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VELOCITY OBSERVATIONS OF MULTIPLE-MODE ASYMPTOTIC GIANT BRANCH VARIABLE STARS

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ABSTRACT

Numerous infrared spectroscopic observations were obtained of nine asymptotic giant branch (AGB) field M giants that have multiple periods of light variability. Each star has a short period of several months, which is typical of low amplitude pulsation for stars on the AGB, as well as a long period of 1–3 yr, which is significantly longer than the predicted fundamental-mode pulsations for these stars. The location of these stars in the AGB period-luminosity relation is discussed. For six of the nine giants we found radial-velocity periods that confirm the long-period light variability. Although we considered the possibility that the velocity variations result from orbital motion, we conclude that the long-period velocity changes in most, if not all of the sample stars, likely result from a currently unknown type of pulsation rather than duplicity.

Key words: binaries: general — stars: AGB and post-AGB — stars: variables: other

1. INTRODUCTION

The broad group of long-period variables encompasses, among other variable types, the pulsating M-giant Mira variables and semiregular variables (SRVs). The division of these two classes is the result of historically based, optical criteria. At visual wavelengths the Miras show variability amplitudes $\geq$2.5 mag, while the SRVs have smaller amplitudes. In a seminal paper, Wood et al. (1999) used MACHO observations of late-type giant variables in the Large Magellanic Cloud (LMC) to produce a period-luminosity diagram for those variables. In that diagram the division between Mira and SRVs is not obvious, but the division between pulsation modes is, and Wood et al. (1999) identified five separate period-luminosity sequences. The period-luminosity diagram also provides additional evidence that these variables are on the asymptotic giant branch (AGB), since in the LMC Miras and SRVs vanish at luminosities less than the minimum luminosity for thermally pulsing AGB stars with mass $\sim$1 $M_{\odot}$. In the LMC period-luminosity diagram, longer periods, exhibited by the Miras, are also associated with higher luminosity. This confirms the results of Kerschbaum & Hron (1992), Bedding & Zijlstra (1998), and Lebzelter & Hron (1999), who from several lines of research had argued that the SRVs are likely progenitors of Miras.

A number of late-type giant variables have been found to have at least two periods (Houk 1963; Whitelock et al. 1997; Mattei et al. 1997; Kiss et al. 1999). Period ratios divide these stars into two groups (Mattei et al. 1997; Percy & Bagby 1999; Wood et al. 1999). One group consists of variables with period ratios of roughly 1.8. For this group both periods are in the range typical for a SRV. Mattei et al. (1997) found that most SRVs are members of this group and noted that this period ratio is marginally consistent with mode switching between the fundamental and first overtone, a ratio of 2.2 in linear pulsation analysis.

The second group of multiperiod AGB variables has period ratios ranging from about 5 to 13. The LMC period-luminosity diagram shows the extraordinary significance of these objects. They largely fall on a sequence in the period-luminosity diagram that is parallel to the sequence believed to be that of the fundamental-mode pulsators but at longer periods ranging from 250 to over 1000 days. In their Figure 1 Wood et al. (1999) have labeled this period-luminosity sequence as "D." Pulsation theory does not allow a period of radial pulsation longer than the fundamental mode. Thus the D sequence makes clear a result hinted at by the earlier papers: the nature of long periods, which are much longer than the corresponding fundamental modes, is unknown. Wood (2000b) discussed various possible causes of such periods and concluded that the only plausible ones are pulsation in modes connected to the convective stellar-interior structure or duplicity. Mattei et al. (1997) made the additional suggestion that some long periods could be characteristic timescales, typically subharmonics of the main period and perhaps related to the onset of chaotic behavior, rather than true periods.

In the Eighth Catalogue of the Orbital Elements of Spectroscopic Binary Systems (Batten, Fletcher, & MacCarthy 1989) M, S, and C giants account for just over 1% of the systems listed, with only about one-third of these containing a noninteracting, "normal" red giant. The other binaries with M, S, and C giants are peculiar systems, where the binary nature has been made apparent because of mass transfer. The reason for this small number of known nor-

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mal, red giant, binary systems is twofold. First, the red giants are physically large, with radii ranging from $\sim$40 $R_\odot$ to 200 $R_\odot$ (Dumm & Schild 1998). Thus, close companions have merged by the time a star becomes a red giant. The period of the shortest allowed binary orbit for a M giant is a function of the primary mass and is typically $\sim$100 days but can be as short as $\sim$30 days (Mermilliod & Mayor 1996). M giants are typically AGB stars and so have masses in the range 1–2 $M_\odot$. Usually the secondary has a mass less than the M giant primary. Large separations combined with the modest masses of these systems result in spectroscopic binaries that do not have rapid velocity changes and hence will not be easily detected. Second, M giants typically have light and velocity variations due to pulsations that will make any search for orbital motion more difficult. Since the AGB lifetime is brief and AGB stars are highly luminous, the likelihood of detecting a double-lined AGB binary is very small.

Orbits for late-type stars can lead to mass estimates and quantitative information about the epoch and magnitude of mass loss during stellar evolution. Simple arguments based on mass and radius show that Mira variables will have very long orbital periods because of their large radii and low masses. Due to their smaller stellar radii, binary systems with SRVs can have shorter periods, making them more promising objects for study. A review of the literature finds eight SRVs with orbits (see § 5). In addition, Van Eck et al. (2000) surveyed over 200 S stars and determined orbits or preliminary orbits for eight more red giants. However, the majority of currently known M-giant spectroscopic orbits have been determined through spectroscopic surveys of cluster stars (see Mermilliod et al. 1998 and references therein).

The most commonly observed red giant binaries are the symbiotic stars. These are mass-exchange systems that usually consist of a M giant and a hot compact or dwarf companion. The prototype Mira, *o* Ceti, is in fact a system of this type with a low level of interaction between the members. A common feature of many symbiotic stars is that their orbital periods can be detected photometrically even when quiescent. In some symbiotics tidal distortion of the giant by the white dwarf or the reflection of the white dwarf radiation off the surface of the giant results in light variability. Many symbiotics are also found to be eclipsing binaries. Such effects could be detected photometrically in normal, i.e., nonmass-exchange, M giant binaries. Since all M giants are undergoing mass loss, it is also possible that the effects of the companion on the mass-loss process might play some role in helping to detect these stars.

We have extracted a list of stars from Houk (1963) that have multiple photometric periods but are otherwise normal M giants. The multiperiod variables were one of several samples in a spectroscopic program to measure the orbits of late-type binaries. These stars were included at the telescope in a program principally focused on orbital determination of symbiotic binaries (Fekel et al. 2000). We have monitored our small subset of the multiple-period variables spectroscopically for several years. In this paper we report the results of this survey and discuss the nature of these stars.

2. OBSERVATIONS AND REDUCTIONS

The program stars were typically observed four to five times per year between 1995 and 2000. Most of our spectroscopic observations were obtained with the 0.9 m coudé feed telescope and spectrograph system at the Kitt Peak National Observatory (KPNO). The detector was the infrared camera NICMASS with a 256 × 256 HgCdTe array, developed at the University of Massachusetts by M. Skrutskie. At the coudé feed the standard observing configuration resulted in 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) and Fekel et al. (2000).

Additional observations were obtained with the Phoenix cryogenic echelle spectrograph at the f/15 Cassegrain focus of either the KPNO 2.1 or 4 m telescopes. A complete description of the spectrograph can be found in Hinkle et al. (1998). Typically the widest slit was used, giving a resolution $\sim$50,000, but a few of the observations have a resolution $\sim$70,000. The Phoenix observations were centered at either 1.563 or 2.226 μm. An expanded discussion of the experimental setup has been given in Fekel et al. (2000).

Radial velocities of the program stars were determined with the same techniques described in Fekel et al. (2000), by cross correlation with the M-giant radial-velocity standard stars δ Oph or α Cet. The velocities of those two standards were adopted from Scarfe et al. (1990). The velocity errors are estimated to be less than 1 km s^{-1}.

A period search was carried out on the radial velocities of each program star. The range of trial periods was usually 1 to 1000 days, but for the three program stars with velocity variations greater than 750 days the range of trial periods was increased to 1 to 2000 days. For each trial period a sine curve was fitted to the velocities phased with that period. The minimum value of the summed squared residuals from the sine curve fit was identified initially as the best period.

Two computer programs were used to determine possible orbital elements of the various systems. Preliminary elements were determined with BISP, a computer program that uses a slightly modified version of the Wilsing-Russell method (Wolfe, Horak, & Storer 1967). A differential corrections program called SB1 of Barker, Evans, & Laing (1967) was then used to compute the single-lined spectroscopic orbit.

3. SAMPLE SELECTION

The program stars were drawn solely from a list of long-period variables with multiple periods, produced by Houk (1963) from a search of the 1958 edition of the General Catalogue of Variable Stars and its 1960 supplement. We only included stars with large period ratios in our sample. The intent was to select systems where the long and short periods could be easily separated. However, as has been discussed above, we now realize that this criteria restricts the sample to include only potential Wood et al. (1999) sequence-D stars.

A further set of restrictions on the sample was imposed by the observing equipment and data reduction tools. Because of the sensitivity limitations imposed by observing with a 0.9 m telescope, only giants that are relatively bright in the infrared, as determined by inclusion in the Two Micron Sky Survey (Neugebauer & Leighton 1969), were considered. The initial program included carbon- and oxygen-rich sources. Difficulties were encountered in measuring the velocities of the carbon-rich sources because the presence of strong CN red-system lines made their spectra very different from the reference spectra (§ 2). The data for carbon-rich stars

TABLE 1
BASIC PARAMETERS OF THE PROGRAM STARS

Var. Name	HD	Spec. Type	Var. Type	P_1 (days)	P_2 (days)	P_3 (days)	P_l/P_1	Period Ref.	π (mas)	M_K
SS And.....	218942	M7 II:	SRc	152.5	650	...	4.3	1	2.87	−6.74
SV And	225192	M6.5e	Mira	316	930	...	2.9	1	6.82	−3.23
RR CrB.....	140297	M3	SRb	61	377	...	6.1	1	3.67	−6.28
RS CrB	143347	M7	SRa	69.5	183	331	4.8	1, 2	2.53	−6.21
AF Cyg	184008	M4	SRb	93	163	921	9.9	2, 3	3.30	−7.11
X Her.....	144205	M8	SRb	102	178	746	7.3	1, 3	7.26	−6.99
g Her.....	148783	M6 III	SRb	62	90	888	14.3	2, 3	9.03	−7.26
V574 Oph....	165510	M4	SRa	71.5	500	...	7.0	1	...	...
BI Peg	...	M9	SRa	60–80	500	...	7.1	1	...	...

REFERENCES.—(1) Houk 1963; (2) Mattei et al. 1997; (3) Kiss et al. 1999.

are not discussed here. The sample was also restricted by excluding all stars south of the equator and north of declination +60°. The northern limit was imposed by vignetting in the telescope. The sample was limited to objects in the right ascension range 15–24 hr because of the observing season selection. Basic properties of our nine stars are listed in Table 1. Our sample includes three SRa stars, four SRb stars, one SRc, and one Mira.

A search of the literature did not produce any evidence that duplicity had been previously found for any of the stars in our sample. In particular, the *Hipparcos* catalog (ESA 1997) gives no indication of any companions. Recently, multiple-period variables have been discussed by several groups. Since our observational program started in 1995, our selection of objects was not influenced by more recent works such as those of Mattei et al. (1997), Kiss et al. (1999), and Wood et al. (1999).

4. INDIVIDUAL STARS

In the following subsections we discuss the velocity changes seen in each of the multiply periodic program stars. On the basis of a comparison of the short periods with typical values for SRVs, we assumed that the short periods of our program stars result from pulsation that is normal for their variable-star class. Each variable also has a second, much longer period that we were particularly interested in detecting spectroscopically. SRa variables have a mean period of 291 days, and SRb variables a mean period of 167 days (Kerschbaum & Hron 1992). A caveat, however, is that, while the vast majority of SRa– and SRb–type variables listed in the General Catalogue of Variable Stars (Kholopov et al. 1985–1988) have periods less than 250 to 300 days, there is a tail to the distribution with periods over 600 days (Kerschbaum & Hron 1992). The range of the program stars' short periods is 60 to 316 days, while the range of their long periods is 331 to 960 days.

Lebzelter (1999) examined the short-period velocity variability of SRVs. As in the current work, velocities were measured in the near-infrared by the use of the second-overtone lines of CO. Variability with an amplitude as large as a few kilometers per second was found in all SRVs investigated. As shown by Lebzelter, Kiss, & Hinkle (2000), such variations are correlated with the light variability of these stars. However, the short-period light variability in these SRVs is not strictly regular in period and amplitude, which inhibits a "subtraction" of the short-period changes. Since our velocity data contain both short and long-period variations, the short-period velocity changes have sometimes contributed to larger than expected uncertainties in the long-period quantities.

To examine the possibility that the long periods seen in the light variability of our stars are the result of binary motion, we determined orbital elements for those stars having radial-velocity periods greater than 300 days. The orbital elements are listed in Table 2.

4.1. *SS And*

Houk (1963) listed periods of 152.5 days and 650 days for this SRc–type variable. The original observations are reported in Florya (1949). The periods for SS And are based on photographic magnitudes spanning 14,500 days. During this time SS And experienced brightness changes of about 0.4 mag with a ∼150 day period and brightness changes of about 1.4 mag with a much longer and highly irregular period.

TABLE 2
"ORBITAL" ELEMENTS

Name	P (days)	γ (km s^{-1})	T (HJD)	K (km s^{-1})	e	ω (deg)	$f(m)$ ($M_\odot$)
RS CrB	328.3 ± 2.6	−80.9 ± 0.2	2,451,770.9 ± 21.9	2.4 ± 0.3	0.35 ± 0.11	251 ± 20	0.0004 ± 0.0002
AF Cyg	926.3 ± 36.4	−14.8 ± 0.2	2,451,224.6 ± 330.0	1.8 ± 0.4	0.08 ± 0.20	58 ± 128	0.0006 ± 0.0004
X Her.....	658.3 ± 17.0	−90.3 ± 0.2	2,451,770.9 ± 62.1	1.6 ± 0.3	0.32 ± 0.15	319 ± 29	0.0002 ± 0.0001
g Her.....	843.7 ± 21.1	1.2 ± 0.2	2,451,918.2 ± 43.9	2.3 ± 0.3	0.37 ± 0.11	246 ± 21	0.0009 ± 0.0004
V574 Oph.....	690.0 ± 26.6	−35.7 ± 0.2	2,451,540.0 ± 61.8	1.7 ± 0.3	0.33 ± 0.17	251 ± 26	0.0003 ± 0.0002
BI Peg	548.4 ± 17.3	−28.2 ± 0.3	2,451,368.9 ± 42.3	3.1 ± 0.7	0.36 ± 0.18	240 ± 14	0.0013 ± 0.0009

TABLE 3
RADIAL VELOCITIES OF SS AND

HJD 2,400,000 +	Phase	Velocity (km s^{-1})
49,923.987	0.177	−21.2
49,997.858	0.688	−22.2
49,999.836	0.702	−22.2
50,319.999	0.916	−20.8
50,385.780	0.371	−22.9
50,569.982	0.644	−22.1
50,627.977	0.046	−21.0
50,629.946	0.059	−21.2
50,688.960	0.467	−23.4
50,750.800	0.895	−21.3
50,933.964	0.162	−20.3
50,982.872	0.500	−22.0
51,052.974	0.985	−21.8
51,106.802	0.357	−22.7
51,135.748	0.557	−23.3
51,302.006	0.707	−22.0
51,478.799	0.930	−20.3

TABLE 4
RADIAL VELOCITIES OF SV AND

HJD 2,400,000 +	Visual Phase	Velocity (km s^{-1})
49,924.960	0.48	−90.0
49,997.895	0.70	−83.7
49,999.879	0.71	−84.9
50,000.902	0.71	−84.1
50,320.018	0.72	−84.6
50,385.799	0.93	−78.8, −100.4
50,569.996	0.51	−90.7
50,629.981	0.70	−84.7
50,688.977	0.88	−81.3
50,750.817	0.07	−83.6, −101.5
50,982.966	0.81	−82.7
51,053.003	0.02	−84.8, −102.5
51,106.890	0.19	−97.7
51,135.808	0.28	−96.0
51,478.814	0.36	−92.9
51,833.845	0.51	−91.5

Seventeen velocities were measured for SS And between 1995 July and 1999 October (Table 3). Only a single period of 144.6 days was found for the velocity variations, and the total amplitude is rather small, only 3.1 km s^{-1}. The velocity measurements phased to fit a period of 144.6 days are shown in Figure 1. The velocity variations correspond to the short-period brightness changes and the long-period variability of this star either did not exist during the epoch of our observations or had an amplitude too small to be detected.

4.2. *SV And*

Van der Bilt (1934) presented an analysis of visual light variations of the Mira variable SV And and from times of maxima determined a period of 315.8 ± 1.3 days. From an analysis of visual observations Sterne & Campbell (1936) determined light variability with a period of 315.66 days. Van der Bilt (1934) also detected brightness changes of the maxima with a period of 930 days. This long period is a modulation of the brightness rather than the time of maximum, so it is clearly different from period changes associated with helium shell flashes (Wood & Zarro 1981).

Between 1995 July and 1999 October, 16 observations of SV And were made (Table 4). Visual phases were determined from the AAVSO times of maxima (J. Mattei 2001, private communication) and an assumed period of 315.66 days. This star is the only Mira in the sample, and, as might be expected, it has a velocity amplitude that is by far the largest of the nine stars investigated. A period of 311 days is suggested by the velocities. The velocities have an amplitude of 24 km s^{-1} and show a linear increase with phase followed by a discontinuous jump to the next cycle (Fig. 2).

The velocity curve determined for SV And is nearly identical in shape and amplitude to that seen for several prototype Miras (e.g., Hinkle, Hall, & Ridgway 1982; Hinkle, Scharlach, & Hall 1984; Hinkle, Lebzelter, & Scharlach 1997). The doubled line phase near maximum light is also a typical feature. In addition to the main pulsation periods of Miras, small variations from cycle to cycle in their light and velocity curves are readily detectable. Lebzelter, Hinkle, &

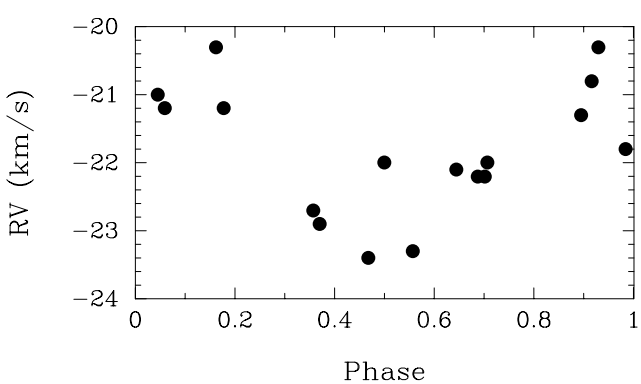

FIG. 1.—Velocities of SS And phased to a 144.6 day period. Zero phase is HJD 2,450,766, which is a time of maximum velocity for a sinusoidal fit to the velocities.

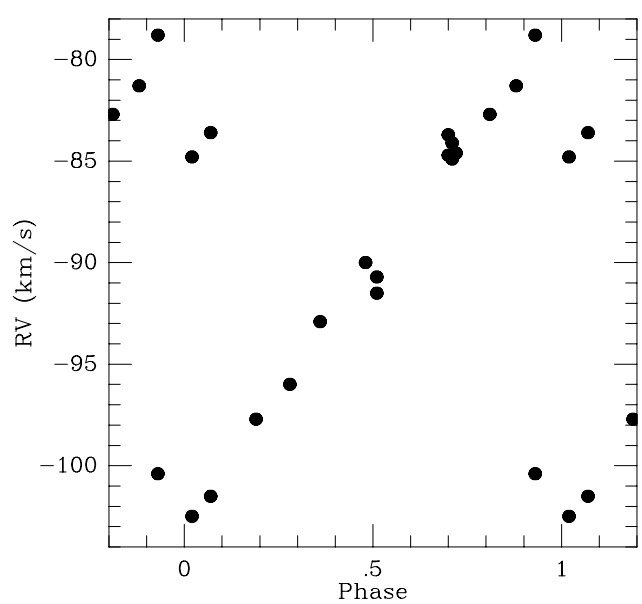

FIG. 2.—Velocities of the Mira SV And phased to the photometric period of 315.7 days. Zero phase is visual light maximum. The data are plotted over more than one cycle for clarity. This type of velocity curve is typical for a Mira variable observed at 1.6 μm.

Aringer (2001) suggested that the velocity changes could result from stellar surface structures. For most Miras the period, if any, of such variations is unknown. Again, SV And has a typical cycle-to-cycle dispersion in the velocity curve.

4.3. *RR CrB*

Based on Harvard survey plates, Payne-Gaposchkin (1952a) found two periods for this SRb–type variable, a short period of light variations with a mean of 60.8 days and a better defined long period of 377 days. We obtained 23 spectrograms of RR CrB between 1995 March and 2000 April (Table 5). A period search of the velocities resulted in possible periods of 54.5 and 214 days. However, the total velocity amplitude of our data is relatively small, only 2.4 km s^{-1}, about 3 times the uncertainty of a single measurement. We note that the results of Lebzelter (1999) indicate that small velocity variations do occur in this star. While it is possible that our velocity period of 54.5 days is associated with the short-period light variations detected by Payne-Gaposchkin (1952a), we find no radial-velocity evidence of the 377 day period.

4.4. *RS CrB*

Payne-Gaposchkin (1952a) examined the light variations of RS CrB from photographic observations obtained between 1899 and 1941. During those years, this SRa–type variable was about 2 mag fainter, ranging from about 9–11 mag, than it is currently. Payne-Gaposchkin (1952a) found two periods, the most obvious of which was 331 days; superposed upon this period was a much shorter cycle for which only a few times of maxima and minima could be determined when the star was bright and the light amplitude was large. The mean value of the Payne-Gaposchkin (1952a) short period is 69.5 days. Mattei et al. (1997) analyzed visual observations from the AAVSO International Database that were obtained between 1961 and 1996. They found periods of 183.0 and 331.6 days. Another analysis of recent visual observations was done by Kiss et al. (1999), who found only a single period of 331 days.

From 1995 March through 2000 April we made twenty-three observations of RS CrB (Table 6). An analysis of the velocities resulted in a period of 331 days. Thus, the 331 day period is seen in both the radial-velocity data and light variations. However, the shorter periodicities apparent at various times in the light variability are not detected in our velocity data. Among the long secondary periods of SRVs in our sample, the 331 day period is the shortest.

The orbital solution to the RS CrB data resulted in a revised period of 328.3 ± 2.6 days. The standard error of an observation of unit weight is 0.8 km s^{-1}. The fit of the orbit to the data is shown in Figure 3. As noted above, a 328 day period is only slightly outside the main range of SRV peri-

TABLE 5
Radial Velocities of RR CrB

HJD 2,400,000 +	Velocity (km s^{-1})
49802.752	−58.9
49803.737	−59.4
49874.751	−58.2
49875.734	−58.1
49923.650	−59.2
49997.580	−59.0
50161.806	−60.2
50162.807	−60.2
50253.682	−58.7
50319.657	−58.5
50386.541	−59.1
50568.723	−59.1
50627.656	−59.2
50751.550	−57.8
50932.797	−59.4
50981.713	−59.4
51051.631	−58.6
51107.549	−59.2
51301.630	−59.2
51345.754	−58.4
51415.615	−59.1
51480.547	−60.2
51649.862	−60.0

TABLE 6
Radial Velocities of RS CrB

HJD 2,400,000 +	Phase	Velocity (km s^{-1})	$O-C$ (km s^{-1})
49,801.825	0.003	−82.1	−0.2
49,802.840	0.006	−81.3	0.5
49,874.780	0.225	−77.9	0.9
49,875.687	0.228	−78.0	0.8
49,923.658	0.374	−80.5	−1.0
49,997.593	0.599	−82.0	−0.8
50,161.816	0.099	−79.9	−0.6
50,162.817	0.102	−79.7	−0.4
50,253.693	0.379	−79.7	−0.1
50,319.671	0.580	−78.9	2.1
50,386.549	0.784	−83.2	−0.3
50,568.733	0.339	−80.4	−1.1
50,627.667	0.518	−80.5	0.0
50,752.544	0.898	−82.8	0.8
50,932.804	0.447	−80.1	−0.1
50,981.721	0.596	−81.3	−0.1
51,051.637	0.809	−83.6	−0.5
51,107.554	0.980	−82.6	0.0
51,301.636	0.571	−80.9	0.1
51,345.746	0.705	−81.6	0.5
51,415.621	0.918	−84.3	−0.7
51,480.552	0.116	−78.7	0.4
51,649.865	0.631	−81.8	−0.3

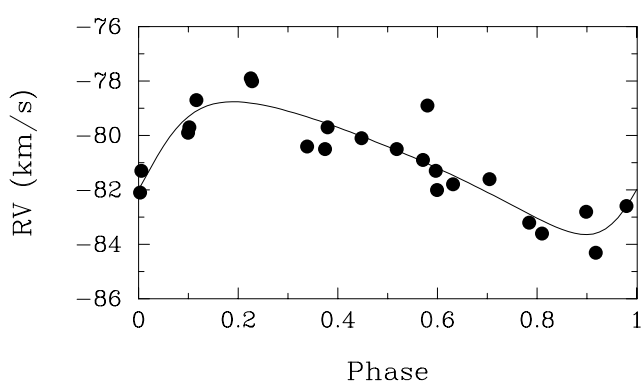

Fig. 3.—Velocities for RS CrB phased by a period of 328.3 days. Zero phase is the time of periastron passage. The line is a best-fit orbit for the data.

ods and is certainly within the period range of known SRV systems.

4.5. *AF Cyg*

AF Cyg is a SRb–type variable for which Houk (1963) listed light variability periods of 94.1 and 960 days. Using AAVSO data Mattei et al. (1997) found periods of 92.9 and 165.9 days. An analysis of four sets of visual observations by Kiss et al. (1999) identified periods of 93 and 163 days, confirming those of Mattei et al. (1997) and also detected a longer period of 921 days, similar to that listed by Houk (1963).

Twenty-seven observations of AF Cyg were obtained over a 5 year interval between 1995 March and 2000 October (Table 7). A search for periodicities in the radial-velocity data resulted in a value of 927.5 days. The longer light-variability period is essentially identical to that found for our radial velocities. A comparison of the light (L. L. Kiss 2001, private communication) and velocity data, obtained over the same time period, is shown in Figure 4. From the envelope of the light and velocity curves, the light minima and maxima of the long-period variation can be seen to roughly coincide with the minima and maxima, respectively, of the velocity curve.

The orbital solution to the AF Cyg data gives a 926.3 ± 36.4 day period, resulting in a standard error of 1.2 km s^{-1} for an observation of unit weight. This orbital fit is shown in Figure 5. The large standard error noted above suggests that this star has additional velocity variability. Thus, we subjected our velocity residuals from the orbital fit to a period analysis. The results suggested several possible periods, one of which, at 176.2 days, is similar to the light-variability periods of 163 and 165.9 days. However, most of the velocity residuals are similar in value to our measurement uncertainties, and so the reality of this second period in the velocities is questionable at best.

TABLE 7
RADIAL VELOCITIES OF AF CYG

HJD 2,400,000 +	Phase	Velocity (km s^{-1})	$O-C$ (km s^{-1})
49,801.951	0.464	−16.3	−0.4
49,803.997	0.466	−15.8	0.1
49,874.948	0.543	−15.3	0.0
49,923.770	0.596	−15.5	−0.7
49,997.694	0.675	−13.8	0.2
49,999.691	0.678	−14.4	−0.4
50,161.976	0.853	−13.0	−0.1
50,253.855	0.952	−12.2	1.0
50,319.783	0.023	−14.2	−0.2
50,385.618	0.094	−15.0	−0.1
50,568.907	0.292	−17.0	−0.5
50,627.847	0.356	−17.3	−0.8
50,688.741	0.421	−15.3	0.9
50,750.624	0.488	−12.5	3.2
50,932.874	0.685	−12.8	1.1
50,981.851	0.738	−14.3	−0.9
51,051.767	0.813	−13.5	−0.5
51,106.740	0.873	−13.1	−0.2
51,296.900	0.078	−14.4	0.3
51,346.977	0.132	−16.8	−1.4
51,438.822	0.231	−14.6	1.7
51,478.689	0.274	−16.2	0.2
51,648.027	0.457	−17.0	−1.0
51,650.942	0.460	−16.1	−0.1
51,677.973	0.489	−17.4	−1.7
51,736.817	0.553	−16.4	−1.2
51,831.696	0.655	−12.5	1.7

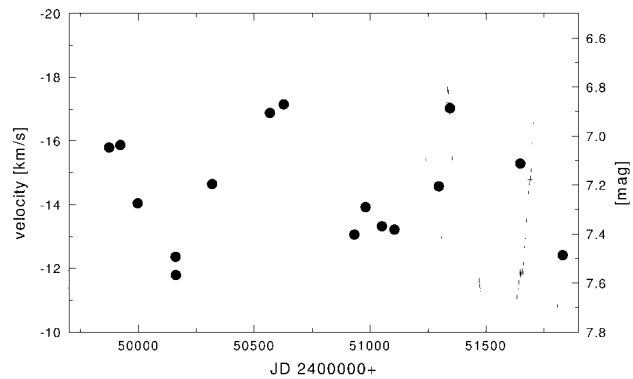

FIG. 4.—*V* magnitudes (see below) and velocities (current paper) for AF Cyg. For comparison with the light curve the velocities have been plotted in reverse order (*largest velocity at bottom*) as in Lebzelter, Kiss, & Hinkle (2000). The magnitudes are sampled much more precisely and regularly on the right side of the figure due to the use of data from the Vienna APT (F. Kerschbaum 2001, private communication). Magnitudes on the left side of the figure are visual estimates (L. L. Kiss 2001, private communication). The Kiss light-curve data have been averaged over 7 day intervals.

4.6. *X Her*

Payne-Gaposchkin (1952b) analyzed Harvard photographic plates of the field containing X Her that were taken between 1895 and 1938. She found light variations with periods of 95 and 746 days and commented that "the short cycle is well defined and the long cycle definitely indicated." Kiss et al. (1999) identified periods of 102 and 178 days from an examination of more recent, visual observations.

We obtained 25 spectrograms of this SRb–type variable over a 5 year period from 1995 March to 2000 April (Table 8). A search of our velocity data resulted in a period of 666 days. Long-period velocity variations are obvious in the current data set, while short-period velocity variations were detected by Lebzelter (1999) using much more closely sampled data. The short-period variations could be responsible for some of the scatter of the long-period velocity curve.

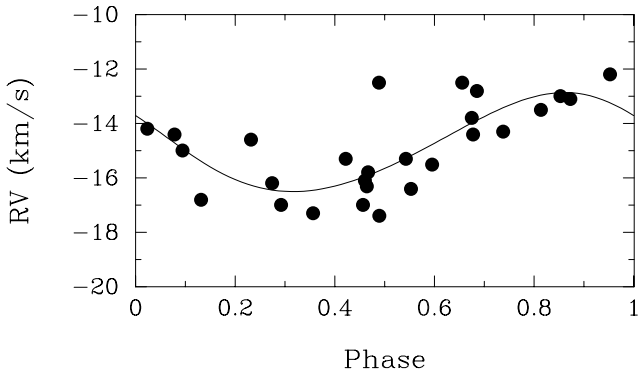

FIG. 5.—Velocities for AF Cyg phased by a period of 926.3 days. Zero phase is the time of periastron passage. The line is a best-fit orbit for the data.

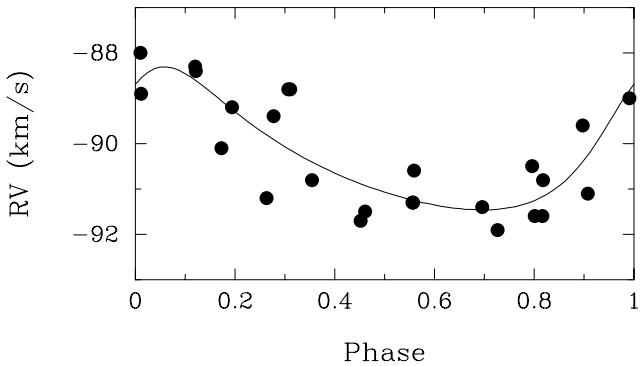

FIG. 6.—Velocities for X Her phased by a period of 658.3 days. Zero phase is the time of periastron passage. The line is a best-fit orbit for the data.

An orbital fit to the X Her data resulted in a period of 658.3 ± 17.0 days with the standard error of 0.8 km s^{-1} for an observation of unit weight. The fit of the orbit to the radial velocity data is shown in Figure 6.

CO emission lines from the circumstellar shell of X Her have been detected in the microwave by Kerschbaum & Olofsson (1999). The microwave line shape for X Her is more complex than for typical AGB stars (Kahane & Jura 1996). Circumstellar shells are orders of magnitude larger than the stellar radius and have lifetimes orders of magnitude longer than the long-period variation. Shorter term velocity variations, from pulsations or orbital velocity variations, are averaged. As expected, the X Her CO circumstellar velocity of −90 km s^{-1} is essentially identical to the γ velocity, −90.3 km s^{-1}, found from the infrared velocities.

4.7. *g Her = HR 6146*

Both Mattei et al. (1997) and Kiss et al. (1999) have found g Her, a SRb–type variable, to have multiple periods. Mattei et al. (1997) found periods of 62.3, 89.5, and 888.9 days, while Kiss et al. (1999) determined periods of 90 and 887 days. In addition to the extensive sets of visual observations, photoelectric photometry covering the interval of our spectroscopic observations also is available. From 1986 through 1999 Percy, Wilson, & Henry (2001) obtained *V*-band photometry of g Her with the 0.25 m telescope at Fairborn Observatory. Analysis of that photometry identified periods of 93 and 833 days, in approximate agreement with the visual observations. The long period is roughly 2.5 yr, so several decades of monitoring are required to establish the period to a few percent. Recently, Kerschbaum, Lebzelter, & Lazaro (2001) have also monitored this star with an automatic photometry telescope and confirm the ∼90 day period and the presence of a much longer period.

From 1995 March to 2000 April we collected 25 spectrograms of g Her (Table 9). An analysis of the radial velocities resulted in a period of 838.5 days, in agreement with the long-period light variability seen in the *V*-band photometry. From the data of Percy, Wilson, & Henry (2001) a light curve of g Her is shown in Figure 7 plotted with the simultaneous velocity measurements. Both the velocity and photometric data in Figure 7 show long- and short-period variations. As noted in Lebzelter, Kiss, & Hinkle (2000) the velocity changes roughly resemble the visual light changes. The interval between velocity observations is on the order of the short period pulsation, greatly complicating the comparison of the velocity and photometry data.

An orbital fit to the g Her data resulted in a period of 843.7 ± 21 days with 0.9 km s^{-1} for the standard error of an

TABLE 8
RADIAL VELOCITIES OF X HER

HJD 2,400,000 +	Phase	Velocity (km s^{-1})	*O*−*C* (km s^{-1})
49,802.770	0.010	−88.0	0.6
49,803.765	0.012	−88.9	−0.4
49,874.831	0.120	−88.3	0.3
49,875.764	0.121	−88.4	0.2
49,923.664	0.194	−89.2	0.0
49,997.600	0.306	−88.8	1.3
50,000.626	0.311	−88.8	1.3
50,161.828	0.556	−91.3	−0.1
50,162.835	0.557	−91.3	−0.1
50,253.711	0.695	−91.4	0.1
50,319.679	0.796	−90.5	0.8
50,386.555	0.897	−89.6	0.8
50,567.817	0.173	−90.1	−1.0
50,627.678	0.263	−91.2	−1.4
50,751.546	0.452	−91.7	−0.8
50,932.855	0.727	−91.9	−0.5
50,981.772	0.801	−91.6	−0.3
51,051.642	0.907	−91.1	−0.8
51,106.552	0.991	−89.0	−0.2
51,295.030	0.277	−89.4	0.5
51,345.742	0.354	−90.8	−0.4
51,415.669	0.460	−91.5	−0.6
51,480.557	0.559	−90.6	0.7
51,649.896	0.816	−91.6	−0.4
51,650.893	0.818	−90.8	0.4

TABLE 9
RADIAL VELOCITIES OF G HER

HJD 2,400,000 +	Phase	Velocity (km s^{-1})	*O*−*C* (km s^{-1})
49,802.776	0.493	2.3	0.5
49,803.769	0.494	1.4	−0.4
49,874.836	0.578	1.1	−0.1
49,923.668	0.636	1.6	0.8
49,997.602	0.724	−0.1	−0.2
50,000.630	0.727	0.4	0.4
50,161.830	0.918	−2.6	−1.1
50,162.835	0.919	−2.3	−0.8
50,253.714	0.027	1.3	0.5
50,319.681	0.105	2.6	0.0
50,386.556	0.185	3.3	0.2
50,567.820	0.399	1.5	−0.9
50,627.680	0.470	2.1	0.1
50,751.548	0.617	0.0	−0.9
50,932.856	0.832	−0.1	0.9
50,981.775	0.890	−0.4	1.0
51,051.643	0.973	−0.1	0.8
51,106.554	0.038	0.4	−0.7
51,295.028	0.261	2.1	−0.9
51,345.741	0.322	4.0	1.2
51,415.670	0.404	2.9	0.5
51,480.558	0.481	2.3	0.4
51,649.902	0.682	−1.5	−1.9
51,650.895	0.683	1.1	0.7
51,651.819	0.684	0.4	0.0

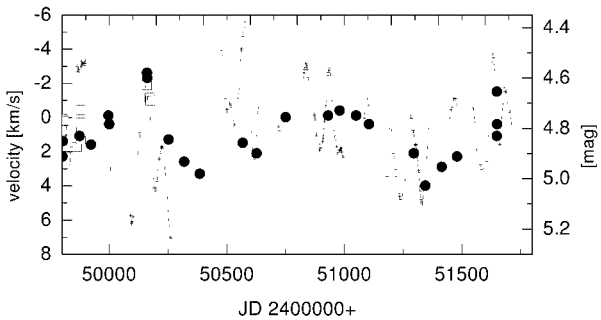

FIG. 7.—Velocity measurements for g Her plotted on top of the light curve of this star. Filled circles mark measurements from the current investigation; open boxes denote data from Lebzelter (1999) (see also Lebzelter, Kiss, & Hinkle 2000). For comparison with the light curve the velocities have been plotted in reverse order (*largest velocity at bottom*) as in Lebzelter, Kiss, & Hinkle (2000). The light curve is APT data from Percy, Wilson, & Henry (2001).

observation of unit weight. The fit of the orbit to the radial-velocity data is shown in Figure 8.

CO emission lines from the circumstellar shell of g Her have been detected in the microwave by Kerschbaum & Olofsson (1999). The CO line shape for g Her is unremarkable and the γ velocity found from the infrared results (+1.2 km s^{-1}) matches the CO circumstellar velocity (+1.3 km s^{-1}).

4.8. *V574 Oph*

The light-variability periods of 71.5 and 500 days listed by Houk (1963) for this SRa–type variable originate from a publication by Hoffmeister (1943). Hoffmeister (1943) undertook an analysis of 180 plates dating from 1928 through 1941. This work confirmed the previously known short period (71.5 days) and also suggested for the first time a longer period.

From 1995 March to 1999 June we made 17 observations of V574 Oph (Table 10). A period search of our velocities resulted in a period of 691 days. It is unclear whether this spectroscopic period is associated with the estimated light-variability period. When compared with the short period, both long periods result in period ratios that are similar to the other stars in our sample.

An orbital fit to the V574 Oph data resulted in a period of 690.0 ± 26.6 days with a standard error of 0.6 km s^{-1} for an observation of unit weight. The fit of the orbit to the radial-velocity data is shown in Figure 9.

TABLE 10
RADIAL VELOCITIES OF V574 OPH

HJD 2,400,000+	Phase	Velocity (km s^{-1})	$O-C$ (km s^{-1})
49,801.922	0.481	−35.7	−0.4
49,803.847	0.484	−35.6	−0.3
49,876.720	0.589	−36.1	−0.2
49,923.699	0.658	−35.1	1.2
49,997.630	0.765	−37.3	−0.3
50,000.655	0.769	−37.7	−0.7
50,161.904	0.003	−36.4	0.0
50,253.768	0.136	−34.4	0.0
50,319.723	0.231	−33.8	0.5
50,385.594	0.327	−34.3	0.3
50,568.803	0.592	−35.9	0.0
50,629.738	0.681	−35.6	0.8
50,751.604	0.857	−37.2	0.3
50,933.002	0.120	−34.6	−0.1
50,982.784	0.192	−34.3	−0.1
51,052.619	0.294	−34.8	−0.4
51,345.777	0.719	−37.2	−0.5

4.9. *BI Peg*

Two light-variability periods of ~60 and 500 days for this SRa–type variable were originally reported by Beyer (1951) from an analysis of 134 plates obtained between 1932 and 1939. We obtained 14 spectrograms of BI Peg between 1995 March and 1999 October (Table 11). An analysis of the velocities resulted in a period of 555.5 days.

An orbital fit to the BI Peg data resulted in a period of 548.4 ± 17.3 days with a standard error of 0.6 km s^{-1} for an observation of unit weight. The fit of the orbit to the radial-velocity data is shown in Figure 10.

5. DISCUSSION

Among our sample stars the lone Mira exhibits normal behavior and will not be discussed further. Rather, we will examine the properties of the eight SRVs and will attempt to identify the cause of their long-period variability. For those SRVs the short-period light variability is generally well determined, while the longer period is frequently not as well known. For six of the eight SRVs we have confirmed spectroscopically the long-period light variations, and for SS And, which is the only SRc–type variable in our sample,

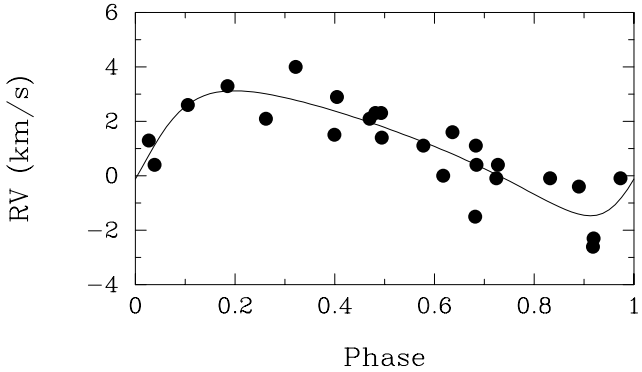

FIG. 8.—Velocities of g Her phased by a period of 843.7 days. Zero phase is the time of periastron passage. The line is a best-fit orbit for the data.

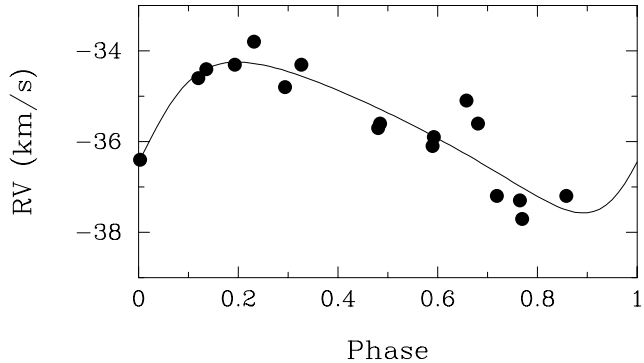

FIG. 9.—Velocities of V574 Oph phased by a period of 690 days. Zero phase is the time of periastron passage. The line is a best-fit orbit for the data.

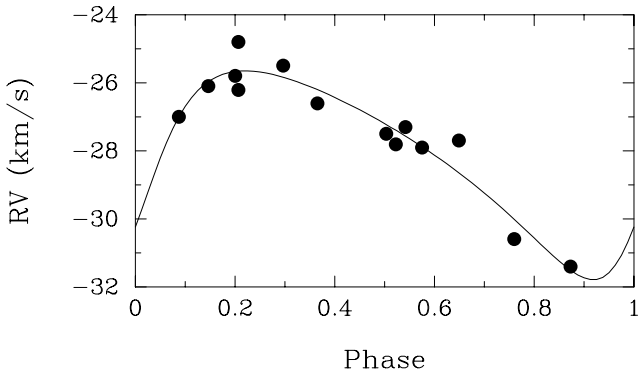

FIG. 10.—Velocities of BI Peg phased by a period of 548.4 days. Zero phase is the time of periastron passage. The line is a best-fit orbit for the data.

we have detected the short period. During the time of our observations SS And and RR CrB had very low amplitude velocity variations and this may be the reason that we were also not able to detect convincingly the long-period variations in these stars. Since for six of the program stars at least two periods have been detected in brightness changes and one or both confirmed in velocity changes, we find that multiple periods are convincingly present in these stars.

The six SRVs for which we have found long-period velocity variations have periods between 328 and 926 days and a mean near 670 days. The same six stars have short periods with an average near 80 days and hence a mean period ratio $P_l/P_s \sim 8$. The periods and the period ratio are similar to those found for the multiple-period stars in the LMC (Wood et al. 1999). For four of these six stars (RS CrB, AF Cyg, X Her, g Her) there are *Hipparcos* parallaxes (ESA 1997). The log period, absolute K band magnitude of these four stars are in the range (2.52, −6.2) through (2.95, −7.3). Even with relatively large uncertainties of field star luminosities, the luminosities and periods strongly connect the program stars with the sequence-D variables identified by Wood et al. (1999) in their LMC period-luminosity diagram. (The short-period variations of these stars are normal SRV variations and are on sequences A or B of the Wood period-luminosity diagram.) Barthès et al. (1999) have provided evidence that the LMC and field period-luminosity relations for AGB stars differ. However, these population differences are not large enough to explain the nature of the long-period variation of our program stars, and our SRVs remain clearly associated with the sequence-D variables. Thus, our results for six of the eight field SRVs in our sample indicate that they are Galactic analogs of the LMC sequence-D variables of Wood et al. (1999).

TABLE 11
RADIAL VELOCITIES OF BI PEG

HJD 2,400,000 +	Phase	Velocity (km s^{-1})	$O-C$ (km s^{-1})
49,804.005	0.146	−26.1	−0.1
49,923.978	0.365	−26.6	−0.4
49,999.824	0.503	−27.5	−0.3
50,319.985	0.087	−27.0	0.0
50,385.766	0.207	−26.2	−0.5
50,568.976	0.541	−27.3	0.3
50,627.964	0.649	−27.7	0.9
50,688.946	0.760	−30.6	−0.6
50,750.775	0.873	−31.4	0.1
50,933.980	0.207	−24.8	0.9
50,982.867	0.296	−25.5	0.3
51,106.797	0.522	−27.8	−0.4
51,135.744	0.575	−27.9	0.0
51,478.774	0.200	−25.8	−0.1

Wood et al. (1999) compared the various period-luminosity sequences that they identified for the LMC variables with theoretical radial-pulsation models. They found that most SRVs are first, second, or third overtone pulsators, although some could pulsate in the fundamental mode with low amplitudes. However, none of these modes fits the period-luminosity relation of the sequence-D variables, a result confirmed independently by Percy & Pollano (1997). To explain the sequence-D variables Wood et al. (1999) also considered but rejected nonradial modes and the dust κ-mechanism as the cause of variability. Kiss et al. (1999) similarly found that the long-period variability has an amplitude too large for nonradial pulsation and by the same reasoning eliminated an origin associated with stellar rotation, modulated by star spots, etc. Wood et al. (1999) noted that although strange modes of stellar pulsation (Saio, Baker, & Gautschy 1998) exist for these variables with roughly the correct periods, current theoretical models indicate that the modes are damped and so should not be seen. Thus, Wood et al. (1999) proposed that the long-period variability seen in their LMC sequence-D stars resulted from eclipses. In their binary model the pulsating AGB star loses mass via a stellar wind or Roche-lobe overflow. This material forms a dusty, roughly comet-shaped cloud around the secondary (Theuns & Jorissen 1993) and eclipses the AGB star. In light of our new observations we examine possible causes of variability.

First, we look at the circumstellar environment of the program stars. The small-amplitude, sequence-D variables hardly seem likely to have pulsation driving major mass loss, and this is supported by observations. Circumstellar dust around the program stars can be detected from near infrared and *IRAS* colors (van der Veen & Habing 1988). None of the program stars has a large infrared excess. RR CrB and g Her can be fitted with a single blackbody curve, indicating that no substantial flux from circumstellar material is seen (Kerschbaum & Hron 1996; Hron, Aringer, & Kerschbaum 1997). The other three stars were fitted best by two blackbody curves, indicating the existence of some circumstellar dust. One of the most sensitive tracers of circumstellar gas is CO microwave line emission, which has been detected toward X Her and g Her (Kerschbaum & Olofsson 1999). The mass loss is the largest for X Her, 10^{-7} $M_\odot$ yr^{-1} (Kahane & Jura 1996), a value typical for a late-type SRV, but 2 orders of magnitude less than that of high mass-loss AGB stars. From the perspective of mass loss the sequence-D SRV stars appear indistinguishable from other SRVs. The small circumstellar mass-loss rates clearly show that these stars are not candidates for variability from dust formation events in the circumstellar shell (Whitelock et al. 1997). Furthermore, the low mass-loss rates are yet further evidence that these stars have not experienced fundamental mode pulsations, where large amplitude pulsation is expected to drive mass loss (e.g., Bowen & Willson 1991).

Wood et al. (1999) argued that the best explanation for the LMC sequence-D SRVs is that they are semidetached eclipsing binaries. They concluded that the ultimate test of

their binary hypothesis would come from radial-velocity observations. As noted previously, we started our observing program because we independently thought that the field LPVs with long light-variability periods might well be binaries. Orbital elements derived for the six SRVs with long-period velocity variations are given in Table 2. For comparison, in Table 12 we present the orbital elements of known field AGB binaries. (There are many more known cluster AGB binaries; see, for example, Mermilliod et al. 1998. But we do not include these stars because of possible biases in the selection and population.) Unfortunately, the sample of field AGB binaries is not large and of the eight M giants listed only five have periods less than 1000 days, similar to our six SRVs in Table 2. Comparing the elements K, e, and ω of the two groups of orbits, for the field M giants the semiamplitudes range from 4.4 to 16.9 km s^{-1}, while the eccentricities range from zero to 0.24. Values for ω, the longitude of periastron, are between 99° to 337°. In contrast, the orbits of the program SRVs are surprisingly similar to each other. All the semiamplitudes are quite small and have similar values, ranging from 1.6 to 3.1 km s^{-1}. Also, except in the case of AF Cyg, all the orbits have nearly identical values for the eccentricity and the longitude of periastron, resulting in velocity curves which are suspiciously similar. The similarity is all the more striking given the rather sparse sampling of the velocity curves and the presence of a second pulsation period in the data, both of which must affect the computed orbital elements.

If AF Cyg or the other SRVs are binaries, it is necessary to explain the light variability, which has an essentially identical period to the velocity variations. One scenario suggested by Wood et al. (1999) is a cloud of dusty accreted matter surrounding an invisible secondary, which eclipses the SRV. However, the eclipse cannot be symmetric because of the comet-like shape of the dust cloud, as suggested by the results of Theuns & Jorissen (1993). Thus, in a circular orbit the predicted eclipse should occur at and after the conjunction with the SRV behind the cloud. In that case minimum light corresponds to the time when the SRV begins its motion toward us, i.e., the portion of the orbit when the AGB star is at its center-of-mass velocity and then decreases in velocity, but before velocity minimum occurs. Although our orbits are not circular, in a binary with a relatively modest eccentricity, the relation of the light and velocity minima will not be changed appreciably. From Figures 4 and 7 it is seen that the predicted alignment of velocities and light minima seem to occur for AF Cyg or g Her. However, the short period variations make the data difficult to assess. Nevertheless, for AF Cyg the computed values of K, e, and ω differ substantially from those found for the other orbits, suggesting that its long-period velocity variation is possibly the result of orbital motion. On the other hand, the velocities of this system also have the largest residuals to the computed orbit, and the true shape of the velocity curve is not as certain.

A number of objections can be raised to the binary scenario. First, as noted above, the periods of the hypothesized binaries cover a fixed range of ratios to the short pulsation periods. We know of no mechanism that would create such a ratio. Second, the orbital period–stellar luminosity must define a linear relation on the period-luminosity diagram. No plausible mechanism to produce such binaries has been presented. Third, the hypothesized cloud of eclipsing material would affect the light curve over a large part of the period, not just within a limited range in phase when the secondary is near the line of sight to the primary. Fourth, the secondary cannot make measurable contributions of emission lines or continuum to the spectrum at either infrared or ultraviolet wavelengths. Fifth, assuming that the primary has a mass near 1 $M_\odot$, the derived mass functions imply very small masses for the secondary, $\sim$0.1 $M_\odot$. It seems even more unlikely that a very low mass companion could result in an obscuring circumstellar ring.

Perhaps one of the most significant remaining doubts about the velocity curves presented here is concern that these curves are aliases resulting from severe undersampling. Mattei et al. (1997) noted this possible effect in discussing the light curves of these systems. While the velocity data are indeed severely undersampled, there can be no question that long periods are present in these stars. Wood et al. (1999) detected similar long periods in well-sampled MACHO data, and the long period in g Her has now been detected in well-sampled APT data (Percy, Wilson, & Henry 2001). Furthermore, the long periods from the velocity data match the long periods of the photometry data.

6. CONCLUSIONS

For five of the six SRVs, the nearly identical values of K, e, and to a lesser extent of ω, strongly suggest that the veloc-

TABLE 12
ORBITS FOR NORMAL FIELD M III STARS

Name	HD	Sp. Type	P (days)	γ (km s^{-1})	K_1 (km s^{-1})	e	ω (deg)	$f(m)$ ($M_\odot$)	Ref.
η Gem	42995	M 3 III	2983	+17.6	8.8	0.53	168	0.13	1
	80655	gM	834	+33.2	4.4	0.0	...	0.0074	2
μ UMa	89758	M 0 III	230.1	−20.4	7.4	0.06	236	0.01	3
4 Dra.....	108907	M 3 III	1703	−14.4	3.7	0.30	244	0.008	4
RR UMi	132813	gM7	748.9	+6.2	8.3	0.13	212	0.0043	5
	147395	gM2	335.5	−20.1	16.9	0.24	337	0.15	6
V1472 Aql...	190658	M 2.5 III	198.7	−111.8	13.0	0.05	99	0.045	7
	220007	M 3 III	1520	−0.8	5.1	0.51	236	0.013	8

REFERENCES.—(1) McLaughlin & Van Dijke 1944; (2) Griffin 1983; (3) Jackson, Shane, & Lynds 1957; (4) Reimers, Griffin, & Brown 1988; (5) Batten & Fletcher 1986; (6) Carquillat & Ginestet 1996; (7) Lucke & Mayor 1982; (8) Griffin 1979.

ity variations of those variables do not result from orbital motion. The existence of a close binary companion to these stars also seems unlikely on the basis of the mass function and the properties of the light curve. Instead the similar velocity-curve shapes of the stars in the sample imply that some as yet unknown type of pulsation is responsible for the velocity variations. Recently, a new possible explanation for the long-period variability has been proposed by Wood (2000a), who identified theoretically a family of strange pulsation modes that occur because of the interaction of stellar oscillations and convective energy transport. While his analyses yielded highly damped modes, he suggested that other treatments of convection might produce unstable modes with periods similar to the range of long secondary periods found in SRVs.

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REFERENCES

Barker, E. S., Evans, D. S., & Laing, J. D. 1967, R. Obs. Bull., 130
Barthès, D., Luri, X., Alvarez, R., & Mennessier, M. O. 1999, A&AS, 140, 55
Batten, A. H., & Fletcher, J. M. 1986, PASP, 98, 647
Batten, A. H., Fletcher, J. M., & MacCarthy, D. G. 1989, Publ. DAO, 17
Bedding, T. R., & Zijlstra, A. A. 1998, ApJ, 506, L47
Beyer, M. 1951, Astron. Nachr., 279, 161
Bowen, G. H., & Willson, L. A. 1991, ApJ, 375, L53
Carquillat, J. M., & Ginestet, N. 1996, A&AS, 117, 445
Dumm, T., & Schild, H. 1998, NewA, 3, 137
ESA. 1997, The Hipparcos and Tycho Catalogues (ESA SP-1200) (Noordwijk: ESA)
Fekel, F., Joyce, R. R., Hinkle, K. H., & Skrutskie, M. F. 2000, AJ, 119, 1375
Florya, N. F. 1949, Tr. Moscow Sternberg Inst., 16, 187
Griffin, R. F. 1979, Observatory, 99, 198
———. 1983, Observatory, 103, 56
Hinkle, K. H., Cuberly, R. W., Gaughan, N. A., Heynssens, J. B., Joyce, R. R., Ridgway, S. T., Schmitt, P., & Simmons, J. E. 1998, Proc. SPIE, 3354, 810
Hinkle, K. H., Hall, D. N. B., & Ridgway, S. T. 1982, ApJ, 252, 697
Hinkle, K. H., Lebzelter, T., & Scharlach, W. W. G. 1997, AJ, 114, 2686
Hinkle, K. H., Scharlach, W. W. G., & Hall, D. N. B. 1984, ApJS, 56, 1
Hoffmeister, C. 1943, Kleine Veröff. Universitätssternw. Berlin-Babelsberg, 28, 74
Houk, N. 1963, AJ, 68, 253
Hron, J., Aringer, B., & Kerschbaum, F. 1997, A&A, 322, 280
Jackson, E. S., Shane, W. W., & Lynds, B. T. 1957, ApJ, 125, 712
Joyce, R. R., Hinkle, K. H., Meyer, M. R., & Skrutskie, M. F. 1998, Proc. SPIE, 3354, 741
Kahane, C., & Jura, M. 1996, A&A, 310, 952
Kerschbaum, F., & Hron, J. 1992, A&A, 263, 97
———. 1996, A&A, 308, 489
Kerschbaum, F., Lebzelter, T., & Lazaro, C. 2001, A&A, 375, 527
Kerschbaum, F., & Olofsson, H. 1999, A&AS, 138, 299
Kholopov, P. N., et al. 1985–1988, General Catalogue of Variable Stars (4th ed.; Moscow: Nauka)
Kiss, L. L., Szatmáry, K., Cadmus, R. R., & Mattei, J. A. 1999, A&A, 346, 542
Lebzelter, T. 1999, A&A, 351, 644
Lebzelter, T., & Hron, J. 1999, A&A, 351, 533
Lebzelter, T., Kiss, L. L., & Hinkle, K. H. 2000, A&A, 361, 167
Lebzelter, T., Hinkle, K. H., & Aringer, B. 2001, A&A, 377, 617
Lucke, P. B., & Mayor, M. 1982, A&A, 105, 318
Mattei, J. A., Foster, G., Hurwitz, L. A., Malatesta, K. H., Willson, L. A., & Mennessier, M. O. 1997, in *Hipparcos* Venice '97, ed. B. Battrick (ESA SP-402) (ESA: Noordwijk), 269
McLaughlin, D. B., & Van Dijke, S. A. E. 1944, ApJ, 100, 63
Mermilliod, J. C., & Mayor, M. 1996, in ASP Conf. Ser. 109, Cool Stars, Stellar Systems, and the Sun, ed. R. Pallavicini & A. Dupree (San Francisco: ASP), 373
Mermilliod, J.-C., Mathieu, R. D., Latham, D. W., & Mayor, M. 1998, A&A, 339, 423
Neugebauer, G., & Leighton, R. B. 1969, Two Micron Sky Survey: A Preliminary Catalog (NASA SP-3047) (Washington: NASA)
Payne-Gaposchkin, C. 1952, Ann. Harvard College Obs., 118, No. 11, 89
———. 1952, Ann. Harvard College Obs., 118, No. 21, 165
Percy, J. R., & Bagby, D. 1999, PASP, 111, 203
Percy, J. R., & Pollano, S., 1997, in ASP Conf. Ser. 135, A Half Century of Stellar Pulsation Interpretations, ed. P. A. Bradley & J. A. Guzik (San Francisco: ASP), 249
Percy, J. R., Wilson, J. B., & Henry, G. W. 2001, PASP, 113, 983
Reimers, D., Griffin, R. F., & Brown, A. 1988, A&A, 193, 180
Saio, H., Baker, N. H., & Gautschy, A. 1998, MNRAS, 294, 622
Scarfe, C. D., Batten, A. H., & Fletcher, J. M. 1990, Publ. Dom. Astrophys. Obs. Victoria, 18, 21
Sterne, T. E., & Campbell, L. 1936, Ann. Harvard College Obs., 105, 459
Theuns, T., & Jorissen, A. 1993, MNRAS, 265, 946
van der Bilt, J. 1934, MNRAS, 94, 846
van der Veen, W. E. C., & Habing, H. J. 1988, A&A, 194, 125
Van Eck, S., Jorissen, A., Udry, S., Mayor, M., Burki, G., Burnet, M., & Catchpole, R. 2000, A&AS, 145, 51
Whitelock, P. A., Feast, M. W., Marang, F., & Overbeek, M. D. 1997, MNRAS, 288, 512
Wolfe, R. H., Horak, H. G., & Storer, N. W. 1967, in Modern Astrophysics, ed. M. Hack (New York: Gordon & Breach), 251
Wood, P. R. 2000a, in ASP Conf. Ser. 203, The Impact of Large-Scale Surveys on Pulsating Star Research, ed. L. Szabados & D. W. Kurtz (San Francisco: ASP), 379
———. 2000b, PASA, 17, 18
Wood, P. R., Alcock, C., Allsman, R. A., et al. 1999, in IAU Symp. 191, Asymptotic Giant Branch Stars, ed. T. Le Bertre, A. Lébre, & C. Waelkens (San Francisco: ASP), 151
Wood, P. R., & Zarro, D. M. 1981, ApJ, 247, 247