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ECLIPSES OF U GEMINORUM

S. ARNOLD, R. A. BERG,* AND J. G. DUTHIE*
Department of Physics and Astronomy, University of Rochester

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ABSTRACT

Seven precise eclipse times for the cataclysmic variable star U Geminorum have been obtained during the 1974–1975 observing season. These, together with 65 others, have been used to re-evaluate the eclipse parameters. We have, with some selection of the eclipses used, found a statistically significant slowdown of the binary system. Using previously published masses for the components of U Gem, we infer a mass transfer rate of $8.1 \times 10^{-8}\ M_{\odot}\ \mathrm{yr}^{-1}$ *away* from the primary. This direction of mass transfer is opposite to that required by current theoretical understanding of these systems.

Subject headings: stars: dwarf novae — stars: eclipsing binaries — stars: individual — stars: mass loss

I. INTRODUCTION

The prototype dwarf nova, U Geminorum, is a typical eruptive binary. These are generally believed to consist of a red dwarf which is transferring matter onto a white dwarf companion. Some mass may be leaving the system. A detailed study of the binary period of such systems may be the only means of establishing the mass transfer rate. In a report on the slowdown rate of nine such systems, Pringle (1975) notes that spectroscopic observations for these objects are difficult to use in determining the rate of increase of the orbital period because of the breadth of the dominant spectral lines and because they come from the accretion disk around the white dwarf. U Geminorum was one of the nine systems examined by Pringle, and he found that evidence for orbital deceleration of that system is not strong. We have determined seven new eclipse times for U Geminorum and have repeated Pringle's analysis with some discrimination as to the selection of the published data. We find somewhat stronger formal evidence for a secular increase in orbital period that he published.

II. OBSERVATIONS

As part of a program of studying the power spectra of rapid variations in compact blue objects, we have observed seven new eclipses of the U Gem system during the 1974–1975 observing season. These were all obtained at Kitt Peak National Observatory using the No. 1 and No. 2, 91 cm telescopes as indicated in Table 1. A dichroic beam-splitter fed light to two photomultipliers, an FW-129 and an FW-130, each of which was operated without additional bandpass filters. The dichroic beam-splitter splits roughly at λ5500; thus the signals are basically "blue" and "red," and the effective bandpasses are 1500–2000 Å wide. A 15″ diaphragm restricted sky background, and continuous offset guiding was used.

We recorded the photon rates using the University of Rochester data recording system (details of which are to be published elsewhere). This system is controlled by a master clock which can be set to ±1 μs UT. It can measure the photon counts at sampling rates between 1 ms and 10 s and record as many as three channels of information continuously on magnetic tape for extended periods. Throughout the present observations the recordings were made every second, and the times of the observations were known by comparison with WWV to within ±1 s, which was satisfactory for present purposes. A limit of 2^{16} counts per sampling time can be recorded, and this was well above our needs. Pulse pair resolution of the system is 8×10^{-8} s.

One of the eclipses is shown on Figure 1. Several features of the eclipse are relevant to the present discussion. The primary eclipse is asymmetric and flat-bottomed. It occurs during the descending portion of the shoulder in the light curve. Outside of the eclipse there is considerable flickering on time scales of the order of minutes. The degree of flickering is related to the eruptive activity of the U Gem system, being most prominent immediately after eruption. The asymmetric eclipse, believed to be the eclipse of a hot spot in the disk of material which is accreting around the white dwarf (Warner and Nather 1971; Smak 1971), is found to vary in width as a function of time since eruption (see, e.g., Krzemiński 1965). The phase of several possible estimates of the eclipse time, such as the moment of the middle of egress or the intersection of the eclipse bisector, varies markedly with the eruptive activity.

Krzemiński gives a definition for the time of eclipse minimum which is currently used and which he claims is independent of eruptive activity. He defines an eclipse bisector as the locus of points on the light curve which are at the same magnitude and average time of points on the ingress and egress. He then finds the time on

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* Visiting Astronomers, Kitt Peak National Observatory, which is operated by AURA, Inc., under contract with the NSF.

TABLE 1

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Color	HJD 2,440,000+	Cycle	O − C (day)	Eclipse Depth (mag)	Eclipse Width (day)
		Kitt Peak No. 1 91 cm Telescope			
Red.........	2365.9366	26721	+0.0068	0.69	0.0138
Blue.........	2365.9366	26721	+0.0068	0.68	0.0134
Red.........	2366.8210	26726	+0.0066	0.72	0.0136
Blue.........	2366.8208	26726	+0.0064	0.70	0.0141
Red.........	2367.8827	26732	+0.0069	0.84	0.0135
Blue.........	2367.8825	26732	+0.0067	0.79	0.0140
Red.........	2420.7775	27031	+0.0068	0.72	0.0104
Blue.........	2420.7774	27031	+0.0067	0.73	0.0106
		Kitt Peak No. 2. 91 cm Telescope			
Red.........	2476.6796	27347	+0.0066	0.55	0.0136
Blue.........	2476.6796	27347	+0.0066	0.54	0.0136
Red.........	2694.9820	28581	+0.0071	0.49	0.0101
Blue.........	2694.9821	28581	+0.0072	0.48	0.0101
Red.........	2696.9279	28592	+0.0071	0.53	0.0095
Blue.........	2696.9279	28592	+0.0071	0.51	0.0095

NOTE.—Table 1 gives the details of the observed eclipses reported in this work. In sequence the columns identify the color in which the eclipses were observed, the eclipse time, the cycle number, the difference between Krezmiński's (1965) elements and our observations, the depth and width of the eclipses.

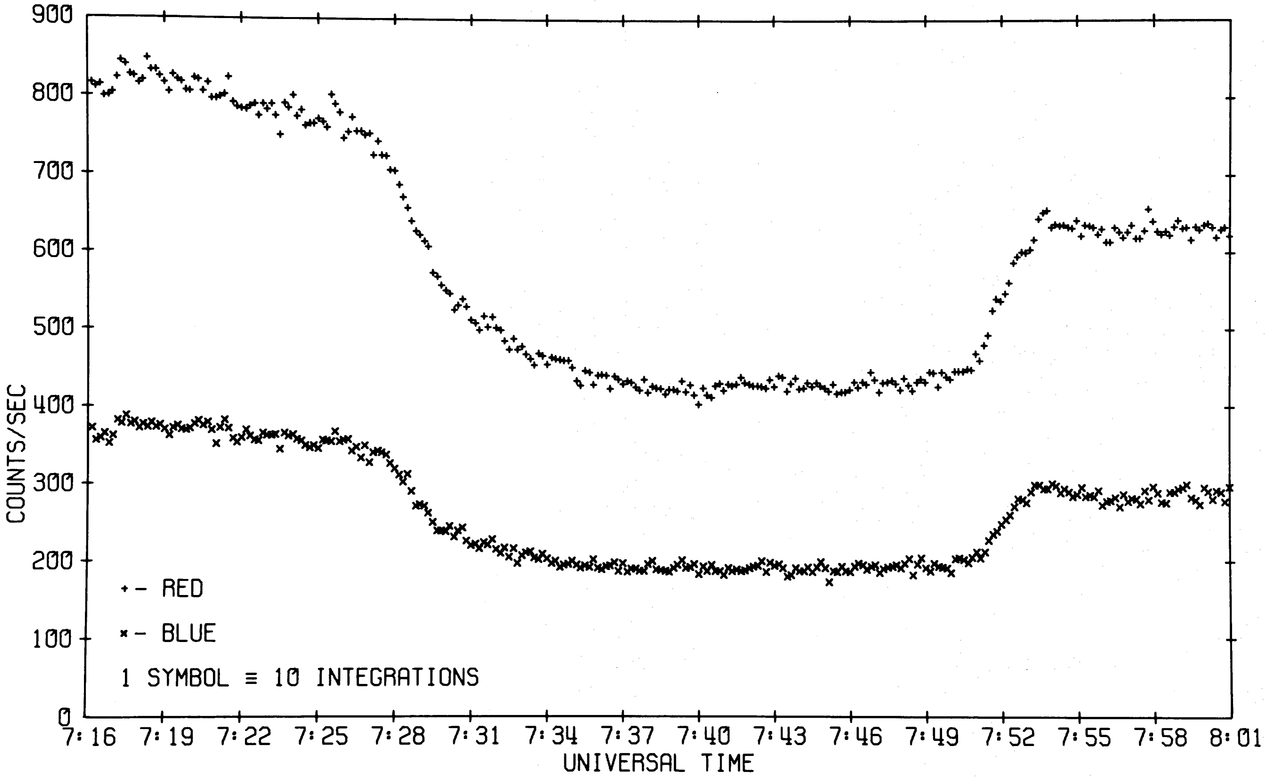

FIG. 1.—A typical eclipse of U Gem. This eclipse was recorded in two colors during our observing run of 1974 November 15. Note the asymmetry of the eclipse and the descending nature of the light curves outside the eclipse. Detailed examination of this and other light curves indicate considerable flickering outside of the eclipses and stability within counting statistics during the eclipse.

this bisector where the magnitude is halfway between that of the eclipse bottom and the estimated shoulder in the absence of the eclipse. This point is taken as the time of eclipse, but there is no dynamical reason to suppose it corresponds to any stable physical phase of the system. Depending as it does on the estimated light curve in the absence of eclipse, the precision with which the time of eclipse occurs must deteriorate with eruptive activity. This is perhaps doubly so as the depth of the eclipse has been estimated to be constant in intensity units (e.g., Krezmiński 1965) whereas the system gains as much as 5 mag during eruptions.

III. ECLIPSE PARAMETERS

Krzemiński's (1965) eclipse elements, referred to the heliocenter, are

$$T_{\rm min} = \mathrm{HJD}\ 2437638^{\rm d}.82704 + 0^{\rm d}.17690591E\,.$$

Pringle (1975) has reanalyzed the residuals for 97 published eclipses with respect to this ephemeris. He finds them to be well fitted by a linear relation and also finds that his best quadratic term has a 97.5 percent significance level. He correctly concludes that the evidence for an increase in period is weak.

We have analyzed our new data, together with the data reported by Pringle and seven other eclipses reported by Mumford (1970, 1975). However, Pringle has apparently used the same eclipses twice (or more) where they have been reported in more than one color. Instead, we have averaged such eclipse times. Also, we have discarded all eclipses known to occur within 5 days of an eruptive maximum since, from the above discussion, these must be regarded as of low weight. They apparently contribute excessively to the residuals discussed by Pringle (1975). In all, we include 72 separate eclipses. Table 2 presents our compilation of these eclipses, with the O − C residuals computed from Krzemiński's elements.

Two fits of the O − C residuals were made, one linear and one quadratic. The best linear fit was

$$\mathrm{HJD} = \underset{\pm 5}{2437638^{\rm d}.82645} + \underset{\pm 6}{0^{\rm d}.17690617}E$$

while the best quadratic fit was

$$\mathrm{HJD} = \underset{\pm 3}{2437638^{\rm d}.82685} + \underset{\pm 2}{0^{\rm d}.17690602}E + \underset{\pm 6}{5^{\rm d}.4} \times 10^{-12}E^2\,,$$

where errors refer to the least significant digit and correspond to one standard deviation.

The parameter λ, defined by Pringle (1975), has a value 81 with $n = 72$. This parameter measures the confidence level at which one can exclude the null hypothesis that the quadratic term is zero. In this case the hypothesis can be ruled out at well beyond the 99.9 percent confidence limit. We conclude that the formal evidence for the slowdown of the U Gem orbital system is very strong—being at the nine standard deviation level.

That this is at variance with Pringle's (1975) result is certainly due, in large part, to the fact that his residuals were dominated by the observations close to eruption and we have excluded those data. Our result assumes, of course, that the eclipse time is defined by a stable phase in the system. Only continued, careful observations over a period of years can clarify that question.

IV. CONCLUSIONS

If mass transfer is occurring with no loss from the system and if orbital angular momentum is conserved, then we can use equation (4.1) of Pringle (1975), which states that

$$-\dot{M}_2 = \dot{M}_1 = \frac{M_1 M_2}{3\tau_p(M_1 - M_2)}\,,$$

where

$$\tau_p = P\frac{dP^{-1}}{dt} = \frac{P^2}{2\lambda_2}\,,$$

where P is the binary period, M_1 (M_2) the mass of the white dwarf primary (red dwarf secondary), and λ_2 is defined by

$$O - C = \alpha_2 + \beta_2 E + \lambda_2 E^2\,.$$

Using the values $M_1 = 0.65\,M_\odot$, $M_2 = 0.98\,M_\odot$, given by Warner (1973*b*), and our eclipse elements, we find

$$\dot{M}_1 \approx -8.1 \times 10^{-8}\,M_\odot\,\mathrm{yr}^{-1}\,.$$

Current theoretical understanding of U Geminorum systems (Smak 1971; Warner and Nather 1971) demands that the mass exchange be from the secondary onto the white dwarf. To be consistent with such a constraint, our results require that the white dwarf has the larger mass. To resolve this difficulty, one may wish to discard all theories involving mass transfer onto the white dwarf, or one might question the assumptions giving rise to equation (4.1) of Pringle (1975). We prefer a third alternative, which is to question the values of the masses assigned to the U Gem system. Warner (1973*b*), in computing these masses, notes that U Gem is anomalous in two respects. Its period and mass ratio do not follow the well-defined relationship he finds for the other cataclysmic variables. Also, in all other systems he finds masses of the white dwarfs to be 1 $M_\odot$ or more. Improved determination of the masses is clearly needed.

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Note added in proof.—Robinson (*Ap. J.*, 1976, **203**, 485) has recently redetermined the masses of the U Gem system and finds $M_1 = 0.92\,M_\odot$ and $M_2 = 053.\,M_\odot$. This gives, according to the model above, mass transfer onto the white dwarf at a rate of $5.25 \times 10^{-8}\,M_\odot\,\mathrm{yr}^{-1}$.

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TABLE 2

Eclipses Used in Present Analysis

Average JD⊙ (1)	Cycle (2)	No. of Obs. (3)	(O − C) (4)	Reference (5)
2437638.8269	0	1	−0.0001	K
7639.0038	1	1	−0.0001	K
7639.8883	6	1	−0.0002	K
7676.8617	215	1	−0.0001	K
7691.7221	299	1	+0.0002	K
7696.6754	327	1	+0.0001	K
7725.6878	491	1	0.0000	K
7725.8649	492	1	+0.0002	K
7748.6858	621	1	+0.0002	K
7757.7084	672	1	+0.0006	K
7777.6979	785	1	−0.0003	K
7783.7129	819	1	−0.0001	K
7930.0140	1646	1	−0’0002	P
7937.9753	1691	4	+0.0004	K, P
7943.9896	1725	3	−0.0001	P
7963.9797	1838	3	−0.0004	P
8017.7595	2142	1	0.0000	P
8025.0124	2183	1	−0.0002	K
8028.7279	2204	3	+0.0002	K
8030.8506	2216	1	+0.0001	K
8031.0275	2217	1	+0.0001	K
8045.7103	2300	1	−0.0003	P
8056.8556	2363	3	−0.0001	P
8057.0323	2364	1	−0.0003	P
8074.7231	2464	1	−0.0001	P
8087.8140	2538	3	−0.0002	P
8117.7117	2707	3	+0.0004	P
8345.9198	3997	1	−0.0002	Ma
8409.9601	4359	1	+0.0002	Ma
8410.8443	4364	1	−0.0001	Ma
8411.9059	4370	1	0.0000	Ma
8430.8348	4477	1	0.0000	P
8493.6367	4832	1	+0.0003	Ma
8496.6440	4849	1	+0.0002	Ma
8674.9658	5857	1	+0.0008	Ma
8879.6464	7014	1	+0.0013	Ma
9053.8987	7999	1	+0.0013	Ma
9054.9596	8005	1	+0.0008	Ma
9231.6897	9004	1	+0.0018	Ma
9527.6533	10677	1	+0.0019	Ma
9527.8300	10678	1	+0.0017	Ma
9913.8392	12860	1	+0.0022	Ma
9919.9548	12894	1	+0.0030	Ma
2440593.8666	16704	1	+0.0032	Mb
0594.9279	16710	1	+0.0031	Mb
0597.9360	16727	1	+0.0038	Mb
0679.6662	17189	1	+0.0035	W
0680.7279	17195	1	+0.0037	W
0976.8680	18869	1	+0.0033	W
1281.9543	20593	1	+0.0039	W
1296.8915	20678	1	+0.0041	W
1297.7760	20683	1	+0.0040	W
1356.6862	21016	1	+0.0046	W
1361.8161	21045	1	+0.0042	W
1365.7083	21067	1	+0.0045	W
1368.7153	21084	1	+0.0041	W
1676.5322	22824	1	+0.0047	W
1978.8655	24533	1	+0.0058	Mc
1979.9269	24539	1	+0.0057	Mc
1980.9887	24545	1	+0.0061	Mc
1981.8731	24550	1	+0.0060	Mc
2365.9366	26721	2	+0.0068	ABD
2366.8209	26726	2	+0.0065	ABD
2367.8826	26732	2	+0.0068	ABD
2420.7775	27031	2	+0.0068	ABD
2476.6796	27347	2	+0.0066	ABD
2511.7073	27545	1	+0.0070	Md
2513.6535	27556	1	+0.0072	Md
2514.7151	27562	1	+0.0074	Md
2516.6610	27573	1	+0.0073	Md
2694.9821	28581	2	+0.0072	ABD
2696.9279	28592	2	+0.0071	ABD

Note.—Table 2 gives the details of eclipses used in the present analysis. Column (1) is the Heliocentric Julian Date of the eclipse, column (2) the cycle number, column (3) gives the number of observations of that eclipse, column (4) is the observed minus calculated time of eclipse according to the elements of Krzemiński (1965) and column (6) denotes the source of the observed times.

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STEVEN M. ARNOLD, RICHARD A. BERG, and J. GRAEME DUTHIE: 419 Space Science Center, University of Rochester, NY 14627