

## THE ORBIT OF THE CLASSICAL CEPHEID U AQUILAE

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## ABSTRACT

A total of 62 new radial-velocity observations of the classical Cepheid U Aql have been obtained during the interval 1969–86. We present the first determination of a spectroscopic binary orbit for this star. The orbital elements derived from both new and published velocities are:

$$\begin{aligned}
 P &= 1856.4 \pm 4.3 \text{ days} \\
 K_1 &= 7.81 \pm 0.22 \text{ km s}^{-1} \\
 \gamma &= 1.15 \pm 0.15 \text{ km s}^{-1} \\
 e &= 0.165 \pm 0.027 \\
 \omega &= 190.5 \pm 7.7 \text{ deg} \\
 T &= 2442754 \pm 38 \text{ JD} \\
 a_1 \sin i &= 196.7 \pm 5.5 \text{ Gm} \\
 &= 1.311 \pm 0.037 \text{ AU} \\
 f(m) &= 0.0881 \pm 0.0074 \mathcal{M}_\odot
 \end{aligned}$$

*IUE* observations reported by Böhm-Vitense and Proffitt (1985) indicate the presence of an early-type main-sequence companion. The orbital elements combined with estimates of the companion mass result in upper limits for the mass of the Cepheid in the range 6.4–8.8  $\mathcal{M}_\odot$ . The possibility of spatially resolving the system using interferometric techniques is discussed.

*Key words:* Cepheids—spectroscopic binaries—radial velocities

## I. Introduction

There are only a handful of Cepheids in binary systems which have well-determined orbital elements. The list of these stars currently comprises  $\alpha$  Ursae Minoris (Roemer 1965), S Sagittae (Herbig and Moore 1952), FF Aquilae (Abt 1959), SU Cygni (Imbert 1984), S Muscae and V636 Scorpii (Lloyd Evans 1982), and the double-mode Cepheid Y Carinae (Balona 1983). The orbital elements derived for these systems provide limits on the masses, ages, and evolutionary histories of Cepheids. In this pa-

per we report the first determination of the orbit of the Cepheid variable U Aquilae.

## II. U Aql = HD 183344 = HR 7402

Albrecht (1906) first reported the radial-velocity variability of the star U Aql but did not publish any observations. Sanford (1930) presented 22 new one-prism radial-velocity observations made at Mount Wilson on the 1.5 and 2.5-m reflectors at a reciprocal dispersion of 37  $\text{\AA}$   $\text{mm}^{-1}$ . Two of these measurements were obtained in 1918

and the remainder during the 1929 and 1930 observing seasons. The next set of observations reported in the literature were those of Lloyd Evans (1980) who obtained eleven new velocities using the South African Astrophysical Observatory (SAAO) 1.9-m telescope *c*-camera spectrograph at a reciprocal dispersion of  $49 \text{ \AA mm}^{-1}$ .

Madore (1977) examined the loops described by Cepheids in the  $(U-B)/(B-V)$  plane for the presence of excess ultraviolet flux which might be due to an early-type, main-sequence companion. U Aql was found to have an opening of its color-color loop which could be accounted for by a B8 V companion.

Slovak, Van Citters, and Barnes (1979) were the first to call attention to the center-of-mass radial-velocity variations of U Aql. Their velocities were obtained using the coude photoelectric radial-velocity spectrometer on the 2.1-m telescope at McDonald Observatory. The best fit between the six unpublished McDonald velocities and those of Sanford (1930) was obtained assuming a phase shift of 0.17 and a velocity shift of  $23 \text{ km s}^{-1}$ .

More recently, Böhm-Vitense and Proffitt (1985) reported the detection of the ultraviolet flux of the secondary using the *International Ultraviolet Explorer* (IUE). Two short-wavelength, low-resolution IUE spectra (SWP 16732 and 10063) revealed approximately equal flux densities at  $1950 \text{ \AA}$  and  $1550 \text{ \AA}$ . They estimated the effective temperature of the secondary to be  $9300 \text{ K} \pm 100 \text{ K}$ . The implications of this determination are discussed in Section VI.

Finally, Beavers and Eitter (1986) list three radial velocities for U Aql. The radial-velocity spectrometer (RVS) used to obtain these observations makes use of a spectrograph with a reciprocal dispersion of  $2.62 \text{ \AA mm}^{-1}$ . The instrument and reduction procedures are detailed in the same reference.

### III. Observations and Reduction

The new radial velocities reported in this paper were obtained by a number of different investigators using several different instruments and methods of reduction. In this section the source of each set of velocities is described.

During the summer of 1969, C. Scarfe (University of Victoria) obtained two spectra of U Aql using the 21121 spectrograph on the Dominion Astrophysical Observatory (DAO) 1.83-m telescope. These spectra have a reciprocal dispersion of  $15 \text{ \AA mm}^{-1}$  at a central wavelength of  $4200 \text{ \AA}$ . They have been reduced on the ARCTURUS oscilloscope measuring device of the DAO.

Five velocities were obtained by B. Madore during the 1976 observing season using the Griffin photoelectric RVS on the Cambridge 0.9-m telescope. This instrument has been described by Griffin (1967).

Between 1978 and 1980 Barnes, Moffett, and Slovak (1987) acquired 31 velocities with the McDonald Obser-

vatory radial-velocity meter (RVM) on the 2.1-m telescope. The RVM and its reduction procedure have been described by Slovak *et al.* (1979) and by Barnes, Moffett, and Slovak (1986). In brief, the RVM operates from  $3850 \text{ \AA}$  to  $4250 \text{ \AA}$  at  $8.5 \text{ \AA mm}^{-1}$ . The entrance slit was  $0.88 \text{ arc sec}$  which projects to  $34 \text{ km s}^{-1}$  in the spectrum. The typical exit slot in the infinite negative mask was  $27 \text{ km s}^{-1}$ .

Two Reticon spectra of U Aql were obtained during the 1980 observing season by J. Tomkin using the coude Reticon system on the 2.7-m reflector at McDonald Observatory. A  $220 \text{ \mu m}$  slit was used for the observations resulting in a two-diode resolution of  $0.22 \text{ \AA}$ . The central wavelength of both spectra was  $6430 \text{ \AA}$ .

During the 1982, 1983, 1984, and 1986 observing seasons, spectra of U Aql were obtained by N.R.E. and R.W.L. using the Cassegrain spectrograph attached to the 1.88-m telescope at the David Dunlap Observatory (DDO) at reciprocal dispersions of  $12 \text{ \AA mm}^{-1}$  and  $8 \text{ \AA mm}^{-1}$  on vacuum-sensitized IIA-O plates. The reduction of Cepheid spectra taken using this instrument configuration has been described by Evans and Lyons (1986).

A total of 40 observations of U Aql were obtained using the RVS on the 1.2-m telescope at DAO. The RVS has been described in detail by Fletcher *et al.* (1982). The mask contains lines found in the spectrum of Arcturus at a reciprocal dispersion of  $2.4 \text{ \AA mm}^{-1}$  centered at  $4525 \text{ \AA}$  with a spectral range of  $350 \text{ \AA}$ . A slot width of  $80 \text{ \mu m}$  is used and velocity steps of  $0.56 \text{ km s}^{-1}$  are employed. The instrumental FWHM of the correlation dip is 28 steps or  $16 \text{ km s}^{-1}$ .

During the 1986 observing season a device designed to minimize the effect of guiding errors on velocities was added to the optical train of the DAO RVS. Known as the "Guiding Error Minimizer," or GEM, this instrument consists of an optical rotator located behind the image slicer which is toggled between two rotations  $90^\circ$  apart (to effect the apparent rotation of the slit through  $180^\circ$  about the optical axis) every five scans. This device has been found to reduce random errors in velocities by a factor of two.

The 1983 and 1984 velocities were obtained by H. C. H. and the 1986 velocities by D. L. W. Standards from the lists of Fletcher *et al.* (1982) and Harris and McClure (1983) were employed. The 1986 observations were reduced using a routine written by Peter Stetson (DAO). This routine fits the even terms of a fourth-order polynomial to the data comprising the correlation dip.

To bring all the velocities on to the IAU system of Pearce (1957), we have adopted the zero-point corrections listed in Table I for each data set. The columns in this table are the instrument, reciprocal dispersion, correction to be added to published or observed velocities to bring them onto the IAU system, and a code used to indicate the source of observation in Table II.

TABLE I  
Adopted Velocity Zero-point Corrections

Instrument	Dispersion ( $\text{\AA mm}^{-1}$ )	$V_r(\text{IAU}) - V_r$ ( $\text{km s}^{-1}$ )	Code
MW 1.5+2.5m One-prism	37	-0.40	A
SAAO 1.9m c-camera	49	-0.40	B
DAO 1.83m	15	1.00	C
Cambridge 0.9m RVS	3.2	-1.14	D
McDonald 2.1m RVM	8.5	0.00	E
Fick 0.61m	2.6	-0.60	F
McDonald 2.7m Reticon	4.4	0.00	G
DDO 1.88m	12	0.00	H
DAO 1.2m RVS	2.4	0.00	I

#### IV. The Pulsation Period of U Aql

Slovak *et al.* (1979) recognized that the velocity curve of Sanford (1930) could not be reconciled with modern observations without a phase correction. They estimated a phase correction by shifting their velocity curve relative to Sanford's in both phase and velocity to obtain the best match. It is clearly desirable to estimate the phase correction without reference to the velocity curve. We have estimated the phase correction from observed times of maximum brightness.

The most comprehensive study of the period of U Aql is by Parenago (1958). He derived a parabolic ephemeris which represented photographic and visual light-curve maxima over the interval JD2410100–JD2424220. The more recent photoelectric light curves of Eggen (1951), Wisniewski and Johnson (1968), Kelsall (1971), Pel (1976), Dean (1977), and Moffett and Barnes (1984) indicate that the period has been quite stable over the interval JD2432000–JD2444000. It appears that an abrupt change in the rate of period change must have occurred in the interval JD2424220–JD2432000.

We will adopt a single phase correction for all the Sanford data based on the difference between the ephemeris of Parenago (1958) and Moffett and Barnes (1985) at JD2426000. This correction amounts to 0.045 with an uncertainty of roughly 0.010 of a cycle which must be added to the phases of the Sanford (1930) observations calculated using the Moffett and Barnes ephemeris:

$$JD_{\max} = 2443302.062 + 7.024100 E$$

In Figure 1 are illustrated the agreement between the Sanford velocities, corrected for orbital motion, and the pulsation velocity curve (derived from DAO RVS velocities) with and without the phase correction of 0.045 cycle. It is clear from this figure that the correct phase shift has been chosen.

#### V. Derivation of the Orbital Elements

The instantaneous observed radial velocity of a Cepheid binary is composed of the sum of the velocity of

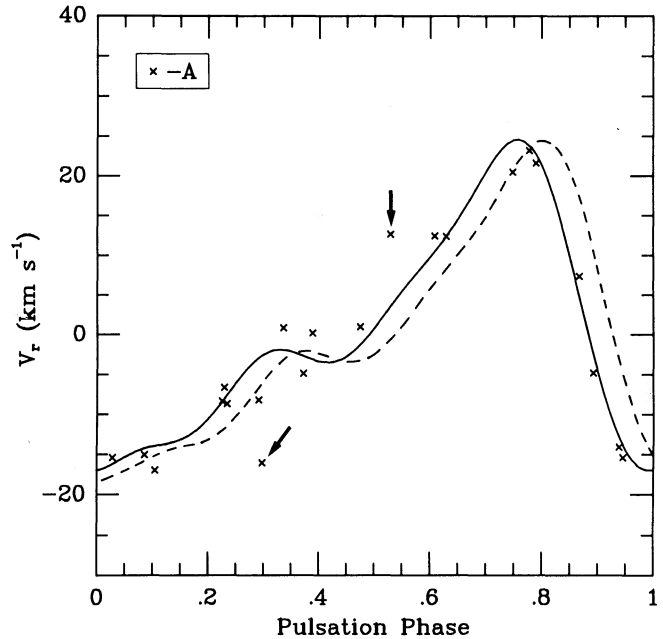


FIG. 1—The radial velocities of Sanford (1930) are shown, corrected for orbital motion. The solid line is the pulsation-velocity curve corrected by a phase shift of +0.045 and the dashed line is the same curve with no phase shift. The Moffett and Barnes (1985) ephemeris,  $JD_{\max} = 2443302.062 + 7.024100 E$  has been used. Points given zero weight in the orbit solution are indicated by an arrow.

the Cepheid photosphere due to pulsation and the velocity resulting from orbital motion. An iterative procedure was adopted to deconvolve the two velocity curves. Initially, a pulsation velocity curve was constructed using velocities from the 1986 season alone in order to minimize the contribution of orbital velocity change. A Fourier series curve of order  $n = 4$  was fit to the DAO RVS velocities and this fit was used to subtract the pulsation velocity from the modern (1969+) velocities of U Aql.

A period-finding program based on the method of Scargle (1982) written by Alex Fullerton (University of Toronto) was used to identify periodicities in the data. Assuming possible orbital periods, the data were phased and the correct period was identified as being near 1860 days. A preliminary orbit was then found using the orbital-element-fitting routine SBCM described by Morbey and Brosterhus (1974). This solution was used to remove the orbital-velocity component from the observed velocities and the process was then repeated until convergence. The final pulsation curve was defined from all velocities obtained using the DAO RVS. By using velocities from one instrument alone, we expect the true pulsation curve to be most clearly defined. Such an approach will also facilitate the search for systematic differences between the velocities produced by different instruments as described by Hindsley and Bell (1986).

In the final analysis all elements (including the period) were allowed to be free parameters. In Table II are listed

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 TABLE II  
 U Aql Radial Velocity Observations

HJD -2400000	Observed Velocity (km s <sup>-1</sup> )	Ref*	$\phi_{\text{orb}}$	$V_{\text{orb}}$	$\phi_{\text{pul}}$	$V_{\text{pul}}$	O-C	HJD -2400000	Observed Velocity (km s <sup>-1</sup> )	Ref*	$\phi_{\text{orb}}$	$V_{\text{orb}}$	$\phi_{\text{pul}}$	$V_{\text{pul}}$	O-C
				(km s <sup>-1</sup> )		(km s <sup>-1</sup> )	(km s <sup>-1</sup> )					(km s <sup>-1</sup> )		(km s <sup>-1</sup> )	(km s <sup>-1</sup> )
21831.167	-14.60±0.00	A	0.729	1.89	0.298	-2.63	-13.86	44179.550	-11.80±6.00	E	0.768	0.15	0.925	-10.57	-1.38
21849.215	8.40 3.00	A	0.739	1.47	0.868	4.64	2.29	44198.531	14.24 6.00	E	0.778	-0.34	0.628	12.17	2.41
25777.356	-21.60 3.00	A	0.855	-4.20	0.105	-13.95	-3.45	44199.525	19.26 4.00	E	0.779	-0.37	0.769	24.32	-4.69
25811.355	-20.90 3.00	A	0.873	-5.07	0.946	-13.96	-1.87	44200.547	-2.58 4.00	E	0.779	-0.40	0.915	-8.26	6.08
25813.347	-12.20 3.00	A	0.874	-5.12	0.229	-8.13	1.05	44444.845	23.02 4.00	E	0.911	-6.62	0.695	19.80	9.84
25842.192	-5.40 3.00	A	0.890	-5.80	0.336	-1.95	2.35	44445.811	9.30 4.00	E	0.911	-6.64	0.832	14.71	1.23
25843.165	-5.30 3.00	A	0.891	-5.83	0.474	-1.35	1.88	44447.749	-19.70 0.50	G	0.912	-6.67	0.108	-13.91	0.88
25844.254	6.10 3.00	A	0.891	-5.85	0.629	12.34	-0.39	44472.717	9.00 0.50	G	0.926	-7.10	0.663	15.92	0.18
25845.301	16.90 3.00	A	0.892	-5.87	0.778	23.80	-1.03	44543.609	15.21 4.00	E	0.964	-7.86	0.755	24.54	-1.47
25865.181	5.70 3.00	A	0.902	-6.30	0.609	10.43	1.57	45152.764	4.34 0.45	H	0.292	5.18	0.479	-1.01	0.17
25866.160	13.70 3.00	A	0.903	-6.33	0.748	24.40	-4.37	45155.739	-1.20 0.45	H	0.294	5.23	0.902	-5.28	-1.15
25867.176	-11.60 3.00	A	0.903	-6.35	0.893	-2.66	-2.59	45161.899	30.90 0.60	I	0.297	5.33	0.779	23.73	1.84
25868.130	-22.20 3.00	A	0.904	-6.37	0.029	-16.23	0.40	45169.908	-5.10 0.60	I	0.301	5.46	0.920	-9.38	-1.18
25905.096	-15.70 3.00	A	0.924	-7.05	0.291	-2.97	-5.68	45180.709	3.36 0.45	H	0.307	5.63	0.457	-2.43	0.16
26108.398	-16.20 3.00	A	0.033	-7.05	0.235	-7.60	-1.55	45198.787	-9.60 0.60	I	0.317	5.89	0.031	-16.14	0.65
26109.479	-7.30 3.00	A	0.034	-7.03	0.389	-3.15	2.88	45199.754	-6.40 0.60	I	0.317	5.91	0.169	-12.57	0.26
26110.469	5.20 0.00	A	0.035	-7.01	0.530	3.55	8.66	45206.793	-6.40 0.60	I	0.321	6.00	0.171	-12.47	0.07
26133.373	14.60 3.00	A	0.047	-6.58	0.790	22.66	-1.48	45233.565	-9.76 0.45	H	0.336	6.35	0.982	-16.83	0.72
26134.415	-21.10 3.00	A	0.047	-6.56	0.939	-12.95	-1.59	45252.661	25.70 0.60	I	0.346	6.57	0.701	20.55	-1.42
26135.451	-22.00 3.00	A	0.048	-6.54	0.086	-14.28	-1.18	45254.747	-10.70 0.60	I	0.347	6.59	0.998	-16.99	-0.30
26136.431	-15.30 3.00	A	0.048	-6.52	0.226	-8.46	-0.32	45255.642	-6.30 0.60	I	0.348	6.60	0.125	-13.69	0.79
26137.458	-11.80 3.00	A	0.049	-6.49	0.372	-2.70	-2.61	45258.531	9.66 0.60	H	0.349	6.63	0.537	4.20	-1.17
40397.637	4.90 2.80	B	0.731	1.83	0.506	1.30	1.77	45466.837	2.19 0.00	H	0.461	7.69	0.193	-11.22	5.72
40410.588	-1.90 2.80	B	0.738	1.53	0.350	-2.14	-1.29	45472.852	-8.23 0.45	H	0.465	7.69	0.049	-15.44	-0.48
40411.581	2.30 2.80	B	0.738	1.51	0.491	-0.03	0.82	45479.954	-8.10 0.60	I	0.468	7.69	0.060	-15.02	-0.77
40418.863	3.50 1.00	C	0.742	1.33	0.528	3.36	-1.19	45480.972	-1.40 0.60	I	0.469	7.69	0.205	-10.30	1.21
40422.485	-9.70 2.80	B	0.744	1.25	0.043	-15.66	4.71	45492.957	0.00 0.60	I	0.475	7.67	0.911	-7.45	-0.22
40436.780	-13.10 1.00	C	0.752	0.90	0.078	-14.46	0.46	45493.947	-7.70 0.60	I	0.476	7.67	0.052	-15.31	-0.06
40439.528	3.00 2.80	B	0.753	0.83	0.470	-1.68	3.85	45514.832	-10.49 0.45	H	0.487	7.63	0.025	-16.35	-1.77
40457.454	-12.70 2.80	B	0.763	0.38	0.022	-16.48	3.40	45570.595	-7.98 0.45	H	0.517	7.43	0.964	-15.91	0.50
40796.506	-12.10 2.80	B	0.946	-7.59	0.292	-2.95	-1.56	45581.665	13.60 0.60	I	0.523	7.37	0.540	4.54	1.69
40809.508	-18.80 2.80	B	0.953	-7.71	0.143	-13.40	2.31	45582.668	26.20 0.60	I	0.524	7.36	0.683	18.39	0.45
40815.458	-26.80 2.80	B	0.956	-7.76	0.990	-16.97	-2.07	45584.659	-6.40 0.60	I	0.525	7.35	0.966	-16.07	2.32
42954.550	0.86 1.50	D	0.108	-3.62	0.526	3.19	1.29	45898.779	23.40 0.45	H	0.694	3.31	0.687	18.85	1.24
42962.530	14.36 1.50	D	0.112	-3.38	0.662	15.83	1.91	45929.616	-14.20 0.45	H	0.711	2.66	0.077	-14.50	-2.36
43002.420	-2.34 1.50	D	0.134	-2.17	0.341	-2.00	1.83	45961.545	13.40 0.45	H	0.728	1.96	0.623	11.69	-0.25
43013.440	-8.44 1.50	D	0.140	-1.83	0.910	-7.12	0.51	46550.956	-4.32 0.60	I	0.045	-6.64	0.535	4.08	-1.76
43027.390	-5.04 1.50	D	0.147	-1.41	0.896	-3.51	-0.12	46554.953	-22.60 0.60	I	0.047	-6.55	0.104	-13.96	-2.09
43616.971	27.55 4.00	E	0.465	7.69	0.833	14.57	5.29	46557.950	-3.02 0.60	I	0.049	-6.49	0.531	3.68	-0.21
43617.948	-6.36 4.00	E	0.465	7.69	0.972	-16.40	2.35	46558.925	10.28 0.60	I	0.050	-6.47	0.670	16.78	-0.03
43618.970	-0.98 4.00	E	0.466	7.69	0.117	-13.79	5.12	46571.890	-3.64 0.60	I	0.057	-6.19	0.516	2.22	0.33
43619.990	4.81 6.00	E	0.466	7.69	0.262	-5.03	2.15	46576.890	-13.91 0.60	I	0.059	-6.07	0.227	-8.30	0.46
43620.983	3.82 6.00	E	0.467	7.69	0.404	-3.44	-0.43	46578.955	-3.80 0.60	I	0.060	-6.02	0.521	2.77	-0.55
43622.951	19.38 4.00	E	0.468	7.69	0.684	18.51	-6.82	46582.850	-19.92 0.60	I	0.063	-5.93	0.076	-14.53	0.54
43683.854	6.32 4.00	E	0.501	7.56	0.355	-2.24	1.00	46583.940	-13.84 0.60	I	0.063	-5.91	0.231	-7.95	0.02
43683.856	13.35 4.00	E	0.501	7.56	0.355	-2.25	8.04	46603.856	-19.63 0.60	I	0.074	-5.41	0.066	-14.80	0.58
43684.826	17.40 4.00	E	0.501	7.55	0.493	0.15	9.70	46604.884	-15.49 0.60	I	0.074	-5.38	0.213	-9.63	-0.48
43684.827	10.85 4.00	E	0.501	7.55	0.493	0.16	3.14	46605.904	-6.60 0.60	I	0.075	-5.35	0.358	-2.33	1.08
43685.768	32.69 4.00	E	0.502	7.55	0.627	12.11	13.03	46615.826	18.60 0.60	I	0.080	-5.09	0.771	24.26	-0.57
43688.834	1.95 4.00	E	0.504	7.54	0.064	-14.90	9.31	46616.952	-17.05 0.60	I	0.081	-5.06	0.931	-11.63	-0.36
43712.769	6.90 1.00	F	0.516	7.43	0.471	-1.57	1.04	46617.850	-19.88 0.60	I	0.081	-5.03	0.059	-15.06	0.21
43750.633	10.10 1.00	F	0.537	7.21	0.862	6.42	-3.53	46619.744	-6.26 0.60	I	0.082	-4.98	0.328	-1.94	0.66
43750.638	11.10 1.00	F	0.537	7.21	0.862	6.21	-2.32	46619.833	-5.33 0.60	H	0.082	-4.98	0.341	-2.00	1.65
43821.566	-2.37 4.00	E	0.575	6.63	0.960	-15.58	6.58	46626.784	-7.11 0.60	I	0.086	-4.79	0.331	-1.94	-0.38
43822.561	-4.36 6.00	E	0.576	6.62	0.102	-14.00	3.02	46631.779	-20.38 0.60	I	0.089	-4.65	0.042	-15.71	-0.02
43938.993	26.49 6.00	E	0.638	5.14	0.678	17.77	3.58	46649.733	6.26 0.60	I	0.099	-4.14	0.598	9.51	0.89
43940.024	34.90 4.00	E	0.639	5.13	0.825	16.51	13.26	46654.740	-7.12 0.60	I	0.101	-3.99	0.311	-2.18	-0.95
43941.019	-10.64 4.00	E	0.639	5.11	0.966	-16.07	0.32	46656.734	6.19 0.60	I	0.102	-3.93	0.595	9.23	0.89
43941.993	-4.56 4.00	E	0.640	5.10	0.105	-13.95	4.29	46710.648	-7.50 0.60	I	0.131	-2.31	0.270	-4.39	-0.80
44044.866	30.04 4.00	E	0.695	3.26	0.751	24.47	2.31	46713.655	17.71 0.60	I	0.133	-2.22	0.698	20.23	-0.30
44045.885	-0.19 4.00	E	0.696	3.24	0.896	-3.52	0.09	46719.639	3.75 0.60	I	0.136	-2.03	0.550	5.44	0.34
44059.853	5.54 4.00	E	0.703	2.95	0.884	-0.31	2.90	46766.576	-8.73 0.60	I	0.161	-0.61	0.232	-7.82	-0.30
44060.892	-12.80 4.00	E	0.704	2.93	0.032	-16.09	0.36								
44063.883	5.05 4.00	E	0.706	2.86	0.458	-2.38	4.57								
44177.559	19.48 4.00	E	0.767	0.20	0.642	13.60	5.68								

\* see Table I for code

the data used in the analysis. The heliocentric Julian Date, velocity and uncertainty (on the IAU system), source code, predicted orbital phase and velocity, predicted pulsation phase and velocity, and  $(O - C)$  value are listed in this table. The three points given zero weight in the orbit solution have 0.00 as the velocity uncertainty in the Observed Velocity column of Table II. All other observations were weighted by their uncertainties in the usual fashion.

Given phase  $\phi$ , the observed pulsation velocity (relative to the systemic velocity) is predicted by:

$$V_r(\text{Pul}) = \sum_{n=1}^4 a_n \cos(2\pi n \phi) + b_n \sin(2\pi n \phi) .$$

The values of the Fourier coefficients found from the iterative fit are:

$a_1$	-8.0380	$b_1$	-13.1047
$a_2$	-8.6252	$b_2$	-0.3616
$a_3$	-0.8386	$b_3$	2.1963
$a_4$	0.5255	$b_4$	2.1524 .

The final elements derived from the data in Table II are:

$$\begin{aligned} P &= 1856.4 \pm 4.3 \text{ days} \\ K_1 &= 7.81 \pm 0.22 \text{ km s}^{-1} \\ \gamma &= 1.15 \pm 0.15 \text{ km s}^{-1} \\ e &= 0.165 \pm 0.027 \\ \omega &= 190.5 \pm 7.7 \text{ deg} \\ T &= 2442754 \pm 38 \text{ JD} \\ a_1 \sin i &= 196.7 \pm 5.5 \text{ Gm} \\ &= 1.311 \pm 0.037 \text{ AU} \\ f(m) &= 0.0881 \pm 0.0074 \mathcal{M}_\odot . \end{aligned}$$

The uncertainties quoted are mean errors. A total of 127 observations are listed in Table II. Only 124 of these velocities were used in the solution, the remaining three having zero weight. The mean error of a velocity of unit weight (corresponding to an observational uncertainty of  $0.45 \text{ km s}^{-1}$  in Table II) was found to be  $0.69 \text{ km s}^{-1}$ . The discrepancy between the observational uncertainty and estimate of the mean error can likely be accounted for by the subtle differences in standardization between the many instruments and reduction techniques used to produce the measurements. The orbital-velocity curve and observed velocities (corrected for pulsation) are shown in Figure 2. The pulsation-velocity curve is illustrated in Figure 3. Note that filled symbols typically have high weight in both these figures.

The McDonald RVM velocities seem to have a zero point which is systematically positive relative to the other velocities. A number of checks have been run on the observations taken on the same night as the U Aql data, and we have not been able to account for the zero-point discrepancy. The McDonald RVM velocities enter the orbit solution with low weight because of their relatively large uncertainties, so no significant change in the ele-

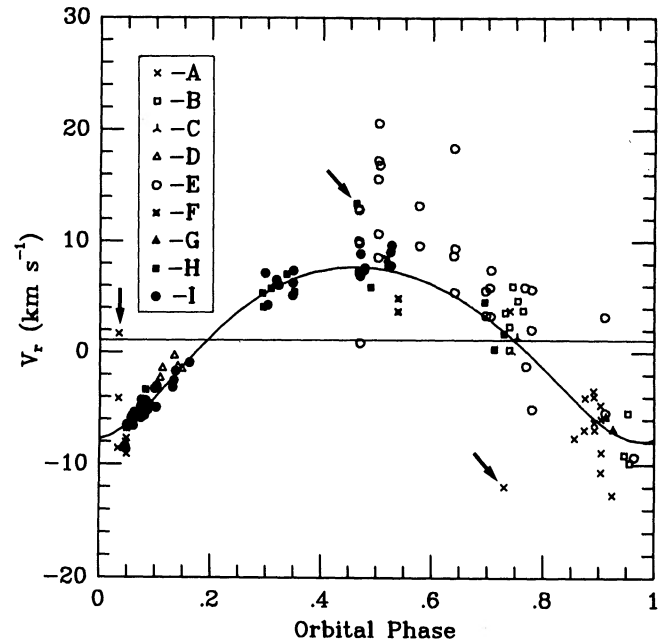


FIG. 2—The orbital velocity of the Cepheid U Aql. The key may be interpreted using Table I. The data are phased with a period of 1856.4 days (5.08 years). Observations given zero weight in the solution are indicated by arrows. The horizontal line indicates the systemic velocity of the binary,  $+1.15 \text{ km s}^{-1}$ .

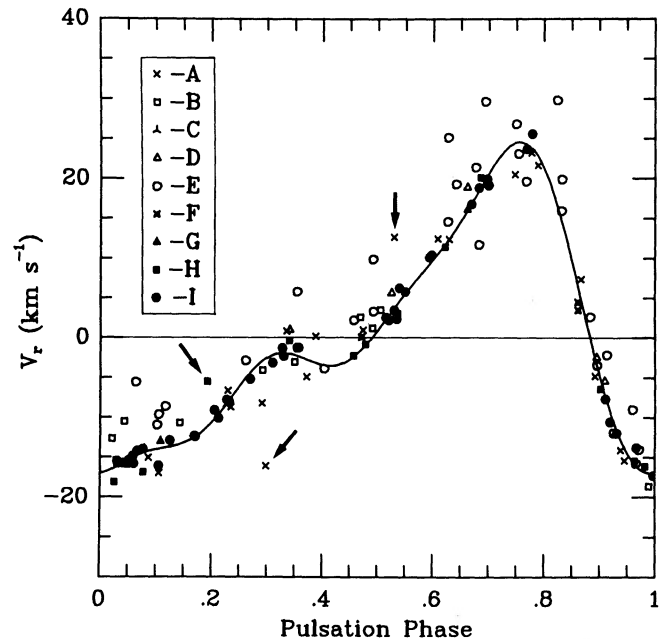


FIG. 3—The pulsation velocity of the Cepheid U Aql. This solid curve is a fourth-order Fourier series fit to the DAO RVS velocities corrected for orbital motion. The coefficients of the Fourier series are given in the text. Observations given zero weight in the solution are indicated by arrows.

ments results from their exclusion. Details on the tests applied to the RVM velocities are given in Barnes *et al.* (1987).

## VI. Discussion and Conclusions

The temperature derived by Böhm-Vitense and Proffitt (1985) for the companion of U Aql was  $9300 \text{ K} \pm 100 \text{ K}$  corresponding to a main-sequence star of spectral type of  $A2 \pm 1$ . This is consistent with their derived companion radius of  $2.1 R_{\odot}$ . Popper (1980) reports mass determinations for main-sequence A2 stars in the range  $1.8\text{--}2.2 M_{\odot}$ , which may be combined with  $f(m)$  to produce upper limits for the mass of the Cepheid in the range  $6.4\text{--}8.8 M_{\odot}$ . According to Pel (1985), a Cepheid having the period of U Aql would be expected to have an evolutionary mass of  $7 M_{\odot}$ . Since competing mass estimates are smaller than the evolutionary mass, no useful constraints on the Cepheid mass problem may be derived from the orbit of U Aql.

Adopting  $7 M_{\odot}$  for the mass of U Aql and  $2.0 M_{\odot}$  for the secondary, it is possible to estimate the inclination and the size of the semimajor axis of the binary orbit. From the mass function,  $f(m)$ , the inclination is found to be  $74^{\circ}$ . Combining this with  $a \sin i$ , the semimajor axis is found to be  $6.1 \text{ AU}$ , or  $1310 R_{\odot}$ . Using the four period-radius relations of Fernie (1984), U Aql would be expected to have a radius of  $44 R_{\odot}$  to  $58 R_{\odot}$ , with a most probable value near  $55 R_{\odot}$ . The large separation of the two components indicates that they have remained detached throughout their evolutionary history.

The moderate eccentricity ( $e = 0.17$ ) and favorable orientation ( $\omega = 190^{\circ}$ ) of the orbit of U Aql raise the possibility of resolving the two components interferometrically at apastron. The separation of the two stars at that time is roughly  $7.1 \text{ AU}$ . At a distance of  $490 \text{ pc}$  (Böhm-Vitense and Proffitt 1985),  $7.1 \text{ AU}$  would subtend  $0.015$  arc sec, a separation measurable by the Fine Guidance Sensor (FGS) of the *Hubble Space Telescope*. Unfortunately, the bluest bandpass available on the FGS has an effective wavelength of  $5500 \text{ \AA}$  where the companion will be about  $3.9 \text{ mag}$  fainter than the primary even at minimum light. Hence, the proposed observation would be difficult, if not impossible. Ground-based speckle observations at wavelengths longward of the Balmer jump using large telescopes may allow resolution of this system. At  $3800 \text{ \AA}$  a  $5\text{-m}$  telescope is capable of resolving the components of U Aql at apastron. However, other Cepheid binaries are better candidates for this last approach.

While direct measurement of both components of the binary will be very difficult with the FGS, it will almost certainly be possible to detect the movement of U Aql relative to the center of mass of the system. The FGS is capable of measuring relative positions of stars to an accuracy of  $1.6$  milliarc sec. The total displacement of U Aql using the orbital elements and distance given above is  $5.6$  milliarc sec. Unfortunately, in the case of U Aql, such a measurement would provide little additional informa-

tion about the system because of the measurement uncertainty. Perhaps the most promising program will employ the High Resolution Spectrograph to measure radial velocities of both components of the binary. An *IUE* proposal to explore this possibility has been submitted by Böhm-Vitense and several of the authors of this paper. Finally, it is worth noting that it should be possible to follow U Aql through an entire orbit during the operational lifetime of the *Hubble Space Telescope*.

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