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INFRARED SPECTROSCOPY OF SYMBIOTIC STARS. II. ORBITS FOR FIVE S-TYPE SYSTEMS WITH TWO-YEAR PERIODS

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ABSTRACT

Infrared radial velocities have been used to determine orbital elements for the cool giants of five well-known symbiotic systems, Z And, AG Dra, V443 Her, AX Per, and FG Ser, all of which have orbital periods near the two-year mean period for S-type symbiotics. The new orbits are in general agreement with previous orbits derived from optical velocities. From the combined optical and infrared velocities, improved orbital elements for the five systems have been determined. Each of the orbital periods has been determined solely from the radial-velocity data. The orbits are circular and have quite small mass functions of 0.001–0.03 $M_\odot$. The infrared velocities of AG Dra do not show the large orbital velocity residuals found for its optical radial velocities.

Key words: binaries: symbiotic — infrared: stars — stars: individual (Z Andromedae, AG Draconis, V443 Herculis, AX Persei, FG Serpentis) — stars: late-type

1. INTRODUCTION

This is the second in a series of papers on the orbits of symbiotic stars determined from infrared spectra. The motivation for this work, as well as a brief review of symbiotic stars, was presented in Fekel et al. (2000; Paper I). To summarize, it has only been within the last two decades, mainly through a combination of visual and ultraviolet spectroscopy, that indisputable evidence has been presented revealing symbiotic stars to be mass-transfer binary systems containing a cool giant and a hot star (Kenyon & Webbink 1984; Garcia 1986; Mürset et al. 1991). While the hot component is typically a white dwarf, in a small fraction of cases the evidence is ambiguous, leaving open the possibility that the secondary is a main-sequence star.

Orbital elements are an important starting point for understanding symbiotic systems. However, as discussed in Paper I, the elements are not easily determined because of the complexity of the blue spectra and the long periods and low velocity amplitudes of most systems. Of the nearly 200 symbiotic systems listed in the recent catalog of Belczyński et al. (2000), only 20, or ~10%, have had orbital elements determined for the cool giant.

Paper I presented orbital elements for six low mass transfer, S-type symbiotics (Webster & Allen 1975; Kenyon 1988), whose orbital periods span the known period range. That work demonstrated that infrared spectroscopy can be used to derive spectroscopic orbits for the late-type stars. Basic data for the five S-type symbiotics of this paper, one of which is the prototype symbiotic Z And (Payne-Gaposchkin 1957), are given in Table 1. The spectral types of the cool stars are nearly identical with the exception of AG Dra, which contains a metal-poor K giant. The five systems have periods of roughly 2 yr, ranging from 549 to 759 days, which places them near the mean of the period distribution for S-type symbiotics. Stellar mass estimates of the symbiotic components range from 1–2.5 $M_\odot$ for the cool giant (subscript *c* in Table 1) and 0.4–0.7 $M_\odot$ for the hot secondary (subscript *h*).

As in Paper I, for each system we compare the orbit of the cool giant, computed with our infrared velocities, with previously published results. We then combine the infrared and optical data sets to determine improved orbital elements for the five systems, Z And, AG Dra, V443 Her, AX Per, and FG Ser.

2. OBSERVATIONS AND REDUCTIONS

Most of our spectroscopic observations of the five program stars were obtained with the 0.9 m coudé feed telescope and spectrograph system at the Kitt Peak National Observatory (KPNO). We employed the NICMASS camera, a 256 × 256 HgCdTe imager developed at the University of Massachusetts, at the focus of camera 5 in the location normally occupied by an optical CCD detector. With the 31.6 line mm^{-1} echelle grating, we obtained a 2 pixel resolving power of 44,000, quite sufficient for obtaining radial velocities to a precision better than 1 km s^{-1}. The observations are obtained through a narrowband (1% FWHM) 1.623 μm filter mounted inside the NICMASS cryostat. The spectral coverage defined by the array (~0.3%) fits well within the filter bandpass. The spectral region selected is ideal for this project, as it contains a

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[2] Operated by AURA, under cooperative agreement with the NSF.

TABLE 1

Basic Properties of Program Stars

Name	K[a] (mag)	H−K[a] (mag)	Primary Spec. Type[b]	Orbital Period (days)	M_c ($M_\odot$)	M_h ($M_\odot$)	$\dot{M}^c(M_\odot\ \mathrm{yr}^{-1})$
Z And	4.9	0.3	M4 III	759	2	0.75	2×10^{-7}
AG Dra	6.2	0.2	K2 III	549	1	0.5	$<2 \times 10^{-8}$
V443 Her.............	5.4	0.3	M5 III	599	2.5	0.4	...
AX Per	5.4	0.3	M4 II–III	682	1.1	0.4	3×10^{-7}
FG Ser (AS296)......	4.5	0.4	M5 III	634	1.7	0.6	2×10^{-7}

[a] Kenyon 1988.

[b] Temperature classes: Mürset & Schmid 1999; luminosity classes: Kenyon & Fernandez-Castro 1987.

[c] Seaquist, Krogulec, & Taylor (1993).

number of lines in the 6–3 CO band and is essentially free of telluric absorption lines. Exposure times ranged from less than 1 minute to 1 hr. A more complete description of the experimental setup may be found in Joyce et al. (1998), as well as in Paper I.

Additional observations were obtained with the Phoenix spectrograph at the f/15 Cassegrain focus of either the KPNO 2.1 or 4 m telescopes. Phoenix is a cryogenic echelle spectrograph employing a 31.6 line mm^{-1} grating and a 512 × 1024 InSb array. Typically the widest slit was used, giving a resolution ∼50,000, but a few of the observations have a resolution ∼70,000. A complete description of the spectrograph can be found in Hinkle et al. (1998). As with the NICMASS observations, a narrowband blocking filter was used. The Phoenix observations were centered at either 1.563 μm, a spectral region totally free of telluric absorption lines that is dominated by 3–0 CO lines in cool stars, or 2.226 μm, a spectral region dominated by modestly strong atomic lines. Representative 1.563 μm spectra of the program stars are shown in Figure 1.

Standard observing and reduction techniques were used (Joyce 1992). Wavelength calibration posed a challenge because the spectral coverage was far too small to include a sufficient number of ThAr emission lines for a dispersion solution. Our approach was to utilize absorption lines in a K III star to obtain a dispersion solution. Several sets of lines were tried, including CO, Fe I, and Ti I. These groups all gave consistent results.

Radial velocities of the program stars were determined with the IRAF cross-correlation program FXCOR (Fitzpatrick 1993). The velocities are referenced to observations of M-giant IAU velocity standards, δ Oph or α Cet, which were obtained multiple times during the course of each night. The radial velocities of the standard stars were adopted from the work of Scarfe, Batten, & Fletcher (1990).

Several different computer programs, used to determine the orbital elements of the various systems, are mentioned in the individual orbital-elements sections. If needed, 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) has been used to compute eccentric orbits of single-lined systems. For each system the orbital eccentricity is small enough that a circular-orbit solution may be appropriate. Such orbits were computed with SB1C (D. Barlow 1998, private communication), which also uses differential corrections to determine the orbital elements. As recommended by Batten, Fletcher, & MacCarthy (1989), for circular orbits we have identified T_0 as a time of maximum velocity.

Velocity sets from other observatories were used to obtain the final orbital solutions. For a given group of velocities, if the phase distribution was relatively uniform and the number of velocities large enough, an independent orbit was computed and compared with a similar orbit computed with our velocities alone. The weights of the indi-

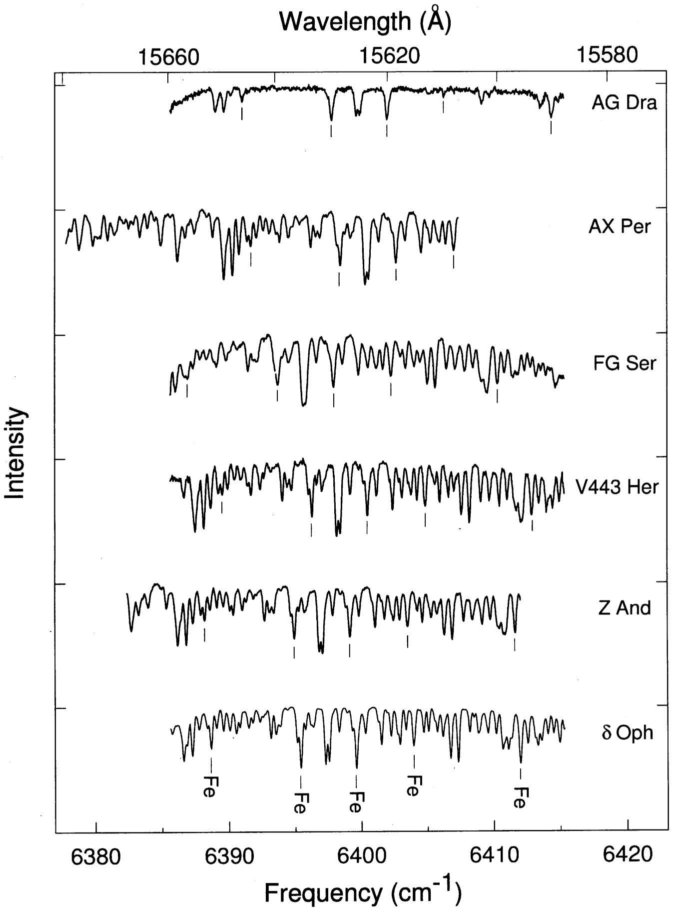

Fig. 1.—Representative spectra of the five program stars and the velocity standard δ Oph (M0.5 III) obtained with the cryogenic Phoenix spectrograph. Each spectrum is offset by 1.0 in relative intensity. The spectra were obtained on different dates and cover slightly different spectral regions. The spectra have not been shifted to remove either the stellar radial-velocity or the heliocentric-velocity correction. Tick marks indicate several moderate-strength iron features. The paucity of lines in the AG Dra spectrum is consistent with its much earlier spectral type (K2 III) compared with the other program stars (M4 or M5 III).

vidual velocities in each data set were determined from the ratio of the variance of the velocities for the two solutions.

3. Z ANDROMEDAE = HD 221650

3.1. *Brief Orbital History*

Z And is the prototype of the symbiotic star class, and observations of it have been collected for over 100 years. Kenyon & Webbink (1984) combined brightness measurements from photographic Harvard plates with observations of visual observers and determined a period of 756.85 days for Z And. Formiggini & Leibowitz (1994), who used photographic, visual, and photoelectric observations obtained during quiescent intervals spanning 98 yr, revised the period to 758.8 ± 2.0 days.

Garcia & Kenyon (1988) measured 19 radial velocities of the M giant from echelle spectroscopic observations centered at 5200 Å, which were obtained with the telescopes of the Smithsonian Astrophysical Observatory (SAO). They found a period of 750 days from velocities covering two orbital cycles. Using a total of 52 SAO velocities plus several velocities of Merrill (1948), Mikołajewska & Kenyon (1996) revised the period to 758.0 ± 8.6 days. For their orbital solution, however, they assumed the photometric period of 758.8 days and concluded that the orbit is likely circular.

3.2. *Orbital Elements*

From 1996 October to 2000 July we collected 11 radial velocities of Z And (Table 2). We adopted the 758.8 day period of Formiggini & Leibowitz (1994) and used SB1C to determine a circular-orbit solution with our data alone. In Table 3 our elements are compared with those of Mikołajewska & Kenyon (1996). The semiamplitudes are in excellent accord, while the center-of-mass velocities differ by 1.2 km s^{-1}.

Next, we prepared to combine the data into a single solution. To determine weights for the velocities of Mikołajewska & Kenyon (1996), we obtained a circular-orbit solution of their SAO velocities. A comparison of the variance of this solution with the one for the KPNO circular-orbit solution resulted in the SAO velocities being given weights of 0.6. In addition, a value of 1.2 km s^{-1} was added to each SAO velocity.

With the 63 velocities, which cover more than 7.5 cycles, and the period as a free parameter, we computed a circular-orbit solution of the combined data sets. For comparison, with SB1 we determined an eccentric-orbit solution using all the data. The eccentricity of the that solution was 0.030 ± 0.038. According to the precepts of Lucy & Sweeney (1971), the circular orbit is to be preferred, and its elements are listed in Table 3. Since the orbit is circular, the time of periastron passage is undefined, and so T_0, a time of maximum velocity, is given instead. All the velocities and their residuals to the final solution are given in Table 2. In Figure 2 the velocities and computed velocity curve are compared, and zero phase is a time of maximum velocity.

3.3. *Discussion*

For noneclipsing symbiotic systems, such as Z And, reflections of the light from the white dwarf-accretion disk off the primary result in the photometric detection of the orbital period (Formiggini & Leibowitz 1990). From photometry Formiggini & Leibowitz (1994) provided the follow-

TABLE 2

RADIAL VELOCITIES OF Z ANDROMEDAE

HJD (2,400,000+)	Phase	Velocity (km s^{-1})	$O-C$ (km s^{-1})	Weight	Source[a]
45,950.628......	0.072	8.3	2.8	0.6	MK96
46,095.478......	0.263	−1.6	−0.5	0.6	MK96
46,249.781......	0.466	−5.3	1.9	0.6	MK96
46,605.732......	0.935	6.8	1.2	0.6	MK96
46,626.697......	0.963	5.7	−0.3	0.6	MK96
46,682.834......	0.037	7.2	1.2	0.6	MK96
46,699.568......	0.059	5.1	−0.6	0.6	MK96
46,719.536......	0.085	5.7	0.5	0.6	MK96
46,739.697......	0.112	6.3	1.8	0.6	MK96
46,779.522......	0.164	2.9	0.0	0.6	MK96
46,784.674......	0.171	3.9	1.3	0.6	MK96
46,801.559......	0.193	3.1	1.3	0.6	MK96
46,832.499......	0.234	−1.1	−1.2	0.6	MK96
46,957.761......	0.399	−6.8	−0.8	0.6	MK96
47,020.686......	0.482	−7.4	−0.1	0.6	MK96
47,070.815......	0.548	−4.9	2.1	0.6	MK96
47,095.651......	0.581	−6.3	0.2	0.6	MK96
47,128.600......	0.624	−6.6	−1.2	0.6	MK96
47,166.477......	0.674	−5.4	−1.7	0.6	MK96
47,396.605......	0.977	5.8	−0.3	0.6	MK96
47,428.776......	0.020	6.0	−0.1	0.6	MK96
47,460.762......	0.062	4.5	−1.1	0.6	MK96
47,481.603......	0.089	5.6	0.5	0.6	MK96
47,512.551......	0.130	3.1	−0.9	0.6	MK96
47,570.471......	0.206	−0.5	−1.7	0.6	MK96
47,725.724......	0.411	−7.0	−0.7	0.6	MK96
47,777.848......	0.480	−10.8	−3.5	0.6	MK96
47,834.668......	0.555	−6.8	0.1	0.6	MK96
47,868.599......	0.599	−6.8	−0.7	0.6	MK96
47,895.489......	0.635	−5.1	−0.1	0.6	MK96
48,131.860......	0.946	4.9	−0.9	0.6	MK96
48,196.462......	0.031	4.8	−1.2	0.6	MK96
48,163.790......	0.988	4.8	−1.3	0.6	MK96
48,459.985......	0.378	−5.3	0.1	0.6	MK96
48,483.651......	0.410	−6.2	0.1	0.6	MK96
48,528.778......	0.469	−8.1	−0.9	0.6	MK96
48,547.667......	0.494	−9.4	−2.1	0.6	MK96
48,636.563......	0.611	−5.4	0.3	0.6	MK96
48,965.634......	0.045	2.3	−3.6	0.6	MK96
49,198.954......	0.352	−3.9	0.7	0.6	MK96
49,256.809......	0.428	−4.8	1.8	0.6	MK96
49,289.745......	0.472	−6.7	0.5	0.6	MK96
49,314.633......	0.504	−6.4	0.9	0.6	MK96
49,326.604......	0.520	−6.4	0.9	0.6	MK96
49,358.579......	0.562	−6.1	0.7	0.6	MK96
49,351.558......	0.553	−7.3	−0.4	0.6	MK96
49,507.802......	0.759	1.2	1.4	0.6	MK96
49,526.816......	0.784	3.8	3.0	0.6	MK96
49,555.992......	0.822	3.1	0.7	0.6	MK96
49,594.863......	0.873	5.5	1.4	0.6	MK96
49,625.833......	0.914	4.7	−0.5	0.6	MK96
49,636.768......	0.929	5.0	−0.5	0.6	MK96
50,386.811......	0.917	5.6	0.4	1.0	KPNO
50,751.818......	0.398	−4.4	1.6	1.0	KPNO
50,982.921......	0.702	−2.3	0.3	1.0	KPNO
51,106.841......	0.865	2.4	−1.5	1.0	KPNO
51,135.775......	0.904	4.6	−0.3	1.0	KPNO
51,347.924......	0.183	3.4	1.2	1.0	KPNO
51,363.881......	0.204	2.0	0.7	1.0	KPNO
51,474.829......	0.350	−5.8	−1.2	1.0	KPNO
51,477.836......	0.354	−5.3	−0.6	1.0	KPNO
51,676.973......	0.617	−6.3	−0.7	1.0	KPNO
51,736.914......	0.696	−2.9	−0.1	1.0	KPNO

[a] MK96: Mikołajewska & Kenyon (1996); KPNO: this paper.

TABLE 3

Orbital Elements of Z Andromedae

Orbital Parameters	Mikołajewska & Kenyon (1996)	KPNO Data Solution	Final Solution
P (days)............	758.8	758.8 (fixed)	759.0 ± 1.9
T_0[a] (HJD)	...	2,450,457.3 ± 7.0	2,450,449.9 ± 5.4
γ (km s^{-1})..........	−1.8 ± 0.2	−0.60 ± 0.31	−0.59 ± 0.17
K_1 (km s^{-1})........	6.8 ± 0.4	6.86 ± 0.51	6.73 ± 0.22
e.....................	0.0	0.0	0.0
$a_1 \sin i$ (km)........	$70.3 \pm 4.5 \times 10^6$	$71.6 \pm 5.4 \times 10^6$	$70.2 \pm 2.3 \times 10^6$
$f(m)$[b] ($M_\odot$)	0.024 ± 0.005	0.0255 ± 0.0057	0.0240 ± 0.0023

[a] T_0 = time of maximum velocity.
[b] $f(m) = (m_2)^3 \sin^3 i/(m_1 + m_2)^2$.

ing ephemeris for the light minima of Z And

$$\mathrm{Min} = \mathrm{JD}\ 2{,}442{,}666(\pm 10) + 758.8(\pm 2)E\ .$$

The orbital period from the radial velocities alone is 759.0 ± 1.9 days (Table 3), essentially identical to the photometric period of Formiggini & Leibowitz (1994). From our orbital elements the ephemeris for conjunction with the M III in front is

$$T_{\mathrm{conj}} = \mathrm{JD}\ 2{,}450{,}260.2(\pm 5.4) + 759.0(\pm 1.9)E\ .$$

It predicts that conjunction should occur only 4.2 days earlier than the epoch of Formiggini & Leibowitz (1994), which is 10 cycles earlier than the spectroscopic epoch. Thus, as pointed out by Mikołajewska & Kenyon (1996), photometric minima occur at spectroscopic conjunctions.

4. AG DRACONIS = BD +67°922

4.1. *Brief Orbital History*

Unlike most symbiotics, AG Dra contains a high-velocity, metal-poor, K bright-giant primary (see e.g., Mikołajewska et al. 1995; Smith et al. 1996). From 1974 through 1978 Meinunger (1979) obtained *UBV* photoelectric photometry of AG Dra. The *U*-band observations showed large-amplitude variability with a period of 554 days, which Meinunger (1979) suggested is related to binary motion. Friedjung et al. (1998) found variability in the *B* and *V* bands with a very different period of about 350 days.

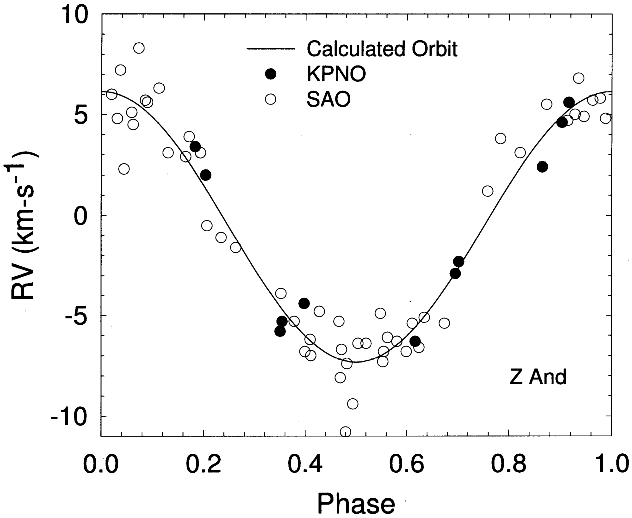

FIG. 2.—Computed radial-velocity curve of Z And compared with the observed velocities. Zero phase is a time of maximum velocity.

Mikołajewska et al. (1995) collected 47 echelle spectra, each centered at about 5200 Å, with the telescopes of the SAO. Absorption-line velocities from those spectra have a period of 547 days. Adopting the photometric period of 554 days, they concluded that a circular orbit provided the best fit to their velocities. Smith et al. (1996) used 20 Coravel velocities to determine an independent orbit, whose elements were in good agreement with those of Mikołajewska et al. (1995). Smith et al. (1996) noted that when compared with their computed orbit, their velocities of AG Dra had a large scatter, similar to that seen in some other evolved late-type giants. Gális et al. (1999) analyzed the 73 radial velocities of Mikołajewska et al. (1995), Smith et al. (1996), and Tomov & Tomova (1997). In addition to the orbital period, they detected a period of 352 days, which they suggested was most likely due to nonradial pulsations of the cool giant.

4.2. *Orbital Elements*

Our 10 radial velocities of AG Dra (Table 4), obtained from 1997 May to 2000 May, cover almost exactly two orbital cycles. Using SB1C and allowing the period to be a free parameter, we determined a circular-orbit solution from our data. In Table 5 we compare those orbital elements with the elements of Mikołajewska et al. (1995). The center-of-mass velocities differ by 1 km s^{-1}, and the semiamplitudes are in reasonable accord. Our orbital period of 552.3 ± 7.4 days is in agreement with previous spectroscopic and photometric results.

For our solution the standard error of an observation of unit weight is 0.6 km s^{-1}. This value is typical of most of the orbits in Paper I and this paper but significantly smaller

TABLE 4

Radial Velocities of AG Draconis

HJD (2,400,000+)	Phase	Velocity (km s^{-1})	$O-C$ (km s^{-1})	Weight	Source[a]
50,569.753......	0.375	−151.1	0.3	1.0	KPNO
50,629.679......	0.485	−153.7	−0.6	1.0	KPNO
50,933.744......	0.039	−141.2	0.3	1.0	KPNO
50,983.671......	0.130	−144.0	−0.8	1.0	KPNO
51,301.696......	0.709	−149.0	−0.3	1.0	KPNO
51,362.737......	0.821	−144.5	0.2	1.0	KPNO
51,363.677......	0.822	−144.4	0.3	1.0	KPNO
51,647.788......	0.340	−149.5	0.9	1.0	KPNO
51,649.838......	0.344	−151.0	−0.5	1.0	KPNO
51,676.869......	0.393	−152.0	−0.2	1.0	KPNO

[a] KPNO: this paper.

TABLE 5

Orbital Elements of AG Draconis

Orbital Parameters	Mikołajewska et al. (1995)	KPNO Data Solution	Final Solution
P (days)............	554.0	552.3 ± 7.4	548.65 ± 0.97 (fixed)
T_0[a] (HJD)	...	2,450,908.3 ± 7.1	2,450,912.5 ± 4.1
γ (km s^{-1})..........	−148.3 ± 0.3	−147.25 ± 0.21	−147.22 ± 0.19
K_1 (km s^{-1})........	5.1 ± 0.5	6.02 ± 0.34	5.86 ± 0.30
e.....................	0.0	0.0	0.0
$a_1 \sin i$ (km)	38.9 ± 4.5 × 10^6	45.7 ± 2.6 × 10^6	44.2 ± 2.3 × 10^6
$f(m)$[b] ($M_\odot$)..........	0.0076 ± 0.0025	0.0125 ± 0.0021	0.0115 ± 0.0018

[a] T_0 = time of maximum velocity.

[b] $f(m) = (m_2)^3 \sin^3 i/(m_1 + m_2)^2$.

than the values of 1.7 km s^{-1} for the solutions of both Mikołajewska et al. (1995) and Smith et al. (1996). Thus, our velocities measured at wavelengths of 1.563 and 2.226 μm show *no evidence* of the large velocity residuals interpreted by Gális et al. (1999) as nonradial pulsations of the K giant.

To improve the spectroscopic period, we combined the three earlier sets of velocities with ours, gave a weight of 0.15 to each of the older velocities, added 1 km s^{-1} to the velocities of Mikołajewska et al. (1995), and then computed a circular-orbit solution. The resulting period, 548.65 ± 0.97 days, was adopted for eccentric- and circular-orbit solutions of our velocities alone. The former solution produced an eccentricity of 0.071 ± 0.051. The tests of Lucy & Sweeney (1971) indicated that the circular-orbit solution is to be preferred, and so the elements of this final solution are given in Table 5. In Figure 3 our velocities are compared with the computed velocity curve. Zero phase is a time of maximum velocity.

4.3. *Discussion*

From our final orbital elements in Table 5 the ephemeris for conjunction with the K giant in front is

$$T_{\rm conj} = {\rm JD}\ 2{,}450{,}775.3(\pm 4.1) + 548.65(\pm 0.97)E\ .$$

Gális et al. (1999) state that a well-covered minimum in the U band results in a time of minimum of JD 2,443, 629.17 ± 2.30, a date that is 13 cycles earlier than our epoch. Our ephemeris predicts a photometric minimum that is only 13.7 days earlier than the epoch of Gális et al. (1999), which, given the uncertainties, is in good agreement with their result.

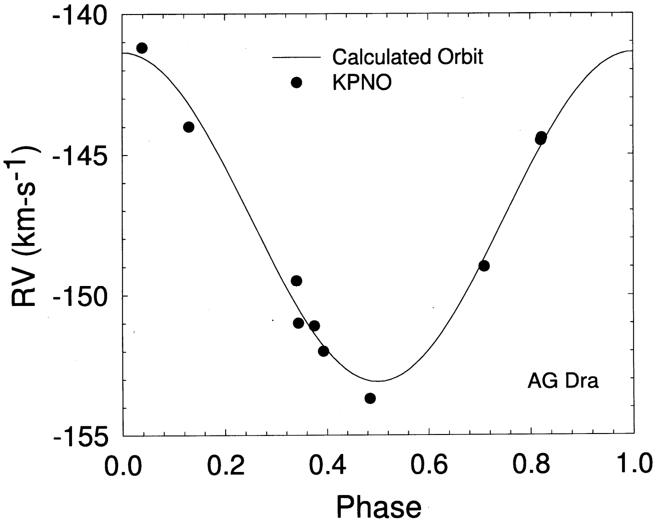

Fig. 3.—Computed radial-velocity curve of AG Dra compared with our infrared velocities. Zero phase is a time of maximum velocity.

In some bright, single K giants, very low-amplitude velocity variations have been seen on timescales of hundreds of days (e.g., Walker et al. 1989; Hatzes & Cochran 1993; Larson, Yang, & Walker 1999). Some of the giants are multiperiodic with additional timescales of days or weeks. Hatzes & Cochran (1993) noted possible causes of the long-period variations include rotational-modulation of surface features, nonradial pulsation, and planetary companions.

Henry et al. (2000) presented the results of a photometric and spectroscopic survey of 187 G, K, and a few M0 field giants. They found photometric variability on timescales of days or weeks in 43% of the giants, while only two of the giants had timescales greater than 100 days. They concluded that the radial-pulsation mechanism operating in the M giants extends into the K giants up to about spectral class K2, while for hotter giants the variability mechanism is most likely nonradial, g-mode pulsations.

One of the K giants in the Henry et al. (2000) survey, HD 165195, is an extremely metal-poor K1: III star with $M_V = -1.3$ mag. Thus, the properties of this star are somewhat similar to those estimated for the cool giant in the AG Dra system. While HD 165195 shows probable low-amplitude velocity variations, its light variations have a timescale of 10 days, much shorter than the period of about 1 yr found by Friedjung et al. (1998) for AG Dra.

The 352 day radial-velocity variations of AG Dra reported by Gális et al. (1999) have a period similar to the timescales seen in some single K giants (Hatzes & Cochran 1998). However, the amplitude of the velocity variations found by Gális et al. (1999) is about an order of magnitude greater than those listed by Hatzes & Cochran (1998). The 350 day photometric period identified by Friedjung et al. (1998) is an order of magnitude longer than the vast majority of periods found by Henry et al. (2000). The amplitudes of the B and V variations seen in AG Dra (Friedjung et al. 1998) are also at least an order of magnitude greater than the K-giant variability amplitudes detected in the survey by Henry et al. (2000). Thus, several aspects of the 350 day variability of AG Dra are anomalous when compared with the results so far determined for single K giants.

Smith et al. (1996) suggested that their large velocity residuals were related to greater line broadening associated with AG Dra's high luminosity. However, our Figure 1 indicates that the line broadening of AG Dra, at least at 1.563 μm, is similar to that of the other symbiotics observed in this paper.

As noted earlier, unlike the visual-wavelength velocities, our infrared velocities of AG Dra do not show unusually large velocity residuals to the computed orbit. This lack of large residuals is a significant constraint on any explanation of the reported 350 day photometric and velocity variations. However, due to the different wavelengths at which our data and the data of other observers were obtained, we cannot rule out the existence of pulsation phenomena that are much more readily detectable in the visual than in the infrared.

5. V443 HERCULIS

5.1. *Brief Orbital History*

Tifft & Greenstein (1958) found V443 Her to be photometrically variable. Taranova & Yudin (1987) determined a period of 597 days from their more extensive photometric observations. Dobrzycka, Kenyon, & Mikołajewska (1993) refined the period to 598 ± 29 days from an analysis of *U*-band data.

The only previous orbit is that of Dobrzycka et al. (1993), who measured 35 radial velocities from echelle spectroscopic observations at 5200 Å, which were obtained with the telescopes of the SAO. Their best spectroscopic period of 617 ± 45 days was in good agreement with their photometric period. Adopting the more accurate photometric period, Dobrzycka et al. (1993) computed eccentric- and circular-orbit solutions and preferred the latter.

5.2. *Orbital Elements*

From 1997 October to 2000 May we obtained 13 radial velocities of V443 Her (Table 6). Using the photometric period of 598.0 days (Dobrzycka et al. 1993), we computed preliminary orbital elements with BISP and refined them with SB1. Allowing the period to be a free parameter, we next computed circular orbital elements for our KPNO velocities with SB1C. Table 7 compares the elements of our circular orbit with those of Dobrzycka et al. (1993). Given that the total velocity variation is small, only 5–6 km s^{-1}, the semiamplitudes are in reasonable agreement, differing by 0.9 km s^{-1}, which is the sum of the individual uncertainties. The center-of-mass velocities, however, differ by 6.3 km s^{-1}, much larger than the 1–2 km s^{-1} zero-point shifts that we have typically encountered in our comparisons with other symbiotic orbits (Paper I; this paper). For V443 Her, Dobrzycka et al. (1993) used a spectrum of CH Cyg, whose velocity was determined relative to a set of K–M dwarfs, as their cross-correlation template. The velocity zero point for some other symbiotic stars observed with SAO telescopes has been similarly determined. Thus, the reason for such a large zero-point difference between the two sets of velocities for V443 Her is not obvious.

TABLE 6

RADIAL VELOCITIES OF V443 HERCULIS

HJD (2,400,000 +)	Phase	Velocity (km s^{-1})	$O-C$ (km s^{-1})	Weight	Source[a]
46,189.800......	0.064	−53.2	0.0	0.15	D93
46,249.671......	0.164	−54.5	−0.3	0.15	D93
46,282.582......	0.218	−54.1	0.9	0.15	D93
46,361.497......	0.350	−58.1	−1.1	0.15	D93
46,490.916......	0.566	−58.3	−0.5	0.15	D93
46,564.709......	0.689	−56.0	0.4	0.15	D93
46,600.811......	0.749	−55.7	−0.2	0.15	D93
46,626.671......	0.793	−53.5	1.3	0.15	D93
46,654.689......	0.839	−55.3	−1.1	0.15	D93
46,682.644......	0.886	−48.3	5.3	0.00	D93
46,699.554......	0.914	−50.6	2.7	0.15	D93
46,719.469......	0.947	−53.0	0.1	0.15	D93
46,739.454......	0.981	−53.5	−0.5	0.15	D93
46,786.444......	0.059	−52.8	0.4	0.15	D93
46,907.825......	0.262	−56.9	−1.2	0.15	D93
46,924.820......	0.290	−57.5	−1.4	0.15	D93
46,948.719......	0.330	−56.0	0.7	0.15	D93
47,020.616......	0.450	−55.9	2.0	0.15	D93
47,071.499......	0.535	−58.7	−0.7	0.15	D93
47,095.459......	0.575	−57.6	0.1	0.15	D93
47,128.458......	0.630	−57.2	0.0	0.15	D93
47,220.930......	0.784	−53.9	1.1	0.15	D93
47,249.908......	0.832	−60.1	−5.8	0.00	D93
47,346.765......	0.994	−51.7	1.3	0.15	D93
47,390.550......	0.067	−50.9	2.3	0.15	D93
47,424.548......	0.124	−55.6	−1.9	0.15	D93
47,458.534......	0.180	−53.1	1.3	0.15	D93
47,480.416......	0.217	−53.8	1.2	0.15	D93
47,612.885......	0.438	−60.3	−2.5	0.15	D93
47,675.814......	0.543	−58.9	−1.0	0.15	D93
47,719.713......	0.616	−57.8	−0.4	0.15	D93
47,777.597......	0.713	−56.9	−0.8	0.15	D93
47,844.509......	0.824	−55.8	−1.4	0.15	D93
48,106.609......	0.262	−53.5	2.2	0.15	D93
48,192.485......	0.405	−59.5	−1.9	0.15	D93
50,752.682......	0.677	−57.7	−1.1	1.00	KPNO
50,933.809......	0.979	−52.8	0.2	1.00	KPNO
50,981.899......	0.059	−53.1	0.1	1.00	KPNO
51,051.726......	0.176	−54.8	−0.4	1.00	KPNO
51,108.650......	0.270	−56.0	−0.2	1.00	KPNO
51,296.834......	0.584	−56.8	0.9	1.00	KPNO
51,301.774......	0.593	−57.4	0.2	1.00	KPNO
51,347.766......	0.669	−56.5	0.2	1.00	KPNO
51,363.691......	0.696	−55.8	0.5	1.00	KPNO
51,415.788......	0.783	−55.0	0.0	1.00	KPNO
51,480.657......	0.891	−54.4	−0.9	1.00	KPNO
51,647.936......	0.170	−54.2	0.1	1.00	KPNO
51,649.941......	0.174	−54.3	0.0	1.00	KPNO

[a] D93: Dobrzycka et al. 1993; KPNO: this paper.

To combine the data into a single solution, with SB1C we computed a circular orbit for the 35 SAO velocities. From a comparison of the variances of the KPNO and SAO solutions, the SAO velocities were given weights of 0.15 relative to our KPNO velocities. In addition, a value of −6.3 km s^{-1} was added to each SAO velocity. With the 48 velocities, which cover nearly nine orbital cycles, and the period as a free parameter, we determined both circular- and eccentric-orbit solutions. However, in each case the SAO velocities of JD 2,446,682.644 and 2,447,249.908 had 3 σ residuals. Thus, both were given zero weight, and the two solutions were recomputed. For the all-data eccentric solution $e = 0.088 \pm 0.072$, suggesting that a circular orbit is appropriate. The tests of Lucy & Sweeney (1971) indicated that this is the case, and we have listed the circular-orbit solution as our final one in Table 7. The SAO and KPNO velocities and residuals to the final solution are given in Table 6. Figure 4 compares the radial velocities with the computed velocity curve. Zero phase is a time of maximum velocity.

5.3. *Discussion*

Kolotilov, Munari, & Yudin (1995) obtained *UBV* photometry of V443 Her on 62 nights, most of which were

TABLE 7

ORBITAL ELEMENTS OF V443 HERCULIS

Orbital Parameters	Dobrzycka et al. (1993)	KPNO Data Solution	Final Solution
P (days)............	598	594.0 ± 19.1	599.4 ± 2.1
T_0[a] (HJD)	...	2,450,949.1 ± 15.3	2,450,347.2 ± 6.8
γ (km s^{-1})..........	−49.2 ± 0.3	−55.50 ± 0.17	−55.50 ± 0.13
K_1 (km s^{-1})........	3.2 ± 0.6	2.28 ± 0.28	2.52 ± 0.21
e.....................	0.0	0.0	0.0
$a_1 \sin i$ (km)	$26.9 \pm 6.0 \times 10^6$	$18.6 \pm 2.4 \times 10^6$	$20.8 \pm 1.7 \times 10^6$
$f(m)$[b] ($M_\odot$)..........	0.0021 ± 0.0008	0.00073 ± 0.00027	0.00100 ± 0.00024

[a] T_0 = time of maximum velocity.

[b] $f(m) = (m_2)^3 \sin^3 i/(m_1 + m_2)^2$.

between 1991 July and 1993 November. Their observations showed sinusoidal light variations with a period of 597 ± 8 days. The amplitude of the variations decreased with increasing wavelength, a result seen in a number of symbiotic systems. Thus, Kolotilov et al. (1995) concluded that the light variability in V443 Her is primarily the result of the reflection effect. Kolotilov et al. (1995) combined their U-band data with that of Tifft & Greenstein (1958) and Belyakina (1992) to produce the following ephemeris:

$$\mathrm{Min}(U) = \mathrm{JD}\ 2{,}443{,}660(\pm 30) + 594(\pm 3)E\ .$$

From our final orbital solution in Table 7 the ephemeris for conjunction with the red giant in front is

$$T_{\mathrm{conj}} = \mathrm{JD}\ 2{,}450{,}197.3(\pm 6.8) + 599.4(\pm 2.1)E\ .$$

Our spectroscopic ephemeris predicts that conjunction should occur 56 days later than the epoch of Kolotilov et al. (1995). Given the uncertainties of the two ephemerides, there is reasonable agreement between the predictions.

6. AX PERSEI

6.1. *Brief Orbital History*

Analyzing photographic observations from 1891 to 1944, Payne-Gaposchkin (1946) determined a period of 675 days for AX Per. Kenyon (1982) used the photographic data of Mjalkovskij (1977) taken between 1957 and 1972, analyzed the quiescent light curve, and found a period of 681.6 days for the light minima. Mikołajewska & Kenyon (1992) stated that the light variations result from eclipses of the hot component by the cool giant. They combined a dozen times of minima to compute an improved period of 680.8 ± 0.2 days.

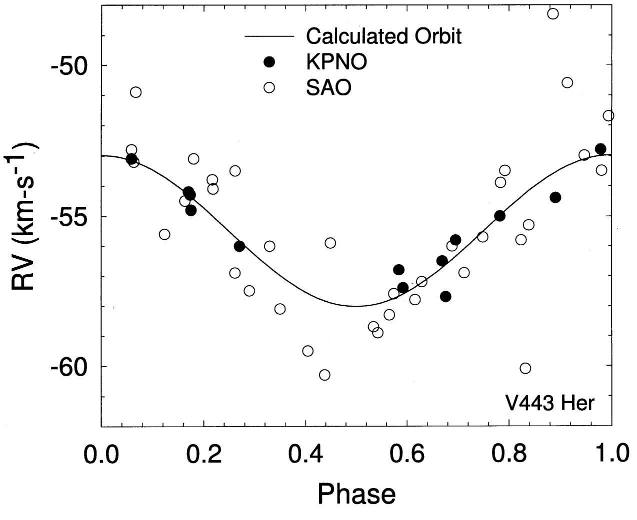

FIG. 4.—Computed radial-velocity curve of V443 Her compared with the observed velocities. Zero phase is a time of maximum velocity.

From 1979 to 1987, Iijima (1988) obtained red- and yellow-wavelength spectra of AX Per with the 1.82 m reflector at the Cima Ekar station of the Astronomical Observatory of Padova. Small-amplitude absorption-line velocity variations seen in nine spectra were consistent with orbital motion. With the telescopes of the SAO, Mikołajewska & Kenyon (1992) determined 26 radial velocities from echelle spectra centered at about 5200 Å. Their computed spectroscopic period of 705 ± 32 days agreed with their photometric determination of 680.8 days, and so they adopted the more accurate photometric period in their orbital-element solutions. Since there was little difference between their eccentric- and circular-orbit solutions, they favored the latter.

Mikołajewska & Kenyon (1992) cross-correlated seven spectra, taken during an outburst of AX Per, with an A-type reference star. If the A-type absorption features correspond to the hot component, the resulting semiamplitude of 18.1 km s^{-1} produces a mass ratio of 2.4 ± 0.4.

6.2. *Orbital Elements*

We obtained 10 radial velocities of AX Per between 1996 October and 2000 July (Table 8). Using SB1C, we assumed the photometric period of Mikołajewska & Kenyon (1992) and determined a circular-orbit solution for our velocities. Table 9 shows that our solution is in good accord with that of Mikołajewska & Kenyon (1992). The semiamplitudes differ by 0.5 km s^{-1} and the center-of-mass velocities, by 1.0 km s^{-1}.

To combine the two sets of velocities, which cover over 8.5 orbital cycles, we obtained a circular-orbit solution of the velocities of Mikołajewska & Kenyon (1992). A comparison of the variances for the two solutions indicated that their velocities should be given weights of 0.07 relative to ours. With the velocities appropriately weighted, the period made a free parameter, and −1 km s^{-1} added to the velocities of Mikołajewska & Kenyon (1992), we determined a circular-orbit solution of the combined data sets. We also obtained a solution that included the nine absorption-line velocities of Iijima (1988), each given a weight of 0.03 and corrected by +9 km s^{-1}, but in that solution the errors of the elements were not improved.

Next, with SB1 we obtained an eccentric-orbit solution for our velocities and those of Mikołajewska & Kenyon

TABLE 8

Radial Velocities of AX Persei

HJD (2,400,000+)	Phase	Velocity (km s^{-1})	$O-C$ (km s^{-1})	Weight	Source[a]
45,717.648......	0.059	−112.3	−2.1	0.07	MK92
46,096.624......	0.615	−123.0	0.3	0.07	MK92
46,133.588......	0.669	−124.7	−3.5	0.07	MK92
46,250.928......	0.841	−113.9	−0.7	0.07	MK92
46,362.645......	0.005	−106.0	3.7	0.07	MK92
46,418.803......	0.087	−112.5	−1.7	0.07	MK92
46,438.651......	0.116	−112.3	−0.6	0.07	MK92
46,461.636......	0.150	−112.8	0.1	0.07	MK92
46,490.614......	0.193	−116.2	−1.5	0.07	MK92
46,507.603......	0.217	−114.9	1.0	0.07	MK92
46,627.914......	0.394	−122.5	1.1	0.07	MK92
46,699.674......	0.499	−126.4	−1.2	0.07	MK92
46,719.660......	0.528	−121.5	3.6	0.07	MK92
46,747.802......	0.570	−126.5	−2.0	0.07	MK92
46,784.716......	0.624	−123.0	0.0	0.07	MK92
46,801.661......	0.649	−118.6	3.5	0.07	MK92
46,832.575......	0.694	−119.1	1.0	0.07	MK92
46,865.615......	0.742	−118.2	−0.4	0.07	MK92
47,020.880......	0.970	−108.8	1.0	0.07	MK92
47,081.885......	0.059	−110.8	−0.6	0.07	MK92
47,132.876......	0.134	−112.2	0.1	0.07	MK92
47,167.656......	0.185	−116.0	−1.6	0.07	MK92
47,184.711......	0.210	−114.2	1.3	0.07	MK92
47,521.714......	0.704	−119.9	−0.2	0.07	MK92
47,543.702......	0.736	−121.0	−2.9	0.07	MK92
47,569.628......	0.774	−116.1	0.2	0.07	MK92
50,386.920......	0.904	−110.7	0.3	1.00	KPNO
50,750.892......	0.438	−124.6	0.0	1.00	KPNO
51,107.029......	0.960	−110.0	−0.1	1.00	KPNO
51,135.852......	0.002	−109.9	−0.2	1.00	KPNO
51,363.890......	0.337	−120.9	0.6	1.00	KPNO
51,414.970......	0.411	−124.2	−0.2	1.00	KPNO
51,438.983......	0.447	−125.4	−0.6	1.00	KPNO
51,474.899......	0.499	−125.5	−0.3	1.00	KPNO
51,477.917......	0.504	−124.8	0.4	1.00	KPNO
51,736.995......	0.884	−111.5	0.2	1.00	KPNO

[a] MK92: Mikołajewska & Kenyon (1992); KPNO: this paper.

(1992). With an eccentricity of 0.028 ± 0.032 the precepts of Lucy & Sweeney (1971) indicated that a circular orbit is to be preferred. Thus, in Table 9 we have listed the circular-orbital elements determined for our velocities combined only with those of Mikołajewska & Kenyon (1992). Since periastron passage is undefined, the elements include T_0, a time of maximum velocity. Table 8 lists the two sets of velocities and their residuals to the final orbit. Figure 5 compares the same sets of velocities with the computed radial-velocity curve, where zero phase is computed from T_0.

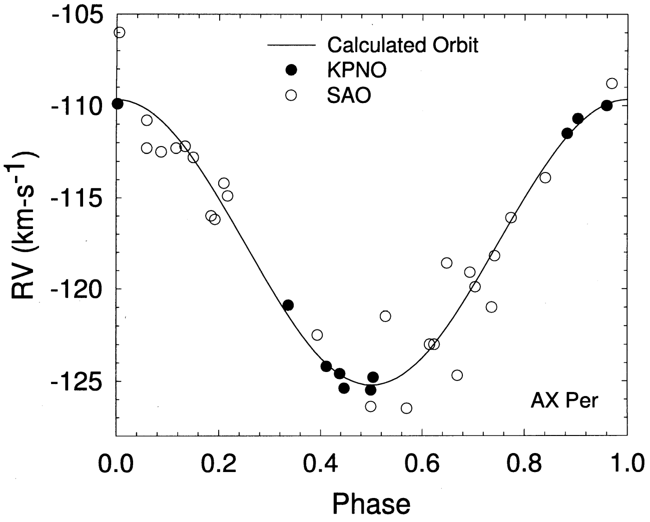

Fig. 5.—Computed radial-velocity curve of AX Per compared with the observed velocities. Zero phase is a time of maximum velocity.

6.3. *Discussion*

From our final orbital solution in Table 9 our eclipse ephemeris is

$$T_{\text{conj}} = \text{JD } 2{,}450{,}963.8(\pm 5.6) + 682.1(\pm 1.4)E .$$

This ephemeris predicts to within 2.4 days the last time of minimum (JD 2,448,233 ± 2) listed in Table 10 of Mikołajewska & Kenyon (1992).

Compared with that found by Mikołajewska & Kenyon (1992), our semiamplitude of the M giant is increased by 0.3 km s^{-1}, which slightly reduces the mass ratio to 2.3 ± 0.3.

7. FG SERPENTIS = AS 296

7.1. *Brief Orbital History*

FG Ser began its first recorded outburst in 1988 June (Munari 1988). From additional photometric observations Munari et al. (1992) discovered two eclipses of the hot component by the M giant, from which they determined an orbital period of 650 days. Observation of the next predicted eclipse enabled Munari et al. (1995) to revise the eclipse period to 658 days.

Mürset et al. (2000) very recently determined the first spectroscopic orbit for FG Ser. They obtained 10 velocities with the coudé echelle spectrograph fed by the 1.4 m coudé

TABLE 9

Orbital Elements of AX Persei

Orbital Parameters	Mikołajewska & Kenyon (1992)	KPNO Data Solution	Final Solution
P (days)	680.8	680.8 (fixed)	682.1 ± 1.4
T_0[a] (HJD)	...	2,451,134.7 ± 5.6	2,451,134.3 ± 5.6
γ (km s^{-1})	−116.5 ± 0.4	−117.44 ± 0.14	−117.44 ± 0.14
K_1 (km s^{-1})	7.5 ± 0.9	7.98 ± 0.23	7.78 ± 0.21
e	0.0	0.0	0.0
$a_1 \sin i$ (km)	...	74.7 ± 2.1 × 10^6	73.0 ± 1.9 × 10^6
$f(m)$[b] ($M_\odot$)	...	0.0359 ± 0.0031	0.0333 ± 0.0027

[a] T_0 = time of maximum velocity.
[b] $f(m) = (m_2)^3 \sin^3 i/(m_1 + m_2)^2$.

TABLE 10

RADIAL VELOCITIES OF FG SERPENTIS

HJD (2,400,000+)	Phase	Velocity (km s^{-1})	$O-C$ (km s^{-1})	Weight	Source[a]
48,374.000......	0..555	65.2	−1.6	0.2	M00
48,511.500......	0.772	75.8	1.5	0.2	M00
48,698.900......	0.068	79.5	−0.1	0.2	M00
48,757.800......	0.161	76.7	−0.3	0.2	M00
48,831.600......	0.277	70.9	−1.2	0.2	M00
49,132.700......	0.753	71.7	−1.7	0.2	M00
49,486.800......	0.312	72.4	1.7	0.2	M00
49,550.600......	0.412	67.8	0.4	0.2	M00
49,857.800......	0.897	78.3	−0.6	0.2	M00
49,974.500......	0.082	81.9	2.5	0.2	M00
50,147.900......	0.355	69.9	0.8	0.2	M00
50,569.961......	0.022	79.4	−0.8	1.0	KPNO
50,629.768......	0.116	78.3	−0.2	1.0	KPNO
50,752.624......	0.310	69.6	−1.2	1.0	KPNO
50,934.780......	0.597	68.2	0.5	1.0	KPNO
50,981.871......	0.672	70.3	0.2	1.0	KPNO
51,052.694......	0.784	74.8	0.0	1.0	KPNO
51,108.629......	0.872	77.7	−0.4	1.0	KPNO
51,294.929......	0.166	77.6	0.8	1.0	KPNO
51,346.873......	0.248	73.9	0.5	1.0	KPNO
51,363.699......	0.275	72.8	0.5	1.0	KPNO
51,415.751......	0.357	68.6	−0.4	1.0	KPNO
51,480.624......	0.459	66.2	−0.4	1.0	KPNO
51,647.923......	0.723	72.2	0.0	1.0	KPNO
51,649.983......	0.726	72.7	0.4	1.0	KPNO

[a] M00: Mürset et al. (2000); KPNO: this paper.

auxiliary telescope at the European Southern Observatory (ESO). Most of their red-wavelength spectra were centered at Hα or 7453 Å. Combining their velocities with one from Wallerstein et al. (1993) and using the time of the 1991 eclipse as a constraint, they determined a period of 650 ± 5 days and adopted a circular orbit.

7.2. *Orbital Elements*

Between 1997 May and 2000 May we obtained 14 radial velocities of FG Ser (Table 10). Adopting a period of 650 days (Mürset et al. 2000), we computed a circular-orbit solution for our velocities using SB1C. When this orbit was compared with the orbit of Mürset et al. (2000), the center-of-mass velocities differed by ~2 km s^{-1}, and the semi-amplitudes by 17%. More importantly however, the predicted time of the 1991 eclipse differed by more than 60 days. With the period as a free parameter, a circular-orbit solution (Table 11) of our velocities alone produced a period of 641 ± 6 days. We then added 2 km s^{-1} to the velocities used by Mürset et al. (2000) and made a period search with all 25 velocities, which resulted in a best period of 633.8 ± 2.5 days. With that period adopted, we obtained independent circular-orbit solutions for our data set and that used by Mürset et al. (2000). From a comparison of the variances of the velocities of the two solutions, we assigned weights of 0.2 to the velocities used by Mürset et al. (2000). Combining the two sets of velocities, which cover nearly five orbital cycles, we computed both eccentric and circular orbits. According to the precepts of Lucy & Sweeney (1971), the circular orbit is to be preferred, and that orbit is listed in Table 11. The 25 radial velocities and their velocity residuals to the final orbit are given in Table 10. Figure 6 compares the radial velocities with the computed velocity curve. Zero phase is T_0, a time of maximum velocity.

7.3. *Discussion*

Our orbital period of 633.5 ± 2.4 days is 24.5 days shorter than the most recent photometric estimate by Munari et al. (1995). To make a more extensive comparison, we determined mideclipse times from their photometric observations. Of the three observed eclipses, the 1991 eclipse is the one most extensively covered, and we determined a mideclipse time of JD 2,448,492, in agreement with Munari et al. (1992). From the 1993 eclipse data (Munari et al. 1995) we estimated a mideclipse time of JD 2,449,129, which produces a period of 637 days. The data for the 1989–

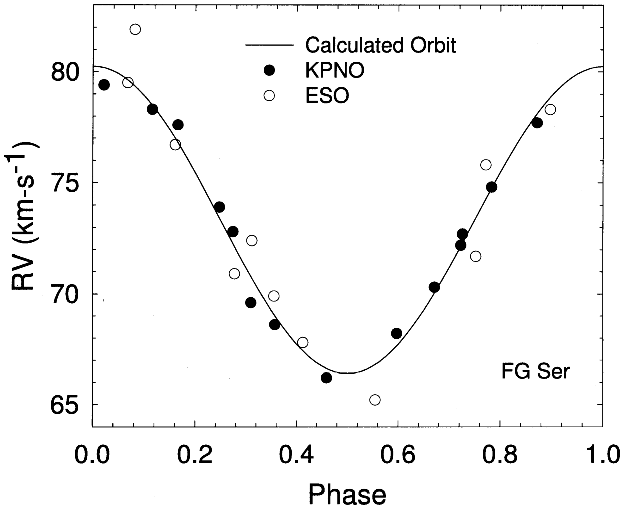

FIG. 6.—Computed radial-velocity curve of FG Ser compared with the observed velocities. Zero phase is a time of maximum velocity.

TABLE 11

ORBITAL ELEMENTS OF FG SERPENTIS

Orbital Parameters	Mürset et al. (2000)	KPNO Data Solution	Final Solution
P (days)............	650 ± 5	641.4 ± 6.2	633.5 ± 2.4
T_0[a] (HJD)	...	2,451,188.1 ± 2.9	2,451,189.8 ± 2.9
γ (km s^{-1}).........	71.2 ± 0.2	73.33± 0.16	73.32 ± 0.16
K_1 (km s^{-1})........	8.3 ± 0.2	6.92 ± 0.29	6.92 ± 0.26
e....................	0.0	0.0	0.0
$a_1 \sin i$ (km)	...	61.0 ± 2.6 × 10^6	60.3 ± 2.3 × 10^6
$f(m)$[b] ($M_\odot$)..........	0.039 ± 0.004	0.0221 ± 0.0027	0.0218 ± 0.0025

[a] T_0 = time of maximum velocity.

[b] $f(m) = (m_2)^3 \sin^3 i/(m_1 + m_2)^2$.

1990 eclipse are insufficient to determine an accurate time of mideclipse. Thus, the photometric and spectroscopic periods are in good accord. We note that adopting the center-of-mass velocity for the two mideclipse Julian dates and including them with unit weight in a circular-orbit solution increased the period slightly to 633.9 days. From our final orbital elements, our eclipse ephemeris is

$$T_{\rm conj} = {\rm JD}\ 2{,}451{,}031.4(\pm 2.9) + 633.5(\pm 2.4)E\ .$$

8. SUMMARY

A total of 11 orbits, over half of the number listed in the recent catalog of Belczyński et al. (2000), have been revised and discussed in Paper I and this paper. As in Paper I, we have found that our velocities, measured in the infrared, give an orbital solution in basic agreement with solutions obtained with visual-wavelength radial velocities, although our velocities are more precise. Thus, we have used our infrared velocities combined with other velocity data sets in the literature to determine improved orbital elements for the cool giant in five symbiotic systems.

All the systems in this paper, Z And, AG Dra, V443 Her, AX Per, and FG Ser, have circular orbits. The mass functions of the orbits are quite small, 0.001–0.03 $M_{\odot}$, implying that the secondary components are white dwarfs or perhaps low-mass main-sequence stars. Our orbital periods, determined from the radial velocities alone, are in excellent agreement with and often have smaller uncertainties than the previously derived photometric periods. The infrared velocities of AG Dra do not show the large orbital velocity residuals found for its visual-wavelength velocities.

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