THE ECLIPSING BINARY U GEMINORUM*

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ABSTRACT

The dwarf nova U Geminorum has been observed over several complete cycles of the eruptive activity since December 4, 1961, when it was found to be an eclipsing binary. Some 4500 photoelectric observations were made. The anomalous light-curve, which repeats well from cycle to cycle, shows a total primary eclipse that becomes shallower as the system brightens and is not detectable at all at the peak of the outburst. The width of eclipse is a function of time since the last eruption; it increases to a value 0 11 P during eruption and then diminishes exponentially to about 0.05 P before the next outburst. Analysis of the light-curve leads to a model of the system in which the larger, cooler component fills the Roche limit, while the smaller and hotter one is surrounded by a rotating ring or disk. The anomalies of the light-curve (shoulder, deformed eclipse) can be qualitatively explained on the assumption of mass loss by the cooler component. Contrary to theories of the phenomenon, the cooler component of U Gem is shown to be the seat of the eruptions An eruption of the system consists of a large rise in the surface temperature of the cooler component and a moderate and initially directional increase in its effective radius Consequently the rapid outflow of matter from the outer layers of the larger star may be supposed to occur as a result of the growth of the star's dimensions.

I. INTRODUCTION

A number of U Geminorum stars and stars spectroscopically similar to old novae which have been found (Kraft 1962)(hereinafter cited as "Paper I") to exhibit large radial velocity variations due to binary motion and/or doubled emission lines, have subsequently been observed photoelectrically by the writer with the aim of detecting eclipses. In this survey it was found (on December 4, 1961) that U Gem, the prototype of the dwarf novae, is an eclipsing binary. The existence of a well-repeated light-curve showing a total eclipse stimulated a more detailed investigation of the system. The purpose of the photometric observations of U Gem over a few complete cycles of nova activity was twofold: to learn which component is the seat of the eruptions, and to develop a more satisfactory model of the system.

Theoretical interpretations presented to date for eruptions of U Gem stars have generally assumed *a priori* that the hot, blue component of a binary pair is the seat of the nova-like phenomenon (Zuckermann 1961; Kraft 1963); the presumed outburst of the blue component begins with the expansion and subsequent cooling of its photosphere. The photometric data obtained by the writer and discussed in this paper show that this is not the case for U Gem: *the eruption occurs in the red, cooler component of this system* (Krzeminski 1964). It should also be emphasized that spectroscopic observations of dwarf novae during outbursts show no evidence of any expanding shell.

The spectroscopic data for U Gem (Paper I) are as follows: there is a continuous spectrum with superimposed double emission lines of the Balmer series and Ca II, having a separation corresponding to a rotating ring with $v \sin i = 580$ km/sec. The line shifts give $K_1 = 265$ km/sec, and $a_1 \sin i = 6.46 \times 10^{10}$ cm was derived from the photometric period. (The value of 6.31×10^{10} given by Kraft was based on his preliminary period.) A direct determination of the mass ratio is not possible since only one spectrum, of type sdBe, is visible. The radial velocity-curve, phased with the exactly determined photo-

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metric period, shows that the blue star is eclipsed at primary minimum. Higher members of the Balmer series are the strongest near phase 0.75 *P*; they disappear near phase 0.00 *P*. The *V/R* ratio reverses at opposite elongations, indicating greater brightness of the ring along the line joining the centers of the components and along the following hemisphere of the blue one; in other words, it indicates asymmetry of the ring or disk around the hot star. This effect is known for DQ Her (Greenstein and Kraft 1959) and a close analogy could be drawn between U Gem and the model of DQ Her advanced by Kraft (1959).

II. OBSERVATIONS

Photoelectric measurements were secured in either one (yellow or blue) or three colors (yellow, blue, ultraviolet) with *UBV* filters and a refrigerated 1P21 photomultiplier on the 21- and 42-inch telescopes at the Lowell Observatory, on the 69-inch Perkins telescope near Flagstaff, Arizona, and on the 36-inch Crossley telescope at the Lick Observatory, in the period December, 1961–January, 1963. The following combinations of filters were used on the particular instruments: At the 21-inch telescope: *y*, 3.6-mm Corning 3384; *b*, 5-mm Corning 5030 + 2-mm Schott GG 13; *u*, 3-mm Corning 9863.

TABLE 1

PHOTOMETRIC DATA ON COMPARISON STARS

Star*	*V*	*B* − *V*	*U* − *B*	*n*
85 .	8 62	+0 34	+0 11	8
114..	11 41	+ 51	+ 06	7
119	11 59	+0 52	+0 03	3

* Identified by the visual magnitudes marked on the chart of Brun and Petit (1959)

At the 42- and 69-inch: *y*, 2-mm Corning 3384; *b*, 0.5-mm BG 12 + 1-mm GG 13; *u*, 3-mm Corning 9863. At the Crossley: filters identical with those used by Preston and Paczynski (1964). Three stars served as comparisons: 85(= BD + 22° 1808), 114 (primary comparison star), and 119; identified on the chart of Brun and Petit (1959), the photometric data for these stars are given in Table 1 (where *n* denotes the number of nights when tie-ins to the *UBV* system were made). The probable errors of the values given in Table 1 for stars 85 and 114 are V: ± 0.004, $B - V$: ± 0.004, $U - B$: ± 0.007 mag. The three-color observations of U Gem have been transformed to the *UBV* system by means of a method essentially identical with that described by Preston and Paczynski. Due to the great difference $\Delta(U - B)$ between U Gem and its comparison stars, the $U - B$ values obtained for U Gem might be in error by as much as ± 0.02 mag. because of errors made in determining the slope, a_{U-B}, of the transformation equation. One-color observations reduced to no atmosphere and expressed as the difference U Gem minus star 114 have been left in the instrumental system of the given telescope. The tables of detailed photoelectric observations will be published elsewhere (Krzeminski 1965).

In order to check the accuracy of the observations and to test the reality of the brightness fluctuations of very brief duration and small amplitude, simultaneous observations were carried out on two nights on the 42-inch and the Crossley telescopes in co-operation with Drs. J. Smak and B. Paczynski. Observations on December 8, 9, and 10, 1962 were secured by Dr. Paczynski; the results are included in this paper.

Polarimetric observations of U Gem were obtained on the 21-inch Lowell reflector with a photoelectric photometer equipped with a rotating polaroid and depolarizer. The results are described in § IV*c*.

III. THE ORBITAL PERIOD

The light-curves discussed in §§ IV and V indicate that the descending branch of eclipse consists of two easily distinguishable parts, the lower one frequently being quite distorted. The changeable shape of the ingress has an influence on the determination of times of eclipse. To minimize the effect of this distortion the observed times of minima t_0 have been determined at half the depth of eclipse (cf. Fig. 1); the depth of eclipse is defined by the magnitude difference between the minimum, m_2, and the level, m_1, obtained by the intersection of the bisector KL of the eclipse with the tangent to the shoulders preceding and following the eclipse. The period so determined is

$$\begin{aligned}\text{Primary minimum} = \text{JD}_\odot\ 2437638\ 82704 &+ 0^{\mathrm{d}}17690591 \cdot E \\ \pm 0\ 00004 &\pm 0\ 00000003\ \text{(p.e.)}\ . \end{aligned} \quad (1)$$

Table 2 contains the observed times of minima and the residuals $(O - C)$. In the period determination only the best observed eclipses have been used.

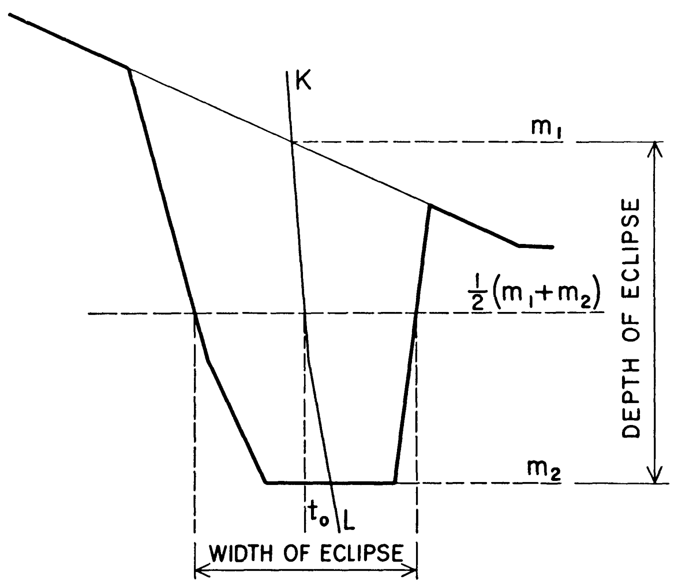

FIG. 1.—Schematic shape of the U Gem eclipse and its characteristic parameters. See text for explanation.

If we determine times of minima from the moments defined by the intersection of bisector KL with the bottom of an eclipse, as is usually done to derive times of minima of eclipsing binaries, we get elements having larger residuals; the respective errors of the determination of moment of epoch and period are 2.5 times those given in equation (1). Other methods to determine times of minima (e.g., moment of the middle of egress) are strongly correlated with the degree of eruptive activity, i.e., the time elapsed since the last eruption. The most accurate determination of the period is of basic importance for future investigation of mass transfer in this system.

Phasing of radial velocities of U Gem (Paper I) with the elements of equation (1) indicates that the phase of spectroscopic conjunction comes after the moment of eclipse, near phase 0.05 P. It is premature, however, to speculate on the meaning of this phenomenon since it may result from the way the spectral lines are measured.

TABLE 2

OBSERVED ECLIPSES OF U GEMINORUM AND THEIR PHOTOMETRIC DATA

Instrument, Color	$JD_{\odot}$ 2430000+	O-C (day)	m_2 (mag.)	V	B-V	U-B	Eclipse depth (mag)	Eclipse width (day)	Days after Maximum
42 y	7637.9 *		3.58				0.66:		61
42 y	7638 8269*	-0 0001	3.46				.74	0.0101	62
42 y	7639.0038*	- .0002	3.44				.60	.0099	62
21 b	7639.8883	- .0002	3 22				.73	.0104	63
21 b	7675 8		-1.63				.02		8
21 b	7676 8617*	- .0001	-1.14				.034	.0184	9
21 b	7691.7221	+ .0002	3.08				.54	.0133	24
42 y	7696.6754*	+ .0001	3.48				.69	.0124	29
21 b	7725 6878*	.0000	3.18:				.61:	.0100	58
21 b	7725.8649	+ .0001	3.14				.57	.0102	58
42 y	7732.7640*	- .0001	3.00	14 42	+0.41	-1 04	.56	.0122	65(-2)
42 b	7732.7641*	.0000	2.89				.65	.0122	65(-2)
36 b	7732 7641*	.0000	2.92				.63	.0123	65(-2)
42 y	7748.6858*	+ .0002	3.51				.70	.0145	14
69 y	7757.7084	+ .0006	3.65				.81	.0122	23
42 u	7777.6979†	- .0003	2.32				.69	.0113	43
42 b	7783.7129*	- .0001	3.37				.73	.0109	49
42 y	7937.9750*	+ .0001	3.29				.62	.0131	26
36 y	7997.9		3.51:	14 93	+0.27	-1.08:	.76:	.0087:	86
36 b	7997.9		3.27:				.80:	.0095:	86
36 u	7997.9		2.17:				.58:	.0103:	86
36 y	8002.8979†	- .0015	1.79				.27:		-1
36 y	8003.0742	- .0021	1.31				.29	.0128	-1
36 y	8003 7812†	- .0027	-1.40:				.06:		0
36 y	8003 9580	- .0028	-1.49	9.93	-0.015	-0.73	.045	.0153	0
36 b	8003.9574	- .0034	-1.995				.042	.0125:	0
36 u	8003.9591†	-0.0017	-2.77				0.02	0.0158:	0
36 y	8006.9689	+0.0007	-0.56	10.86	-0.08	-0.95	0.049	0.0182	3
36 b	8006.9680	- .0002	-1.14				.044	.0187	3
36 u	8006.9688	+ .0006	-2.10				.042	.0213:	3
36 y	8007.8525	- .0003	0.02	11.44	-0.09	-0.955	.066	.0186	4
36 b	8007 8514	- .0014	-0.575				.062	.0191	4
36 u	8007.8520†	- .0008	-1.53				.055	.0195	4
36 y	8008.0295	- .0002	0.16	11.58	-0.09	-0.97	.068	.0184	4
36 b	8008.0301	+ .0004	-0.425				.062	.0191	4
36 u	8008.0289	- .0008	-1.395				.060	.0212:	4
36 y	8008 7381	+ .0008	0.73				.121:	.0173	5
36 y	8008.9143	+ .0001	0.90	12 32	-0.095	-0.98	.090	.0170	5
36 b	8008.9150†	+ .0008	0.31				.069	.0172	5
36 u	8008.9		-0.67				.054:		5
36 y	8025.0124*	- .0002	3.61				.71	.0130	21
36 y	8028.7280†	+ .0003	3.54	14.97	+0.24	-1.19	.67:	.0123	25
36 b	8028.7280†	+ .0003	3.28				.76:	.0123	25
36 u	8028 7277†	.0000	2.07				.42:	.0126	25
36 y	8030.8506*	+ .0001	3.68				.83	.0123	27
36 y	8031 0275*	+0.0001	3.68				0.78	0.0121	27

* used in deriving the period

† low weight

IV. OBSERVATIONAL DATA

a) Light-Curves at Minimum Brightness

The light-curves that repeat well from cycle to cycle show a total primary eclipse with a long flat bottom that is well visible in observations taken with a high signal-to-noise ratio, and a short ingress and steeper egress. No secondary eclipse has been detected. The most characteristic feature of the light-curves is the existence of a shoulder that lasts half the period, from phase 0.6 P to 0.1 P, and is eclipsed during primary minimum. The

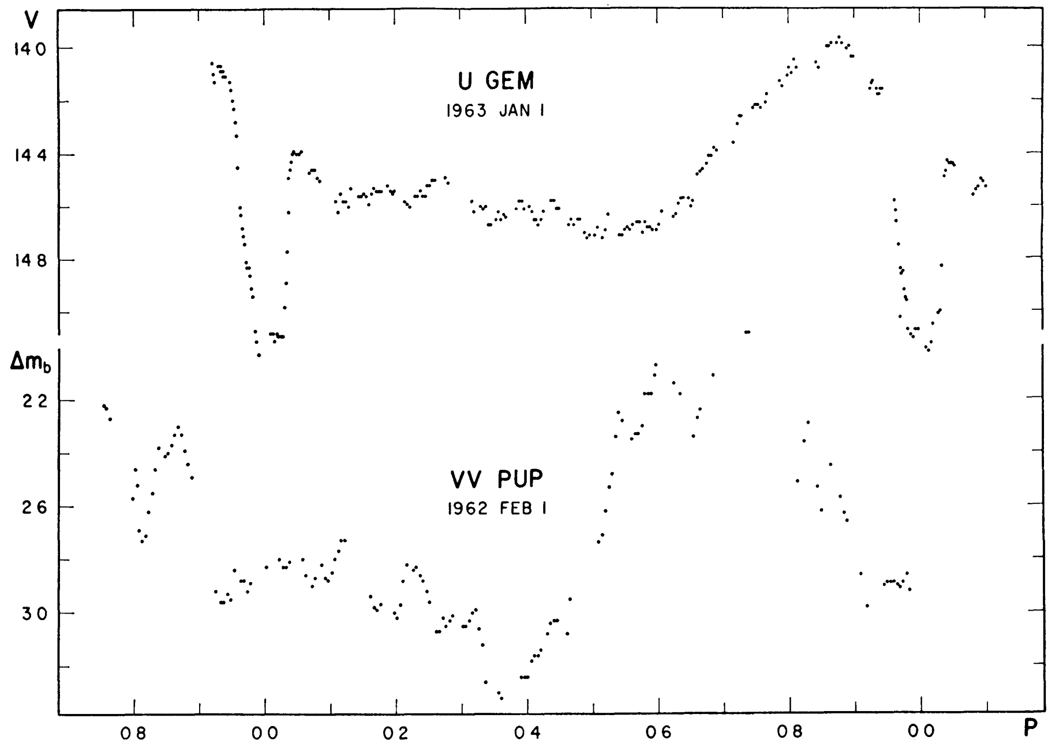

FIG. 2.—Photoelectric observations of U Gem and VV Pup The ordinate for U Gem is the V magnitude on the UBV system, and for VV Pup the blue-light magnitude difference between it and the comparison star. The abscissa is the phase in the orbital period computed for U Gem from elements given in the text, and for VV Pup from elements given by Thackeray, Wesselink, and Oosterhoof (1950) with a 0.29 P shift of epoch to make the phase 0 0 P correspond to the spectroscopic conjunction when the emission line object is behind, according to Herbig (1960).

shoulder is symmetrical around its maximum at phase about 0.85 P: that is, its descending branch (omitting the eclipse) is a reflection of the ascending branch. The only binary system known hitherto with a similar light-curve, but determined photographically, is VV Pup (Herbig 1960; Kraft 1963); this similarity inspired photoelectric observations of VV Pup by the writer. The light-curves of U Gem and VV Pup are compared in Figure 2. The comparison star for VV Pup is 185″ north, 152″ west of the variable, and has $V = 12.28$, $B - V = +0.39$, $U - B = -0.10$. The photoelectric light-curve of VV Pup seems to contain eclipses between phases 0.9 and 0.1 P that were not detected photographically.

The light-curves of U Gem reveal rapid, irregular fluctuations with amplitudes of a few hundredths of a magnitude and duration of a few minutes.

The color-curves $B - V$ and $U - B$ of U Gem resemble those characteristic of the UX UMa-class subdwarf binaries (e.g., RW Tri: Walker 1963); the $U - B$-curve is a reflection of the $B - V$-curve. The ultraviolet excess with respect to the surrounding curve amounts to about 0.2 mag. during eclipse. The upper part of the ingress shows a large positive jump in $B - V$; the lower part seems to be almost undistinguishable from the $B - V$ color of the minimum. The limited UBV data for U Gem are shown in Figures 3 and 4, and the photometric data for eclipse are given in Table 2. The magnitudes m_2 of minima (cf. Fig. 1) in the sense of U Gem minus star 114 are left in the instrumental system of the particular telescope and filter.

b) *Light-Curves during Eruptions*

Four out of the five eruptions noted in 1962 were observed. As the system rises to maximum brightness, the eclipses remain total but get shallower (Figs. 4 and 5 and Mumford's 1964 observations just preceding the night of December 4, 1962). Due to the

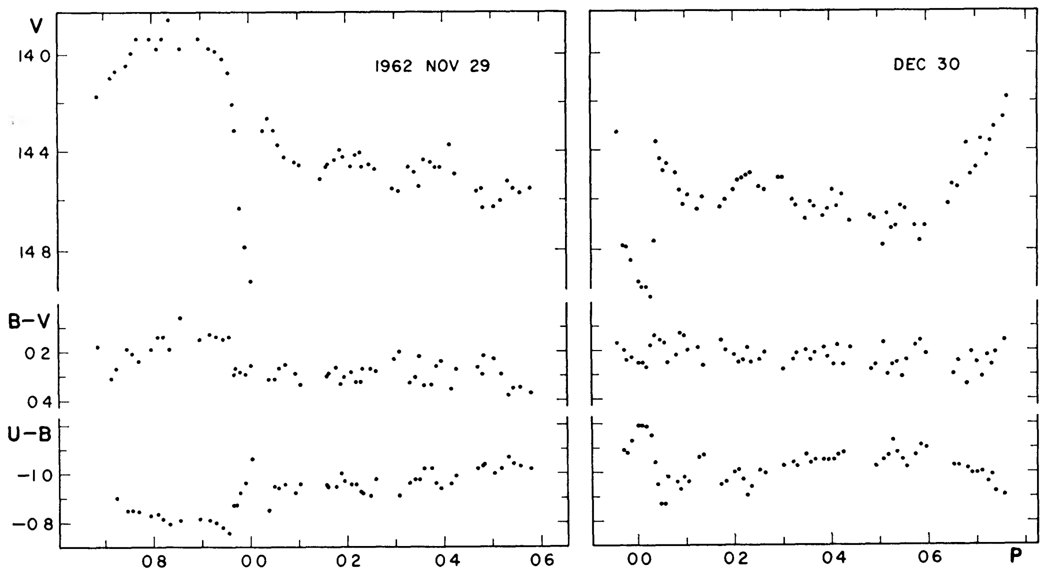

FIG. 3.—Three-color observations of U Gem at brightness minimum Phase in the orbital period computed from the elements given by eq. (1).

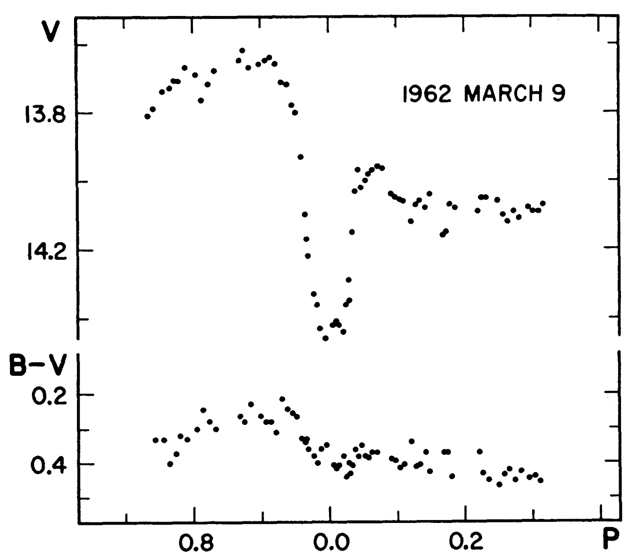

FIG. 4.—Two-color observations of U Gem at the beginning of eruption. Abscissa as in Fig. 3.

shallowness of the eclipse observed on December 5, 1962, it is not possible to decide whether it is partial or total. Judging from the changes in the depth of eclipse along with the increase in the over-all brightness of the system, we find that the eclipsed object does not become more than fivefold brighter during a 5-mag. outburst, on the assumption that the eclipses remain total. No eclipses are detectable at maximum. Especially accurate observations to detect eclipses at the maximum were made on the nights of January 3–6 and 10–12, 1962; some of them are shown in Figure 6. As the system fades again, the eclipses become detectable among the fluctuations. Observations indicate that erratic fluctuations are larger in the longer maxima than in the shorter ones. The intensity of the light contributing to the shoulder remains constant within a factor of 2 during eruption.

The beginning of the rise is accompanied by total reddening of the system. For example, on the night of March 8, 1962 (JD 2437731.8), three days before maximum, the mean color $B - V$ for phases 0.1–0.5 P was $+0.34$ and for the same phases on the following night, $B - V = +0.41$, whereas for normal nights $B - V$ was about $+0.25$. The respective increase in V for the same phases was 0.38 mag. The effect of this reddening is shown in the upper part of Figure 7; the colors at eclipse observed by Mumford

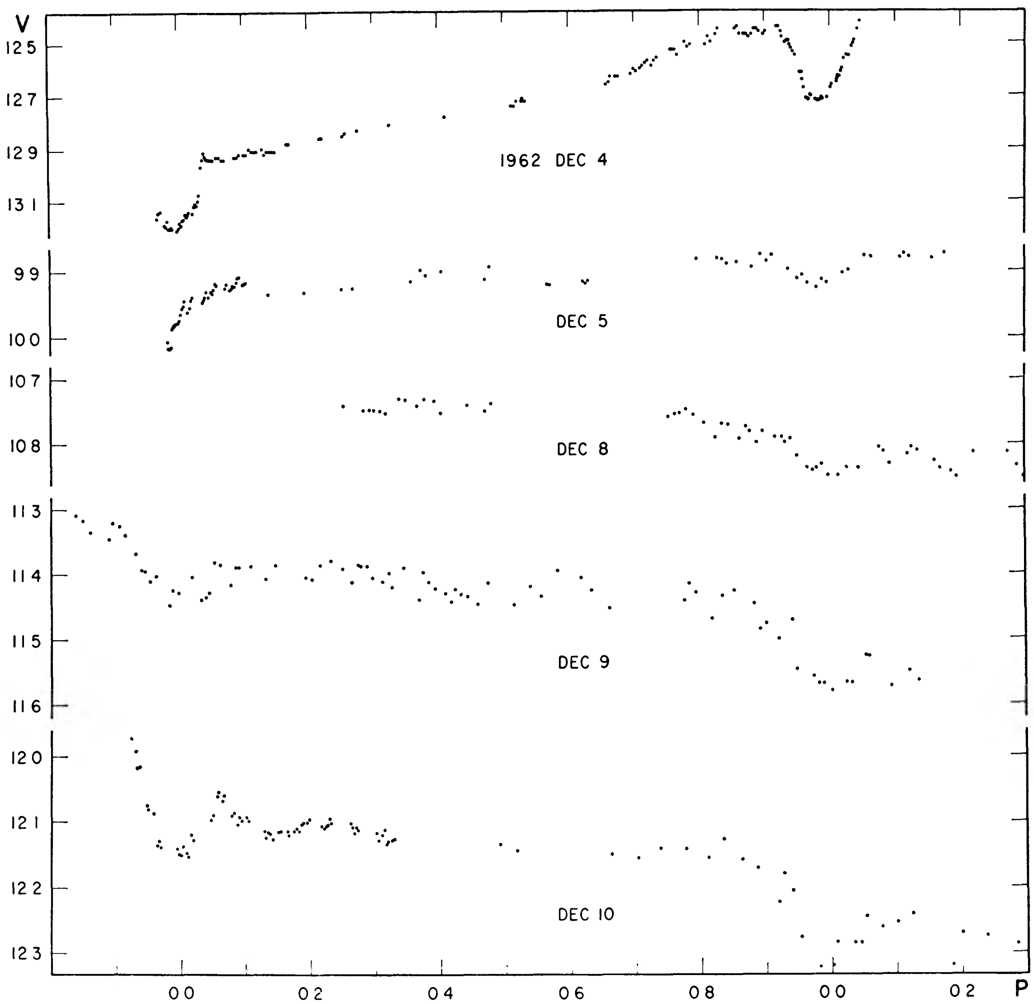

FIG 5.—Photoelectric observations of U Gem during eruption. The ordinate is the V magnitude on the UBV system; the abscissa as in Fig. 3.

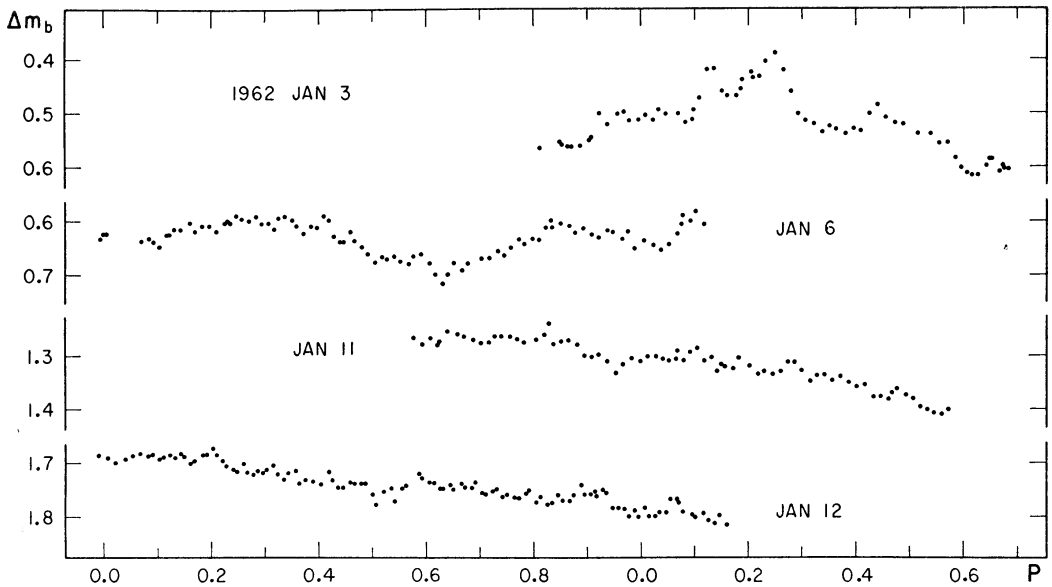

FIG. 6.—Photoelectric observations of U Gem during eruption. The ordinate is the magnitude difference, in blue light, U Gem minus comparison star 85; the abscissa as in Fig. 3.

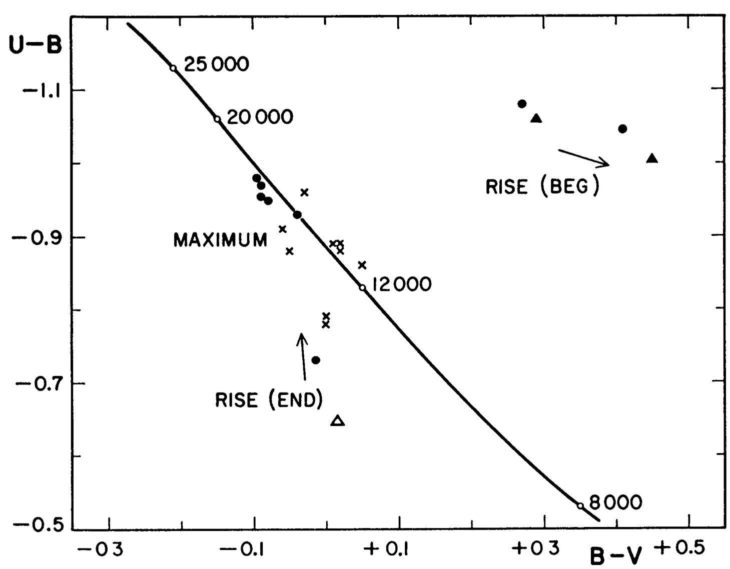

FIG. 7.—The $B - V$ versus $U - B$ diagram for U Gem during eruption and the black-body locus computed by Matthews and Sandage (1963). *Filled circles:* colors at eclipse; *crosses:* colors from Table 3 when no data at eclipse were available; *open triangle:* beginning of the *UBV* run on December 5, 1962, at phase 0.2 *P; filled triangles:* colors at eclipse derived from Mumford's (1964) observations.

(1964) have been derived from his data by the method for transformation to the *UBV* system given by Preston and Paczynski (1964).

Some of the observational data dealing with the further development of the rise, maximum and beginning of the decline are shown in Figure 7; these are taken from Table 2 for moments of eclipse and from Table 3 when no data at eclipse were available. Data from Table 3 are based on fewer observations, and consequently have less weight, than those in Table 2. It is evident from Figure 7 that farther on in the rise there is a pronounced ultraviolet deficiency as compared with the black-body-curve (observations on January 3 and December 5, 1962). At maximum the star colors correspond to those of a black body at a temperature of 15000° K, irrespective of phase in the orbital period. Note

TABLE 3

UBV OBSERVATIONS OF U GEMINORUM DURING ERUPTIONS IN JANUARY AND MAY, 1962

JD⊙ 2437000+	Phase	V	$B-V$	$U-B$	Remarks
667 808	0 821	9 50	0 00	−0 79	Rise
667 933 . . .	528	9 47	00	− .78	Rise
668 700	864	9 46	+ 02	− 88	Max.
668 969 .	.384	9 52	+ 01	− 89	Max.
669 918 . . .	749	9 56	+ 05	− .86	Max.
676 891 . . .	.165	10 78	− 03	− 96	Decline
677 688	670	11 17	− 06	− 91	Decline
677 748	009	11 17	− 04	− 93	Decline
809 669 .	722	10 03	− 05	− 88	Max.
810 676	0 414	10 38	+0 02	−0 89	Max.

TABLE 4

POLARIZATION MEASUREMENTS DURING ERUPTION OF U GEMINORUM

JD⊙ 2437000+	Phase	p (mag)	θ_E	V	$B-V$	Remarks
807 683	0 496	0 012	172°	10 50	. . .	Rise
808 678 .	0 120	0 009	161	9 88	−0 05	Max.

the scatter of points along the black-body-curve which indicates higher or lower temperatures of the system. It is not feasible to infer, however, a relation between the length and brightness of the maximum and the corresponding temperature. The characteristic "loop" exhibited by U Gem on the two-color diagram has been found in other dwarf novae: SS Cyg (Grant and Abt 1959), Zuckermann (1961), Chuvayev (1962), 2.1937 Cet (Paczynski 1963), and SS Aur and Z Cam (Krzeminski, unpublished). During the early decline of U Gem the ultraviolet excess at eclipse begins to appear slowly; it amounts to about 0.02 mag. for the nights of December 9 and 10, 1962.

c) *Polarization and Spectroscopic Observations during Eruptions*

Polarization measurements in integrated light, but behind a 2-mm Schott GG 13 filter, were secured on the rise and at maximum, and are given in Table 4, where p denotes the amount of polarization and θ_E is the position angle of the plane of vibration expressed in equatorial coordinates. The zero point of the values of θ_E was determined from observations of highly polarized stars taken from Hall's (1958) catalogue, and instrumental polarization was checked against nearby stars (within 15 pc); no instrumental polarization was detected. The negative result—lack of polarization during eruption of U Gem—is in accordance with similar results for SS Cyg (Kraft 1956) and Nova Her 1963 (Clarke 1964). The polarization data for U Gem may also serve as an indirect argument for the lack of its interstellar reddening which has been expected to be negligible (Paper I).

Low-dispersion spectrograms obtained with the Crossley nebular spectrograph at 430 Å/mm give the following information: JD 2438004.06 = December 5, 1962, at the end of rise: very wide, shallow and diffuse hydrogen absorption lines are present, resembling those in white dwarfs. Their widths at half-depth are around 30 Å. The Balmer continuum starts about λ 3850, and thus higher members of the Balmer series are not visible. A faint absorption line of He I λ 4471 and a very faint λ 4026 are present. JD 2438004.92 = December 6, 1962, at maximum: the spectrum is continuous, with He II λ 4686 and Hβ very faintly visible in emission. JD 2438005.97 = December 7, 1962, at maximum: the spectrum is continuous with very feeble He II λ 4686 in emission and the faintest trace of Hβ in emission.

d) Relation between the Characteristic Observational Quantities and the Nova Activity

Parameters that characterize the light-curves and especially the eclipses appear to be strongly correlated with the time t elapsed since a maximum. Proper choice of the zero point for t (at the beginning, middle, or any other phase of eruption) is difficult because the observational data at maxima are incomplete. Conventionally we choose the first day of maximum as the zero point. For the 1961–1962 eruptions, the first day of maximum is JD 2437577.0, 7667.5, 7735.0, 7808.5, 7912.0, 8004.0 according to the writer's observations and A.A.V.S.O. data (Mayall 1964). Table 2 gives the *explicit* number of days from the first day of maximum to the particular eclipse.

1. *Width of eclipse.*—The widths of eclipses determined at half-depth (cf. Fig. 1) are given in Table 2. Note that the eclipses are wider in the ultraviolet than in blue or yellow light. The eclipse width changes regularly during the whole cycle of nova activity; it increases to 0.11 P at maximum, when eclipses are still distinguishable from the fluctuations, and then exponentially diminishes to about 0.05 P before the next eruption starts. The cyclic behavior of the width changes is shown in Figure 8; for eclipses observed in several colors the mean widths have been used. It should be emphasized that the scatter of points around the exponential curve along the horizontal axis is largely due to the choice of the zero point of t; i.e., to the duration of maximum.

2. *The phase shift of eclipse times.*—As the brightness rises to maximum, eclipses occur *earlier* than predicted from the ephemeris of equation (1). The phase shift of times of eclipses for the observations in yellow light is shown in Figure 9. The greatest shift for maximum light (to phase 0.98 P) was found from the observations secured on December 5, 1962, in blue light; the residuals $(O - C)$ are given in Table 2. When the system fades after maximum the eclipses return to phase 0.00 P.

3. *Egress of eclipse.*—The duration of the ascending branch of the eclipse, and its slope, is correlated with the degree of nova activity. The duration of egress is very short, 1.5 to 3 min, and therefore the amount of photometric information at the observer's disposal is quite sparse. Consequently, only observations of the highest weight secured in one color have been used in Figure 10 to find the relation between the duration of egress and the time elapsed since maximum. The ascending branch of the eclipse lasts longer after eruption and becomes shorter by a factor of around 2 before the next eruption occurs. The observations of egress during the rise to maximum have not been plotted in Figure 10 because of their lower weight. However, they indicate that during the rise to maximum the egress again increases in length by a factor of more than 2.

4. *Other correlations.*—The small amount of UBV data gathered by the writer does not permit conclusions to be drawn as to the dependence of color upon the degree of

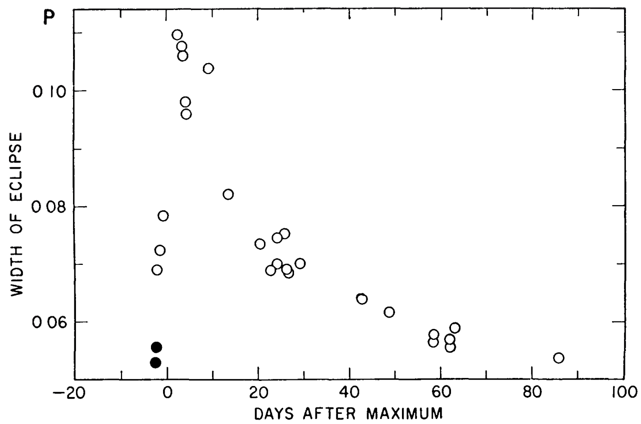

FIG 8 —Width of eclipse of U Gem as a function of time since outburst Eclipse width is measured at half-depth and expressed in units of the orbital period. Mumford's (1964) observations are shown as filled circles.

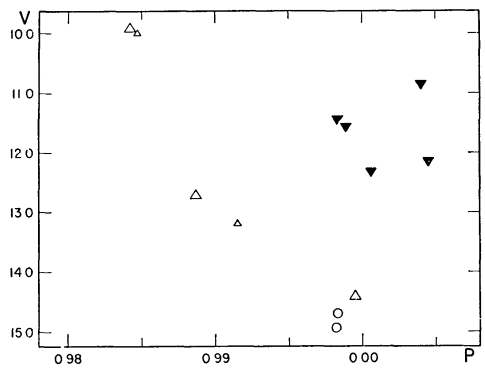

FIG. 9 —Phase shift of the times of eclipse of U Gem during an outburst as observed in yellow light The ordinate is the V magnitude on the UBV system of the bottom of eclipse; the abscissa is as in Fig 3. Open triangles denote observations on the rising branch to maximum, filled triangles the decline Data derived from Mumford's (1964) observations shown as open circles. Smaller symbols have lower weight

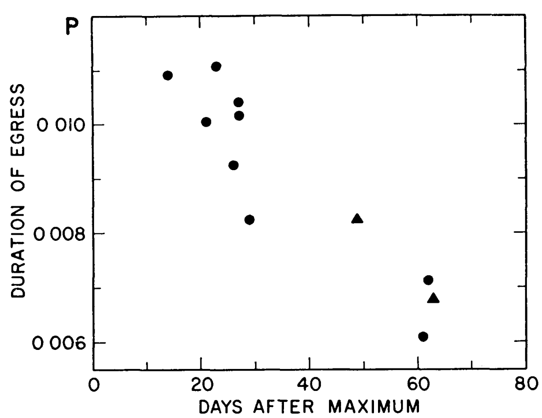

FIG 10 —Duration of egress of U Gem as a function of time since outburst. Duration of egress is expressed in units of the orbital period. Circles are for observations in yellow light, triangles in blue light.

nova activity. The observations of Mumford (private communication) and Paczynski (1965) indicate that the $U - B$ color is more negative after than before the eruption. This fact is in accordance with the observations secured on November 29 and December 30, 1962 (see Table 2).

It is found from the depth of the eclipse (see Fig. 1) that the brightness of the eclipsed object is constant within ± 0.1 mag. in the minimum light of U Gem. If the depth of the eclipse is defined in another way, namely, as the difference between the magnitude at minimum and either the magnitude of shoulder maximum (phase 0.85 P) or the magnitude of the deepest light-curve depression (phase 0.5–0.6 P) we get the same result: that the brightness of the eclipsed object is constant between eruptions. This remark is also valid for the shoulder, which is constant in intensity units at minimum light of U Gem.

V. TENTATIVE INTERPRETATION AND DISCUSSION

The body of basic observational data presented in the previous sections makes possible an approach to a model of U Gem; this model must explain the features observed at minimum and maximum brightness of the system. The observations cover 13 months,

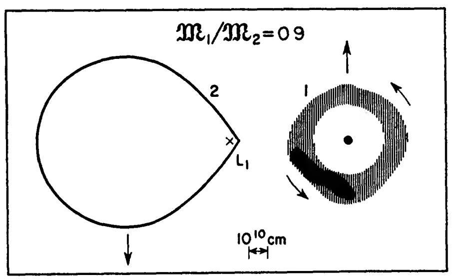

FIG. 11.—Schematic model of U Gem. The mass ratio $\mathfrak{M}_1/\mathfrak{M}_2$ is assumed to be equal to 0.9. The rotation is counterclockwise, and the cross marks the center of mass. The gaseous ring is marked by vertical and horizontal hatching.

not much longer than the mean cycle of nova activity (about 100 days), and since many of the observed quantities are related to this activity, only a rather qualitative attempt at interpretation is possible. To clarify the discussion it seems advisable first to present a model of the system (Fig. 11) and then to give an interpretation of the observed facts. We therefore postulate the following model for U Gem:

1. The system is a binary star with a mass ratio close to unity. The cooler component (*2* in Fig. 11), probably slightly the more massive, fills its Roche limit. Its effective radius, 1 order of magnitude larger than that of the hotter component, is largest at maximum and then gradually diminishes, becoming smallest just before the eruption starts. During the rise to maximum light, the small increase in the radius of the cooler component is accompanied by a large increase in its surface temperature. The initial expansion of the cooler star is asymmetric, being larger in the direction of its orbital motion. The radius of the hotter star (*1* in Fig. 11) is at the most a few times that of a white dwarf; there is a hot spot on or near its following hemisphere. The physical parameters of the hotter star (brightness, radius) are roughly constant between eruptions.

2. The hotter star is surrounded by a rotating ring. The ring is asymmetrical: its brighter part is in the vicinity of the inner Lagrangian point L_1 and spreads along the following hemisphere of the hotter star. Matter is supplied to this quasi-permanent ring by the cooler component of the system; the rate of injection of matter is greatest during eruption.

3. The primary eclipse consists of total eclipse of the hotter star and its hot spot and

partial eclipse of the ring. Between the first and second contacts as well as between the third and fourth we have an atmospheric eclipse.

4. The cooler star is the seat of the eruptions. The outburst consists of a rapid, small, initially directional increase in the effective radius of the cooler star. This is accompanied by an increase in its surface temperature. The star *2* overflows its Roche limit and loses matter to the inner lobe around the hotter component. The inflowing matter probably causes an increase in the surface brightness of the eclipsed object: hot star plus ring.

Below we shall consider some of the observational data on which the postulated model is based. The orbit will always be assumed to be circular. It should be emphasized, however, that only some limited estimates are possible since the absence of an observed spectrum for star 2 does not permit a direct determination of the mass, while the complicated shape of the light-curve rules out a determination of the geometrical elements of the system.

a) Masses of the Components

A mass ratio $q = \mathfrak{M}_1/\mathfrak{M}_2$ (subscript "1" always refers to the hotter star) has to be assumed in order to derive the component masses from the mass function. For other dwarf novae with spectra of both components visible, the total masses of the systems

TABLE 5

RANGE OF U GEMINORUM MASS

$q = \mathfrak{M}_1/\mathfrak{M}_2$	$\mathfrak{M}_1 \sin^3 i$ (⊙)	$\mathfrak{M}_2 \sin^3 i$ (⊙)	$a \sin i \times 10^{-10}$ (cm)	$r_{wd} \times 10^3$ (in orbital units)
1 1 . . .	1 65	1 50	13 6	. . . .
1 0	1 36	1.36	12 9	2 0
0 9	1 11	1 23	12 2	4 0
0 8 . .	0 88	1 10	11 6	5 7
0 5. . .	0 38	0 76	9 7	11 6
0 3. . . .	0 17	0 57	8 4	18 2

probably run from 1.5 to 3.0 $\mathfrak{M}_\odot$ and $\langle q\rangle = 0.87$ ($q = 0.90, 0.86, 0.85$ for SS Cyg, Z Cam, and RU Peg, respectively: Kraft 1962, 1964). This implies a certain restriction upon the masses since U Gem itself would not be expected to differ drastically from other stars of its class. In Table 5 the minimal masses for the components are given for assumed q's of 1.1 to 0.3 along with the minimum values of the absolute dimensions of the system, $a \sin i$.

If the motion of the gaseous particles in the ring around the hotter component is caused only by gravitational forces and if we neglect the perturbations of this motion by the secondary component, the mean radius of the ring is $r_{\text{ring}} = G\mathfrak{M}_1/(v \sin i)^2$ (Huang and Struve 1956), where $v \sin i = 580$ km/sec is found from the separation of the emission components. The mean radius of the ring proves greater than the corresponding Roche limit (Plavec 1964) for those minimum masses $\mathfrak{M}_1$ that result from q equated to 1.1 and 1.0. This gives an upper limit on the mass ratio; the actual value of q for U Gem is therefore probably less than unity.

b) Geometry of Eclipses, Radii of Components

A change in the effective radius of the cooler component causes a change in the eclipse width. Therefore, judging from the correlation between the eclipse width and the nova activity (see Fig. 8), the effective radius of the cooler, eclipsing star is subject to changes during the entire cycle of nova activity. It is least just before an eruption starts.

The correlation between the duration of egress and the time t elapsed since maximum (see Fig. 10) may be interpreted in either of two ways: (1) by a change in the effective radius of the hotter, eclipsed star, caused by its increase during eruption, or (2) by the effect of an atmospheric eclipse. From Figure 10 it may be inferred that for $14 < t < 63$ days the egress duration diminished by half and, consequently, on the first alternative, the eclipsed object would have its surface area reduced fourfold, which would affect its brightness and temperature. However, the observational data (§ IV*d*) show that the brightness of this object is constant. Consequently, we have to accept the second alternative, that a contraction of the extended atmosphere of the eclipsing star is responsible for the relation shown in Figure 10. The wavelength dependence of the eclipse width bolsters the argument in favor of the atmospheric eclipse: the eclipses are wider in the ultraviolet than in the yellow light just as in the case of ζ Aur (Roach and Wood 1952).

The rapid increase of $B - V$ in the upper part of ingress indicates that first the hotter star is eclipsed and then the brighter part of the ring, which spreads along the following hemisphere of the hotter component (the brighter part of the ring contributes about 15 per cent of the total light of the system). During eclipse the source responsible for the shoulder is also eclipsed. The fact that the bottom of the primary minimum is flat indicates that this source cannot be associated with the eclipsing star and, furthermore, its visibility during exactly one half-period implies that it has to be associated directly with the surface of the eclipsed star. The simplest way to explain this feature is to postulate the existence of a hot spot on the following hemisphere of the blue star, a hypothesis already suggested by Mumford (1963). However, the scarcity of *UBV* data does not permit one to derive quantitative parameters for this feature.

The maximal radius r_1 of the hotter star, expressed in units of the dimensions of the system, a, can be derived from the egress duration; for an egress duration of 0.006 P we get $r_1 \leq 0.019$, the equality corresponding to $i = 90°$. On account of the lack of two-color observations, such calculations cannot be performed for ingress. The last column of Table 5 gives the white-dwarf radius r_{wd} obtained from the mass-radius relation for white dwarfs (Chandrasekhar 1939; Hamada and Salpeter 1961) for the minimum mass $\mathfrak{M}_1$. It is seen that for $q = 0.3$ the radius of the eclipsed star is almost equal to the radius of the white dwarf (for $i = 90°$), which gives us the lower limit for the mass ratio of the components. This condition is too stringent, however, since the orbit inclination is presumably less than 90° and since the hotter component of U Gem might be brighter than the white dwarf. Consequently, we shall assume 0.5 as the lower limit on q. The values of q found in other dwarf novae lie within the limits found from these estimates for U Gem ($0.5 < q < 1.0$).

From the widths of eclipses (see Fig. 8), which are determined at half-depth and which are, to sufficient accuracy, proportional to the diameter of the eclipsing star, we find that its radius is $r_2\,(\text{min}) \geq 0.17$ and $r_2\,(\text{max}) \geq 0.35$, where "min" refers to the minimum of the brightness of the system just before an outburst starts, and "max" refers to eruption. The greatest value of the ratio of the radii of the components is $k = r_1(\text{min})/r_2(\text{min}) = 0.11$.

Despite the absence of direct observational evidence of transfer of matter from the cooler to the hotter component, we may by indirect methods (cf. § V*c*) conclude there is some such flow. The mass loss by the cooler star indicates that it fills its Roche limit at some phase of nova activity. The ultraviolet excess and visibility of doubled emission lines during totality indicates that the ring around the hotter component is only partially eclipsed. This implies that for $q < 1.0$, where the Roche limit around the hotter star is smaller than that around the cooler, the orbital inclination is less than 90°.

In the following estimates we assume $q = 0.9$. With the assumption that the cooler star fills its Roche limit at minimum brightness of the system shortly before eruption (eclipse width 0.055 P) we get an orbital inclination of $i = 71°$, and if it fills the Roche limit at maximum (eclipse width 0.11 P) we get $i = 81°$ (cf. tables given by Plavec 1964).

During eruption the eclipse width increases by a factor of about 2. If the inclination of the orbit were 90° this would imply that the radius of the eclipsing star also increases by a factor of 2. With the assumption that the cooler star fills the Roche limit at minimum ($i = 71°$) we find that its radius increases by a factor of about 1.2 during eruption; the same situation for maximum ($i = 81°$) gives a radius increase by a factor of about 1.6. In view of the flow of matter into the inner lobe around the hot component it should be assumed that during eruption the cooler star fills in, or perhaps overflows, its Roche limit. Therefore the increase in the effective radius of the cooler star should lie somewhere between 1.3 and 1.5.

During the rise to maximum the times of the eclipses (see Fig. 9) are observed to undergo a phase shift along with an increase in the eclipse width. This effect is to be explained by the asymmetrical increase in the radius of the eclipsing star; we find this increase to be larger in the direction of the orbital motion. A quantitative estimation of this initial asymmetry is not feasible at the present time since we do not know precisely the geometrical elements of the system.

c) Transfer of Matter

No direct observational data are as yet available on the stream of matter flowing from the cooler star. The results of numerical computations (Kopal 1956; Gould 1959; Plavec, Sehnal, and Mikulas 1964; Kruszewski 1964) indicate that matter flowing from the cooler component at the Roche limit streams toward the following hemisphere of the hotter component and may form a rotating ring or disk around it. The observational data for U Gem that support the picture of such flow are: existence of the ring, from the double emission lines and the ultraviolet excess during totality; and the fact that its brighter part lies in the vicinity of the Lagrangian point L_1 and along the following hemisphere of the hotter star, from changes in the V/R ratio and the shape of ingress. The dependence of the $U - B$ color upon time elapsed since maximum would indicate that the outflow of this matter is largest during eruption. The transfer of matter obviously changes the orbital period, and, by watching the period during the next few years, we should get much information about the amount of mass transferred.

d) The Eruption of U Geminorum

The brightness of the eclipsed object (i.e., the hotter star plus part of the ring) can be determined from the eclipse depth. From the observational data (§ IV*b*) it follows that the total brightness of the eclipsed object during eruption is at the most 5 times that at minimum. Even on the assumption that during eruption the eclipse is no longer total, the brightness of the hot component with the whole ring cannot exceed their minimum brightness by a factor of more than 10. But during eruption we observe a 100-fold increase in the brightness of the system. The increase in the brightness of the hotter star and ring may be responsible for 10 per cent of the total brightness of the system during eruption. The remaining 90 per cent must be attributed to brightening of the red component. Consequently, *the red star must be the seat of the observed eruptions in U Gem.*

At maximum the temperature of the system is $T = 15000°$ K. This is approximately the temperature of the eclipsing star during eruption. In minimum light its spectrum is not visible, and therefore its brightness is then a small fraction of the total brightness of the system. Consequently during eruption its brightness must increase more than 100-fold. Neglecting the bolometric corrections, we get

$$\frac{L_2(\max)}{L_2(\min)} = \frac{r_2^2(\max)}{r_2^2(\min)} \cdot \frac{T_2^4(\max)}{T_2^4(\min)} > 100 . \qquad (2)$$

Since $r_2(\max) \approx 1.4\, r_2(\min)$ and $T_2(\max) \approx 15000°$ K, we obtain $T_2(\min) < 5600°$ K; this temperature corresponds to a spectral type later than G5. In other dwarf novae with two spectra visible, the cooler star is of a spectral type between G5 and K0 (Paper I). Therefore our result for U Gem is not in contradiction with data for other dwarf novae.

The eruption of U Gem is thus the result of a large rise in the surface temperature of the red component and a relatively small increase in its dimensions. It may be supposed that at the beginning of eruption, matter from the outer layers of the cooler star begins to flow out rapidly through the vicinity of the Lagrangian point L_1 to the lobe around the blue component as the result of the increase in the radius of the cooler star. Such outflow should explain the fact that during eruptions the brightness of the eclipsed object (hot star plus ring) is observed to increase several fold. As a consequence of such outflow the deeper and hotter layers of the red component become exposed, thus causing the observed large increase in the surface temperature. Theoretical arguments indicating the possibility of such a process have been given by Paczynski (1965). After eruption the effective radius of the cooler star diminishes along with the slow contraction of its atmosphere.

VI. CONCLUSIONS

Spectroscopic work by Joy and Kraft has shown that U Gem–type stars are binaries. It has been the general opinion (cf. Zuckermann 1961; Kraft 1963) that the small, hotter components of the dwarf nova systems were the seat of the semiperiodic eruptions. U Gem, the prototype of the dwarf novae, since it is an eclipsing binary itself, poses a very favorable situation for determining on the basis of observations during an outburst which of the two components of this double system produces the eruptions. Discussion of its photometric observations (§ V) has shown that the seat of the eruptions is the cooler component which is at the Roche limit. The anomalous light-curve (shoulder, deformed eclipse) can be qualitatively explained on the assumption of loss of matter by the cooler component. The matter streams toward the following hemisphere of the hotter star; this stream is very likely the cause of the brighter part of the ring and of the hot spot on the hotter star. Part of this matter does not fall on the blue star but forms a quasi-stationary ring around it. This picture is in good agreement with the results of computations for the trajectories taken by particles of gas flowing out in the vicinity of the Lagrangian point L_1. Paczynski has shown that the process of matter flowing out from a star filling its Roche limit may be unstable on the pulsational time scale if this star has an envelope in convective equilibrium. This instability may explain the observed eruptions of dwarf novae. Convective envelopes may be expected to exist in the red components of these systems owing to their low surface temperatures, since the spectral types are G5–K0.

TABLE 6

ELEMENTS OF U GEMINORUM

$$\mathfrak{M}_1 = 1.2\,\mathfrak{M}_\odot$$
$$\mathfrak{M}_2 = 1.3\,\mathfrak{M}_\odot$$
$$r_1 = 1.8 \times 10^9 \text{ cm} = 0.026\, R_\odot$$
$$r_2 = 4.8 \times 10^{10} \text{ cm} = 0.69\, R_\odot$$
$$k = r_1/r_2 = 0.04$$
$$a = 12.4 \times 10^{10} \text{ cm}$$

It is premature on the basis of the observational data for U Gem alone to generalize these conclusions about the character of the eruption to the whole class of dwarf novae. The existing observational data for other U Gem-type stars (Zuckermann 1961), however, are not in contradiction with the view that in these systems the red star is the seat of the eruptions observed.

The dimensions of U Geminorum, on the assumption of a mass ratio of $\mathfrak{M}_1/\mathfrak{M}_2 = 0.9$ and orbital inclination of $i = 80°$, are given in Table 6.

This work has been made possible by the suggestions and co-operation of a number of persons. Most of all, thanks go to Dr. R. P. Kraft for suggesting the photometric observations of U Gem and for taking a lively interest in the work, and to Dr. B. Paczynski for permitting me to use his observations of U Gem and for his generous advice and much valuable discussion. Thanks are due to Dr. G. H. Herbig, Dr. A. Kruszewski, Mrs. Margaret W. Mayall, Dr. G. S. Mumford, Professor S. L. Piotrowski, and Dr. J. Smak for many helpful comments or for providing me with their unpublished results.

REFERENCES

Brun, A., and Petit, M. 1959, *Peremennye Zvezdy*, **12**, 18.
Chandrasekhar, S. 1939, *An Introduction to the Study of Stellar Structure* (Chicago: University of Chicago Press).
Chuvayev, K K. 1962, *Bull. Crimean Astr. Obs.*, **28**, 141.
Clarke, D. 1964, *Observatory*, **84**, 28.
Gould, N. L. 1959, *A.J.*, **64**, 136.
Grant, G., and Abt, H. A. 1959, *Ap. J.*, **129**, 323.
Greenstein, J. L., and Kraft, R. P. 1959, *Ap. J.*, **130**, 99.
Hall, J. S. 1958, *Pub. U.S. Naval Obs.*, Vol. **17**, Part VI.
Hamada, T., and Salpeter, E. E. 1961, *Ap. J.*, **134**, 683.
Herbig, G. H. 1960, *Ap. J.*, **132**, 76.
Huang, S.-S , and Struve, O. 1956, *A.J.*, **61**, 300.
Kopal, Z. 1956, *Ann d'ap.*, **19**, 298.
Kraft, R. P. 1956, *Carnegie Institution Yearbook* (Washington, D.C : Carnegie Institution of Washington), p. 56.
———. 1959, *Ap. J.*, **130**, 110.
———. 1962, *ibid.*, **135**, 408.
———. 1963, *Advances in Astronomy and Astrophysics*, ed. Z. Kopal (New York: Academic Press), **2**, p. 43.
———. 1964, *Ap. J.*, **139**, 457.
Kruszewski, A. 1964, *Acta Astr.*, **14**, 231.
Krzeminski, W. 1964, *A J.*, **69**, 549.
———. 1965, *Acta Astr.* (in preparation).
Matthews, T. A., and Sandage, A. R. 1963, *Ap. J.*, **138**, 30.
Mayall, M. W. 1964, private communication.
Mumford, G. S 1963, *Sky and Tel.*, **26**, 190.
———. 1964, *Ap. J.*, **139**, 476.
Paczynski, B. 1963, *Pub. A.S.P.*, **75**, 278.
———. 1965, *Acta Astr.* (in press).
Plavec, M. 1964, *Bull. Astr. Insts. Czech* , **15**, 165.
Plavec, M., Sehnal, L , and Mikulas, J. 1964, *Bull. Astr. Insts. Czech.*, **15**, 171.
Preston, G. W , and Paczynski, B. 1964, *Ap. J.*, **140**, 181.
Roach, F. E., and Wood, F. B. 1962, *Ann d'ap* , **15**, 21.
Thackeray, A. D., Wesselink, A. J., and Oosterhoff, P. Th. 1950, *B.A.N.*, **11**, 193.
Walker, M. F. 1963, *Ap. J.*, **137**, 485.
Zuckermann, M. C. 1961, *Ann. d'ap.*, **24**, 431.