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High speed photometry of PG 1012–029

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Abstract. High speed optical photometric observations of PG 1012 – 029, conducted during 1990–1991, confirm the nova-like classification of the object. Several eclipses observed by us have been used to refine the orbital period of the system. Variations in the light curves and in particular, the presence of a bright hot spot in our 1991 data are highlighted. We also deduce a maximum mass transfer rate of 1.5 $10^{-8} M_{\odot}$ yr^{-1} for the system.

Key words: stars: novae, cataclysmic variables – stars: binaries, eclipsing – stars: individual: PG 1012 – 029

1. Introduction

Cataclysmic variables are close binary systems in which a Roche lobe-filling late-type star (usually referred to as the secondary) transfers matter to a white dwarf (primary) star. The transferred gas forms an accretion disc around the primary in systems where the magnetic field of the white dwarf is not strong enough to disrupt the disc and to channel the accreted matter directly on to the white dwarf. In many systems, a bright hot spot is formed on the disc where the freshly accreted material impacts the gas already circling the white dwarf in Keplerian orbits. Conservation of angular momentum ensures that the hot spot on the disc leads the line of centers between the stars.

Optical and UV luminosities of CVs are often dominated by the radiations from the disc and the hot spot. Eclipses of the disc and the hot spot can therefore provide vital diagnostic information on their sizes and spatial structure (Horne 1983). Eclipse analysis, in association with a measurement of radial velocities of the two stars can be used to derive the masses of the stars, the dimensions of the system and the orbital inclination. In addition random light flickering that is a characteristic of most CVs is generally assumed to originate from the hot spot. Patterson (1981) and Horne (1983) have however shown that the flickerings in several CVs do arise from extended regions such as the inner and the outer disks. "Eclipsing" CVs therefore offer an additional opportunity to probe the origin and location of flickerings. Hence photometric and spectroscopic observations of these objects have attracted considerable attention in recent years.

PG 1012 – 029 (SW Sex) is a nova-like eclipsing cataclysmic variable, discovered by Green et al. (1982) during the Palomar Green survey for the detection of UV excess objects. It belongs to a select group of 26 eclipsing CVs. Photometric, spectroscopic and spectrophotometric observations by Penning et al. (1984, hereafter referred to as PFMLG) and Honeycutt et al. (1986) have revealed many physical parameters of the system, including the masses of the two stars, their separation, radii and the inclination of the orbital plane. PG 1012 – 029 has an orbital period of 3 h 14 m 18.7 s. It exhibits round-bottomed eclipses that have depths of about 1.9 mag. Its spectrum reveals strong high-excitation emission lines at optical and UV wavelengths. PFMLG have concluded that the object is probably an old nova system observed in quiescence. They have provided evidence to show that the source of flickering is not confined to the hot spot alone, but is rather extended over the entire accretion disc.

Since PG 1012 – 029 is a relatively new eclipsing CV, extended photometric monitoring of the object would help refine many of the orbital and physical parameters of the system. Further, in order to check the effects of long term mass transfer in the system, we decided to redetermine its orbital period and look for any variations in it. We also decided to search for the presence of coherent short periods in the system. With this motivation, we conducted optical high speed photometric observations of the object during 1990–1991. Results from these observations are presented in this paper.

2. Observations

The observations were carried out with the ISRO two star photometer (Venkat Rao et al. 1990) attached to the Cassegrain focus of the 1 and 2.34 m telescopes at the Vainu Bappu Observatory, Kavalur. A 24″ diaphragm was

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Send offprint requests to: T.M.K. Marar used in the main channel and the second channel had a 10% smaller diaphragm. Offset guiding using an 8″ guide telescope was adopted at the 1 m telescope, while a CCD guiding unit at the Cassegrain focus was employed on the 2.34 m telescope. Sky measurements were taken approximately once an hour, but care was taken to see that they were not taken at strictly periodic intervals. Typical integration times were 5 s. Observations were made in white light (i.e. without any filter) in both channels.

Figure 1a, b shows the sky subtracted light curves of PG 1012 − 029 and a nearby field star respectively, measured with the 2.34 m telescope on 18 February 1991. The light curves look continuous because of an enormous compression of 5850 integrations, each of 5 s duration, on the time axis. Figure 1c represents the extinction corrected light curve of the star. The full night observation of PG 1012 − 029 on 18 February 1991 enabled us to detect three consecutive eclipses during the same run. This in turn allowed us to search for changes in eclipse patterns and periodic oscillations in the system.

In order to highlight the flickerings in the system, we show a small portion of the extinction corrected light curve in Fig. 1d. Here each point on the abscissa corresponds to an integration time of 5 s. Typical flickerings in the light curves have durations of 3–5 min and amplitudes around 5–10% (see e.g. in Fig. 1d the flicker at 18.50 h UT, with a signal to noise ratio of 12.1). S/N is calculated for the full amplitude of the flicker with respect to the corresponding nearest minimum count value. Large flickers with amplitudes around 15% and lasting for about 30 min can also be noticed (see e.g. in Fig. 1c the flicker at 20.70 h UT, with a signal to noise ratio of 19.1). These flickerings are characteristic of CVs. We wish

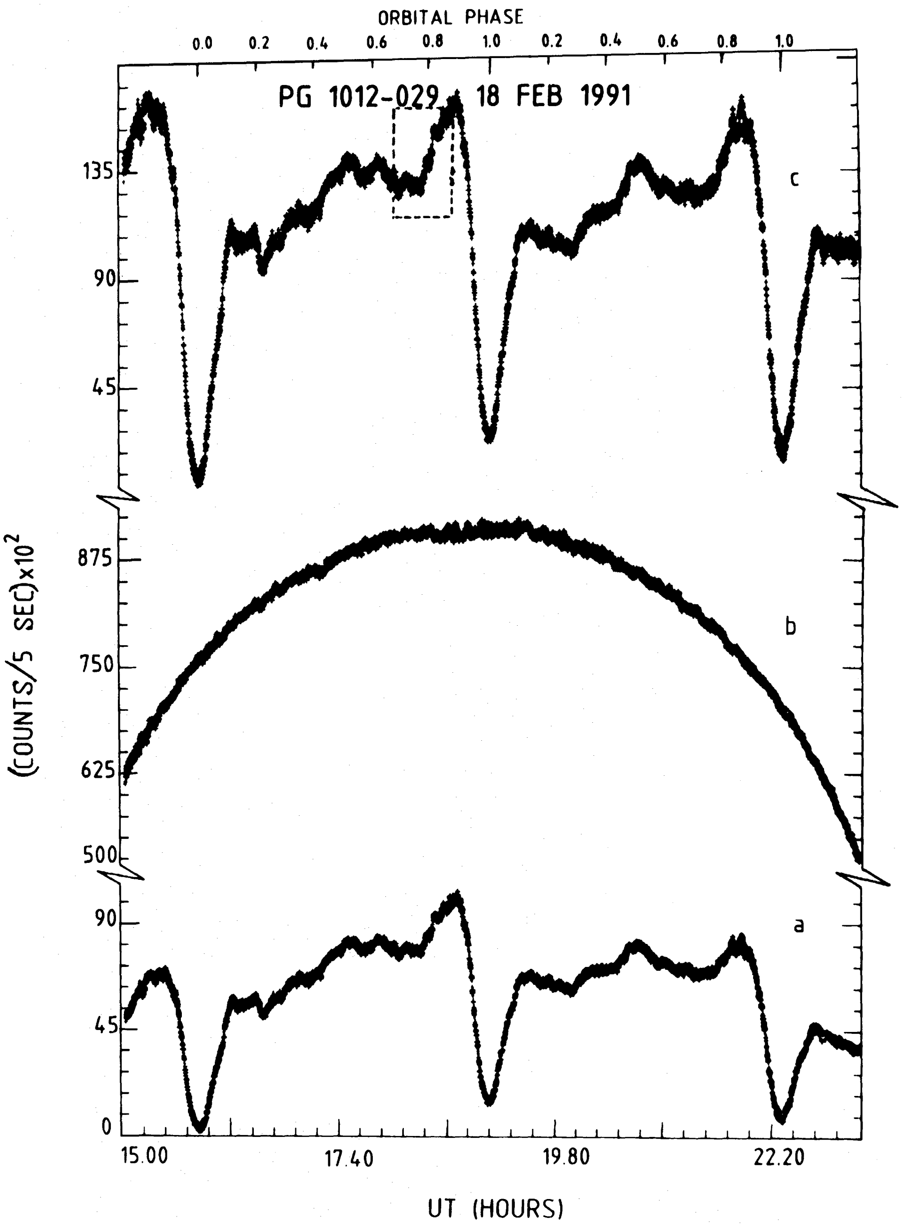

Fig. 1a–c. Sky-subtracted light curve of data recorded on 18 February 1991: **a** of PG 1012−029, **b** of a nearby field star, **c** extinction-corrected data of PG 1012−029

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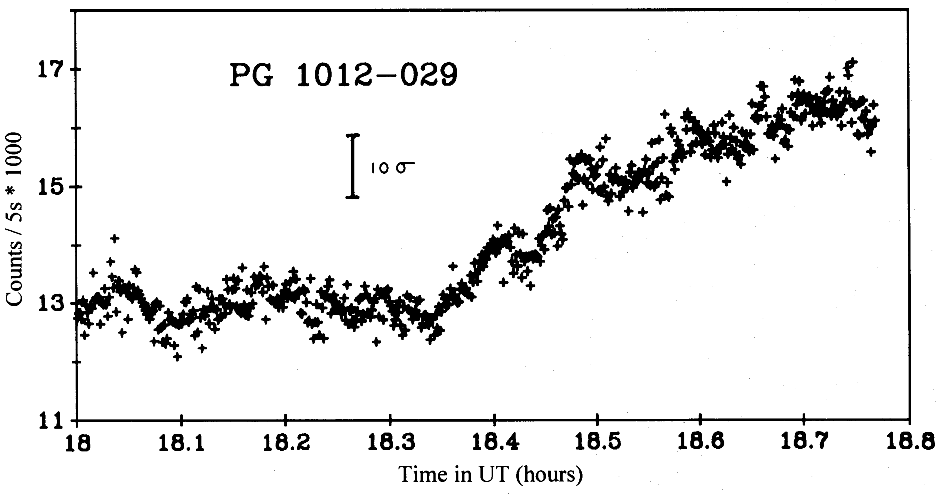

Fig. 1d. A portion of Fig. 1c (marked by a window) to highlight the flickers. One tenth of the vertical bar in the figure gives the uncertainty (± 1σ) in photon counting

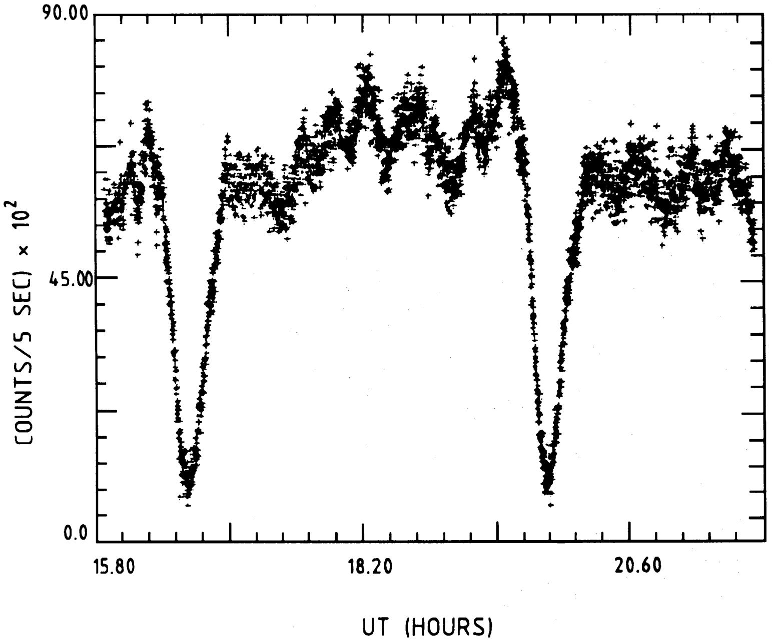

Fig. 1e. Sky-subtracted light curve of PG 1012−029 on 27 February 1990

to emphasize the fact that, even though small-scale ripples are seen in the second channel light curve (Fig. 1b), they have typically around 1% amplitude only and are caused mainly due to guiding errors and possibly by small transparency variations. The guiding errors will not get reflected into the first channel because the diameter of the second channel diaphragm was deliberately kept 10% smaller than that of the main channel, thereby allowing us to manually guide the telescope before the guiding errors show up in the main channel.

Our light curves have reasonable length and good resolution (5 s) that enable us to study the eclipse profiles in some detail. The different eclipse depths in Fig. 1c are caused by the poor signal to noise ratio at the minimum of the eclipses recorded at large hour angles. Figure 1e is the sky subtracted light curve of PG 1012 − 029, measured with the 1 m telescope on 27 February 1990. Table 1 gives a journal of the observations and Table 2 the timings of the eclipse minima. These times of minima were derived by fitting a second order polynomial to each of the minima in the light curves.

3. Results and discussion

Using the times of minima listed in Table 2 and the ephemeris quoted by PFMLG we derived the cycle number E for each of the minima. We then fitted the times of minima and the cycle no. with a linear fit,

$$T_{\rm min}({\rm HJD}) = T_0({\rm HJD}) + PE, \qquad (1)$$

and derived a T_0 and orbital period P as follows:

$$T_0({\rm HJD}) = 2444339.650833,$$

$$P = 0\overset{\rm d}{.}1349384331\,.$$

Table 1. Log of observations

Date	Telescope (m)	Integration time (s)	Data duration (h)	Remarks
29 January 1990	1.02	10	4.3	Two eclipses recorded
27 February 1990	1.02	5	5.8	Two eclipses recorded
18 February 1991	2.34	5	8.5	Three eclipses recorded

Table 2. Observed eclipse minima for PG 1012−029

Serial no.	HJD	Cycle	(O−C) (s)	Remarks
1	2444339.650873	0	2.5	Penning et al.
2	2444340.730546	8	16.9	Penning et al.
3	2444348.826485	68	−14.8	Penning et al.
4	2444631.927579	2166	+08.4	Penning et al.
5	2444676.861953	2499	−02.2	Penning et al.
6	2444721.796362	2832	−09.8	Penning et al.
7	2447921.321666	26543	+7.2	Present work
8	2447921.456334	26544	−16.1	Present work
9	2447950.198418	26757	+1.0	Present work
10	2447950.333208	26758	−11.8	Present work
11	2448306.166560	29395	+49.4	Present work
12	2448306.300999	29396	+6.6	Present work
13	2448306.435989	29397	+11.1	Present work

The (O − C) value for each eclipse minimum was calculated using the above values. These are also given in Table 2. Note that serial number 11 in Table 2 which is the time corresponding to the first eclipse of Fig. 1c has the maximum deviation of about 50 s. We attribute this deviation to the large hour angle of the star when this eclipse was recorded. Here the counting rate at the minimum was nearly the same as the sky value and the scatter in count rate was large. If we use this point also for deriving an ephemeris it would end up in assigning equal weightage to a point which we know has inherent noise. We therefore omit this point and recalculate the values of T_0 and P in Eq. (1) as follows:

$$T_0(\mathrm{HJD}) = 2444339.650843\,,$$

$$P = 0^{\mathrm{d}}\!.1349384297\,.$$

We then do a linear fit of the (O − C) values listed in Table 2 again, omitting serial no. 11 with the above T_0 and P values and derive corrections for T_0 and P and give the final ephemeris as follows:

$$T_{\min}(\mathrm{HJD}) = \underset{\pm 56}{2444339.650843} + \underset{\pm 29}{0^{\mathrm{d}}\!.1349384292}\,E\,.$$

Figure 2 gives the (O − C) values plotted as a function of the cycle number along with the final fit. The refined orbital period is therefore 3 h 14 m 18.68 s.

Our eclipse light curves are of particular interest since we have been able to record for the first time three consecutive eclipses during a single night, as shown in Fig. 1a, c. The duration of the eclipses, measured as the average full width at half depth is 19 min and the eclipse depths approach 1.9 mag. The eclipses exhibit round-bottomed minima and are asymmetric in shape. We have plotted in Fig. 3 the central eclipse of Fig. 1c separately. The flickerings are seen even during the eclipse, but are more prominently seen during the egress portion of the light curve, thereby indicating that the source of the flickerings is not localised to the hotspot.

In order to demonstrate that flickerings are seen even during the eclipses, we fitted the eclipse in Fig. 3 with a polynomial which is shown as a dashed line in the same figure. We then subtracted the fit from the eclipse light curve and the resultant subtracted curve is shown in Fig. 4. Also marked on Fig. 4 are two smooth lines which indicate ± 1σ variation on the polynomial fit, i.e. the square root of counts corresponding to the fit as a function of time. This figure illustrates clearly that there exist flickers during the eclipse well above the 1σ level. To demonstrate the efficacy

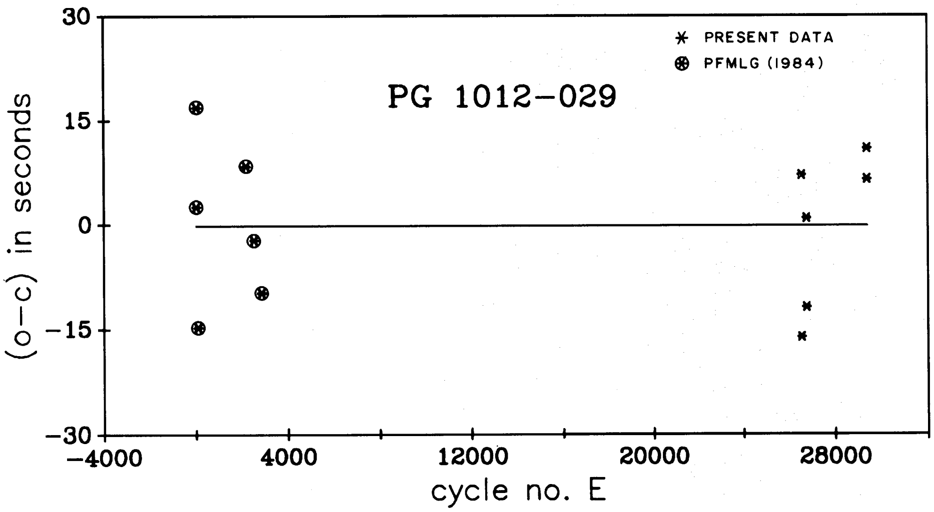

Fig. 2. (O – C) versus cycle no E for the eclipse minima

of this procedure we apply the same technique to a portion of the light curve having large flickers which are visually discernible. For this we choose the light curve from 18.40 h UT to 18.80 h UT (which is also shown in Fig. 1d). This portion of light curve fitted with a polynomial is shown in Fig. 5. We then subtracted the fit from the light curve and the residuals are plotted in Fig. 6 along with the $\pm 1\sigma$ boundaries of the fit. One can easily notice the flickers that stand out above the 1σ boundaries. We note here that because the fit corresponds to a mean level of the light curve the significance of flickers appears to be reduced as compared to what one would measure directly from the light curve. However this method clearly demonstrates the existence of flickers present especially in rapidly changing light levels as in the case of the eclipse and as is illustrated in Fig. 4.

For a comparison of the differences between eclipses, we show in Fig. 7 all our eclipse light curves aligned around their minima. One can notice that the asymmetry varies even between the consecutive eclipses recorded during a single night (see, for example, the bottom three curves in Fig. 7).

In Fig. 1c one notices prominent pre-eclipse humps and a significant difference in the pre- and post-eclipse light levels. We attribute this to the presence of an "enhanced" bright spot on the disc. It can be interpreted, following Nather & Robinson (1974), as due to a geometrical effect in which the hot spot, leading the line of centers between the two stars, is facing the observer more directly and hence contributes, in the present case, as much as 30% to the ambient light level. We also note that with respect to the eclipse minimum at 15.866 h UT as phase $\phi = 0.0$, there is a continuous increase in light from about 16.6 h UT corresponding to $\phi = 0.25$. If this rise is due to the hot spot contribution, it would indicate that the disc is either relatively optically thin or that a part of the hot spot is seen above (or below) the disc throughout the orbit, except during the eclipse. The enhanced rise starting at 18.60 h UT corresponding to $\phi = 0.85$ is only due to the hot spot being located directly in front of the viewer.

Although PFMLG did not detect in emission lines an S-wave behaviour which is typical of hot spots in CVs, they did notice a drop in continuum and line emission at $\phi = 0.06$ and a flicker where the continuum and emission line fluxes got enhanced significantly at $\phi = 0.95$. They have attributed these observations to the presence of a hot spot in the system. The existence of a faint hot spot can also be discerned in Fig. 1b of PFMLG where there is an increase of about 15% in light level from phase 0.46 to 0.50. But the hot spot contribution in their data is much less than what we see in Fig. 1c of the present paper. In order to highlight the differences between our light curves and those of PFMLG, separated in time by about 10 yr, we have depicted in Fig. 8 the average light curve of both groups, normalised in ordinate at the eclipse minimum (see also Fig. 8 of PFMLG). The hump contribution in our 1991 data can be seen to stand out prominently. Our data of 1990 (Fig. 1e) however do not show the hump prominently. This would indicate that this star does show variability of light from the hot spot over timescales of a year or so. The enhancement of the hot spot clearly seen in our 1991 data could have been produced by a flaring of the secondary star, resulting in an increased mass transfer or an instability in the accretion disk. Further observations are needed to see if the enhancement of the hot spot is a random or a periodic phenomenon in this system.

Our data and that of PFMLG are comparable however as far as other system parameters like eclipse duration, depth, etc. are concerned and there does not seem to exist any drastic change in the system. An average value of mass transfer rate $\dot{M}$ can be derived for this system using a limit of $\dot{P}$ from our (O – C) values. If we fit the (O – C) values with a polynomial of order 2, namely,

$$(\mathrm{O}-\mathrm{C}) = \alpha + \beta E + \gamma E^2 , \tag{2}$$

we get a second order coefficient $\gamma = 1.5\ 10^{-12}$, with an

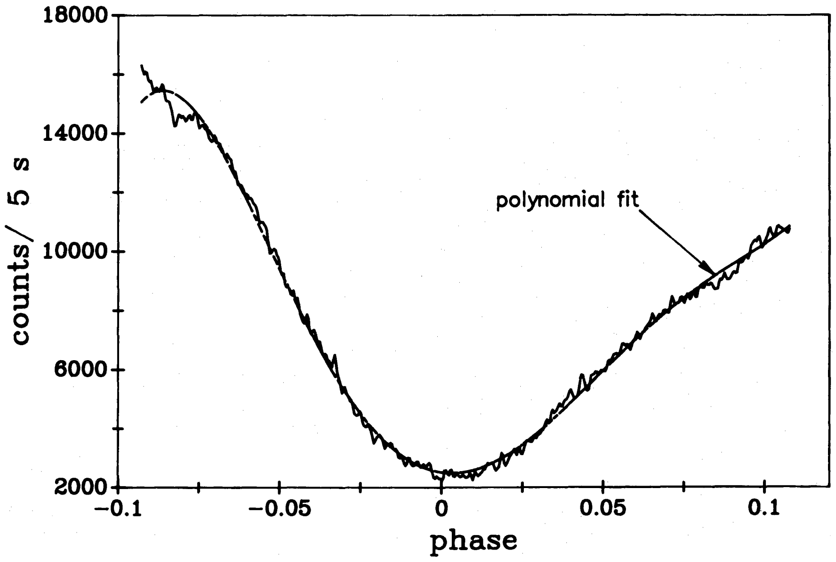

Fig. 3. The central eclipse of Fig. 1c with a polynomial fit shown as a dashed line

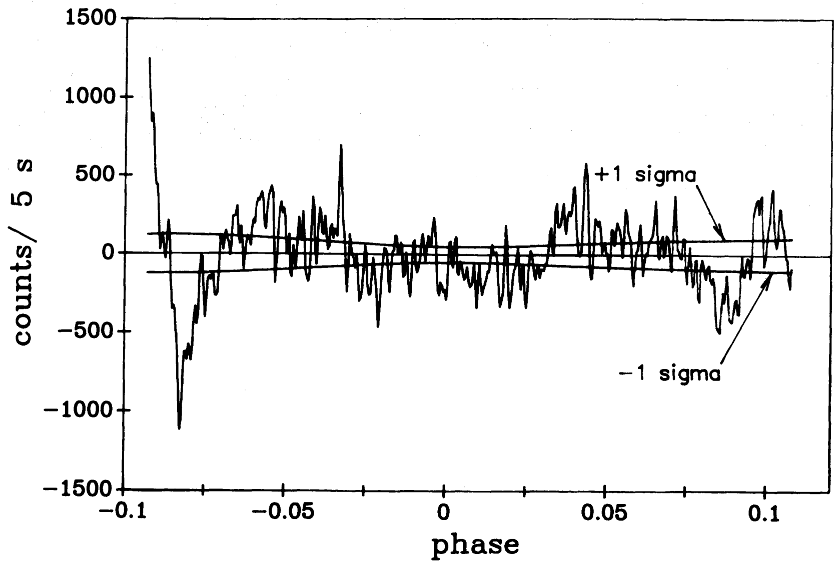

Fig. 4. Residuals between the eclipse light curve and the polynomial fit of Fig. 3. ± 1σ boundaries of the fit are also shown

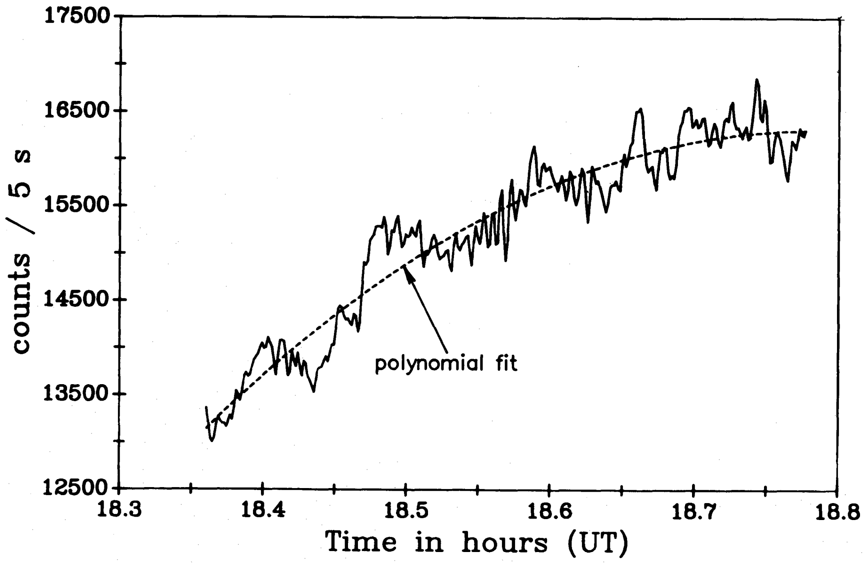

Fig. 5. A portion of the light curve showing easily discernible flickers along with a polynomial fit

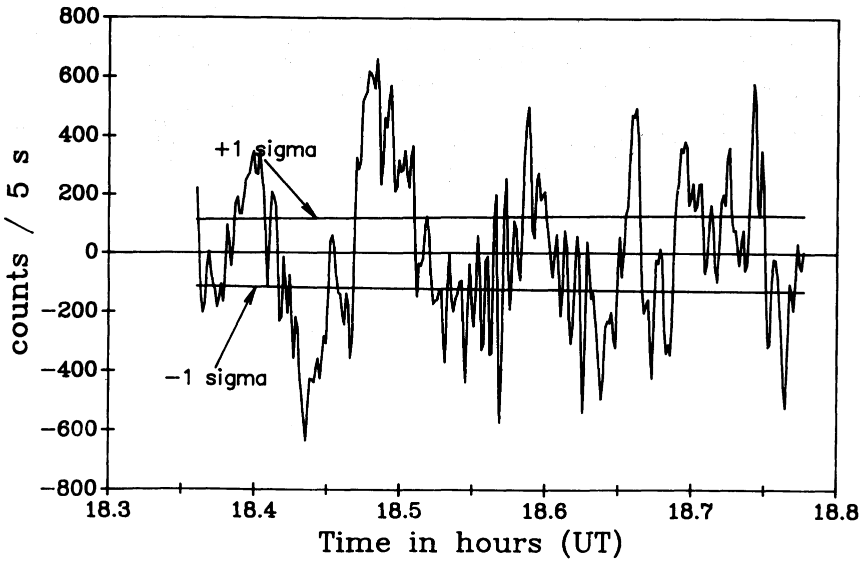

Fig. 6. Residuals between the light curve and the polynomial fit of Fig. 5. ± 1σ boundaries of the fit are also shown

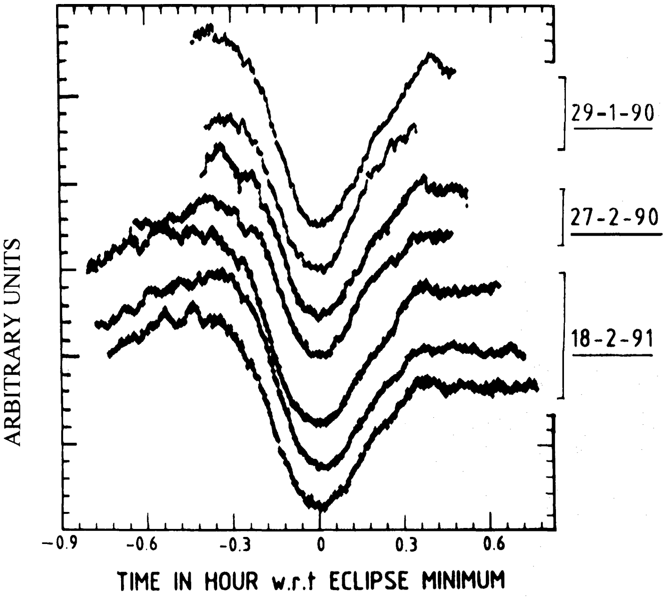

Fig. 7. Display of all eclipses recorded in 1990–1991, aligned about the time of minimum

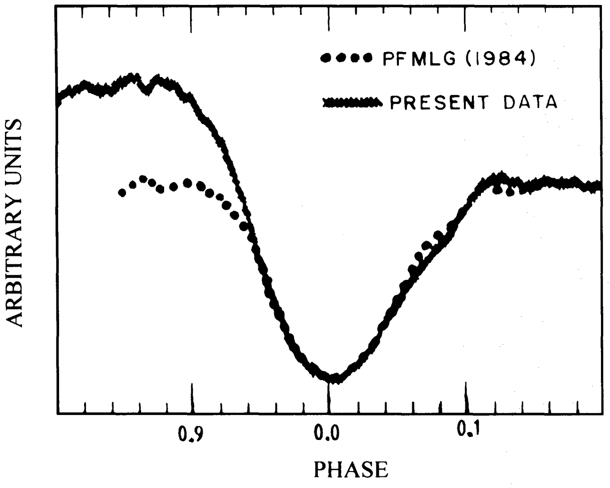

Fig. 8. Averaged eclipse profile of the 1991 data as compared to that of Fig. 8 of Penning et al. (1984)

error of the same order, indicating that it is not significant. Taking this as the limiting value of $\gamma = P\dot{P}/2$ [using Taylor's expansion for Eq. (1)] we obtain an upper limit of $\dot{P} = 2.2\ 10^{-11}$ s s^{-1} and a time scale of change of the orbital period of 1.7 10^7 yr.

The above $\dot{P}$ can be interpreted in terms of mass exchange between the stars in the case of conservative mass transfer, or in terms of mass loss from the system, say in the form of a wind in the case of non conservative mass transfer (Pringle 1985). In the first case

$$\dot{M}_1 = \dot{P} M_1 M_2 / 3P(M_1 - M_2)\,, \tag{3}$$

where P is the orbital period in seconds, $\dot{P}$ is the time derivative in s s^{-1}, and M_1 and M_2 are the masses of the secondary and primary stars respectively in units of $M_\odot$. The sign of period derivative depends on whether the heavier or the lighter star is transferring mass. In the present case, since $M_1 < M_2$, as derived by PFMLG, P is expected to increase.

Substituting the values of M_1 ($= 0.33 M_\odot$ and M_2($= 0.58 M_\odot$) and the above value of P we derive a maximum $\dot{M}_1$ of $-1.5\ 10^{-8} M_\odot\,\mathrm{yr}^{-1}$. Note that the value of $\dot{M}_1$ derived this way is an average estimate over the years and is consistent with typical values for nova-like variables.

Alternately if we assume that the primary star is losing mass in the form of a stellar wind that emanates from the system in a spherically symmetric manner,

$$\dot{M}_2 = -\dot{P}\,(M_1 + M_2)/2P. \tag{4}$$

If the observed upper limit of $\dot{P}$ is interpreted as due to mass loss from the system we get an $\dot{M}_2 \leq 2.7\ 10^{-8} M_\odot$ yr^{-1}. We note that Honeycutt et al. (1986), from an analysis of spectroscopic data, do give evidence for the presence of radiation-driven bipolar winds emanating from the central planar surfaces of the accretion disk in the system. The rate of mass loss that we calculate can therefore be used as a rough estimate for this system.

We note that either way the mass loss limit is consistent with that for other nova-like systems. We only wish to emphasize that though the average properties of this star have not changed drastically short term changes are clearly present as shown by the presence of a pre-eclipse hump over one year.

Finally, we have subjected the data outside the eclipses in Fig. 1c to a discrete Fourier transform analysis to search for the presence of coherent periods in the system. No persistent periodic signals were found in the power spectrum. Therefore all short duration light variations in the system are due to flickerings. No dwarf nova-type outbursts were detected from the system during our observations. These results lend additional support for the nova-like classification of the system.

4. Conclusions

We have described in detail the characteristics of several eclipses of PG 1012 − 029. The presence of an enhanced pre-eclipse hump in our 1991 data is attributed to the presence of a bright hot spot that contributes nearly 30% to the total light. The latter may have been produced by a flaring on the secondary star and the consequent enhanced mass transfer or due to some instability in the disc. Further, the hot spot contribution can be seen all along the light curve, indicating that the accretion disc is optically thin and/or a part of the enhanced hot spot is seen above the disc throughout the orbit. Flickerings are seen throughout the light curve and also during the eclipses, indicating that the location of the flickerings is not localised. We derive a refined orbital period of $0\overset{\mathrm{d}}{.}1349384292$ and a mass transfer rate of $\leq 1.5\,10^{-8} M_\odot$ yr^{-1} for the system. The absence of coherent periods other than the orbital period in our data indicates that the object is not a DQ Her star. We did not detect any dwarf-nova type outbursts from the system during our observations. Our results therefore agree with the nova-like classification of the object.

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