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SPECKLE AND SPECTROSCOPIC ORBITS OF THE EARLY A-TYPE TRIPLE SYSTEM η VIRGINIS

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ABSTRACT

Eta Virginis is a bright ($V=3.89$) triple system of composite spectral type A2 IV that has been observed for over a dozen years with both spectroscopy and speckle interferometry. Analysis of the speckle observations results in a long period of 13.1 yr. This period is also detected in residuals from the spectroscopic observations of the 71.7919 day short-period orbit. Elements of the long-period orbit were determined separately using the observations of both techniques. The more accurate elements from the speckle solution have been assumed in a simultaneous spectroscopic determination of the short- and long-period orbital elements. The magnitude difference of the speckle components suggests that lines of the third star should be visible in the spectrum. In our blue and red spectra only the Mg II 4481 Å line appears to show a third component, however, and it is a very broad and weak feature. The equatorial rotational velocities of the short-period pair are quite low, about 8 km s^{-1} each. The inclinations of the long- and short-period orbits appear to be similar (about 50° each), so the orbits may be coplanar. The best estimate of the distance to the system is 74 pc.

1. INTRODUCTION

Spectroscopy, speckle interferometry, and visual micrometry have been used to determine the nature of the η Vir multiple system [HR 4689=HD 107259=McA 37, $\alpha(2000)=12^{\rm h}19^{\rm m}54\overset{\rm s}{.}3$, $\delta(2000)=-0^\circ40'0''$]. A composite spectral type of A2 IV for η Vir was determined by Conti (1969). Nicolet (1978) listed its visual magnitude as 3.89 mag. Here, our identifications are as follows: the stronger-lined or primary spectroscopic component is called Aa, the weaker-lined or secondary spectroscopic component is called Ab. Component B is the fainter speckle companion.

The variable radial velocity of η Vir was discovered independently at Lick Observatory and Yerkes Observatory in the early 1900's. Shortly thereafter, several spectroscopic orbits were published. Ichinohe (1907) began spectroscopic observations of η Vir in 1903 January at Yerkes Observatory and by 1907, 25 spectrograms had been obtained. The spectrum of Ab was detected with the three-prism spectrograph. Ichinohe found that the spectrum of η Vir looked like that of the "Sirius type," what we now call an early A star. He noted that its spectrum is very easy to recognize and measure for radial velocities and that the absorption line spectrum of Ab is similar to Aa, but has weaker lines. He also identified the chemical elements found in the spectrum of η Vir.

Ichinohe found an orbital period of 71.9 days for Aa and noted that the radial-velocity curve of Aa was very simple but that the radial-velocity curve of Ab was unusual. He concluded that Ab was a distant companion of Aa rather than the secondary of the 71.9 day binary, *i.e.*, there was another component closer to Aa than the second component that was visible in his spectrograms. Yang (1989) noted that Ichinohe's two unusual secondary velocities corresponded to those times when the system was very close to its center-of-mass velocity. Thus, his measurement of secondary lines at these phases was spurious and, as shown by Harper (1935), the Ab component is indeed the secondary of the 71.9 day orbit.

From 43 spectrograms obtained during 1907 at the Dominion Observatory (DO) in Ottawa, Canada, Harper (1908) determined provisional orbital elements for component Aa that are very similar to those determined by Ichinohe (1907). Harper (1935) in his *Reexamination of 64 orbits* reevaluated the η Vir results. He discussed 21 three-prism spectrograms obtained at the DO from 1907 to 1910 and 19 single-prism spectrograms obtained at Dominion Astrophysical Observatory in Victoria from 1923 to 1934. The greater dispersion of the three-prism spectrograph resulted in spectral lines of Aa that were affected less by the lines of Ab throughout the long, flat part of the velocity curve. He asserted that the radial velocities from the three-prism spectrograms are the most reliable and with them he determined an improved set of orbital elements. In these results, he adopted the orbital period of 71.9 days, the same as that determined by Ichinohe. However, he suggested that a period of 71.8 days was better for the later observations.

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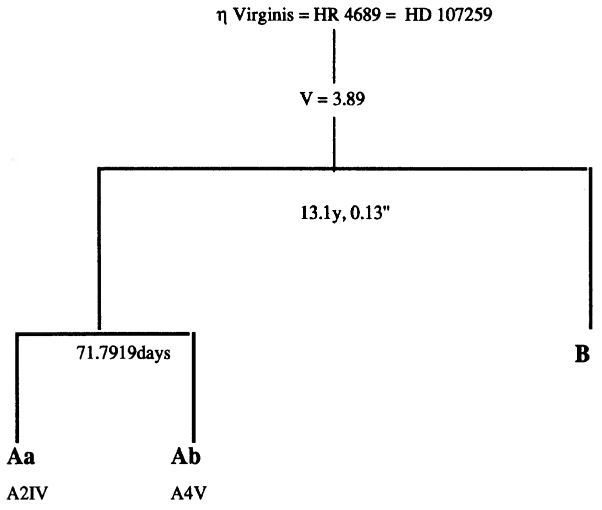

FIG. 1. The mobile diagram model of η Vir.

Harper noted differences in the center-of-mass velocities of the various datasets but suggested that this was most likely due to the different telescope and spectrograph combinations that were used rather than a third body in the system. Nevertheless, the possibility of a third star was again raised.

Conti (1969) made a detailed high-dispersion spectroscopic study of η Vir. He previously (Conti 1965) had classified the system (in single-lined phase) as an early Am star. His abundance analysis of Aa and Ab showed that the short-period secondary, Ab, is deficient in calcium, scandium, and titanium, and he classified it as an Am star. In Aa, these elements are normal.

McAlister and his colleagues have observed η Vir since 1976 when the "visual" companion was discovered with speckle interferometry (McAlister 1977). Speckle observations of the system were originally obtained to examine the possibility that the 71.9 day system might be marginally resolvable (McAlister 1976), but due to the relatively large observed separation and slow orbital motion, McAlister (1978) concluded that the visual companion was not the spectroscopic companion Ab but a third star. Heintz (1978) visually confirmed the new component. As a result of the detection of a close visual companion, one of us (F.C.F.) began a new series of high-dispersion spectroscopic observations.

Balega *et al.* (1984) determined preliminary orbital elements from the speckle observations obtained between 1976 and 1982. They found an orbital period of 13.0 yr, an eccentricity of 0.08, a semimajor axis of 0″135, and an inclination of 49°4. Speckle observations through 1989 have been listed by McAlister & Hartkopf (1988) and McAlister *et al.* (1990).

In this paper, we analyze our extensive speckle and spectroscopic observations to determine the properties of this close multiple system. Eta Vir is a hierarchical system of at least three stars. The system and some of its properties (Fig. 1) are represented in a mobile diagram, following the precepts of Evans (1968).

TABLE 1. Speckle orbital elements for McA 37 AB.

P_L (days)	4791.9	±	18.0
P_L (years)	13.12	±	0.05
a_L	0″136	±	0″012
i_L	51°1	±	0°2
Ω_L	173°0	±	2°4
T_L	1963.80	±	0.02
e_L	0.079	±	0.014
ω_L	1°4	±	2°4

2. ANALYSIS OF THE SPECKLE INTERFEROMETRIC DATA

Over 60 speckle measurements of η Vir have been published since McAlister's (1977) discovery of the long-period pair in early 1976. Speckle observations now cover just over one full revolution of the AB system. While the majority of the speckle data comes from the CHARA program, additional interferometric measurements have been obtained by Balega *et al.* (1984), Tokovinin (1982, 1985), Weigelt & Wirtnitzer (1983), Bonneau *et al.* (1985), Balega & Balega (1985, 1987), Ebersberger *et al.* (1986), Blazit *et al.* (1987), and Ismailov (1992). The complete collection of speckle data through 1988 is given in the catalog of McAlister & Hartkopf (1988), and the most recent published CHARA speckle measurements are presented by McAlister *et al.* (1990). The photographic speckle camera system and reduction technique used by McAlister through 1981 are described in his 1977 paper, while the ICCD speckle system used by CHARA since 1982 is described by McAlister *et al.* (1987).

In addition to these speckle data, a single visual measurement was published by Heintz (1978). This observation established the proper quadrant of the secondary. Classical speckle interferometry is subject to a 180° ambiguity in position angle determinations. The newer method of "directed vector autocorrelation" developed at CHARA by Bagnuolo (Bagnuolo *et al.* 1992) eliminates this ambiguity and has confirmed the quadrant as determined by Heintz.

An orbit for the long-period η Vir system (McA 37 AB), based on all speckle and visual data, was determined with the "grid-search" technique described by Hartkopf *et al.* (1989). Table 1 gives the final orbital elements derived by this technique while Table 2 gives the observational data, including two unpublished measurements obtained during 1990 and 1991, and residuals to this orbit. Column identifications in Table 2 are as follows: column 1 gives the epoch of observation in fractional Besselian year, columns 2 and 3, the observed position angle θ (in degrees) and angular separation ρ (in arcseconds), columns 4 and 5, the calculated θ and ρ, columns 6 and 7, the residuals $(O-C)$ in θ and ρ, column 8, the final assigned weight of the

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TABLE 2. Speckle observations and residuals for McA 37 AB.

Date	θ_{obs}	ρ_{obs}	θ_{calc}	ρ_{calc}	$\Delta\theta$	$\Delta\rho$	Weight	Code
1976.0364	151.7	0.118	155.3	0.119	−3.6	−0.001	20.0	A1
1976.3012	162.2	0.122	161.1	0.122	1.1	−0.000	20.0	A2
1976.3722	162.3	0.120	162.6	0.123	−0.3	−0.003	10.0	A6
1976.4570	162.8	0.124	164.4	0.124	−1.6	0.000	20.0	A2
1976.9236	174.6	0.135	173.9	0.126	0.7	0.009	20.0	A3
1977.0876	177.2	0.123	177.3	0.125	−0.1	−0.002	20.0	A3
1977.1750	177.8	0.129	179.1	0.125	−1.3	0.004	10.0	A6
1977.1778	181.4	0.126	179.1	0.125	2.3	0.001	10.0	A6
1977.1806	178.3	0.120	179.2	0.125	−0.9	−0.005	10.0	A6
1977.3200	159.1	0.130	182.1	0.124	−23.0	0.007	0.0	V
1977.3280	180.4	0.104	182.2	0.123	−1.8	−0.019	0.0	A6
1977.4865	186.7	0.124	185.6	0.122	1.1	0.002	20.0	A4
1977.9201	186.4	0.119	195.5	0.115	−9.1	0.004	0.0	A6
1978.1470	202.1	0.113	201.2	0.110	0.9	0.003	20.0	A5
1978.1498	202.3	0.115	201.3	0.110	1.0	0.005	20.0	A5
1978.3108	208.8	0.110	205.6	0.107	3.2	0.003	10.0	A10
1978.3189	207.4	0.106	205.9	0.107	1.5	−0.001	10.0	A10
1979.0371	228.6	0.101	229.6	0.091	−1.0	0.010	20.0	A7
1979.1874	235.4	0.087	235.6	0.089	−0.2	−0.002	10.0	A10
1979.1900	237.3	0.075	235.7	0.089	1.6	−0.014	10.0	A10
1979.3594	241.9	0.095	242.7	0.087	−0.8	0.008	20.0	A7
1979.3622	240.9	0.095	242.8	0.087	−1.9	0.008	20.0	A7
1980.1539	278.9	0.070	277.4	0.088	1.5	−0.018	20.0	A8
1980.1593	285.9	0.087	277.6	0.088	8.3	−0.001	20.0	A8
1980.4735	286.0	0.085	289.9	0.093	−3.9	−0.008	5.0	F8
1980.4763	292.6	0.093	290.0	0.093	2.6	0.000	20.0	A8
1980.4790	294.1	0.095	290.1	0.093	4.0	0.002	20.0	A8
1980.4817	291.7	0.093	290.2	0.093	1.5	−0.000	20.0	A8
1981.2476	308.0	0.109	313.9	0.112	−5.9	−0.003	5.0	F8
1981.3570	325.4	0.094	316.6	0.115	8.8	−0.021	0.0	R6
1981.4565	318.6	0.117	319.0	0.118	−0.4	−0.001	20.0	A9
1981.4620	317.7	0.116	319.1	0.118	−1.4	−0.002	20.0	A9
1981.4728	318.1	0.117	319.3	0.118	−1.2	−0.001	20.0	A9
1982.1711	330.0	0.124	333.3	0.134	−3.4	−0.010	5.0	F8
1982.3860	335.5	0.137	337.1	0.138	−1.6	−0.001	5.0	G6
1983.0482	347.1	0.153	347.5	0.146	−0.4	0.008	20.0	C2
1983.0699	349.4	0.146	347.8	0.146	1.7	−0.000	20.0	C2
1983.1040	348.7	0.136	348.3	0.146	0.4	−0.010	5.0	G7
1983.3980	65.8	0.091	352.7	0.147	73.1	−0.056	0.0	R12
1983.4141	352.7	0.152	352.9	0.147	−0.2	0.005	20.0	C2
1983.4169	351.9	0.146	352.9	0.147	−1.1	−0.001	20.0	C2
1983.9613	1.0	0.144	1.1	0.145	−0.1	−0.001	5.0	R11
1984.0529	2.2	0.143	2.5	0.144	−0.3	−0.001	20.0	C2
1984.0557	2.2	0.144	2.5	0.144	−0.3	0.000	20.0	C2
1984.0583	2.7	0.145	2.5	0.144	0.2	0.001	20.0	C2
1984.0612	2.1	0.139	2.6	0.144	−0.5	−0.005	20.0	C2
1984.3726	6.9	0.141	7.5	0.140	−0.7	0.001	20.0	C2
1984.3751	6.7	0.138	7.6	0.140	−0.9	−0.002	20.0	C2
1984.4005	10.0	0.137	8.0	0.139	2.0	−0.002	5.0	F11
1985.0004	17.5	0.126	18.7	0.128	−1.3	−0.002	20.0	C2
1985.1805	23.4	0.120	22.4	0.123	1.0	−0.003	5.0	R15
1985.2053	22.5	0.120	22.9	0.123	−0.4	−0.003	5.0	F11
1985.2491	27.0	0.113	23.8	0.122	3.2	−0.009	5.0	F11
1985.4812	29.8	0.115	29.1	0.116	0.7	−0.001	20.0	C2
1986.4067	57.1	0.093	56.9	0.093	0.2	0.000	20.0	C4
1986.4470	61.2	0.087	58.4	0.092	2.8	−0.005	5.0	F12
1987.2640	92.2	0.088	92.8	0.085	−0.6	0.003	20.0	C4
1987.2667	91.3	0.088	92.9	0.085	−1.6	0.002	20.0	C4
1988.1966	126.9	0.102	129.3	0.099	−2.4	0.003	5.0	R18
1988.2496	129.4	0.103	131.0	0.100	−1.6	0.003	20.0	C4
1988.2550	132.5	0.099	131.2	0.100	1.3	−0.002	20.0	C4
1989.2271	157.1	0.118	156.9	0.120	0.2	−0.002	20.0	C5
1989.3033	160.1	0.119	158.6	0.121	1.6	−0.002	20.0	C5
1990.2759	179.0	0.121	178.7	0.125	0.4	−0.004	20.0	†
1990.4401	177.4	0.141	182.1	0.124	−4.7	0.018	0.0	R18
1991.3186	200.7	0.107	202.6	0.109	−1.9	−0.002	20.0	†

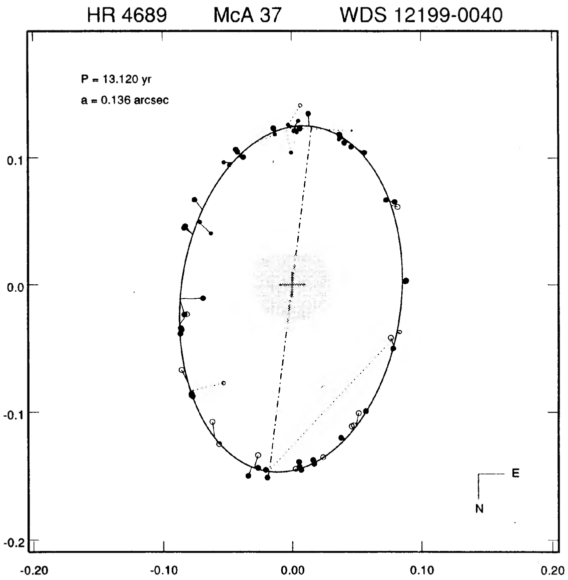

FIG. 2. Speckle orbit of the long-period system McA 37 AB. CHARA speckle observations are shown as filled circles, while other speckle observations are indicated by open circles; the single visual observation (Heintz 1978) is indicated by a plus sign. The shaded region represents the separation regime within 0″.030, the limit of resolution for a 4 m telescope. The line of nodes and O−C lines are also shown; points given zero weight in the final orbit solution are indicated by dotted O−C lines. Axes are in seconds of arc.

observation, and column 9, the source code for the observation (code "C5" is McAlister *et al.* 1990; "R18" is Ismailov 1992; "V" is Heintz 1978; "†" is unpublished; other codes are listed in McAlister & Hartkopf 1988). A plot of the speckle observations against the newly determined orbit is shown in Fig. 2. Eta Vir has also been recently detected as a binary by the *HIPPARCOS* spacecraft (Söderhjelm *et al.* 1992). We chose not to include this measure (ρ=0″.12,θ=163°) because of its preliminary nature and lack of precise epoch; we did find it to be in good agreement with our orbit, however.

Eta Vir was originally observed with speckle interferometry in an attempt to resolve the spectroscopic binary. The star had been observed with interferometry as early as 1921 by Merrill (1922) using Michelson interferometry at the 100 in. telescope on Mt. Wilson. Merrill saw no evidence of a companion and concluded that the separation must be less than 0″.03. McAlister (1976) estimated that the angular separation of 71.9 day system would be at the 0″.030 level, a value just below the limiting resolution of the Kitt Peak 4 m telescope. The uncertainty in this prediction was such that an attempt to resolve the double-lined spectroscopic binary, from which the combined speckle and spectroscopic data would give the individual masses and distance to the system, was worthwhile. It was thus surprising when a companion with four times the predicted angular separation was found in early 1976. The orbital motion observed during that first year of regular observation quickly led to the conclusion that a new component of the system had been observed rather than the spectroscopic secondary.

McAlister (1976) also estimated the astrometric perturbation that might be expected to result from the spectroscopic component and estimated that a photocentric submotion with an amplitude of 0″.002 would be present. In a study of the limiting accuracy obtainable from speckle interferometric observations of binary stars, Al-Shukri (1991) analyzed the residuals that are shown in Fig. 3. Al-Shukri performed a periodogram analysis of the residuals separately in θ and ρ, and concluded that the photocentric motion is not detectable because no significant peak is revealed in the periodograms, shown in Fig. 4, of either coordinate. The spectroscopic system has been recently resolved by the Mark III interferometer on Mt. Wilson at a separation under the diffraction limit of 4-m telescopes (Pan 1992).

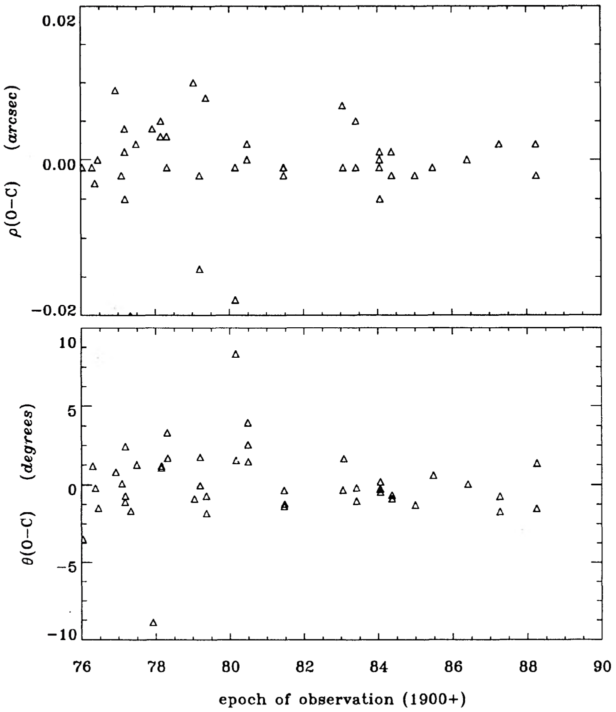

FIG. 3. Residuals in angular separation ρ (above) and position angle θ (below) vs time for McA 37, from Al-Shukri (1991).

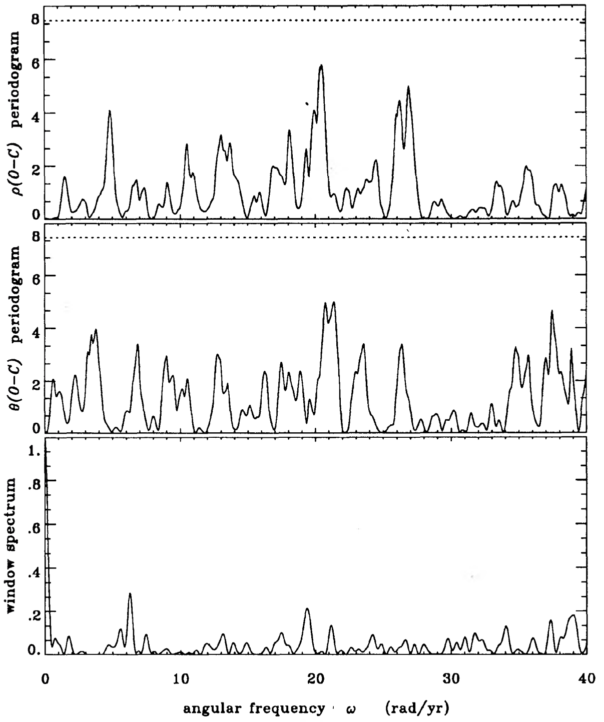

FIG. 4. Periodograms of residuals in ρ (top) and θ (middle) and window power spectrum (bottom) for McA 37, from Al-Shukri (1991). The horizontal dotted lines represent the minimum height required for a peak to come from a real signal.

3. SPECTROSCOPIC OBSERVATIONS AND REDUCTIONS

Our 50 spectroscopic observations of η Vir were obtained from 1978 June to 1991 March, an interval of nearly 13 yr. Among these observations, four were obtained with photographic plates at McDonald Observatory or Kitt Peak National Observatory (KPNO), six with the Reticon detector (Vogt *et al.* 1978) at McDonald Observatory, and 40 with various charge coupled devices (CCD's) at KPNO. Table 3 lists the different telescope and detector combinations. Two main spectral regions were observed. One was the blue region around 4500 Å (Fig. 5) and the other was the red region around 6420 Å (Fig. 6). Column seven of Table 3 lists a source code for each combination of telescope, spectrograph setup, and detector.

The four McDonald Observatory and KPNO plates were measured with Grant measuring machines at Johnson Space Flight Center, Houston, Texas and KPNO, respectively. About 20 lines primarily of Fe I, Fe II, or Ti II were measured for both Aa and Ab.

Details of the reduction procedure for the Reticon and CCD spectra have been given by Fekel *et al.* (1978). Most of the more recent observations have been obtained at red wavelengths because of the better velocity resolution at these longer wavelengths. The determination of accurate velocities for the very weak absorption features in the 6420 Å region is possible because the lines of Aa and Ab are quite narrow and because relatively high signal-to-noise (S/N) ratios are obtainable with solid-state detectors. Usually three to five lines of Aa were used while only two or three lines of Ab could be used.

Ideally, the radial velocity of η Vir should be determined relative to the velocity of a standard or reference star of constant radial velocity and similar spectral type. Unfortunately, there currently are no International Astronomical Union (IAU) radial-velocity standard stars earlier in spectral type than F5 (Pearce 1957). Latham & Stefanik (1992) briefly discuss the current status of early type radial-velocity standard stars. Thus, we will call the stars that we have used to determine the velocities of η Vir "reference" stars.

The five different reference stars used (β Vir, σ Boo, α Lyr, θ Leo, and μ Ori) are listed in Table 4. Of these, the most suitable reference star at red wavelengths, where most of the observations have been obtained, is σ Boo. Although it is an F2 V star, σ Boo has modest strength narrow lines of the same species as those of η Vir. With β Vir used as a reference star of known velocity (Table 4), we measured spectra of σ Boo on 24 nights (Table 5) and found its radial velocity to be $+0.08\pm0.09$ km s^{-1}. This is in excellent agreement with the value of $+0.2$ km s^{-1} determined from Lick Observatory spectrograms (Campbell & Moore 1928).

For the purpose of plotting the short- and long-period orbits, observed velocities have been separated into short- and long-period computed velocities $V_{\rm S}$ and $V_{\rm L}$, respectively (Tables 6 and 7). Each of these velocities is the sum of its calculated orbital velocity and one-half of the total (O−C) residual. Thus, the sum of $V_{\rm S}$ and $V_{\rm L}$ is $V_{\rm obs}$.

TABLE 3. Telescope/detector combinations.

Observatory	Telescope	Detector	Dispersion (Å mm^{-1})	Resolution (Å)	Wavelength Region (Å)	Source Code
McDonald	2.1 m	IIaO plate	8.5	0.17	3800 – 4600	MPb
McDonald	2.7 m	Reticon	4.5	0.24/0.36	4455 – 4560	MRb
McDonald	2.7 m	Reticon	4.4	0.24	6345 – 6445	MRr
Kitt Peak	coudé feed	IIaO plate	8.9	0.18	3800 – 4600	KPb
Kitt Peak	coudé feed	Fairchild CCD	14.8	0.45	6335 – 6500	KFr
Kitt Peak	coudé feed	TI CCD	7.6	0.23	6385 – 6475	KT1r
Kitt Peak	coudé feed	TI CCD	3.8	0.23	4475 – 4520	KT1b
Kitt Peak	coudé feed	TI CCD	4.2	0.18	6400 – 6450	KT2r
Kitt Peak	coudé feed	TI CCD	7.0	0.18	6386 – 6470	KT3r
Kitt Peak	coudé feed	TI CCD	4.7	0.21	3920 – 3976	KT3b

M = McDonald Observatory
K = KPNO
P = photographic plate
R = Reticon detector
F = Fairchild CCD
T1, T2, T3 = TI CCD with different dispersions
b = blue spectral region
r = red spectral region

Table 6 lists our radial velocities of η Vir Aa. Column 1 lists the heliocentric Julian date of each observation. Column 2 gives the total observed velocity while column 3 lists the total velocity residual of the combined long- and short-period orbits. Columns 4 and 5 list the phase and the computed component of the radial velocity in the long-period orbit. Columns 6 and 7 list the phase and the computed component of the radial velocity in the short-period orbit. Columns 8 and 9 list the reference star for the Reticon and CCD observations and source code for the telescope/detector combinations. Table 7 lists the same information for η Vir Ab.

Of all the old spectroscopic data analyzed by Ichinohe (1907) and Harper (1935), only those spectrograms obtained at the DO in Ottawa with the three-prism spectrograph have a dispersion great enough to resolve the lines of Aa and Ab completely. Thus, only the velocities from those observations (Table 6) are included with our data in the present analysis, and were assigned appropriate weights (Yang 1989).

4. SPECTROSCOPIC ORBIT

The observed velocities listed in Tables 6 and 7 consist of the sum of the velocity variations in both the long- and short-period orbits. From these velocities, elements for both orbits were determined for Aa and then for Ab.

Preliminary short-period elements were determined with the Wilsing–Russell method (Wolfe *et al.* 1967) and the assumed 71.9 day period determined by Harper (1935). With this method, a series of sines and cosines is used to solve for the orbital elements if the period is known. These elements were refined with a differential-corrections program.

A general least-squares (GLS) differential-corrections program (Daniels 1966) was used to simultaneously determine the long- and short-period orbital elements. We assumed the values of P_L, T_L, e_L, and $\omega_L+180°$ from the speckle-orbit solution as starting values. Harper's data, obtained up to 80 years ago, were useful in improving the short period from 71.798±0.007 days (our data only) to 71.7919±0.0008 days. A solution of the spectroscopic data with all short- and long-period elements allowed to vary results in the long-period elements listed in Table 8 and compared with the speckle elements. Given the uncertainties of the spectroscopic elements, P_L, T_L, and ω_L are in reasonable agreement. The difference in eccentricity may result from the incomplete phase coverage of the spectroscopic orbit. Since the spectroscopic observations cover less

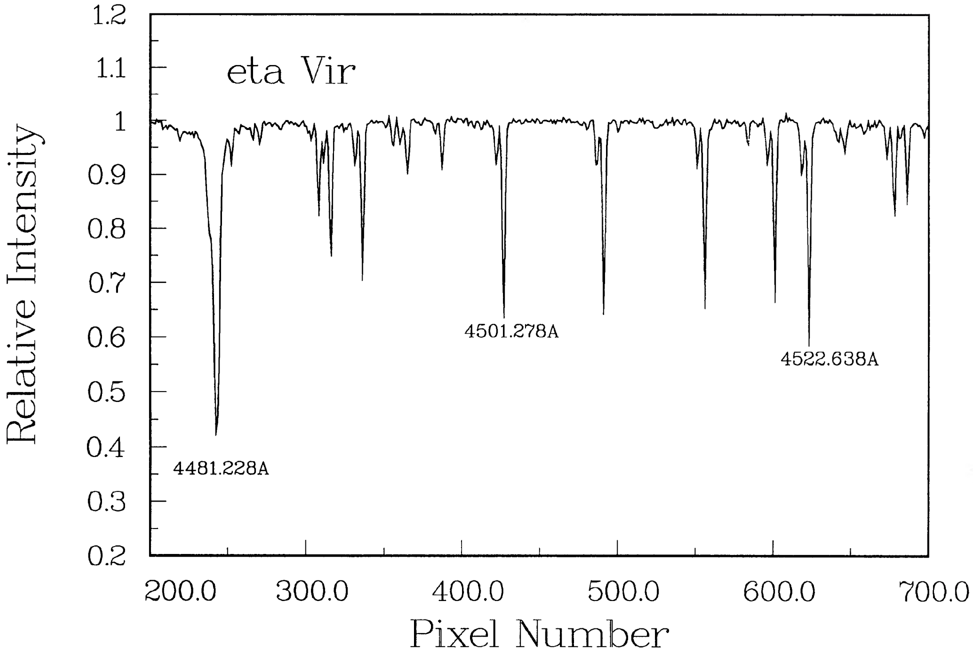

FIG. 5. A portion of a CCD spectrum of η Vir in the 4500 Å region. Wavelengths of several lines are given.

than one cycle of the long period and the speckle elements are significantly more accurate, the long period P_L, T_L, e_L, and $\omega_L+180°$ were fixed at the speckle values. Table 6 lists the results for Aa of this final solution of the long and short periods. The long- and short-period phases and observed velocities for Aa are listed. Figure 7 is a plot of the radial-velocity curve and observations versus phase for the long-period orbit while Fig. 8 is for the short-period orbit. For the solution of Ab, the short period was fixed at $P=71.7919$ days from the solution of component Aa. The other elements of Ab are those found by the GLS program. The velocity results are listed in Table 7 and the final orbital elements are listed in Table 9.

Because the spectral lines of Ab are significantly weaker,

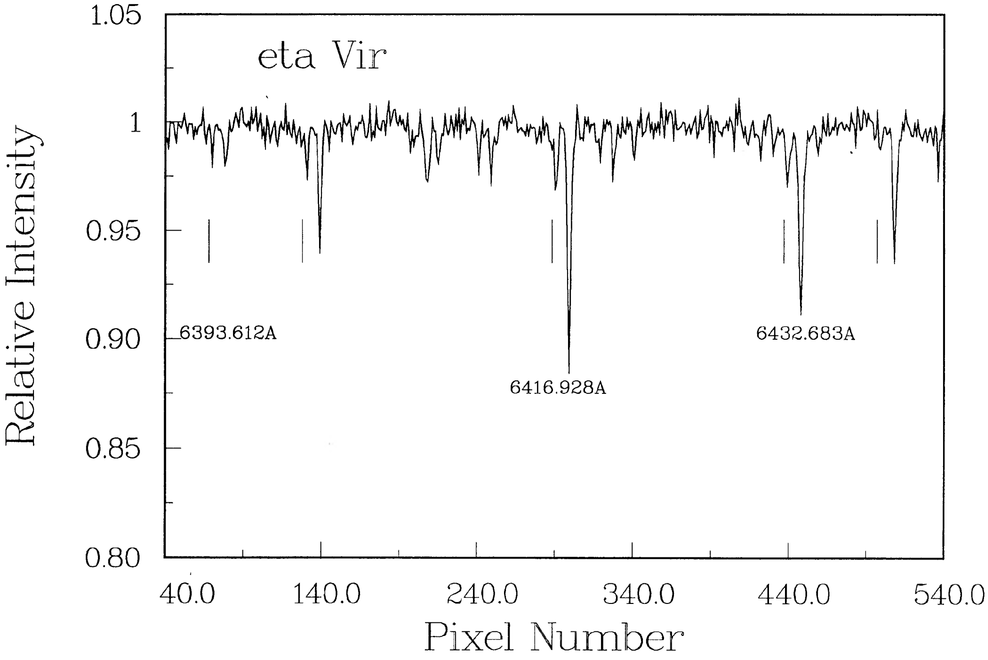

FIG. 6. A portion of a CCD spectrum of η Vir in the 6420 Å region. Short tick marks indicate lines from Ab. Wavelengths of several lines are given.

TABLE 4. Reference stars for η Vir.

Reference star	Spectral type	V ($\mathrm{km\,s^{-1}}$)	Source
β Vir	F9V	+ 4.3	Mayor & Maurice (1985)
σ Boo	F2V	0.0	This paper
θ Leo	A2V	+ 7.9	Fekel (1985)
α Lyr	A0V	−14.2	Campbell & Moore (1928)
μ Ori	Am	+28.6	Unpublished

the orbital elements of the long- and short-period orbits determined for Aa are to be preferred. However, the mutual elements of the Aa and Ab solutions are consistent with each other. The short-period orbit of Ab is shown in Fig. 8.

5. DISCUSSION AND CONCLUSIONS

We have obtained speckle elements of the long-period system that combined with spectroscopic orbital elements of the short- and long-period systems, the magnitude differences of the components, and the spectral types, will be used to determine the properties of the system. The spectral type of the whole system is A2IV (Conti 1969, Cowley *et al.* 1969), or A1IV (Gray & Garrison 1987). The photometric properties of η Vir are as follows: the visual magnitude is V=3.89 mag and the color indices are $B-V=+0.02$ mag, $U-B=+0.06$ mag (Nicolet 1978). The Stromgren color indices are $b-y$=0.017 mag; m_1 = 0.162 mag; c_1 = 1.132 mag; β=2.863 mag (Hauck & Mermilliod 1980). The colors are consistent with an early A spectral type and the c_1 index indicates that at least one of the stars is evolved. The trigonometric parallax is 0.″015 ±0.″012 (Van Altena 1989).

The visual magnitude difference of components B and A

TABLE 5. Radial velocity observations of σ Boo.

HJD 2400000+	V ($\mathrm{km\,s^{-1}}$)	Standard Star	Source Code
46583.7321	0.75	β Vir	KT1r
46586.7083	−0.20	β Vir	KT1r
46866.9147	−0.39	β Vir	KT1r
46867.7925	0.12	β Vir	KT1r
46868.8148	0.33	β Vir	KT1r
46970.7301	0.79	β Vir	KT1r
46971.6876	0.24	β Vir	KT1r
46972.7258	0.31	β Vir	KT1r
46974.6979	0.38	β Vir	KT1r
47244.8728	−0.24	β Vir	KT3r
47245.7551	0.46	β Vir	KT3r
47247.9006	−0.35	β Vir	KT3r
47248.8840	−0.72	β Vir	KT3r
47308.8136	−0.02	β Vir	KT3r
47309.8538	−0.08	β Vir	KT3r
47310.8219	−0.62	β Vir	KT3r
47312.8495	−0.20	β Vir	KT3r
47313.8023	−0.42	β Vir	KT3r
47555.9935	−0.13	β Vir	KT3r
47556.9738	0.66	β Vir	KT3r
47557.0443	0.17	β Vir	KT3r
47623.7730	0.30	β Vir	KT3r
47626.8341	0.12	β Vir	KT3r
47916.0511	0.61	β Vir	KT3r

TABLE 6. Radial velocity observations of η Vir Aa.

HJD 2400000+	V_{obs} ($\mathrm{km\,s^{-1}}$)	(O−C)	PHASE$_L$	V_L ($\mathrm{km\,s^{-1}}$)	PHASE$_S$	V_S ($\mathrm{km\,s^{-1}}$)	Reference Star	Source Code
17710.630	−29.1	−6.9	0.699	0.1	0.890	−29.2		
17714.750	−35.0	−5.8	0.700	0.7	0.947	−35.7		
17716.630	−34.6	−4.8	0.700	1.2	0.973	−35.8		
17739.610	20.5	−0.2	0.705	3.6	0.293	16.9		
17989.880	−2.2	−0.4	0.757	5.0	0.780	−7.2		
18021.810	17.5	0.8	0.764	5.8	0.224	11.7		
18031.820	21.5	−3.5	0.766	3.7	0.364	17.8		
18052.620	12.0	−2.0	0.770	4.6	0.653	7.4		
18077.620	−30.7	−4.9	0.775	3.3	0.002	−34.0		
18087.580	−2.5	−6.5	0.777	2.6	0.140	−5.1		
18089.600	12.3	3.0	0.778	7.3	0.168	5.0		
18103.610	24.4	−1.1	0.781	5.4	0.364	19.0		
18355.790	−19.7	−3.7	0.833	5.7	0.876	−25.4		
18642.930	−12.6	1.7	0.893	10.0	0.876	−22.6		
18706.740	5.8	1.1	0.907	10.0	0.765	−4.2		
18727.820	−10.7	0.7	0.911	9.9	0.058	−20.6		
18736.730	12.5	−2.8	0.913	8.2	0.182	4.3		
18753.790	28.1	−1.4	0.916	9.0	0.420	19.2		
18757.910	28.4	−0.1	0.917	9.6	0.477	18.8		
18759.790	29.6	1.9	0.918	10.6	0.504	19.0		
18764.700	25.3	1.0	0.919	10.2	0.572	15.1		
43670.605	28.7	1.5	0.116	9.5	0.490	19.2		MPb
43671.648	27.7	1.0	0.116	9.2	0.505	18.5		MPb
44040.616	13.8	−2.0	0.193	5.5	0.644	8.3	β Vir	MRr
44178.023	20.4	−0.7	0.222	5.3	0.558	15.2	β Vir	MRb
44356.834	−20.4	−1.7	0.259	3.6	0.049	−24.0	α Lyr	MRb
44357.699	−16.1	−0.2	0.260	4.4	0.061	−20.5	β Vir	MRb
44738.743	21.8	−0.3	0.339	2.3	0.368	19.5	θ Leo	MRb
44739.741	22.1	−0.2	0.339	2.4	0.382	19.7	θ Leo	MRb
45074.843	−22.1	−0.5	0.409	1.1	0.050	−23.2		KPb
45075.799	−15.9	2.5	0.409	2.6	0.063	−18.5	θ Leo	KFr
45076.769	−14.8	0.4	0.410	1.5	0.077	−16.3	θ Leo	KFr
45078.808	−6.6	1.7	0.410	2.2	0.105	−8.8	θ Leo	KFr
45723.009	−15.7	−0.6	0.545	0.7	0.078	−16.4		KPb
45784.822	−28.9	2.2	0.557	2.2	0.939	−31.1	μ Ori	KT1b
45814.672	20.3	−0.2	0.564	1.0	0.355	19.3	θ Leo	KT1r
45855.715	−30.8	−1.0	0.572	0.7	0.927	−31.5	θ Leo	KT1r
46534.709	23.0	−0.8	0.714	3.6	0.385	19.4	θ Leo	KT1r
46583.740	−14.9	−0.4	0.724	4.0	0.068	−18.9	σ Boo	KT1r
46586.716	−4.5	−0.1	0.725	4.2	0.109	−8.7	σ Boo	KT1r
46866.883	−24.3	−0.1	0.783	6.0	0.011	−30.3	σ Boo	KT1r
46867.790	−23.0	−0.8	0.783	5.6	0.024	−28.6	σ Boo	KT1r
46868.780	−19.1	0.4	0.784	6.2	0.038	−25.3	σ Boo	KT1r
46970.723	26.3	0.3	0.805	6.8	0.458	19.5	σ Boo	KT1r
46971.697	24.6	−1.1	0.805	6.1	0.471	18.5	σ Boo	KT1r
46972.719	22.5	−2.8	0.805	5.3	0.486	17.2	σ Boo	KT1r
46974.691	23.9	−0.4	0.806	6.5	0.513	17.4	σ Boo	KT1r
47151.035	−24.8	0.8	0.843	8.2	0.970	−33.0	β Vir	KT2r
47152.040	−25.1	0.1	0.843	7.9	0.983	−33.0	β Vir	KT3r
47153.077	−25.2	−1.1	0.843	7.3	0.998	−32.5	β Vir	KT3r
47244.857	24.5	0.2	0.862	8.5	0.276	16.1	σ Boo	KT3r
47245.752	24.1	−1.0	0.862	7.9	0.289	16.2	σ Boo	KT3r
47246.903	27.1	1.1	0.863	8.9	0.305	18.2	σ Boo	KT3b
47247.897	26.7	0.1	0.863	8.4	0.319	18.3	σ Boo	KT3r
47248.900	27.1	−0.0	0.863	8.4	0.333	18.8	σ Boo	KT3r
47308.807	11.0	−0.9	0.875	8.3	0.167	2.8	σ Boo	KT3r
47309.833	13.7	−0.6	0.876	8.4	0.181	5.3	σ Boo	KT3r
47310.821	15.6	−0.7	0.876	8.4	0.195	7.3	σ Boo	KT3r
47312.819	19.3	−0.6	0.876	8.4	0.223	10.9	σ Boo	KT3r
47313.781	22.4	1.1	0.877	9.3	0.236	13.1	σ Boo	KT3r
47555.984	21.2	−0.7	0.927	9.5	0.610	11.7	σ Boo	KT3r
47556.988	22.5	1.7	0.927	10.7	0.624	11.8	σ Boo	KT3r
47623.768	26.6	0.9	0.941	10.5	0.554	16.1	σ Boo	KT3r
47625.653	24.0	−0.2	0.942	10.0	0.581	14.0	σ Boo	KT3r
47626.832	23.9	0.8	0.942	10.5	0.597	13.4	σ Boo	KT3r
47916.050	19.5	−1.8	0.002	9.5	0.625	10.0	σ Boo	KT3r
48004.756	−11.1	−0.6	0.021	10.1	0.861	−21.2	σ Boo	KT3r
48007.781	−17.7	−0.2	0.021	10.3	0.903	−28.0	σ Boo	KT3r
48056.645	25.6	1.4	0.032	11.0	0.584	14.6	σ Boo	KT3r
48057.633	24.7	1.4	0.032	11.0	0.598	13.7	σ Boo	KT3r
48345.794	21.5	0.2	0.092	9.4	0.611	12.1	σ Boo	KT3r

TABLE 7. Radial velocity observations of η Vir Ab.

HJD 2400000+	V_{obs} (km s^{-1})	(O−C)	PHASE$_L$	V_L (km s^{-1})	PHASE$_S$	V_S (km s^{-1})	Reference Star	Source Code
17710.630	39.3	0.9	0.699	3.6	0.898	35.7		
17714.750	58.4	11.4	0.700	8.9	0.955	49.5		
17716.630	59.6	12.3	0.700	9.3	0.981	50.3		
18077.620	50.6	4.0	0.775	7.4	0.010	43.2		
18103.610	−24.0	−3.3	0.781	3.9	0.372	−27.9		
18355.790	48.1	8.6	0.833	11.5	0.884	36.6		
18757.910	−30.4	−14.1	0.917	2.3	0.486	−32.7		
18759.790	−29.2	−14.0	0.918	2.4	0.512	−31.6		
18764.700	−16.1	−5.4	0.919	6.7	0.580	−22.8		
43670.605	−16.4	0.3	0.116	8.6	0.498	−25.0		MPb
43671.648	−15.4	0.7	0.116	8.8	0.513	−24.2		MPb
44040.616	−11.5	−4.9	0.193	3.7	0.652	−15.2	β Vir	MRr
44178.023	−13.3	2.7	0.222	6.6	0.566	−19.9	β Vir	MRb
44356.834	33.5	−0.7	0.259	3.7	0.057	29.8	α Lyr	MRb
44357.699	29.7	−0.9	0.260	3.6	0.069	26.1	β Vir	MRb
44738.743	−25.8	−1.5	0.339	1.3	0.376	−27.1	θ Leo	MRb
44739.741	−24.5	0.1	0.339	2.1	0.390	−26.6	θ Leo	MRb
45074.843	32.4	1.8	0.409	1.7	0.058	30.7		KPb
45075.799	28.9	2.3	0.409	2.0	0.071	26.9	θ Leo	KFr
45723.009	21.8	0.3	0.545	0.6	0.086	21.2		KPb
45784.822	43.2	−0.6	0.557	0.3	0.947	42.9	μ Ori	KT1b
45814.672	−26.3	−1.0	0.564	0.1	0.363	−26.4	θ Leo	KT1r
45855.715	43.6	1.1	0.572	1.3	0.935	42.3	θ Leo	KT1r
46534.709	−24.2	−1.1	0.714	3.0	0.393	−27.2	θ Leo	KT1r
46583.740	27.6	−0.6	0.724	3.5	0.076	24.1	σ Boo	KT1r
46586.716	16.1	0.7	0.725	4.2	0.117	11.9	σ Boo	KT1r
46866.883	44.3	−0.7	0.783	5.3	0.020	39.1	σ Boo	KT1r
46867.790	40.2	−2.1	0.783	4.6	0.032	35.6	σ Boo	KT1r
46868.780	39.0	0.2	0.784	5.8	0.046	33.3	σ Boo	KT1r
46970.723	−17.3	2.6	0.805	7.6	0.466	−24.9	σ Boo	KT1r
46971.697	−18.3	1.2	0.805	6.9	0.480	−25.2	σ Boo	KT1r
46972.719	−22.1	−3.1	0.805	4.8	0.494	−26.9	σ Boo	KT1r
46974.691	−18.5	−0.8	0.806	6.0	0.521	−24.5	σ Boo	KT1r
47151.035	51.7	−0.0	0.843	7.5	0.978	44.2	β Vir	KT2r
47152.040	51.4	0.5	0.843	7.7	0.992	43.7	β Vir	KT3r
47153.077	48.8	−0.4	0.843	7.3	0.006	41.5	β Vir	KT3r
47244.857	−12.8	0.1	0.862	8.1	0.284	−20.9	σ Boo	KT3r
47245.752	−13.7	0.4	0.862	8.2	0.297	−21.9	σ Boo	KT3r
47246.903	−13.9	1.4	0.863	8.7	0.313	−22.6	σ Boo	KT3b
47247.897	−15.2	1.0	0.863	8.6	0.327	−23.8	σ Boo	KT3r
47248.900	−18.0	−1.1	0.863	7.5	0.341	−25.5	σ Boo	KT3r
47312.819	−8.7	−2.7	0.876	7.1	0.231	−15.8	σ Boo	KT3r
47313.781	−5.9	2.0	0.877	9.4	0.245	−15.3	σ Boo	KT3r
47555.984	−5.9	1.1	0.927	10.1	0.618	−16.0	σ Boo	KT3r
47556.987	−4.2	1.3	0.927	10.2	0.632	−14.4	σ Boo	KT3r
47623.768	−11.7	−0.0	0.941	9.8	0.562	−21.5	σ Boo	KT3r
47625.653	−10.1	−0.5	0.942	9.5	0.589	−19.6	σ Boo	KT3r
47626.832	−9.1	−1.0	0.942	9.3	0.605	−18.4	σ Boo	KT3r
47916.050	−4.8	−0.1	0.002	10.1	0.634	−14.9	σ Boo	KT3r
48004.756	38.9	−0.0	0.021	10.1	0.869	28.8	σ Boo	KT3r
48007.781	48.5	0.4	0.021	10.3	0.911	38.2	σ Boo	KT3r
48056.645	−9.2	−0.1	0.032	10.0	0.592	−19.2	σ Boo	KT3r
48057.633	−6.7	1.1	0.032	10.6	0.606	−17.3	σ Boo	KT3r
48345.794	−6.9	0.5	0.092	9.3	0.620	−16.2	σ Boo	KT3r

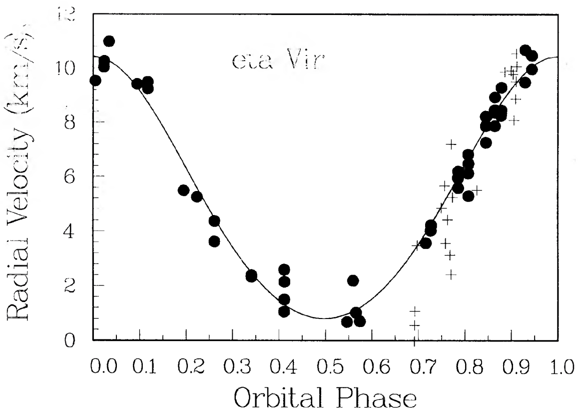

FIG. 7. Computed radial velocities (V_L) and calculated curve for the long-period orbit from the velocities of Aa; plusses = Harper's velocities, dots = our velocities.

has been estimated from speckle observations to be $m_B - m_A = 0.8 \pm 0.5$ (Dombrowski 1989). The magnitude difference between Ab and Aa, obtained from the spectroscopy, is $m_{Ab} - m_{Aa} = 1.3$ mag (Conti 1969). To check this latter magnitude difference, we measured in two spectra of the 6430 Å region the relative line intensities of 3 sets of lines. The average relative intensity is 3.22 ± 0.18 and the corresponding magnitude difference is 1.27 ± 0.06 mag, in good agreement with the value of Conti. Conti (1969) determined a spectral type for Aa of A2 IV. If $V = 3.89$ mag (Nicolet 1978) is the total magnitude of the system, we can determine the magnitude of each component (Table 10). If the spectral type of Ab is A4V (Conti 1969) with an uncertainty of one subclass, its absolute visual magnitude is $M_{Ab} = 1.9 \pm 0.2$ mag (Corbally & Garrison 1984). Here, the spectral type of Aa is not used because absolute magnitudes for subgiants are more uncertain than for main-sequence stars. The photometric parallax can be determined and its result is $\pi = 0\overset{\prime\prime}{.}016$. Surprisingly, the measured trigonometric parallax of $0\overset{\prime\prime}{.}015$ is only slightly different, despite its large uncertainty of $\pm 0\overset{\prime\prime}{.}012$.

From Kepler's third law and the photometric parallax as well as a''_L and P_L from Table 2 the total mass of the system is 3.8 $\mathscr{M}_\odot$. For the measured trigonometric parallax of $0\overset{\prime\prime}{.}015$, the total mass would be 4.4 $\mathscr{M}_\odot$.

The parallax of the system and the masses of the stars can be found by a second method. From an average of five stars (Popper 1980) the mass of a main-sequence star with a spectral type about A4V is 1.95 ± 0.2 $\mathscr{M}_\odot$. If this is assumed to be the mass of component Ab, then our mass ratio yields a mass of 2.34 ± 0.2 $\mathscr{M}_\odot$ for Aa and a total mass for component A of 4.29 ± 0.4 $\mathscr{M}_\odot$. If the mass function, the mass of A, and the inclination of the long-period speckle orbit, i_L (see Table 2), are combined the mass of component B is 1.61 ± 0.1 $\mathscr{M}_\odot$. Therefore, the total spectroscopic mass of the whole system is 5.9 $\mathscr{M}_\odot$ (Table 10). From Kepler's third law and a''_L from Table 2, we can calculate a geometrically based parallax of $0\overset{\prime\prime}{.}0136$ or a distance of 73.5 pc.

Although the actual masses may be poorly constrained, whether the masses are assumed from a photometric or

TABLE 8. A comparison of speckle and spectroscopic elements for McA 37 AB.

Element	Speckle	Spectroscopic
P_L	13.12 ± 0.05 years	12.87 ± 0.38 years
e_L	0.079 ± 0.014	0.24 ± 0.06
ω_L	$181\overset{\circ}{.}4 \pm 2\overset{\circ}{.}4$	$8\overset{\circ}{.}9 \pm 13\overset{\circ}{.}4$
T_L	1963.80 ± 0.02	1964.5 ± 0.9

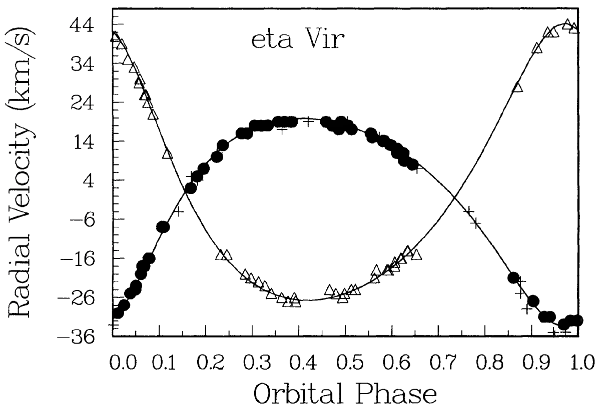

FIG. 8. Computed radial velocities (V_S) and calculated curve for the short-period orbit; plusses = Harper's velocities of Aa, dots = our velocities of Aa, triangles = our velocities of Ab.

spectroscopic relation, a parallax computed with Kepler's third law depends only on the cube root of the assumed sum of the masses. The speckle period and semimajor axis are well determined and their uncertainties combine to change the parallax by only ±0.″001 if the sum of the masses is fixed. When their values from Table 1 are assumed and the sum of the masses is varied from 3.5 to 12$\mathcal{M}_\odot$, the parallax ranges from 0.″016 to 0.″011, and the geometrically based parallax falls midway between the two extremes.

The inclination of the short-period orbit i_S cannot be obtained directly. However, assuming a range of masses for either the Aa or Ab component from Table 10, the inclination of the short-period orbit i_S may be estimated. The value and its uncertainty are 47°±2°. Fekel (1981) compared the short- and long-period orbital inclinations of 20 systems with periods less than 100 yr and found that 33% of them are definitely *not* coplanar. So more than half of these multiple systems are possibly coplanar. The equality of orbital inclinations is a necessary but not a sufficient condition for coplanarity. The Ω's for both orbits must also be known. Since Ω for the short-period orbit cannot be determined from spectroscopy, we cannot conclude coplanarity exists. Nevertheless, the inclinations are quite similar with $i_L=51.^\circ1$ and $i_S=47°$, so that the orbits may be coplanar.

Fekel (1981) examined the mass ratios of multiple stars. For triple systems, about 72% of the systems have mass ratios (in the sense single star to the spectroscopic binary pair) between 0.4 and 0.67. About 40% of the systems have mass ratios greater than 0.6, but only about 20% of the systems have mass ratios greater than 0.9. The mass ratio ($\mathcal{M}_B/\mathcal{M}_A$) of the triple system η/Vir is 0.4. Thus, its mass ratio does not appear to be unusual.

TABLE 9. Final spectroscopic orbital elements of η Vir.

Element	Short Period		Long Period
	Aa	*Ab*	(McA 37 AB)
P (days)	71.7919 ± 0.0009	71.7919 (fixed)	4791.9 (fixed)
T (HJD)	2447583.98 ± 0.25	2447583.4 ± 0.32	2438323.41 (fixed)
γ (km s^{-1})			5.24 ± 0.19 (from *Aa*) 4.85 ± 0.32 (from *Ab*)
K_{Aa} (km s^{-1})	26.67 ± 0.20		
K_{Ab} (km s^{-1})		35.58 ± 0.31	
K_A (km s^{-1})			4.82 ± 0.24 (from *Aa*) 4.94 ± 0.39 (from *Ab*)
e	0.272 ± 0.009	0.258 ± 0.012	0.079 (fixed)
ω (degrees)	200.9 ± 1.5	18.1 ± 1.8	1.4 (fixed)
$a_{Aa}\,sin\,i$ (km)	2.52×10^7		
$a_{Ab}\,sin\,i$ (km)		3.37×10^7	
$M_{Aa}\,sin^3 i_S$ ($M_\odot$)	0.91		
$M_{Ab}\,sin^3 i_S$ ($M_\odot$)		0.76	
M_{Aa}/M_{Ab}	1.194		
$a_A\,sin\,i_L$ (km)			3.18×10^8
f(M) ($M_\odot$)			0.0563

TABLE 10. Magnitudes, masses, and parallax.

Parameter		Result
V magnitude difference	$m_B - m_A$	0.8 ± 0.5 (speckle)
	$m_{Ab} - m_{Aa}$	1.3 ± 0.1 (spectroscopic)
V magnitude	m_{Aa}	4.60
	m_{Ab}	5.90
	m_A	4.32
	m_B	5.12
Parallax (photometric)	π''	$0''.016$
Mass (photometric)	$M_A + M_B$	3.8 $M_\odot$
Mass	M_{Aa}	2.34 ± 0.2 $M_\odot$
	M_{Ab}	1.95 ± 0.2 $M_\odot$ (assumed)
	M_A	4.29 ± 0.4 $M_\odot$
	M_B	1.61 ± 0.1 $M_\odot$
	$M_A + M_B$	5.90 ± 0.5 $M_\odot$
Parallax (geometric)	π''	$0''.0136 \pm 0''.0004$

It is usually stated that a triple system consists of a close pair attended by a distant companion. Evans (1968) has introduced the useful concept of "hierarchy" to describe this arrangement. A triple system like η Vir is considered an example of hierarchy 2 (see Fig. 1). A large ratio in relative distance implies a correspondingly large ratio in relative period, *i.e.*, the ratio of the long period to the short period. There is a very wide range for this ratio. For a spectroscopic system, the period ratio ranges typically from 100 to 1000 (Batten 1973). Since the ratio of the periods of η Vir is 66.8, the third component is not very distant from the binary.

From measuring the widths of the lines in our red wavelength spectra, we find a $v \sin i = 6 \pm 2$ km s^{-1} for Aa and 6 ± 3 km s^{-1} for Ab. If the inclination of the short-period orbit is similar to that of the long-period orbit, the rotational velocities are 8 km s^{-1} each, so both components are rotating quite slowly.

From Table 10, the magnitude of component B compared to Aa is bright enough so that the lines of B should be visible in the spectrum. Only the strong Mg II line at 4481 Å shows any evidence of the speckle secondary. All the other lines in our observed wavelength regions are much weaker. A spectrum obtained at single-lined phase in the short-period orbit shows a shallow depression, about 2% deep, approximately centered on the Mg II line. Its $v \sin i$ is estimated to be 160 ± 20 km s^{-1}. Although the speckle secondary may have been detected spectroscopically, the speckle magnitude difference suggests that its lines should be stronger and, thus, more easily detected.

There is a second problem with the derived properties of η Vir. In Table 10 the mass of Ab is $0.34\mathcal{M}_\odot$ more massive than that of B. But in Table 10 the apparent magnitude of Ab is 0.8 mag fainter than B. If they are both main-sequence stars, the more massive component should be the brighter one. Perhaps some of our derived parameters or assumptions are incorrect. Although the magnitude difference of the speckle binary could be larger, this does not completely alleviate the problem.

As a result of our speckle and spectroscopic observations, our understanding of the η Vir system has been significantly increased. However, the suggested but preliminary parameters of Table 10 lead to several inconsistencies mentioned in the previous two paragraphs. A more accurate parallax, perhaps from *HIPPARCOS*, and a more accurate visual magnitude difference should be of significant help in solving some of these problems.

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