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FIVE YEARS OF PHOTOMETRY OF σ GEMINORUM

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Abstract. Five years of photoelectric photometry of this bright K1 III RS CVn binary has been obtained at thirteen different observatories. Except for one year, the light curve has shown two minima, separated by roughly a half cycle. At the epoch of discovery (1977.2) one minimum was shallower but as of 1980.2 the two became comparable in depth. During the 1979–80 season the light curve changed shape rapidly, the shallower minimum becoming as deep as the other within about 80 days or perhaps less. Times of both minima can be fit with a photometric period of $19\overset{\mathrm{d}}{.}423$, which is 0.9% shorter than the $19\overset{\mathrm{d}}{.}603$ orbital period. The overall brightness range during the five years has been $4\overset{\mathrm{m}}{.}13 < V < 4\overset{\mathrm{m}}{.}29$.

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1. Introduction

In this paper we present five years of photoelectric photometry of this bright ($V = 4^{m}.2$) variable star, which is a long-period RS CVn binary according to the definition of Hall (1976). The variability was discovered by Hall *et al.* (1977) and the photometric period was found to be $19^{d}.46 \pm 0^{d}.02$ by Hall and Henry (1979).

σ Geminorum appears as SVS 100890 in the 1951 *Catalogue of Stars Suspected of Variability*. Specifically it is in the second half of that catalogue, which contains stars for which the authors considered the variability doubtful. We traced the original suspicion to Lau (1913) who, on the basis of visual estimates, suspected a variation around $0^{m}.5$ in amplitude. In that reference σ Gem was one of 79 stars suspected of varying with amplitudes between $0^{m}.3$ and $0^{m}.8$. In the years since then only a few have proven to be variable, and for those few there is no correlation at all between the amplitudes determined photoelectrically and the amplitudes suspected by Lau (Lovell *et al.*, 1978).

The only star visible in the spectrum has been classified K1 III. According to the (assumed circular) spectroscopic orbit of Luyten (1936), $P(\text{orb.}) = 19^{d}.605$, $K = 34.2 \pm 0.8$ km s^{-1}, and $T = 2418962.43 \pm 0^{d}.07$, where T is an instant when the primary star passed through the ascending node. Somewhat later Harper (1938) revised the orbital period to $19^{d}.603$. Several references to the Ca II H and K emission were given by Bidelman (1954) and more recently Young and Koniges (1977) found the emission's equivalent width to be 1.88 Å.

Spangler *et al.* (1977) looked for radio emission from σ Gem and considered it a 'possible detection'. X-ray emission has definitely been detected. Pye and McHardy (1980) observed X-ray flares with Ariel V; Walter *et al.* (1980) measured $L_x = 2.06 \pm 0.31 \times 10^{31}$ erg s^{-1} with HEAO I; and Walter and Bowyer (1981) measured $L_x = 2.04 \times 10^{31}$ erg s^{-1} with HEAO II.

2. Observations

Our five years of photoelectric photometry are summarized in Table I. All measures were made differentially with respect to a comparison star, corrected for extinction, and transformed to V and B of the UBV system. In the table, m is the number of nights on which σ Gem was observed and n is the total number of individual differential measured made. Eaton used υ Geminorum as his comparison star at Pennsylvania State and ρ Geminorum as his comparison star at Kitt Peak whereas all other observers used HR 2896. Magnitude differences between the different comparison stars are $V(\upsilon\,\text{Gem}) - V(\text{HR 2896}) = -1^{m}.270$ and $V(\rho\,\text{Gem}) - V(\text{HR 2896}) = -1^{m}.181$, both determined by Eaton. On nights when σ Gem was observed in V only, a mean value of the color index difference between variable and comparison was used in the data reduction. Those values of $\Delta(B - V)$ were $-0^{m}.37$, $+0^{m}.80$, and $+0^{m}.12$ for υ Gem, ρ Gem, and HR 2896, respectively. Additional details concerning the data in sets A, B, E, K are given by Vaucher (1979). The data in sets C and D were presented earlier by

TABLE I

Photoelectric photometry of σ Geminorum

Set	Year	Observer	Telescope	*V*		*B*	
				m	*n*	*m*	*n*
A	1976–77	Henry	Dyer 24-inch	7	18	1	3
B		Landis	Landis 8-inch	19	39	–	–
C	1977–78	Chambliss	Kitt Peak No. 4 16-inch	8	16	–	–
D		Chambliss	Kutztown 18-inch	11	22	–	–
E		Landis	Landis 8-inch	25	55	–	–
F	1978–79	Eaton	Penn State 24-inch	11	~30	–	–
G		Louth	Louth 11-inch	17	50	–	–
H		McFaul	Shenandoah 8-inch	2	4	–	–
I		Sabia	Keystone 9-inch	1	6	–	–
J		Skillman	Skillman 12.5-inch	3	10	–	–
K		Vaucher	Dyer 24-inch	11	33	11	33
L	1979–80	Chambliss	Kutztown 18-inch	2	4	–	–
M		Fried	Braeside 16-inch	3	9	–	–
N		Henry	Dyer 24-inch	3	9	3	9
O		Henry	Kitt Peak No. 4 16-inch	16	44	16	44
P		Louth	Louth 11-inch	7	21	–	–
Q		Renner	Scuppernong 10-inch	8	23	–	–
R		Sabia	Keystone 9-inch	1	3	–	–
S	1980–81	Eaton	Kitt Peak No. 4 16-inch	18	42	–	–
T		Henry	Dyer 24-inch	22	64	–	–
U		Henry	Kitt Peak No. 4 16-inch	4	12	–	–
V		Hopkins	Hopkins 8-inch	12	39	–	–
W		Krisciunas	Krisciunas 6-inch	5	16	–	–
X		Louth	Louth 11-inch	9	26	–	–
Y		Renner	Scuppernong 10-inch	7	22	–	–

Chambliss (1978) but we have re-reduced them with improved transformation coefficients.

The individual ΔV and ΔB magnitudes (or, in a few cases, nightly means) have been sent to the IAU Commission 27 Archive for Unpublished Observations of Variable Stars (Breger, 1982), where they are available as file No. 124. Nightly means of the ΔV magnitudes are plotted in Figure 1, all with Δ in the sense σ Gem minus HR 2896. Phase has been computed with the ephemeris

$$\mathrm{JD} = 2418\,967.331 + 19\overset{d}{.}603E, \qquad (1)$$

where the initial epoch is a time of conjunction with the K0 primary star behind, derived by adding a quarter cycle to the value of T given by Luyten (1936), and the period is the revised value of the orbital period given by Harper (1938).

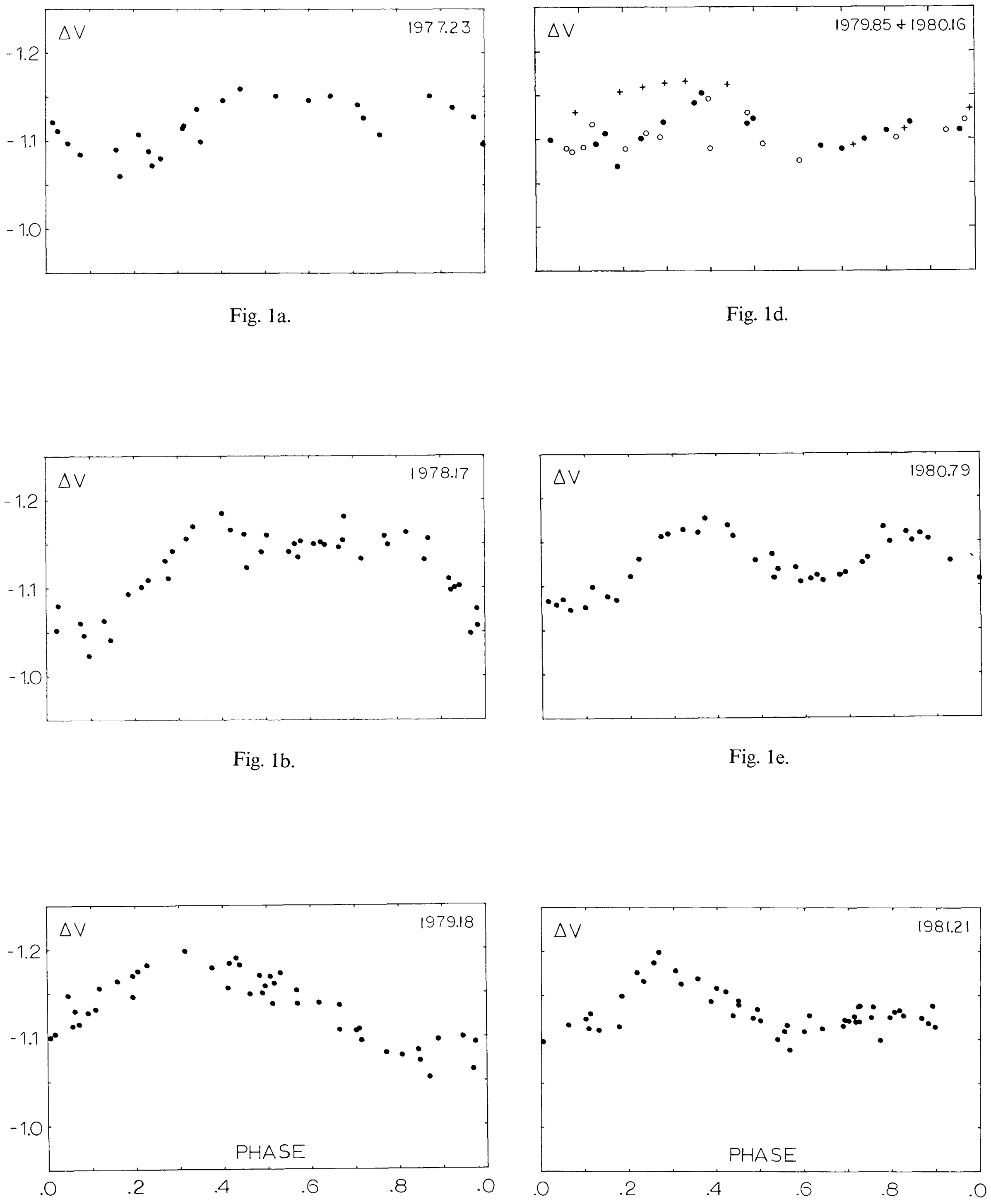

Fig. 1a.

Fig. 1d.

Fig. 1b.

Fig. 1e.

Fig. 1c.

Fig. 1f.

Fig. 1a–f. Six light curves of σ Geminorum, showing the changing shape from year to year. ΔV is differential magnitude in the sense variable minus HR 2896. Phase is computed with the ephemeris in Equation (1), which is based on the orbital period. In all but one light curve there were two minima, separated by roughly a half cycle, which have become comparable in depth. The one light curve plotted with three different symbols underwent significant changes on a time scale of months, as described in the text.

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3. The Unusual 1979–80 Light Curve

When all of the 1979–80 nightly mean ΔV magnitudes were plotted together versus phase computed with Equation (1), the light curve showed so much scatter that hardly any shape was recognizable. By examining three intervals of time separately, however, we could make some sense out of what apparently happened during the entire 204-day interval covered. Observations in the 56-day range JD 2444157.0 to 2444212.9 are plotted in Figure 1 as plusses; those in the 76-day range 2444237.7 to 2444313.6 are plotted as open circles; and those in the 46-day range 2444314.7 to 2444360.7 are plotted as filled circles after having been shifted down by $0\overset{m}{.}015$.

Points from the first group define a light curve with a shallow minimum around $0\overset{p}{.}09$ and a deeper (though less well-defined) minimum around $0\overset{p}{.}72$ or perhaps earlier. Points from the second and third groups blend with the first group in the right half of the figure, defining a minimum around $0\overset{p}{.}60$. In the left half of the figure, however, they all fall below, defining (with some scatter) a comparably deep minimum around $0\overset{p}{.}19$.

We cannot say anything specific about the $0\overset{m}{.}015$ shift between the second group and the third group, but do wish to emphasize how rapidly the deepening of the minimum around $0\overset{p}{.}1$ occurred. Comparing points from the first group with points from the second group at comparable phases, we see that the deepening had occurred within about 80 days (which is only four orbital cycles) and may have occurred sooner.

4. The Migration Curve

Figure 1 shows that in every light curve except 1979.18 there are two minima, which we designate A and B. Table II lists the phases of these minima, θ(min.), computed with

TABLE II

Minima in the light curve

JD (first/last)	Mean epoch	θ(min.)		ΔV	
		A	B	A	B
2443181.6 2443276.6	1977.23	$0\overset{p}{.}14$	$0\overset{p}{.}76$	$0\overset{m}{.}085$	$0\overset{m}{.}050$
2443508.7 2443631.6	1978.17	0.09	0.57	0.135	0.040
2443872.7 2444007.7	1979.18	0.89	none	0.125	0.000
2444157.0 2444212.9	1979.85	0.72	0.09	0.075	0.035
2444237.7 2444360.7	1980.16	0.60	0.19	0.075	0.065
2444499.0 2444554.9	1980.79	0.64	0.06	0.050	0.080
2444617.7 2444742.7	1981.21	0.57	0.00	0.070	0.075

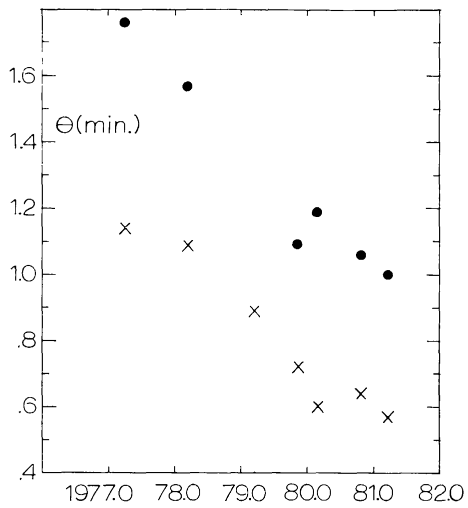

Fig. 2. θ(min.) is the phase of minimum light, computed with Equation (1) and tabulated in Table II. The crosses represent minimum A, the filled circles minimum B. Note that both have drifted towards decreasing orbital phase at a rate of ~ $0^{\mathrm{p}}.2$ per year while remaining separated from each other by ~ $0^{\mathrm{p}}.5$. This implies a photometric period of $19^{\mathrm{d}}.423$, shorter than the $19^{\mathrm{d}}.603$ orbital period by about 0.9%.

respect to the ephemeris in Equation (1), and the depths, measured from the highest maximum in each light curve. Figure 2, a plot of the θ(min.) values versus time, shows that both minima have migrated towards decreasing orbital phase at a rate of about $0^{\mathrm{p}}.2$ per year while remaining separated from each other by about $0^{\mathrm{p}}.5$. A least-squares solution refines these values to $0^{\mathrm{p}}.17$ per year and $0^{\mathrm{p}}.48$ separation.

The relative depths of the two minima are also of interest. Up through 1979.85, minimum B was always shallower than minimum A (or absent). Beginning with the 1980.16 light curve, however, the two became comparable in depth and have remained so.

The migration rate of $0^{\mathrm{p}}.17$ per year or 5.8 yr per cycle corresponds to a photometric period of $19^{\mathrm{d}}.423$, which is 0.9% shorter than the orbital period of $19^{\mathrm{d}}.603$. One could tentatively predict future times of minimum light with knowledge of the photometric period and a representative recent time of minimum light. Minimum B occurred on JD 2444686.5 and minimum A occurred $0^{\mathrm{p}}.48 = 9^{\mathrm{d}}.4$ before.

5. Discussion

The fourth edition of the *Yale Bright Stars Catalogue* gives $V = 5^{\mathrm{m}}.33$ for our comparison star HR 2896. Examination of Figure 1 then shows that σ Gem has varied over the $0^{\mathrm{m}}.16$ range $4^{\mathrm{m}}.13 < V < 4^{\mathrm{m}}.29$.

In the context of the starspot model which is commonly used to interpret light curves of RS CVn binaries, the existence of two minima separated by a half cycle is taken as evidence of two dark regions, on opposite sides of the spotted star. What makes σ Gem significant is the apparent stability of the situation. (Except for the apparent absence of minimum B in 1979.18.) We can say both regions have maintained their identity and the relative separation in stellar longitude for an interval of five years. Future photometry will be very valuable in showing how long this situation continues to persist.

Our observations of σ Gem are also important in showing how rapidly a starspot group can change in its size and/or brightness. In comparing the 1979.85 and 1980.16 light curves, we saw that the depth of minimum B almost doubled within 80 days or possibly less, while not moving appreciably in phase. A similar event, though not defined by as many points in the light curve, was seen in the RS CVn-binary SS Boo (Wilson *et al.*, 1983).

We conclude by pointing out that the K1 III star in σ Gem is rotating very nearly in synchronism with the orbital motion. In fact both the orbital period of $19^{d}.603$ and the photometric period of $19^{d}.423$ are determined with sufficient accuracy that the 0.9% difference between the two (rotation slightly faster than synchronism) is well established.

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