Letter to the Editor

The eclipsing cataclysmic variable GS Pavonis: Evidence for disk radius changes[⋆]

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Abstract. We have obtained differential time series photometry of the cataclysmic variable GS Pavonis over a timespan of 2 years. These show that this system is deeply eclipsing ($\sim$2–3.5 mag) with an orbital period of 3.72 hr. The eclipse depth and out-of-eclipse light levels are correlated. From this correlation we deduce that the disk radius is changing and that the eclipses in the low state are total. The derived distance to GS Pav is 790 ± 90 pc, with a height above the galactic plane of 420 ± 60 pc. We classify GS Pav as a novalike system.

Key words: Binaries:eclipsing – stars: GS Pav – cataclysmic variables

1. Introduction

Eclipsing non-magnetic Cataclysmic Variables (CVs) (for a review see Warner 1995, hereafter W95) are of particular interest not only because the masses of both stars can be determined, but especially because studying their eclipses, e.g., by the eclipse mapping method (Horne 1985), gives the opportunity to learn more about the physics of accretion disks. In this *Letter* we report that GS Pav is an eclipsing CV, that shows substantial disk radius changes.

GS Pav was first discovered by Hoffmeister (1963) who denoted it as star S7040 and gave the comment 'raschwechselnd' (rapidly varying). It was classified as a dwarf nova type CV in the GCVS and in the catalogue of Downes, Webbink and Shara (1997), who also give a finding chart for the object. It was selected for our observations as a possible member of the halo population (Augusteijn, 1994). Zwitter and Munari (1995) show that it has a normal CV spectrum. We determined its location at RA= $20^{\rm h}08^{\rm m}07\overset{\rm s}{.}58$, Dec=$-69°48'58''.1$ (J2000), almost identical to that of Downes, Webbink and Shara (1997).

Table 1. Log of V-band observations of GS Pav.

Date	Start UT	Integr. Time (s)	No. Obs.
Sept 5, 1993	$01^{\rm h}50^{\rm m}$	120	82
Sept 6, 1993	$23^{\rm h}21^{\rm m}$	120	66
Sept 7, 1993	$23^{\rm h}11^{\rm m}$	120	48
Sept 8, 1993	$03^{\rm h}57^{\rm m}$	120	25
March 22, 1995	$08^{\rm h}06^{\rm m}$	240	25
March 23, 1995	$07^{\rm h}15^{\rm m}$	240	30
June 13, 1995	$03^{\rm h}20^{\rm m}$	240	61
July 11, 1995	$05^{\rm h}40^{\rm m}$	240	65
July 25, 1995	$04^{\rm h}23^{\rm m}$	120	24
Aug 16, 1995	$04^{\rm h}52^{\rm m}$	120	54
Sept 15, 1995	$03^{\rm h}23^{\rm m}$	240	21
Sept 19, 1995	$02^{\rm h}50^{\rm m}$	240	20

2. Observations

Photometric observations were obtained with the Dutch 0.9m telescope at ESO La Silla, Chile. A log of the observations is given in Table 1. All observations were made with a 512x512 TEK CCD detector, using a Bessel *V* filter. Standard flatfielding and debiasing were applied to all observations. A photometric calibration was obtained on September 6, 1993 using the standard star EG 21 (Landolt 1992). Table 2 gives the coordinates and magnitudes of the reference stars we have used.

3. Photometric ephemeris

Arrival times of mid-eclipse were determined by fitting a Gaussian profile to the eclipses, and by determining the mid-point between the points of steepest ascent and descent. The final arrival times listed in Table 3 were taken as the average of the results from these two methods. We estimate the accuracy of these arrival times to be $5\cdot10^{-4}$ days, which corresponds to the typical difference between the results from the two methods.

Table 2. Reference stars used for the differential photometry of GS Pav.

No.	Name	RA (J2000)	Dec (J2000)	V[a]
1	GAB J200816–6949	$20^h08^m16\overset{s}{.}47$	$-69°49'36\overset{''}{.}0$	17.31(4)
2	GAB J200810–6949	$20^h08^m10\overset{s}{.}49$	$-69°49'34\overset{''}{.}0$	17.41(4)
3	GAB J200804–6949	$20^h08^m04\overset{s}{.}83$	$-69°49'40\overset{''}{.}4$	17.42(4)
4	GAB J200755–6949	$20^h07^m55\overset{s}{.}45$	$-69°49'14\overset{''}{.}4$	17.09(4)
5	GAB J200802–6948	$20^h08^m02\overset{s}{.}49$	$-69°48'57\overset{''}{.}6$	18.54(7)
6	GAB J200800–6948	$20^h08^m00\overset{s}{.}64$	$-69°48'49\overset{''}{.}5$	16.33(3)
7	GAB J200757–6948	$20^h07^m57\overset{s}{.}63$	$-69°48'19\overset{''}{.}6$	17.87(5)
8	GAB J200810–6947	$20^h08^m10\overset{s}{.}41$	$-69°47'55\overset{''}{.}4$	15.45(2)

[a] The quoted errors reflect the internal errors in the brightness measurements of the stars which do not include a 0.1 mag uncertainty in the transformation to standard magnitudes.

Table 3. Times of arrival, deduced cycle numbers and the observed minus computed (O–C) residuals for the observations of GS Pav

Cycle No.	$HJD_{min}-244\,0000$	O–C (days)
–3062	9235.7370	$-0.70 \cdot 10^{-3}$
–3050	9237.6014	$0.46 \cdot 10^{-3}$
–3044	9238.5330	$0.44 \cdot 10^{-3}$
–3043	9238.6876	$-0.23 \cdot 10^{-3}$
565	9798.9010	$-0.32 \cdot 10^{-3}$
571	9799.8340	$1.05 \cdot 10^{-3}$
1098	9881.6603	$0.16 \cdot 10^{-3}$
1099	9881.8147	$-0.71 \cdot 10^{-3}$
1279	9909.7641	$0.13 \cdot 10^{-3}$
1280	9909.9191	$-0.14 \cdot 10^{-3}$
1369	9923.7376	$-0.66 \cdot 10^{-3}$
1511	9945.7857	$-0.87 \cdot 10^{-3}$
1704	9975.7542	$0.56 \cdot 10^{-3}$
1729	9979.6362	$0.82 \cdot 10^{-3}$

A linear fit to the arrival times listed in Table 3 yields the following ephemeris:

$$HJD_{min} = 244\,9711.17388(17) + 0.155269817(87) \cdot N, \quad (1)$$

with N the cycle number. The error estimates for the parameters are scaled to give a $\chi^2_{red} = 1.0$. The rms value of the arrival times around the fit is $6.4 \cdot 10^{-4}$ days, which is in reasonable agreement with our error estimate.

4. Mass ratio, width of the eclipse and inclination

If the secondary follows the lower main-sequence standard mass-period relation (W95):

$$M_2 = 0.065\, P_{orb}^{5/4}(h) \quad 1.3 \leq P_{orb}(h) \leq 9, \quad (2)$$

with M_2 the mass of the secondary, M_2 is $\sim 0.34\,M_\odot$. Since the mass ratio, $q = M_2/M_1$, has to be smaller than 2/3 for stable mass transfer (W95) and the mass of the primary can at most be the Chandrasekhar mass (1.4 $M_\odot$), the mass ratio is limited to the range $0.67 \geq q \geq 0.24$.

Fig. 1 shows the phase folded eclipse light curves for the 12 epochs listed in Table 1. The light curves of June 13 and July 11, 1995 contain two eclipses each.

The width of the eclipse ($\Delta\varphi$) can be estimated by the phases of steepest descent and ascent. For GS Pav we measure a mean $\Delta\varphi = 0.064 \pm 0.005$, where the error is the scatter on the average of all measurements. From this value and the range in mass ratio's we deduce (Horne 1985) a range in orbital inclination of $74° < i < 83°$.

5. Correlation between eclipse depth and out-of-eclipse light

Fig. 1 shows that GS Pav does not have a constant out-of-eclipse magnitude. In our observations the source varied between V$\sim$14.9 and V$\sim$17.1, being mostly at the bright end. Also the eclipse depth is not constant. We have investigated if these two variations are correlated. Since the eclipses are well represented by Gaussian functions, we have taken the zero-level and depth of the Gaussians, used to determine the times of mid-eclipse, as estimates of the depth in magnitudes of mid-eclipse (Δm) and the out-of-eclipse light level (m_V) (Fig. 2). The numbers in Fig. 2 refer to the eclipses as shown in Fig. 1.

In the following we will make a distinction between the observed radius of the accretion disk, which is the size we infer from our observations, and the physical radius of the accretion disk. The difference between these two is determined by the fractions of the optically thick and thin parts of the accretion disk and the brightness distribution across the disk which determines what parts are visible in the chosen passband (here in the V-band). A changing brightness distribution can mimic a change in the physical disk radius, when observed in only one band.

In Fig. 2 the straight line labeled 'Line of Totality' shows what the correlation between Δm and m_V looks like for a system in which the eclipse is total. A total eclipse means that the observed size of the accretion disk is smaller than the size of the secondary and that at mid-eclipse the amount of observed light from the disk is negligible. In a total eclipse the mid-eclipse light level will be constant and equal to the brightness of the secondary. Every magnitude of brightening of the disk will cause a magnitude of deepening of the eclipse: the system will follow a straight line, with an angle of 45°, in the Δm-m_V diagram. The position of this line in the diagram will be different for each individual system, but can be fixed by determining the brightness of the secondary. If at any time during our observation GS Pas was totally eclipsing, then its mid-eclipse light level will be the brightness of the secondary. The minimum level occured on June 13 and July 11, 1995: $V = 19.9 \pm 0.1$. We use this point to fix the position of the 'Line of Totality' in Fig. 2. We see that points '7' and '8' (which are from June 13 and July 11, 1995) lie on this line. From the fact that the eclipse depths in point '7' and '8' are different, but the brightness at mid-eclipse, we conclude that at these epochs the eclipse is indeed total. It follows that the observed minimum of $V = 19.9 \pm 0.1$ is the brightness of the secondary. The lack of a flat-bottom in the light curves of point '7' and '8' shows that the eclipse is only just total, although the
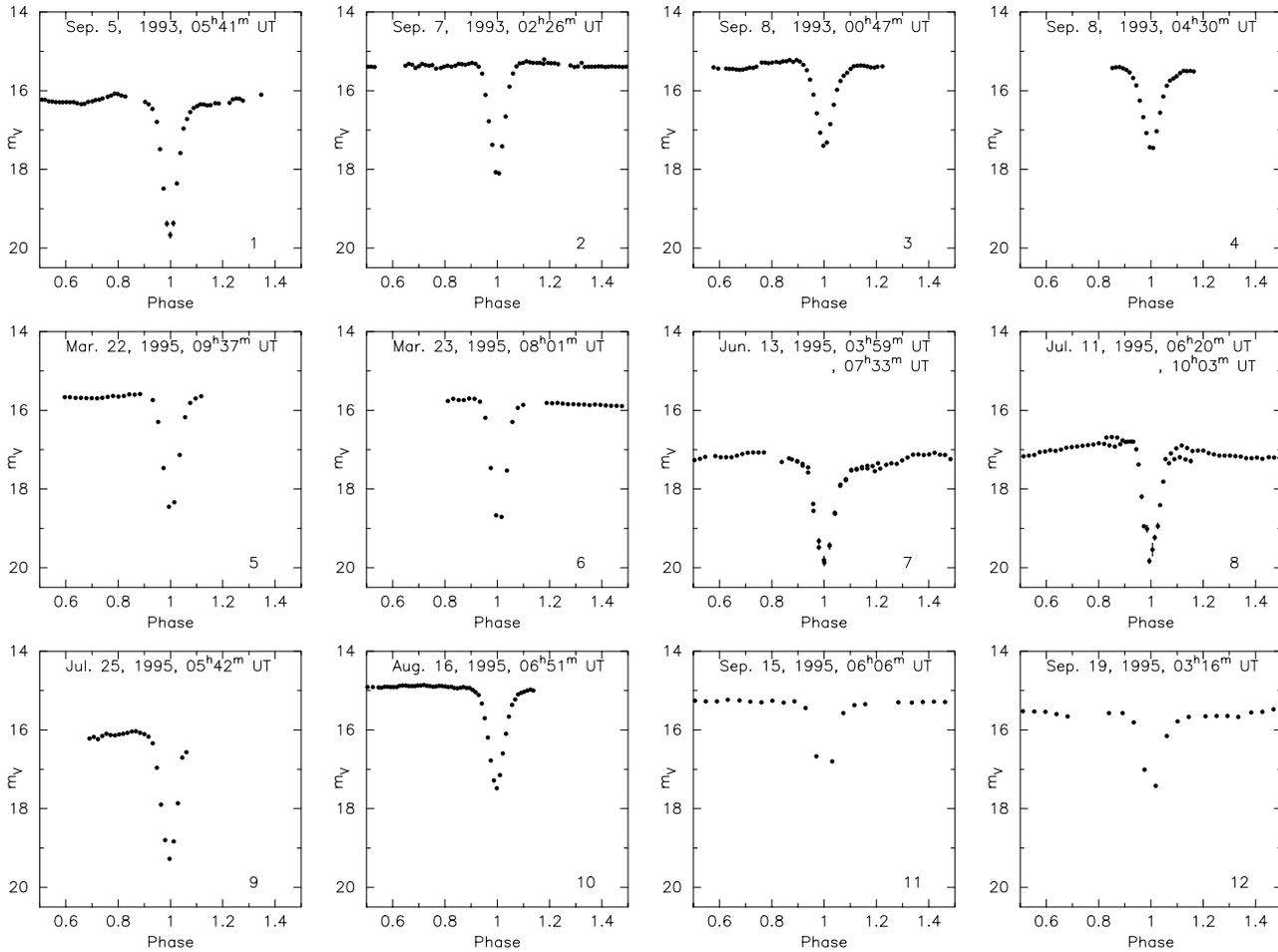
Fig. 1. The phasefolded V-band eclipse light curves for the 12 epochs. The heliocentric corrected time of mid-eclipse of the observations is given in UT.

integration time of 4 minutes may be too long to resolve a flat bottom.

If we now look at the other points in Fig. 2 we see that they do not fall on the 'Line of Totality'. With increasing out-of-eclipse light levels, the depth of the eclipse does not increase anymore (as it would have on the Line of Totality), but decreases. Apparently, between point '7' and '1' on the track the observed size of the disk increases to the extent that the eclipse is no longer total, but that part of the accretion disk remains visible in mid-eclipse. With a further increase of the observed accretion disk radius, more and more of the disk is visible at mid-eclipse and the eclipse becomes less and less deep. This behaviour was first found by Walker (1963) in his study of RW Tri, which shows no total eclipses, but does move back and forth on this part of the track. We have therefore labeled this the 'Walker Branch'. Another transition, which to our knowledge has never been noted before, is the one that happens near point '10' in Fig. 2. The out-of-eclipse light level reaches a maximum, after which it declines again (the curve bends to the right), but the eclipse depth continues to decrease. We have labeled this part the 'Shallow Branch' because of its decreasing eclipse depth.

If the change in the observed radius is caused by a change in the physical size of the disk (rather than a change in the brightness distribution), then the manifestation of the Shallow Branch may be explained by the effect of self-eclipses. Because the height of the disk is correlated with its physical size (Frank, King and Raine 1985), self-eclipses of the hot, and therefore luminous inner parts of the concave disk by its outer parts, will occur when the physical size of the disk exceeds a critical value and therefore a critical height. The out-of-eclipse light level decreases because the more luminous parts of the accretion disk are self-eclipsed, and at the same time the eclipse depth can continue to decrease if the disk radius continues to increase. To eclipse the inner parts the disk flaring angle must be $(90-i)^\circ$ or higher. In our case this would mean a flaring angle of 7°–16°, similar to what has been found in other CVs (e.g. Robinson et al, 1995).

The variations appear to trace out a unique track over a substantial period of time. Changes from one part of the track to another can occur quite rapidly, e.g. the transition from point '1' to '4' took place within 4 days. We are currently modelling these changes in detail to constrain the geometry of the system and the changing disk (Groot et al., 1999).
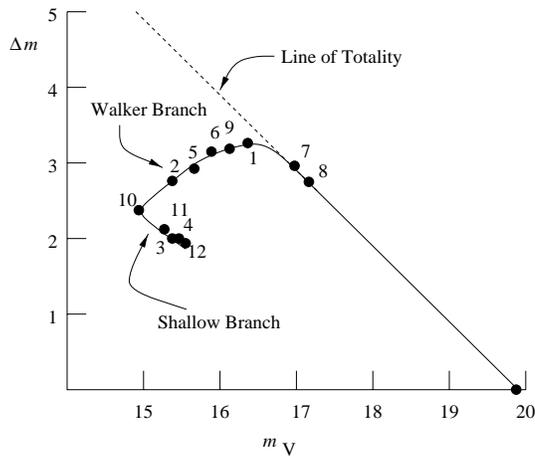
Fig. 2. The depth of the eclipse in GS Pav as function of the out-of-eclipse light. The numbers correspond to the eclipses in Fig. 1.

6. Distance to the system

With the orbital period of 3.72 hr we can use the $M_V - P_{orb}$ relation of W95 to derive a $M_V = 10.4$ with an estimated error of 0.2 magnitudes for the secondary (from Fig. 2.46 in W95). Combined with the apparent magnitude of $V=19.9\pm0.1$, this gives a distance to GS Pav of 790 ± 90pc. Given its position on the sky, the implied height above the galactic plane is 420 ± 60 pc. From the distance we can deduce the absolute magnitude of the system out of eclipse, which is dominated by the accretion disk. To obtain an absolute magnitude of the accretion disk, we correct for the inclination of the disk, according to Eq. 2.63 of W95. This correction varies from 1.0 mag (for $i=74°$) to 2.1 mag (for $i=83°$). The absolute magnitude (M_V) lies therefore between $6.6 \geq M_V \geq 4.4$ (for $i=74°$) and $5.5 \geq M_V \geq 3.3$ (for i=83°). Comparison with the mean absolute magnitudes for NLs and DNe (Fig. 4.16 and 3.9 from W95) shows that the derived range is in the normal regime for NLs, but too bright for DN in quiescence.

7. Classification as a novalike system

From the shape of the light curve and its absolute magnitude, we conclude that GS Pav is a novalike system, and considering its emission line spectrum (Zwitter and Munari, 1995), that it is of the RW Tri subclass, which is defined as having emission line spectra (W95). According to the definition in W95 of the VY Scl subclass, as NL systems having low states in their long term light curves, and showing no DN outbursts during these low states, we should also classify it as a VY Scl star. This is supported by its orbital period, since almost all known VY Scl stars have periods between 3 and 4 hrs. However, the physical interpretation

as outlined in W95 may not apply to GS Pav. In this description a VY Scl system in its low state has a mass-transfer rate $\dot{M}$, that is lower than the critical rate, $\dot{M}_{crit}$, below which DN outbursts are expected to occur, but it does not show these outbursts. This distinguishes VY Scl systems from Z Cam systems, that do show these outbursts in their low state. In our observations GS Pav at all times seems to have an absolute magnitude which was brighter or equal than that of Z Cam systems during standstill, where $\dot{M}$ is thought to be larger than $\dot{M}_{crit}$. We therefore cannot conclude if GS Pav is a VY Scl system or not. However, it could be that all NL systems with periods between 3 and 4 hours turn out to have low and high states if sufficiently long observed (W95).

An interesting example of a system that may be analogous to GS Pav is VZ Scl for which O'Donoghue, Fairall and Warner (1987) concluded that the size of the accretion disk has changed from one observation to the other. Unfortunately they only observed two eclipses. Since this system, in the low state, is also totally eclipsing, a comparison with GS Pav would be of interest.

8. Conclusions

We have shown that GS Pav is a deeply eclipsing cataclysmic variable with a 3.72 hr period. Based on its photometric behaviour, orbital period and absolute magnitude we classify the system as a novalike variable. The depth of the eclipse and the brightness of the system out-of-eclipse are correlated. From this relation we infer that the disk radius changes and that in two of our observations the eclipse is total. Therefore, the apparent visual magnitude of the secondary is $V=19.9\pm0.1$, giving a distance to the system of 790 ± 90 pc.

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