879	-64.63	0.508	-1.77
39661.0[a]	-70.2	-2.55	0.895	-66.33	0.833	-3.87	-2.12	0.880	-66.54	0.513	-3.66
39687.0[b]	-68.2	-0.07	0.900	-65.13	0.867	-3.07	-0.19	0.884	-65.61	0.548	-2.59
39692.0[a]	-69.9	-1.69	0.900	-65.95	0.874	-3.95	-1.92	0.885	-66.48	0.554	-3.42
39724.0[a]	-70.8	-2.26	0.907	-66.27	0.916	-4.53	-3.11	0.891	-67.10	0.597	-3.70
39779.0[a]	-66.6	1.14	0.917	-64.62	0.990	-1.98	0.26	0.902	-65.46	0.669	-1.14
39780.0[b]	-64.1	3.61	0.917	-63.39	0.991	-0.71	2.74	0.902	-64.22	0.671	0.12
39992.0[b]	-66.0	-3.14	0.957	-66.73	0.273	0.73	-2.98	0.942	-67.00	0.951	1.00
40142.0[a]	-63.9	-0.36	0.985	-65.08	0.473	1.18	-0.21	0.970	-65.33	0.150	1.43
40819.0[b]	-57.8	2.09	0.113	-60.81	0.373	3.01	1.80	0.098	-61.21	0.045	3.41
40841.0[a]	-57.1	2.81	0.117	-60.32	0.403	3.22	2.55	0.102	-60.71	0.074	3.61
40872.0[a]	-60.2	-0.21	0.123	-61.65	0.444	1.45	-0.37	0.108	-61.97	0.115	1.77
40872.0[a]	-62.6	-2.61	0.123	-62.85	0.444	0.25	-2.77	0.108	-63.17	0.115	0.57
41093.0[a]	-60.5	1.02	0.165	-59.71	0.738	-0.79	2.13	0.150	-59.38	0.408	-1.12
41239.0[a]	-53.9	8.87	0.192	-54.95	0.932	1.05	7.79	0.178	-55.69	0.601	1.79
41432.0[b]	-56.3	-0.05	0.229	-58.38	0.189	2.08	0.62	0.214	-58.23	0.856	1.93
41529.0[a]	-57.2	-1.50	0.247	-58.65	0.318	1.45	-1.73	0.232	-58.93	0.984	1.73
41542.0[a]	-51.0	4.70	0.250	-55.49	0.336	4.49	4.39	0.235	-55.81	0.002	4.81
41557.0[a]	-64.8	-9.09	0.252	-62.31	0.355	-2.49	-9.45	0.238	-62.66	0.021	-2.14
41561.0[a]	-51.1	4.62	0.253	-55.44	0.361	4.34	4.24	0.238	-55.80	0.027	4.70
41573.0[a]	-55.4	0.34	0.256	-57.53	0.377	2.13	-0.05	0.241	-57.89	0.043	2.49
41588.0[a]	-54.7	1.09	0.258	-57.09	0.397	2.39	0.68	0.244	-57.46	0.062	2.76
41646.0[a]	-53.5	2.54	0.269	-56.12	0.474	2.62	2.38	0.254	-56.37	0.139	2.87
41659.0[a]	-67.4	-11.28	0.272	-62.98	0.491	-4.42	-11.35	0.257	-63.18	0.156	-4.22
41687.0[a]	-43.8	12.50	0.277	-50.98	0.528	7.18	12.68	0.262	-51.05	0.193	7.25
41787.0[a]	-43.8	13.44	0.296	-50.15	0.661	6.35	14.42	0.281	-49.82	0.326	6.02
43422.0[b]	-64.6	-3.71	0.604	-60.09	0.837	-4.51	-3.27	0.590	-60.36	0.488	-4.24
43697.0[b]	-58.0	-0.66	0.656	-59.86	0.203	1.86	0.52	0.642	-59.82	0.852	1.82
43713.0[b]	-58.0	-0.65	0.659	-59.94	0.224	1.94	0.33	0.645	-60.00	0.873	2.00
43777.0[b]	-57.9	-0.19	0.671	-60.03	0.309	2.13	0.08	0.657	-60.46	0.958	2.56
43913.138	-59.2	0.22	0.697	-60.54	0.491	1.34	0.34	0.683	-61.06	0.138	1.86
43917.267	-59.2	0.29	0.698	-60.53	0.496	1.33	0.43	0.684	-61.03	0.144	1.83
44263.275	-65.4	0.29	0.763	-62.34	0.956	-3.06	-0.24	0.749	-63.18	0.601	-2.22
44297.144	-66.2	-1.33	0.770	-63.32	0.002	-2.88	-1.39	0.755	-63.92	0.646	-2.28
44507.607	-60.5	0.86	0.809	-63.21	0.282	2.71	1.36	0.795	-63.50	0.924	3.00
44622.194	-63.9	-1.41	0.831	-64.82	0.434	0.92	-1.60	0.817	-65.42	0.076	1.52
44660.373	-62.9	0.08	0.838	-64.21	0.485	1.31	0.03	0.824	-64.74	0.127	1.84
44692.110	-63.6	-0.17	0.844	-64.45	0.527	0.85	-0.02	0.830	-64.87	0.169	1.27
44974.297	-68.0	0.42	0.897	-64.87	0.903	-3.13	0.02	0.883	-65.49	0.542	-2.51
45279.621	-63.7	-0.76	0.955	-65.55	0.309	1.85	-0.65	0.941	-65.84	0.946	2.14
45360.478	-63.6	-0.27	0.970	-65.20	0.416	1.60	-0.68	0.956	-65.73	0.053	2.13
45392.184	-61.2	2.34	0.976	-63.83	0.459	2.63	1.96	0.962	-64.35	0.095	3.15
45475.199	-64.9	-0.66	0.992	-65.14	0.569	0.24	-0.52	0.978	-65.38	0.204	0.48
45490.162	-64.6	-0.21	0.995	-64.88	0.589	0.28	0.06	0.981	-65.05	0.224	0.45
45507.001	-64.2	0.36	0.998	-64.55	0.611	0.35	0.77	0.984	-64.64	0.246	0.44
45604.862	-66.0	-0.24	0.016	-64.53	0.742	-1.47	0.56	0.002	-64.42	0.376	-1.58
45647.498	-65.5	0.87	0.025	-63.81	0.798	-1.69	1.41	0.010	-63.83	0.432	-1.67
45683.282	-67.7	-0.82	0.031	-64.52	0.846	-3.18	-0.72	0.017	-64.75	0.480	-2.95
45721.218	-67.2	0.05	0.038	-63.92	0.896	-3.28	-0.42	0.024	-64.43	0.530	-2.77
45752.156	-66.7	0.48	0.044	-63.57	0.938	-3.13	-0.26	0.030	-64.21	0.571	-2.49
45776.080	-66.6	0.10	0.049	-63.65	0.969	-2.95	-0.55	0.035	-64.24	0.602	-2.36
45782.082	-66.4	0.11	0.050	-63.61	0.977	-2.79	-0.46	0.036	-64.16	0.610	-2.24
45799.055	-65.9	-0.05	0.053	-63.62	1.000	-2.28	-0.29	0.039	-64.00	0.633	-1.90
45812.076	-64.9	0.33	0.056	-63.36	0.017	-1.54	0.42	0.041	-63.58	0.650	-1.32
45837.034	-64.2	-0.23	0.060	-63.52	0.051	-0.68	0.53	0.046	-63.40	0.683	-0.80
45932.0[c]	-58.2	2.69	0.078	-61.57	0.177	3.37	4.02	0.064	-61.15	0.809	2.95
45948.828	-60.2	0.45	0.081	-62.59	0.199	2.39	1.59	0.067	-62.27	0.831	2.07
45960.0[c]	-55.3	5.22	0.084	-60.14	0.214	4.84	6.22	0.069	-59.89	0.846	4.59
45986.495	-61.5	-1.19	0.089	-63.21	0.249	1.71	-0.56	0.074	-63.13	0.881	1.63
46005.414	-60.3	-0.09	0.092	-62.55	0.275	2.25	0.28	0.078	-62.61	0.906	2.31
46018.341	-59.9	0.26	0.095	-62.30	0.292	2.40	0.46	0.080	-62.44	0.923	2.54
46044.386	-60.3	-0.19	0.099	-62.38	0.326	2.08	-0.30	0.085	-62.67	0.957	2.37
46064.855	-60.5	-0.40	0.103	-62.36	0.354	1.86	-0.70	0.089	-62.75	0.984	2.25
46066.0[c]	-60.0	0.10	0.104	-62.11	0.355	2.11	-0.21	0.089	-62.50	0.986	2.50
46107.908	-60.5	-0.35	0.111	-62.09	0.411	1.59	-0.88	0.097	-62.58	0.041	2.08

TABLE 2. (continued)

JD (2,400,000+)	Observed RV	Eccentric Fit O-C	ϕ_L	V_L	ϕ_S	V_S	Short Period Circular Fit O-C	ϕ_L	V_L	ϕ_S	V_S
46125.872	-60.5	-0.31	0.115	-61.96	0.435	1.46	-0.86	0.101	-62.46	0.065	1.96
46157.791	-61.0	-0.71	0.121	-61.97	0.477	0.97	-1.20	0.107	-62.44	0.107	1.44
46186.830	-61.0	-0.58	0.126	-61.74	0.516	0.74	-0.93	0.112	-62.13	0.146	1.13
46223.774	-60.0	0.62	0.133	-60.92	0.565	0.92	0.55	0.119	-61.16	0.195	1.16
46301.0[c]	-58.7	2.50	0.148	-59.51	0.668	0.81	3.02	0.134	-59.45	0.297	0.75
46303.0[c]	-63.7	-2.48	0.148	-61.99	0.670	-1.71	-1.95	0.134	-61.93	0.299	-1.77
46310.529	-61.7	-0.41	0.150	-60.91	0.681	-0.79	0.16	0.136	-60.83	0.309	-0.87
46344.562	-61.3	0.34	0.156	-60.33	0.726	-0.97	0.99	0.142	-60.20	0.354	-1.10
46426.835	-63.2	-0.55	0.172	-60.29	0.835	-2.91	-0.45	0.158	-60.43	0.463	-2.77
46452.877	-63.2	-0.27	0.177	-60.00	0.870	-3.20	-0.54	0.163	-60.32	0.498	-2.88
46478.799	-63.5	-0.43	0.181	-59.93	0.904	-3.57	-1.04	0.167	-60.42	0.532	-3.08
46492.844	-63.0	0.04	0.184	-59.61	0.923	-3.39	-0.70	0.170	-60.17	0.551	-2.83
46509.786	-62.1	0.75	0.187	-59.16	0.946	-2.94	-0.04	0.173	-59.74	0.573	-2.36
46569.772	-60.2	0.43	0.199	-58.99	0.026	-1.21	0.68	0.185	-59.04	0.652	-1.16
46676.0[c]	-56.1	0.60	0.219	-58.33	0.167	2.23	2.00	0.205	-57.80	0.793	1.70
46677.0[c]	-54.4	2.28	0.219	-57.49	0.168	3.09	3.68	0.205	-56.95	0.794	2.55
46696.608	-56.4	-0.01	0.223	-58.53	0.194	2.13	1.18	0.209	-58.10	0.820	1.70
46721.501	-55.5	0.63	0.227	-58.09	0.227	2.59	1.49	0.213	-57.82	0.853	2.32
46748.537	-54.7	1.27	0.232	-57.63	0.263	2.93	1.72	0.218	-57.56	0.889	2.86
46818.466	-56.3	-0.42	0.246	-58.14	0.356	1.84	-0.81	0.232	-58.49	0.981	2.19
46838.810	-55.7	0.22	0.249	-57.73	0.384	2.03	-0.32	0.235	-58.15	0.008	2.45
46869.183	-56.9	-0.88	0.255	-58.15	0.424	1.25	-1.54	0.241	-58.62	0.048	1.72
46931.016	-56.1	0.24	0.267	-57.33	0.506	1.23	-0.30	0.253	-57.74	0.130	1.64
46949.766	-55.4	1.07	0.270	-56.84	0.531	1.44	0.64	0.256	-57.19	0.155	1.79
46989.0[c]	-55.3	1.48	0.278	-56.48	0.583	1.18	1.36	0.264	-56.68	0.207	1.38
47034.0[c]	-61.2	-3.98	0.286	-59.04	0.643	-2.16	-3.74	0.272	-59.06	0.266	-2.14
47053.636	-56.3	1.14	0.290	-56.41	0.669	0.11	1.51	0.276	-56.37	0.292	0.07
47069.749	-58.1	-0.47	0.293	-57.16	0.691	-0.94	-0.02	0.279	-57.07	0.314	-1.03
47113.295	-58.7	-0.48	0.301	-57.02	0.749	-1.68	0.03	0.287	-56.91	0.371	-1.79
47159.503	-59.7	-0.77	0.310	-57.03	0.810	-2.67	-0.54	0.296	-57.05	0.432	-2.65
47201.195	-59.7	-0.16	0.318	-56.60	0.866	-3.10	-0.43	0.304	-56.88	0.488	-2.82
47229.269	-59.6	0.19	0.323	-56.35	0.903	-3.25	-0.43	0.309	-56.81	0.525	-2.79
47286.152	-58.6	0.52	0.334	-56.05	0.979	-2.55	-0.03	0.320	-56.47	0.600	-2.13
47307.126	-58.9	-0.58	0.338	-56.56	0.007	-2.34	-0.67	0.324	-56.75	0.628	-2.15
47344.045	-56.9	-0.32	0.345	-56.35	0.056	-0.55	0.61	0.331	-56.04	0.677	-0.86
47488.413	-53.6	0.06	0.372	-55.93	0.248	2.33	0.78	0.358	-55.75	0.867	2.15
47540.384	-54.5	-0.79	0.382	-56.31	0.317	1.81	-0.82	0.368	-56.50	0.936	2.00
47783.636	-55.3	0.69	0.428	-55.50	0.641	0.20	0.91	0.414	-55.62	0.258	0.32
47985.231	-60.0	-0.59	0.466	-56.33	0.909	-3.67	-1.10	0.452	-56.87	0.525	-3.13
48352.289	-55.5	-0.49	0.535	-57.10	0.397	1.60	-0.85	0.521	-57.68	0.010	2.18
48353.143	-55.3	-0.28	0.535	-57.00	0.398	1.70	-0.65	0.521	-57.58	0.011	2.28
48377.043	-54.9	0.39	0.540	-56.74	0.430	1.84	-0.08	0.526	-57.38	0.043	2.48
48440.068	-56.2	-0.10	0.552	-57.19	0.514	0.99	-0.46	0.538	-57.80	0.126	1.60
48586.221	-58.6	0.00	0.579	-57.68	0.709	-0.92	0.66	0.565	-57.82	0.320	-0.78
48644.104	-58.8	1.06	0.590	-57.38	0.786	-1.42	1.68	0.576	-57.56	0.396	-1.24

[a]Deutsch *et al.* 1974

[b]Yamashita and Maehara 1979

[c]Yoo and Yamashita 1991

Both the solutions for only the infrared observations and for the combined visual and infrared solution give a short-period eccentricity of 0.32 ± 0.04. However, theoretical considerations suggest that interactions between the secondary and the M giant may be expected to circularize the short-period orbit quite quickly. There are several theories that predict a circularization time scale for a binary system. The various mechanisms combine to work most quickly in stars with outer convective atmospheres. In all the theories the circularization time scale depends strongly on the ratio a/R, where a is the total semimajor axis of the system and R is the radius of the larger star. The dependence ranges from $(a/R)^{6.125}$ to $(a/R)^{10.5}$ (Tassoul 1988). Most theories have been compared with late-type main-sequence stars (e.g., Goldman & Mazeh 1991) where circularization time scales are several billion years for binary orbits with a period of 10 days (Mathieu & Mazeh 1988). However, after a star evolves off the main sequence and increases its radius by at least 50–100 times, circularization occurs quite rapidly even for stars with periods of 100 days or more (e.g., Capella). For the current configuration of CH Cyg the ratio a/R is quite small, almost certainly between 2 and 5. With the theory of Tassoul (1988) such values of this ratio result in a circularization time scale as short as 10 000 yr. However, such a result should be viewed cautiously since even for main-sequence stars agreement between theory and observation has yet to be realized. Nevertheless, the theories suggest that one might expect the short-period orbit of CH Cyg to be circular despite its relatively long 2 yr period.

An observational comparison with other known symbiotic binaries does not answer the question of whether such systems should have circular orbits. Kenyon (1986) lists the orbital elements of 9 symbiotic systems. However, Batten *et al.* (1989) consider only two of the nine to have orbital elements of average quality or better. Of these two

TABLE 3. Orbital elements.

Element	Combined Visual & Infrared Data	Only Infrared Data	Short Period Circular Fit to Combined Data
γ (km s^{-1})	-60.25±0.10	-60.22±0.13	-60.60±0.11
K_S (km s^{-1})	2.85±0.11	2.81±0.13	2.61±0.12
e_S (°)	0.323±0.043	0.320±0.051	0.0[a]
ω_S (°)	233.3±7.2	231.8±8.8	--[b]
T_S (HJD)	2447302±12	2447297±15	2446076.655[a,c]
P_S (days)	751.5±2.3	749.0±4.2	756.0±3.6
$a_S$sin i (km)	2.79×10^7	2.74×10^7	2.71×10^7
f_S(m) ($M_\odot$)	0.00153	0.00147	0.00140
K_L (km s^{-1})	4.70±0.13	4.66±0.17	4.78±0.16
e_L (°)	0.067±0.029	0.092±0.051	0.058±0.035
ω_L (°)	207±23	219±23	215±31
T_L (HJD)	2445517±327	2445679±340	2445592±450
P_L (days)	5298±98	5483±278	5294±117
a_L sin i (km)	3.41×10^8	3.50×10^8	3.48×10^8
f_L(m) ($M_\odot$)	0.057	0.057	0.060

[a]Fixed
[b]Undefined
[c]For a circular orbit T is the time of maximum positive velocity.

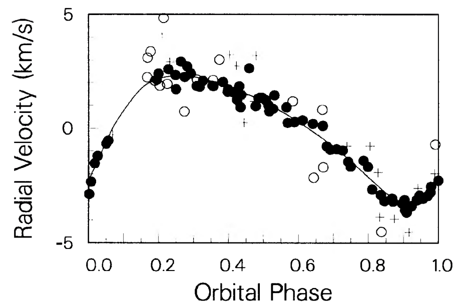

FIG. 3. Short-period velocity predicted from eccentric orbit (solid line) as a function of orbital phase compared with the computed short-period velocities, $V(S)$, from this paper (filled circles), from Deutsch *et al.* (plus signs), and Yamashita and collaborators (open circles).

T CrB has a period of 227.5 days and a circular orbit (Kenyon & Garcia 1986) while the orbit of BL Tel has a period of 778 days and an eccentricity of 0.31 (Wing 1963).

In cataclysmic variables, asymmetric line profiles result from irradiation of the late-type star by the white dwarf and accretion disk. Velocities measured from the asymmetric line profiles of the cool star result in a false orbital eccentricity (Davey & Connon-Smith 1992). Photometric variations resulting from irradiation by the hot star have been seen in broadband colors of the late-type star in symbiotic systems but absorption line asymmetries attributable to this cause have never been reported in a symbiotic system. To investigate possible changes in the line profiles of CH Cyg, the profiles of the $^{12}C^{16}O$ 2-0 R branch lines 18–25 were examined in each spectrum observed at resolution 0.07 cm^{-1}. Most of the dataset was observed at 0.07 cm^{-1}, which corresponds to $R=62\,000$ at the mean frequency of the CO lines. The selected CO lines bracket a very small range in energy and when formed under photospheric conditions should have very similar line profiles. These CO lines are strong lines, with central depths of ~60%. Tsuji (1988) has noted that in normal late M giants these lines contain a circumstellar component. Ideally much weaker lines would have been used but the limited S/N of many of the observations prohibited this. For the best S/N data the line profiles of somewhat weaker Ti lines in the K window were compared to the CO line profiles. In no case was any circumstellar contribution noted to the CH Cyg CO $\Delta v=2$ lines. From Sec. 2, we note that in CH Cyg the strong CO $\Delta v=2$ lines and the weak CO $\Delta v=3$ lines show identical radial velocities which also indicates that no circumstellar contribution is present in the $\Delta v=2$ lines. Comparison of CO $\Delta v=2$ line profiles throughout the time series reveals that the shape of the line profile is a function of short-period phase. Around phase 0.8 in the eccentric orbit solution the lines are asymmetric. At phase 0.4 the lines are more narrow and symmetric. The full width at half-maximum (FWHM) is shown as a function of orbital phase in Fig. 4. The spread in FWHM at a given phase is not due entirely to observational error but appears to be partly a result of cyclic changes in linewidth.

Further complexity is introduced because CH Cyg is a triple system. In triple systems, the third body can cause

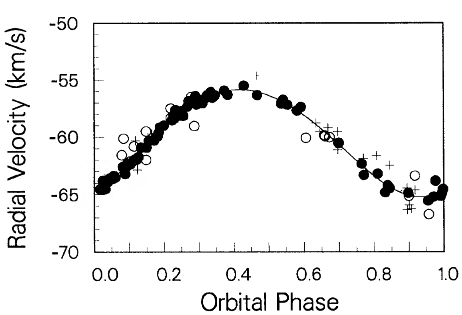

FIG. 2. Long-period velocity predicted from eccentric orbit (solid line) as a function of orbital phase compared with the computed long-period velocities, $V(L)$, from this paper (filled circles), from Deutsch *et al.* (plus signs), and Yamashita and collaborators (open circles).

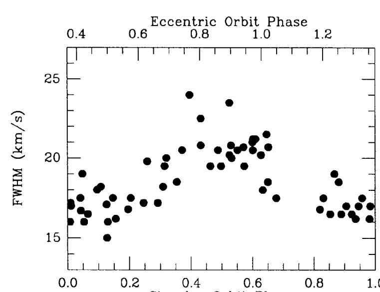

FIG. 4. Average FWHM in velocity units (km s^{-1}) of $^{12}C^{16}O$ $\Delta v=2$ lines $R(18)$ through $R(25)$ as a function of short-period orbit phase. The lower x axis is short-period phase for a circular orbit; the upper x axis is the approximate corresponding phase for an eccentric orbit.

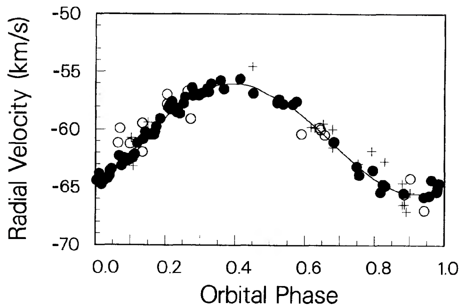

FIG. 5. Long-period velocity (as in Fig. 2) as a function of orbital phase for the circular orbit solution.

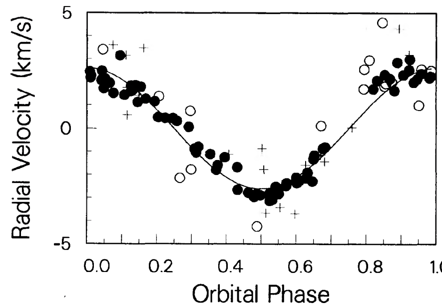

FIG. 6. Short-period velocity (as in Fig. 3) as a function of orbital phase for the circular orbit solution.

perturbations in the orbital elements of the close pair. Changes in the eccentricity have been examined by Mazeh and Shaham (1979) and by Soderhjelm (1984). In such systems while the eccentricity of the short-period orbit decreases with time, it also oscillates about this decreasing value. Mazeh and Shaham found that the modulation amplitude was relatively small, only several percent, in the cases that they examined. Following the suggestion of Mazeh and Shaham, Bailyn and Grindlay (1987) developed a triple-system model that had a variable short-period eccentricity that resulted in the close pair having a variable mass-transfer rate. Again, the amplitude of the eccentricity modulation appeared to be quite small. These results suggest that an eccentricity as large as 0.32 is not due to third-body perturbations. However, the work of Soderhjelm (1984) indicates that under certain conditions, including a small period ratio, it is possible to have large eccentricity amplitudes. We note that the period ratio of 7 for CH Cyg is the smallest known, eclipsing the value of 8 for λ Tau (Fekel & Tomkin 1982).

The small ratio of a/R, almost certainly less than 5, strongly suggests that short-period orbit of CH Cyg should be circularized. Since modeling has not yet demonstrated that the eccentricity of a system like CH Cyg can be increased significantly from zero by interaction with the third body and since strong phase dependent line asymmetries are present, we have computed a third orbital solution with the short-period eccentricity fixed at 0 (Table 3). This solution increases the sum of the weighted residuals squared by about 60% compared to the combined solution where this eccentricity was a free parameter. The new phases and velocities are listed in columns 8 to 12 of Table 2. The observed velocities and the computed orbits for this third solution are shown in Figs. 5 and 6. As a result of the forced fit, there are systematic residuals to the circular short-period orbit at certain phases. The residuals are shown as function of phase in Fig. 7. We note that the long-period eccentricity in all solutions is close to 0 but have kept it as a free parameter. A reasonable fit to the data is possible with the zero-eccentricity solution because the velocity residuals, although having a combined value typically less than 1 km s^{-1}, are a significant fraction of the short-period semiamplitude. The orbital elements of the long-period orbit also act as additional free parameters that can be adjusted in the solution.

A comparison of the solutions in Table 3 indicates that the short-period semiamplitude has been decreased by 0.24 km s^{-1} in the circular-orbit solution and the center-of-mass velocity has decreased by 0.34 km s^{-1}. All other elements have changed by less than their associated errors. We will assume the orbital elements of the circular-orbit solution in our discussion but note that the use of the noncircular-orbit solution would not change significantly the computed quantities in most cases.

5. DISCUSSION

The orbital solution shows that CH Cyg consists of three stars and resolves the long-standing question concerning the reality of the symbiotic 15–16 yr orbit. As noted by Kenyon (1986), such a long period is not in accord with the energetics of the symbiotic system. Periods for symbiotic binaries are in the range 230–1000 days, with a mean period of 650 days (Table 3.1 of Kenyon 1986). This is consistent with our finding that in the CH Cyg triple system the short-period (756 day) orbit is that of the symbiotic pair, i.e., the M giant and the hot star, while the long-period (15 yr) orbit has an unseen third star in orbit with the symbiotic pair.

As reviewed in the introduction, one of the photometric periods reported for CH Cyg is ~770 days. This variation can be seen in the visual with an amplitude at times as great as 1 mag (Mikolajewski *et al.* 1990) as well as in the infrared where H and J band variations have an amplitude

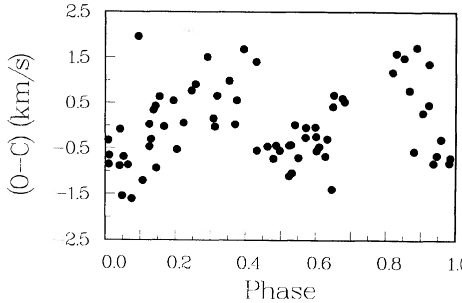

FIG. 7. Short-period velocity residuals as a function of phase for the circular orbit solution.

of ~0.4 mag (Ipatov *et al.* 1984). CH Cyg is also known to undergo periodic spectral-type variations from approximately M5 III to approximately M7 III. We argue that the ~770 day photometric period and the spectral-type variations result from the heating of the hemisphere of the cool giant facing the hot component. This effect is well documented in some other symbiotic systems of similar period (Belyakina 1968, 1970). The phase dependence of the line profiles (Sec. 4) provides conclusive proof that irradiation of the M star by the white dwarf produces significant changes in the surface of the M giant. Interestingly the ~770 day period of CH Cyg was not detected until after the onset of activity. This implies that the luminosity of the white dwarf has been greatly enhanced by the onset of activity. The 1300 day period, which is almost exactly twice this period, is most likely not physically significant but is an alias of the 756 day orbital period.

The velocity amplitude of the 756 day short-period orbit appears too small for orbital information to be derived from the existing *visual* spectra. As mentioned in the introduction, a ~770 day period has been reported in velocities measured from visual lines formed in the M star (Skopal 1989, Mikolajewski *et al.* 1990). The similarity of the semiamplitude of the orbit to the uncertainties of the visually determined velocities makes even the detection of this period difficult from velocities with typical uncertainties of several km s^{-1}.

Further insight into the CH Cyg system requires setting some limits on the masses. Circumstantial evidence points toward the M giant in CH Cyg being a relatively low mass object. The galactic distribution of the known symbiotic stars is similar to that of planetary nebulas and galactic novas, and consistent with membership in the old disk population (Kenyon 1986). The infrared colors of *S*-type symbiotics are similar to galactic bulge M giants (Whitelock & Munari 1992). The bulge giants have low masses ($\sim 1\ \mathscr{M}_\odot$) and solar metallicities. In the case of CH Cyg, the center-of-mass velocity is somewhat high for the galactic latitude ($b=15°$), and suggests that this system is a member of the old disk (Wallerstein 1983). From the above arguments we conclude that the M6 giant is not particularly massive and propose an upper limit of 2 $\mathscr{M}_\odot$.

The single-lined spectroscopic binary solution provides a mass function, which is a function of the inclination and the primary and secondary masses. If two of these parameters are assumed, then the third is determined and the most likely model of the system can be identified. Some limits on the inclination can be derived from the infrared spectra. CO linewidths are greatest when the hot star is in front of the M star. The observed changes with short-period phase shows that the orbit is not viewed from a near pole-on angle. However, a quantitative limit is not readily obtained from this observation. A quantitative limit can be set from the expansion rate of the radio jet on the sky combined with a radial velocity for the jet (measured from the [O III] 5007 A line) and a distance. The expansion rate on the sky seems well established at 1.1 arcsec yr^{-1} (Taylor *et al.* 1988). The minimum distance of 120 parsec indicated by the apparent bolometric magnitude and the luminosity derived from the 100 day period (Sec. 3) combined with the [O III] velocities of Bode *et al.* (1991) give an inclination $\gtrsim 78°$. However, the [O III] line is highly asymmetric and the uncertainty on the expansion velocity and hence on the inclination is likely to be substantial. Of course, this inclination is derived from the polar structure and is not necessarily that of the orbital plane.

In cataclysmic variables the accretion disk lies in the plane of the orbit (Robinson 1976). Similar arguments would indicate that an accretion disk in the CH Cyg system is in the orbital plane and thus that the orbital plane is seen near edge on so that eclipses might take place. Although Mikolajewski *et al.* (1987) have claimed that eclipses occur, the supposed eclipses were in the long-period orbit and their reality is discussed later. Eclipsing symbiotic systems are known; CI Cyg is the best known example. Bensammar *et al.* (1988) and Bensammar (1989) present infrared spectra of CI Cyg. These spectra reveal that the CI Cyg 2.17 μm hydrogen Brackett γ line undergoes strong phase dependent changes. Brackett γ is strongly in absorption (central depth ~50%) at phase 0.5. This results from viewing the M star through the mass flow/accretion disk. We have examined the CH Cyg spectra for changes in the Brackett γ line. As noted above, the changes are limited to nearly undetectable emission in the early 1980's. The line never goes into absorption or undergoes any other phase dependent change. The phase coverage during the short-period orbit is quite complete, with an average interval between spectra of 0.04 in phase. The largest gap in phase coverage is 0.14 between (circular orbit) phases 0.68 and 0.82 with the next largest gap in phase coverage being half this large. Within the constraint of comparing CH Cyg to CI Cyg, we feel confident that eclipses do not occur. Our observations also cover periods of changing activity (including 1984–1985) in the symbiotic system and the lack of evidence in our data for eclipses also eliminates the possibility that eclipses occur only during times of enhanced mass transfer.

The secondary is assumed to be a white dwarf. *IUE* observations have shown no evidence of an O or B star (Kenyon & Webbink 1984) and a white dwarf or perhaps a planetary nebula central star on its way to becoming a white dwarf are the only other possibilities that could produce the reported high jet velocities. In addition our mass function is extremely small, 0.0014 $\mathscr{M}_\odot$, and results in secondary masses significantly below 1 $\mathscr{M}_\odot$ unless the orbital inclination is very low, 15° or less. As noted above the inclination determined for the radio jet implies that this is not the case. A 2 $\mathscr{M}_\odot$ primary in an orbit seen nearly edge on requires a secondary mass of about 0.2 $\mathscr{M}_\odot$. The typical mass of a white dwarf is 0.5–0.6 $\mathscr{M}_\odot$ with 75% of white dwarfs having masses $\pm 0.1\ \mathscr{M}_\odot$ of the mean value (Bergeron *et al.* 1992). While Bergeron *et al.* show that 0.2 $\mathscr{M}_\odot$ white dwarfs are unusual, their results indicate that white dwarfs of this mass occur. These objects cannot be produced by core-helium ignition from single-star evolution. Instead, Iben and Tutukov (1986) have suggested that such objects are the result of mass transfer in close binary systems. However, the orbital period of CH Cyg does not

TABLE 4. Models.

M_1 ($M_\odot$)	M_2 ($M_\odot$)	i_S(°) from f(m)	Kepler's a (total in $R_\odot$)	r(q) ($R_\odot$)	i_S(°) for eclipse if R=r(q)	R_{min}($R_\odot$) if i_S=80° and no eclipse
1	0.5	17	400	176	>64	69
2	0.5	24	474	238	>60	82
1	0.2	40	371	193	>59	64
2	0.2	70	454	262	>55	79

appear to be consistent with such a model. From Table 1 of Iben and Tutukov their model results in a 0.2 $\mathscr{M}_\odot$ white dwarf if the final orbital period is on the order of several weeks and not several years as is seen for CH Cyg.

With the above constraints in mind we have tabulated results for four specific models that span the range of probable component masses for the short-period pair (Table 4). Columns 1 and 2 give the masses of the M giant and the white dwarf, respectively. Column 3 is the short-period inclination computed from the mass function and the assumed masses. Column 4 is the semimajor axis computed from Kepler's third law. Column 5 is the Roche-lobe radius [$r(q)$] of the M giant computed with the formula of Eggleton (1983). Column 6 is the minimum inclination for eclipses if the M giant fills its Roche lobe. Column 7 is the minimum radius of the M giant if the short-period inclination is 80° as suggested by the [O III] observations, and if the system undergoes grazing eclipses. Thus, at an 80° inclination the M giant would have to be smaller than this to have no eclipses.

Of the four models two have the typical white-dwarf mass of 0.5 $\mathscr{M}_\odot$. In both cases the inclination is very low, about 20°, and completely inconsistent with the inclination required by the observations. However, it should also be noted that from column 7 for an inclination of 80°, as seems required by the jet observations, all four models indicate that the radius of the M giant must be relatively small, less than about 64–82 $R_\odot$ for the system not to eclipse. This suggests that the derived inclination from the jet observations cannot be taken too literally.

If CH Cyg does not eclipse and if the inclination is indeed relatively high as seems required by the jet observations, then the orbit must be observed at an angle somewhat outside of the limits for an eclipse to occur. Of our four models, only the one with masses of 2 and 0.2 $\mathscr{M}_\odot$, model No. 4, results in a relatively high inclination, 70°, so we examine the implications of this combination of masses in the following discussion. If the total mass of the symbiotic pair is 2.2 $\mathscr{M}_\odot$, the mass of the third star is 0.86 $\mathscr{M}_\odot$ if the orbit is coplanar with the symbiotic orbit. The mass indicates that the third star is a late G main-sequence star. Such a star would certainly not be detected spectroscopically.

In model No. 4 the Roche-lobe radius of the M giant is 262 $R_\odot$. The radius of a M6 giant is on the order of 200 $R_\odot$ (Wesselink *et al.* 1972). As discussed in the introduction, CH Cyg has both a measured apparent luminosity and a limit on its distance. These values clearly indicate that R is less than 260 $R_\odot$; e.g., the 100 days SRa period combined with the Hughes and Wood (1990) calibration of LMC variables gives $R=154$ $R_\odot$. A radius of 155 $R_\odot$ would have an inclination of 70° if it is not to eclipse. In all cases, a comparison of the estimated stellar and Roche-lobe radii indicates that the system does not fill its Roche lobe. On the basis of ultraviolet flickering and double peaked Fe II and Balmer emission lines, Garcia (1986) classified the CH Cyg system as within a factor of 2 of filling its Roche lobe, which just seems compatible with the above values.

The above ambiguities about the CH Cyg system could be resolved if CH Cyg could be shown to be a double-lined spectroscopic binary. Several attempts have been made to find an orbit for the hot component from visual high excitation lines. Tomov and Luud (1984) claimed that velocities of the absorption lines of ionized metals, seen during recent high activity phases in the late 1970's and 1980's, reflect the motion of the hot component of this symbiotic system. They attempted to determine an orbit with a period of about 5700 days for this hot object. Additional orbital solutions with these assumptions were determined by Mikolajewski *et al.* (1987). The quality of these orbital fits is very poor at best.

As we have shown, the basic assumption that the hot star and the M giant orbit each other with a 15–16 yr period is incorrect. Since the hot star and the M giant are both actually in the short-period orbit, their short-period velocities will be 180° out of phase. However, the center-of-mass velocity of the hot star *should reproduce the long-period velocity curve* rather than being an approximate mirror image of it. We reexamined the velocity data of Tomov and Luud (1984), Skopal (1988), and Skopal *et al.* (1989) with the goal of fitting these velocities to our orbits. The radial velocity curves presented by Skopal for ionized metals, Fe II and [Fe II] are quite different. We were not able to identify a reasonable velocity curve for the secondary from any of these data. Fe II has neither the velocity of the M giant nor the velocity expected for the white dwarf. Bode *et al.* (1991) suggested Hα line is formed in the mass being transferred between the M star and the hot star. We suggest that Fe II lines are formed in this same region.

A discussion of the CH Cyg system would be incomplete without a review of the "eclipse." As noted previously, it has been proposed that the hot component in CH Cyg was eclipsed by the M star for ~20 months starting 1984 July 28 (JD 2445910; Mikolajewski *et al.* 1987). An excellent summary of the observations that were interpreted as evidence for an eclipse is presented by Mikolajewski *et al.* (1988). While an unusual occurrence, it is not at all obvious that the event beginning in 1984 July should be interpreted as an eclipse. For instance, Selvelli (1988) noted that x-ray flickering continued during the eclipse and that in 1986 September the UV flux fell to lower values than during the eclipse. He I 4026 Å line profiles presented by Janaszak and Mikolajewski (1988) are about 4 times broader during the eclipse than before. This would imply that a higher energy region was being observed in the high excitation object, in accord with the x-ray detection and not that the high excitation object was eclipsed. Tomov (1984) and Selvelli and Hack (1985) report that higher excitation emission lines and very broad Balmer wings appeared during the eclipse, in agreement with higher rather than lower excitation.

The discovery that the symbiotic pair is in a 756 day orbit rather than a 15 yr orbit destroys the eclipse interpretation. The 1984 July event lasted ~20 months, which is ~80% of a short-period orbit. If the 1984 July event were an eclipse, similar events should be recorded approximately every 2 yr and they are not. The third star in the system appears to be a main-sequence star incapable of creating eclipses every 15 yr. As noted above, observations of the Brackett γ line indicate that there is never a significant column density of mass flow/accretion disk material along the line of sight to the M star. Since significant mass transfer appears to be taking place, CH Cyg cannot be an eclipsing system.

An original focus of our research was to look at the velocity variations that result from the SR-type variability of the M 6 III. We used the total velocity residuals of the eccentric fit to the Kitt Peak data to search for possible periodic velocity variations due to pulsation. Although we concentrated on periods close to 100 days (as indicated by photometry) we searched for possible periods between 50 and 200 days. No periodicities were evident in our total data sample. We similarly examined two extensive subsets of the data from JD 2445475 to 2445812 and from JD 2445986 to 2446509 but found no periodicities.

6. CONCLUSIONS

The application of moderately high-precision infrared velocities has resolved a number of outstanding issues concerning the CH Cyg system. Both the infrared nature of the velocities and the high precision obtained are of equal importance. Since the symbiotic activity does not alter the infrared velocities, it has been possible to obtain useful data *regardless* of the state of outburst of the system. We are looking forward to the imminent availability of infrared array spectrometers (e.g., Tokunaga *et al.* 1990, Ridgway & Hinkle 1987). With these instruments it will be possible to observe in the 1–2.5 μm infrared nearly all of the symbiotics listed by Allen (1982) at high spectral resolution. The symbiotic systems are of interest not only from the kinematic properties of close binaries but, as mass exchange systems, they should have interesting abundances which could also be explored in the infrared.

The accuracy of the velocity data used in this paper exceeds that of other velocity measurements for this star and most other symbiotic stars by about an order of magnitude. With this increase in precision we have been able to analyze low amplitude accelerations in the CH Cyg system and have been able to demonstrate the triple nature of the system. As symbiotic systems are studied in increasing detail subtile effects are revealed, e.g., phase dependent changes in the M-giant line profiles. Now that CH Cyg has been shown to be a triple system, we question the current binary-star models of other extremely long-period mass-transfer binaries, in particular R Aqr and *o* Cet.

Variations in the transfer of mass between the symbiotic M giant-hot star pair in the CH Cyg triple system must be the origin of the interesting phenomena recorded at shorter wavelengths during the last 20 yr. The misinterpretation of the 1984 mass transfer event as an eclipse needs to stand as a warning to those attempting to interpret observations of these complex systems. An unresolved question is how CH Cyg, which clearly is a mass-transfer but not a Roche-lobe filling system, could be in the extended period of inactivity this system exhibited before 1963.

We are indebted to George Wallerstein for providing encouragement toward the completion of this project and for bringing a key reference to our attention. Scott Kenyon provided a number of important comments that strengthened the discussion section. Teresa Wilson and Crystal Martin provided assistance with some aspects of the data reductions. Bill Lenz and Dave Stultz assisted at the telescope. The publication of this research has been supported in part by a contribution from Weaver C. Barksdale to the Dyer Observatory, Vanderbilt University.

REFERENCES

Allen, D. A. 1982, in The Nature of Symbiotic Stars, edited by M. Friedjung and R. Viotti (Reidel, Dordrecht), p. 27
Andrillat, Y. 1988, Inf. Bull. Var. Stars, 3223
Bailyn, C. D., & Grindlay, J. E. 1987, ApJ, 312, 748
Batten, A. H., Fletcher, J. M., & MacCarthy, D. G. 1989, Publ. Dom. Astrophys. Obs., Victoria, B.C., 17, 1
Belyakina, T. S. 1968, AZh, 45, 139
Belyakina, T. S. 1970, Afz, 6, 49
Bensammar, S. 1989, in Proceedings of 22nd ESLAB Symposium, edited by B. H. Kaldeich (ESO, Paris), p. 339
Bensammar, S., Friedjung, M., Letourneur, N., & Maillard, J. P. 1988, A&A, 190, L5
Bergeron, P., Saffer, R. A., & Liebert, J. 1992, ApJ, 394, 228
Bode, M. F., Roberts, J. A., Ivison, R. J., Meaburn, J., & Skopal, A. 1991, MNRAS, 253, 80
Cester, B. 1968, Inf. Bull. Var. Stars, 291
Daniels, W. 1966, University of Maryland, Dept. of Physics & Astronomy Technical Report No. 579
Davey, S., & Connon-Smith, R. 1992, MNRAS, 257, 476
Deutsch, A. J. 1964, in Annual Report Mt. Wilson and Palomar Obs. 1963–1964, p. 11
Deutsch, A. J., Lowen, L., Morris, S. C., & Wallerstein, G. 1974, PASP, 86, 233
Eggleton, P.P. 1983, ApJ, 268, 368
Fekel, F. C., & Tomkin, J. 1982, ApJ, 263, 289
Garcia, M. R. 1986, AJ, 91, 1400
Goldman, I., & Mazeh, T. 1991, ApJ, 376, 260
Graff, K. 1924a, Beobachtungs-Zirkulare der ANac, 6,5
Graff, K. 1924b, Beobachtungs-Zirkulare der ANac, 6, 36
Gusev, E. B. 1976, Astron. Tsirkular, 901, 2
Hack, M., Rusconi, L., Sedmak, G., Aydin, C., Engin, S., & Yilmaz, N. 1986, A&A, 159, 117

Hack, M., Rusconi, L., Sedmak, G., Engin, S., & Yilmaz, N. 1982, A&A, 113, 250
Hack, M., & Selvilli, P. L. 1982, A&A, 107, 200
Hall, D. N. B., & Hinkle, K. H. 1981, in Solar Instrumentation: What's Next, edited by R. B. Dunn (NSO, Sunspot), p. 246
Hall, D. N. B., Ridgway, S. T., Bell, E. A., & Yarborough, J. M. 1978, Proc. SPIE, 172, 121
Hinkle, K. H., Hall, D. N. B., & Ridgway, S. T. 1982, ApJ 252, 697
Hinkle, K. H., Scharlach, W. W. G., & Hall, D. N. B. 1984, ApJS, 56, 1
Hinkle, K. H., Scharlach, W. W. G., & Johnson, D. S. 1993, in preparation
Hinkle, K. H., Scharlach, W. W. G., & Shaw-Hanson, A. D. 1985, BAAS, 16, 897
Hughes, S. M. G., & Wood, P. R. 1990, AJ, 99, 784
Iben, I. & Tutukov, A. V. 1986, ApJ, 311, 753
Ipatov, A. P., Taranova, O. G., & Yudin, B. F. 1984, A&A, 135, 325
Ivison, R. J., Bode, M. F., Roberts, J. A., Meaburn, J., Davis, R. J., Nelson, R. F., & Spencer, R. E. 1991, MNRAS, 249, 374
Janaszak, E., & Mikolajewski, M. 1988, in The Symbiotic Phenomenon, edited by J. Mikolajewska, *et al.* (Kluwer, Dordrecht), p. 225
Joy, A. H. 1942, ApJ, 96, 344
Kaler, J. B., Kenyon, S. J., & Hickey, J. P. 1983, PASP, 95, 1006
Keenan, P. C. 1963, in Basic Astronomical Data, edited by K. Aa. Strand (University of Chicago Press, Chicago), p. 78
Kenyon, S. J. 1986, The Symbiotic Stars (Cambridge University Press, Cambridge)
Kenyon, S. J., Fernandez-Castro, T., & Stencel, R. E. 1988, AJ, 95, 1817
Kenyon, S. J., & Garcia, M. R. 1986, AJ, 91, 125
Kenyon, S. J., & Webbink, R. F. 1984, ApJ, 279, 252
Kwok, S., Bignell, R. C., & Purton, C. R. 1984, ApJ, 279, 188
Leahy, D. A., & Taylor, A. R. 1987, A&A, 176, 262
Luud, L., Ruusalepp, M., & Vennik, J. 1977, Publ. Tartu Astrofiz. Obs., 45, 113
Mathieu, R. D., & Mazeh, T. 1988, ApJ, 326, 256
Mazeh, T., & Shaham, J. 1979, A&A, 77, 145
Mikolajewski, M., Mikolajewska, J., & Khudyakova, T. N. 1990, A&A, 235, 219
Mikolajewski, M., Szczerba, R., & Tomov, T. 1988, in The Symbiotic Phenomenon, edited by J. Mikolajewska, *et al.* (Kluwer, Dordrecht), p. 221
Mikolajewski, M., & Tomov, T. 1986, MNRAS, 219, 13P
Mikolajewski, M., Tomov, T., & Mikolajewska, J. 1987, Ap&SS, 131, 733
Muciek, M., & Mikolajewski, M. 1989, AcA, 39, 165
Norton, R. H., & Beer, R. 1976, J. Opt. Soc. Am., 66, 259
Ridgway, S. T., & Hinkle, K. H. 1987, in The Impact of Very High S/N Spectroscopy on Stellar Physics, edited by M. Spite (Reidel, Dordrecht), p. 61
Robinson, E. L. 1976, ARA&A, 14 119
Seaquist, E. R., & Taylor, A. R. 1990, ApJ, 349, 313
Selvelli, P. L. 1988, in The Symbiotic Phenomenon, edited by J. Mikolajewska, *et al.* (Kluwer, Dordrecht), p. 209
Selvelli, P. L., & Hack, M. 1985, Astron. Express, 1, 115
Skopal, A. 1988, in The Symbiotic Phenomenon, edited by J. Mikolajewska, *et al.* (Kluwer, Dordrecht), p. 223
Skopal, A. 1989, Cont. Astr. Obs. Skalnaté Pleso, 18, 31
Skopal, A., Mikolajewski, M., & Biernikowicz, R. 1989, Bull. Astron. Inst. Czechoslovakia, 40, 333
Slovak, M. H., & Africano, J. 1978, MNRAS, 185, 591
Soderhjelm, S. 1984, A&A, 141, 232
Solf, J. 1987, A&A, 180, 207
Tassoul, J.-L. 1988, ApJ, 324, L71
Taylor, A. R., Seaquist, E. R., & Kenyon, S. J. 1988, in The Symbiotic Phenomenon, edited by J. Mikolajewska, *et al.* (Kluwer, Dordrecht), p. 231
Taylor, A. R., Seaquist, E. R., & Mattei, J. A. 1986, Nature, 319, 38
Tokunaga, A. T., Toomey, D. W., Carr, J., Hall, D. N. B., & Epps, H. W. 1990, Proc. SPIE, 1235, 131
Tomov, T. 1984, Inf. Bull. Var. Stars, 2610
Tomov, T., & Luud, L. 1984, Afz, 20, 99
Tsuji, T. 1988, A&A, 197, 185
Wallerstein, G. 1968, Obs. 88, 111
Wallerstein, G. 1983, PASP, 95, 135
Wdowiak, T. J. 1977, PASP, 89, 569
Wesselink, A. J., Paranya, K., & DeVorkin, K. 1972, A&AS, 7, 257
Whitelock, P., & Munari, U. 1992, A&A, preprint
Wilson, R. E. 1942, ApJ, 96, 371
Wing, R. F. 1963, MNRAS, 125, 189
Yamashita, Y. 1967, Publ. DAO, 13, 47
Yamashita, Y., & Maehara, H. 1979, PASJ, 31, 307
Yoo, K. H., & Yamashita, Y. 1991, Publ. Natl. Astron. Obs. Japan, 2, 1