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GRS 1009–45 (=X-Ray Nova Velorum 1993): a 'hybrid' soft X-ray transient?*

N. Masetti, A. Bianchini, and M. Della Valle

Dipartimento di Astronomia, Università di Padova, vicolo dell'Osservatorio, 5 I-35122 Padua, Italy

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Abstract. High–time resolution photometry, performed from November 17 to December 11, 1993, on GRS 1009–45 (=X-Ray Nova Velorum 1993) reveals a V light modulation with a periodicity of 0.1996 days ($\sim 4^{\rm h}.79$). If the nature of this modulation is similar to that of the superhumps seen in SU UMa dwarf novae during superoutbursts, then the object would have the shortest orbital period among Soft X-Ray Transients (SXTs). We estimate a lower limit for the mass of the primary of $\sim 1.6\ M_{\odot}$. An optical secondary maximum or 'reflare' around 90 days after the X-ray outburst is also reported. Spectroscopy during light decay confirms the presence of Balmer absorption lines with emission cores.

Key words: accretion, accretion disks – stars: individual (GRS 1009–45 = X-Ray Nova Velorum 1993) – X-rays: stars

1. Introduction

X-ray novae, or more appropriately Soft X-Ray Transients (hereafter SXTs), form a small sub–class of Low Mass X-Ray Binaries (LMXBs). These systems are composed of an accreting compact primary and a Roche–lobe filling late–type secondary star. The accretion disk around the collapsed object experiences on timescales of some decades a sudden enhancement of the mass transfer rate caused by cyclical disk–instability events (Mineshige & Wheeler 1989). This gives rise to a rapid increase of the luminosity in X-rays, in the optical and very frequently also in the radio. The disk–instability model of the outburst of LMXBs has been recently improved by Cannizzo et al. (1995).

The study of the optical counterparts of these X-ray novae is of great interest because, in a handful of cases like V616 Mon (McClintock and Remillard 1986), GU Mus (Remillard et al. 1992), V404 Cyg (Casares et al. 1992), GRO J1655–40 (Bailyn et al. 1995), QZ Vul (Casares et al. 1995), and V2107 Oph (Remillard et al. 1996), it has been found that the mass of the compact object exceeds the maximum stable mass for a neutron star, thus pointing out SXTs among the most suitable targets to probe the existence of black holes. For this reason, these systems are also called Type II SXTs or Black–Hole X-Ray Novae (BHXNe).

In some other cases, like Aql X-1 (Koyama et al. 1981) and Cen X-4 (Matsuoka et al. 1980, Cowley et al. 1988), the detection of X-ray bursts, due to helium thermonuclear runaways onto the surface of the primary (Lewin & Joss 1983), would indicate that the accreting object is a neutron star. These systems are then labelled as Type I SXTs.

In SXTs at maximum the radiation field emitted by the secondary is normally overwhelmed by the continuum produced by the disk irradiated by the X-rays produced by the hot central object. Thus, any modulation seen during the outburst possibly comes from the disk itself, like the case of the superhump phenomenon seen during the superoutbursts of SU UMa–type cataclysmic variables (O'Donoghue 1990). Some SXTs in fact, e.g. QZ Vul (=GS 2000+25; Charles et al. 1991), GU Mus (=X-Ray Nova Muscae 1991; Bailyn 1992), V 518 Per (=GRO J0422+32; Kato et al. 1995), and V2293 Oph (=GRS 1716–249; Masetti et al. 1996), showed a superhump–like behaviour during their light maxima. We know from observations (Warner 1985) that the superhump period differs from the orbital period by only a few percent. If the analogy between SU UMa stars and SXTs holds, theoretical models (Mineshige et al. 1992) tell us that we can estimate a lower limit for the mass of the primary compact object once the superhump period is known.

Another method to estimate the mass of the compact primary of SXTs can be represented by the empirical correlation between the mass of the primary and the *e*–folding rate of decline of the X-ray lightcurve, suggested by Mineshige et al. (1993), which predicts higher masses for longer decay times.

GRS 1009–45 (=X-Ray Nova Velorum 1993) was discovered on September 12, 1993 with the GRANAT and the Compton Gamma–Ray Observatory satellites as a strong X-ray event (Lapshov et al. 1993, Harmon et al 1993). Its X-ray emission was blackbody–like and considerably soft with a power–law tail extending to at least 500 keV, thus showing the typical X–

Send offprint requests to: M. Della Valle, dellavalle@astrpd.pd.astro.it

* Based on observations obtained at the European Southern Observatory, La Silla, Chile.

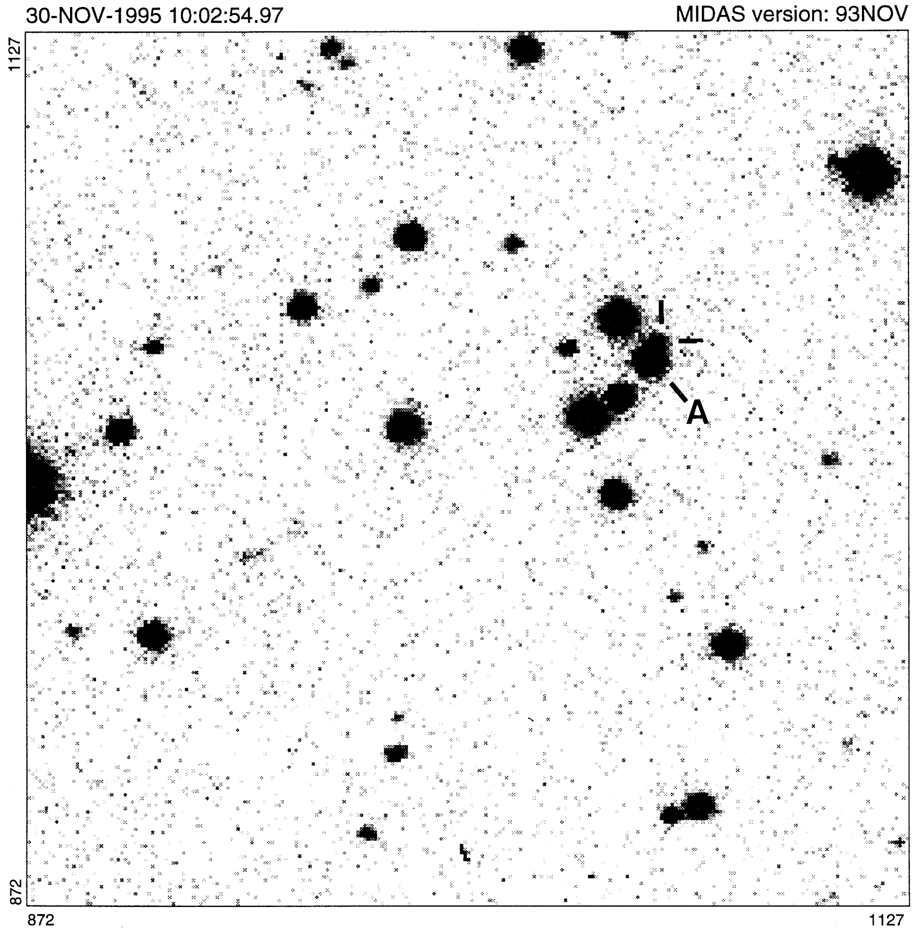

Fig. 1. R–band image of the field of GRS 1009–45 taken on March 3, 1995 (exposure time 40 seconds). North is at top, East is at left. The field is $\sim$ 1' $\times$ 1'. The nova, practically returned to quiescence, is indicated by the dashes, while the neighbor star is labelled with the 'A' letter

ray behaviour of SXTs at maximum. On the contrary, no radio emission has been reported.

The optical counterpart was discovered by Della Valle & Benetti (1993) on November 17, more than 2 months after the X-ray flare as a rather blue object of magnitude V = 14.71 and $B-V$ = 0.13. Spectroscopic observations showed the presence of the H_α line in emission and of OI, HeII and NIII. Della Valle et al. (1996) estimated the distance to the nova to be between 1.5 and 4.5 kpc and suggested that the companion star is a low–mass secondary of spectral type later than G5–K0.

Further photometry performed by Bailyn & Orosz (1995) showed the presence in the declining lightcurve of 'minioutbursts' similar to the ones observed in V 518 Per (=GRO J0422+32) by Chevalier & Ilovaisky (1995) and by Callanan et al. (1995). Bailyn & Orosz (1995) also observed an oscillation of $\sim$ $1^{\rm h}.6$ on June 12, 1994. They also reported the presence of H_α emission characterized by a double–peaked profile and an absorption profile with an emission core for H_β.

In this paper we present the results of a spectrophotometric follow–up of GRS 1009–45 which lasted, though fragmentary, from the optical discovery until March 3, 1995. In Sect. 2 we report the spectrophotometric CCD observations and their reduction. Sect. 3 illustrates the data analysis. In Sect. 4 we discuss the results, with particular attention to the photometry which demonstrates the presence of a clear periodicity. Sect. 5 draws the conclusions.

2. Observations

2.1. Imaging

B, V and R images of the nova were obtained over a period spanning from November 17, 1993 (the day of the discovery of the optical counterpart) to December 11, 1993 using the 3.6m telescope+EFOSC1, the 2.2m ESO/MPI telescope+EFOSC2 and the 0.92m Dutch telescope at La Silla. Further multicolor photometry was performed with NTT+EMMI on March 3, 1995. Unfortunately, due to poor seeing conditions and the disturbing presence of its neighbor star (see Fig. 1), only the R magnitude could be measured (R = 20.6), while only lower limits (fainter than $\sim$ 22 mag) could be given for the B and V bands. Here we present and analyse 106 V, 12 B and 3 R measurements. The upper part of Table 1 reports the journal of the observations. The frames were corrected for bias and flat fields and reduced with the DAOPHOT II package (Stetson 1987) and the MIDAS *ALLSTAR* procedure, which make use of PSF–fitting algorithms. This was necessary because of the presence of the neighbor star at 1".5 NW from the nova (see Bailyn & Orosz 1995), which discourages the use of aperture photometry. Three comparison field stars were then selected among those reported

Table 1. Journal of the observations: imaging (upper part) and spectra (lower part) sequences are reported

Date	Telescope	Filter or passband	Number of frames	Exp. times (minutes)
Imaging				
Nov. 17, 1993	2.2m	B, R	1,1	2,2
Nov. 18, 1993	Dutch	B, V, R	1,33,1	3,2,2
Nov. 19, 1993	3.6m	B, V	2,1	0.66,0.16
Nov. 20, 1993	3.6m	B, V	1,2	0.16,0.5
Dec. 1, 1993	3.6m	B, V	1,2	2,1
Dec. 2, 1993	3.6m	B, V	1,1	3,1
Dec. 3, 1993	3.6m	B, V	1,1	3,1
Dec. 4, 1993	3.6m	B, V	1,1	3,1
Dec. 5, 1993	3.6m	B, V	1,1	3,1
Dec. 6, 1993	3.6m	B, V	1,1	3,1
Dec. 11, 1993	Dutch	B, V	1,62	3,3
Mar. 3, 1995	NTT	B, V, R	1,1,1	1.5,0.83,0.66
Spectroscopy				
Jul. 5, 1994	3.6m	$Grism\ B300$	2	15

Table 2. Equivalent widths of Balmer absorption lines in the spectrum of GRS 1009–45 reported in Fig. 6. H_ϵ may be blended with CII and OII

Balmer line	Equivalent width (Å)
H_β	5.07
H_γ	4.61
H_δ	5.31
H_ϵ	11.1
H_ζ	4.92

by Bailyn & Orosz (1995) and by Della Valle et al. (1996), in order to calibrate the magnitude of the object. The choice has been made on the basis of their $(B-V)$ colors, which had to be as much as possible close to that of the nova. The internal magnitude differences among the comparison stars were practically constant within 0.02 mag. This confirms that, within the errors, only the nova is responsible for the observed variability.

2.2. Spectroscopy

Spectroscopic observations were performed with the 3.6m telescope on July 5, 1994 during the late decline of the nova (see Fig. 6). Two spectra with exposure time of 15 minutes each were taken using a slit width of 1".5, giving a resolution of 6.3 Å/pixel. The journal of these observations is reported in the lower part of Table 1.

After correcting for bias and flat fields, the spectra have been processed with the IRAF package. Wavelength calibration has been made using He–Ar lamps, and flux correction has been performed with the spectroscopical standard Feige 110.

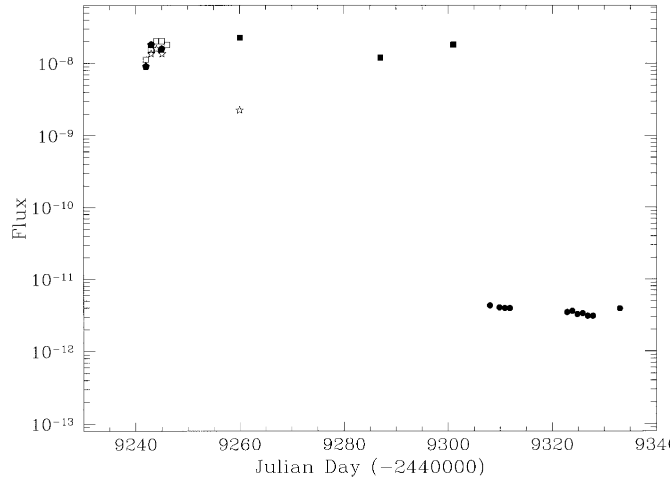

Fig. 2. The observed X-ray and V lightcurves of GRS 1009–45. Symbols indicate different energy bands: 1–10 keV (filled squares), 8–20 keV (stars), 20–60 keV (filled pentangles), 20–500 keV (open squares), and our V data (dots). Fluxes are in units of ergs $cm^{-2}\ s^{-1}$. References for the X-ray data are, in chronological order, Lapshov et al. (1993), Harmon et al. (1993), Kaniovsky et al. (1993), Borozdin et al. (1993), Tanaka (1993)

The spectra were dereddened for interstellar absorption, by using $E(B-V) = 0.2$, estimated by Della Valle et al. (1996) and following the prescription of Cardelli et al. (1989), and, finally, they have been stacked using as wavelength reference the interstellar absorption lines.

3. Data analysis

3.1. The lightcurve and the search for light modulations

Fig. 2 shows a L_X/L_{opt} ratio of $\approx 10^3$, which is rather typical for SXTs at maximum (see Tanaka & Lewin 1995 and references therein). Fig. 3 reports the B and V lightcurves. When more measurements in the same color were available during the same night, we plotted their mean value.

The $(B-V)$ color seems to remain practically constant and equal to 0.17 ± 0.02 mag during the period of time November 18–December 6, 1993. The $(V-R)$, on the night of November 18, 1993, is 0.06 ± 0.01.

We can also notice the presence of a secondary maximum or 'reflare' in the lightcurve around December 9, 1993 (HJD 2449330). It develops in less than five days and brings a luminosity enhancement of ≈ 0.3 mag in V and ≈ 0.4 mag in B, thus decreasing the $(B-V)$ up to 0.04 mag.

The search for light modulations has been carried on by using a Discrete Fourier Transform (DFT) algorithm. Firstly, we have subtracted from the V data the best–fitted linear decay trend. This procedure will eliminate biasing on the DFT power spectrum. Then, we have corrected the 62 magnitudes obtained on December 11 by subtracting the amplitude of the flare with respect to the extrapolated linear decay trend. This procedure could appear somewhat arbitrary, but is suggested by the sinu-

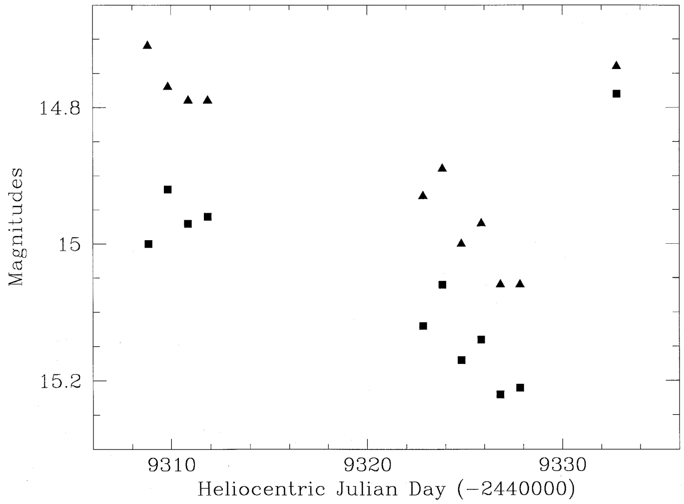

Fig. 3. B (filled squares) and V (filled triangles) lightcurves of GRS 1009–45. Note the decay trend and the reflare around JD = 2449330

soidal shape of the lightcurve of that night (see Della Valle et al. 1996).

The DFT power spectrum on the V data set, shown in Fig. 4a, strongly demonstrates the presence of a signal at $\approx$ 5 cycles/day. The peak of the peaks falls at 0.199608 days although several aliases at frequencies separated by 22.34^{-1} days and 5.74^{-1} days are also probable. Anyway, the CLEAN approach (Roberts et al. 1987; Fig. 4b) confirms as the far more probable modulation the 0.1996–day (= $4^{h}.79$) periodicity suggested by the DFT.

We have also applied two best–fit methods to the V data: Sterken's (1977) method and Schöneich–Lange's (1981) method. The first one fits a linear combination of a sinusoid and a cosinusoid to the data folded with a trial period P. The second one works almost in the same way, but, in addition, it divides the folded data in several phase groups and performs the fit on each of them. These methods confirm the previous results, suggesting a more probable period around 0.190–0.200 days with an error of about 0.06 days.

The V lightcurve folded with the 0.1996–day period is presented in Fig. 5. The asymmetry in the lightcurve will be discussed in Sect. 4.1.

We also notice that the object appears to be marginally bluer ($(B-V) = 0.15 \pm 0.02$ mag) at the minimum of the modulation, and redder ($(B-V) = 0.19 \pm 0.02$ mag) at maximum. This is qualitatively in agreement with the superhump color behaviour in SU UMa cataclysmic variables (e.g. Warner 1995).

3.2. The spectra

The spectrum of GRS 1009–45 taken about 300 days after the X-ray maximum (see Table 1) is shown in Fig. 6. The continuum appears slightly less steep than that displayed 60 days after the outburst (Della Valle et al. 1996; their Fig. 6), although it is difficult to exclude that it could be contaminated by the nearby field star (see below). The Balmer series from H_β to H_ζ is clearly seen in absorption with very broadened profiles, while the H_α is filled in by an emission. A faint emission core is also observed in H_β, as already noticed by Bailyn & Orosz (1995) and by Della Valle et al. (1996). This behaviour is similar to that displayed by V 518 Per (=GRO J0422+32; Callanan et al. 1995). The measurements of the equivalent widths of the Balmer absorption lines are reported in Table 2.

The NIII+HeII emission bump at 4640–4686 Å is also detected. The NIII, in particular, might have a double–peaked profile. Another feature is a broad bump at $\approx$ 5870 Å probably due to a blend of HeI and CII. Interstellar lines are present at 5890 Å (the NaD doublet; EW = 1.21 Å) and 6280 Å (EW = 0.77 Å). The latter could be contaminated by telluric absorption, as suggested by Callanan et al. (1995). No other features are clearly seen.

We have measured the V magnitude and the $(B-V)$ color index of the neighbor star, to estimate the contamination of the spectra of GRS 1009–45, which becomes particularly important at quiescence. We find $V \approx 17.9$ and $(B-V)_{\rm o} \approx 0.7$. This indicates a star of mid or late G spectral type, according to its luminosity class.

4. Discussion

4.1. The superhump phenomenon and the optical lightcurve

Superhumps are phenomena expected to appear in the disks of close binary systems with extreme mass ratios during enhanced mass transfer episodes from the donor star (Whitehurst & King 1991).

Since in GRS 1009–45 the light modulation is very likely produced in the disk, which dominates the light emitted by the outbursting system, and since Type II SXTs such as QZ Vul (Charles et al. 1991), GU Mus (Bailyn 1992), V 518 Per (Kato et al. 1995) and, perhaps, also V 2293 Oph (Masetti et al. 1996), have shown real superhump phenomena, one may hypothesize that this is the general behaviour of all BHXNe. If this is the case, we can tentatively interpret the modulated lightcurve of Fig. 5 as a superhump phenomenon.

We know from observations that superhump periods exceed the orbital ones (Chevalier & Ilovaisky et al. 1993 for QZ Vul, Remillard et al. 1992 for GU Mus and Chevalier & Ilovaisky 1995 for V 518 Per) by a few percent; therefore, in the hypothesis that we are observing a superhump, GRS 1009–45 might have the shortest orbital period ever found for a SXT.

We notice that the folded lightcurve of Fig. 5 shows a rather small dispersion and presents an asymmetric profile with the decline steeper than the rise. This asymmetry results opposite to that shown by superhumps of SU UMa stars during superoutbursts. However, we can argue that also in other SXTs the observed profile of superhumps is rather intriguing. In GU Mus, for example, the profile changes its symmetry during the light decline (Bailyn 1992; his Figs. 4 and 5), whereas in V 2293 Oph (Masetti et al. 1996) the superhump profile depends on the subtraction of smaller amplitude secondary periodicities. In fact, the problem of the asymmetry of the superhump lightcurves

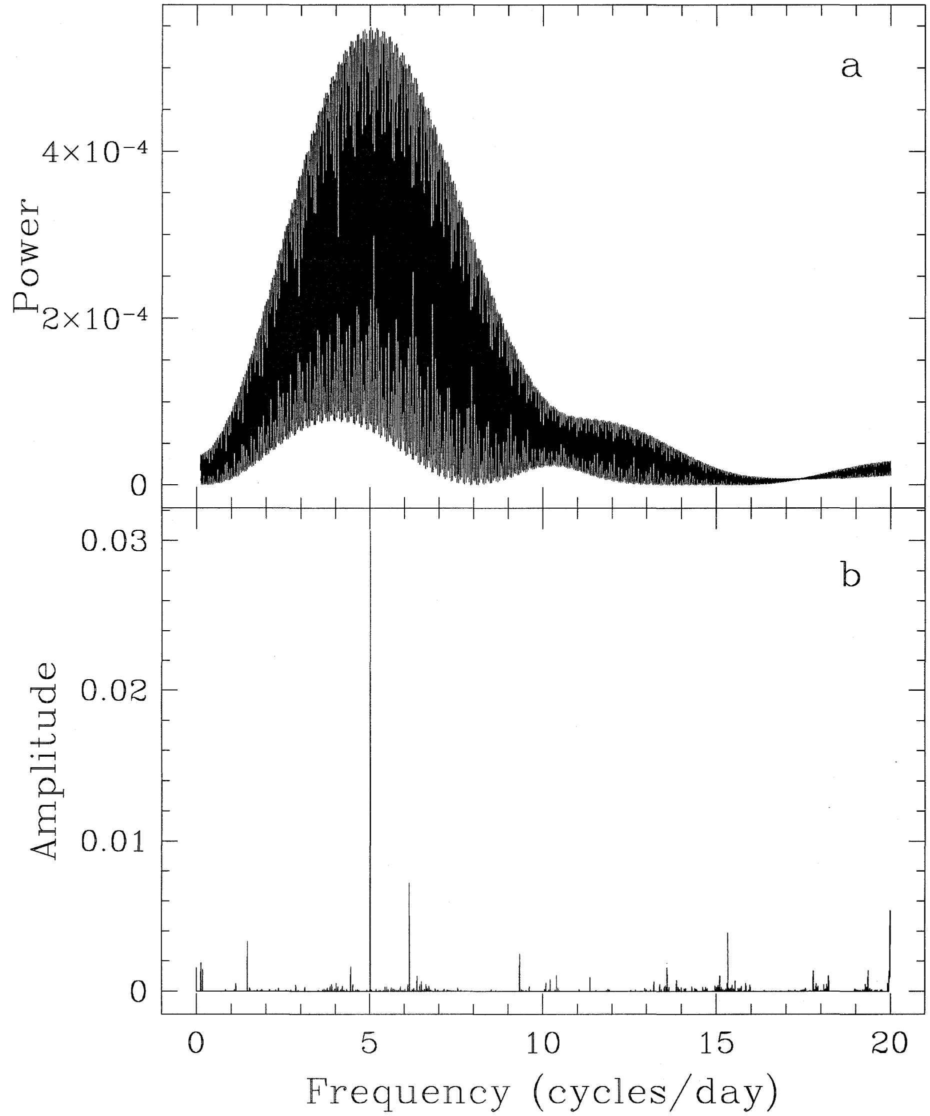

Fig. 4. V data set **a** DFT and **b** CLEANed power spectra. The strongest peak falls at 0.1996 days

observed in SXTs probably remains in the many uncertainties involved in the superhump model calculations.

The $\sim 1^h.6$ modulation of the V lightcurve observed by Bailyn & Orosz (1995) is not shown by our data, therefore it should be regarded as a different phenomenon. We point out that these authors performed their observations six months after our run, when the star had faded down to $\sim$ 18.5 mag and was undergoing a small minioutburst. One possibility is that the $\sim 1^h.6$ modulation is produced by blobs of material orbiting in the inner parts of the disk, similarly to V 2293 Oph (Masetti et al. 1996). We might perhaps suggest that, in general, the smoothness of a superhump lightcurve depends on the lack of orbiting blobs in the inner disk.

From the observations taken from November 17 to December 6, 1993 it can be noticed that the optical lightcurve exhibits a decay rate of 0.0147 mag d^{-1} in both the B and V bands. This seems a quite common trend for SXTs containing black holes, like GU Mus (Della Valle et al. 1991), QZ Vul (Pavlenko et al. 1990) and V616 Mon (Tsunemi et al. 1977). Therefore, by assuming $V_{\rm max}$ = 13.85 $\pm$ 0.15 and $B_{\rm max}$ = 14.00 $\pm$ 0.15 (see Della Valle et al. 1996), we obtain an outburst amplitude Δm $\gtrsim$ 8 mag in both B and V. We also stress the presence of a secondary maximum $\sim$ 90 days after the X-ray outburst: this is typical for SXTs, which generally show an optical 'reflare' at about 70–100 days after the outburst (Tanaka & Lewin 1995).

4.2. The X-ray lightcurve

The 8–20 keV lightcurve given by Lapshov et al. (1994) shows a rather steep first decline with an e–folding time of $\sim$ 10 days. Ten days after maximum, the X-ray lightcurve presents a sort of plateau lasting not less than one month. The harder (20–60 keV) X-ray lightcurve has a similar behaviour, but with larger flickering. The presence of strong flickering in both lightcurves could be an indication of a low inclination of the system, since in this case we would see almost directly the central X-ray source.

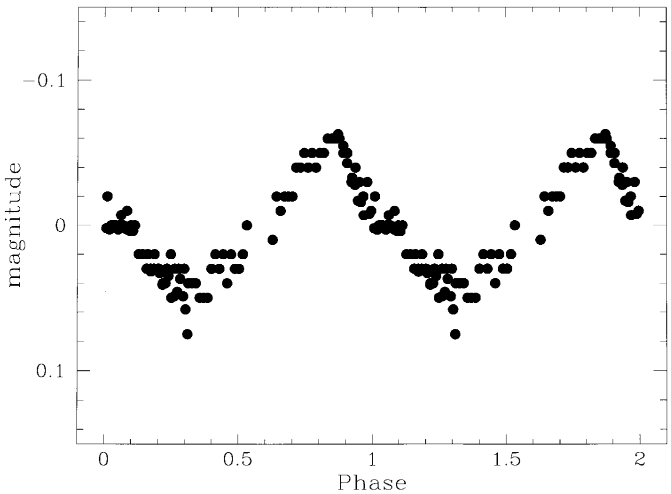

Fig. 5. V data folded with period P = 0.1996 days. Data points have been rescaled to a common zero magnitude level. Phases are arbitrarily referred to JD = 0.00

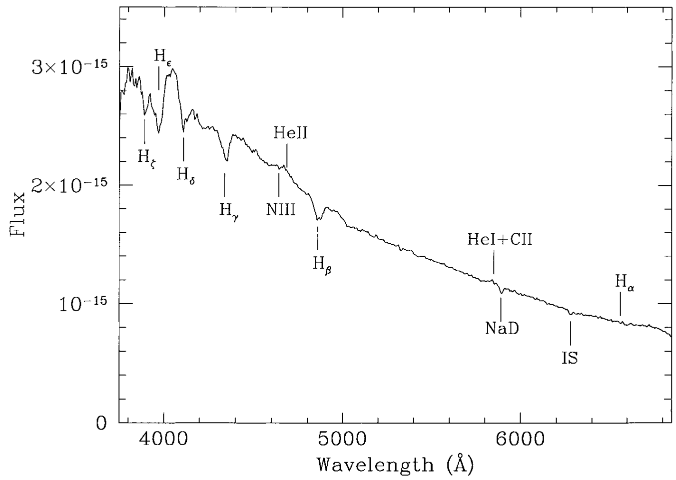

Fig. 6. Mean of the spectra acquired on July 5, 1994. Dereddening has been performed considering $E(B-V)$ = 0.2. Fluxes are in units of ergs cm^{-2} s^{-1}

Even admittedly the scanty statistics, the rapid decay and the presence of a long plateau are quite unusual for BHXNe, since their X-ray lightcurves decay with an e–folding time of $\sim$ 30 days and no plateau is generally seen either before or after the secondary X-ray maximum (see Fig. 3.2 of Tanaka & Lewin 1995). On the contrary, neutron–star SXTs show a more rapid X-ray decay: $\sim$ 10–15 days for Cen X-4 (Fig. 1 of Kaluzienski et al. 1980) and $\sim$ 20 days for Aql X-1 (Fig. 1 of Charles et al. 1980). The plateau, however, is absent also in the X-ray lightcurves of these objects.

Fourier analysis of the X-ray data points (Table 1 of Lapshov et al. 1994) reveals rather weak signals at $4^{\rm h}.6$ and $2^{\rm h}.8$. The first one is close to the optical period we have found, but the folded X-ray lightcurves are quite noisy.

4.3. The mass of the compact object

If the observed modulation is a superhump, we can use the prescription of Mineshige et al. (1992) to determine the lower limit for the mass of the compact object in GRS 1009–45. The value of 1.6 $M_\odot$ is substantially below the maximum mass allowed for a rotating neutron star (i.e. 3 $M_\odot$: Rhodes & Ruffini 1974), nevertheless we can not exclude that this system might contain a small mass black hole like the SXT V 518 Per (=GRO J0422+32). Indeed this object exhibits superhumps, has a mass function of 1.21 $M_\odot$ (Filippenko et al. 1995) and its orbital period (Chevalier & Ilovaisky 1995) is almost as small as that found here for GRS 1009–45. The optical lightcurve and the spectral behaviour during the decline also bear some similarities with GRS 1009–45 (although its X-ray lightcurve has a much slower decline, as reported by Vikhlinin et al. 1992).

On the other hand, as pointed out by Della Valle et al. (1996), it might be that GRS 1009–45 undergoes outbursts with recurrence times of $\approx$ 10 years, which are shorter than those of the BHXNe, whose outbursts recur on a timescale of $\approx$ 50–100 years (Tanaka & Lewin 1995). This behaviour is more similar to that of Aql X-1 and Cen X-4, which are known to contain a neutron star (Koyama et al. 1981, Matsuoka et al. 1980, Cowley et al. 1988).

The X-ray e–folding time also suggests an intermediate or low mass compact object. Indeed, as stated by Mineshige et al. (1993), the rate of decay of the X-ray lightcurve, $t_{1/e}$, is proportional to M_1/α, where M_1 is the mass of the primary and α is the viscosity of the disk. Since the value of $t_{1/e}$ observed in GRS 1009–45 is three times shorter than that of the other BHXNe, we can argue that in this system the mass of the compact object can override the neutron star stability limit only if the viscosity of the disk is considerably higher than that assumed for the other black–hole SXTs.

We know from theoretical models (Whitehurst & King 1991) that the superhump phenomenon takes place only if the mass ratio $q = M_2/M_1$ is $\lesssim 0.25 - 0.33$; therefore, assuming q = 0.33 and $M_1 \approx 1.6 M_\odot$, we find that the mass of the secondary is $\approx$ 0.5 $M_\odot$. For $P_{\rm orb} \approx P_{\rm sh}$, the Roche lobe of the secondary is $\sim$ 0.5 $R_\odot$. Both these values are consistent with a late–type K main sequence star.

5. Conclusions

Our observations of GRS 1009–45 show the presence of a modulation of $\sim 4^{\rm h}.8$ which may be likely due to a superhump phenomenon. No $1^{\rm h}.6$ variations, as reported by Bailyn & Orosz (1995), have been detected in our data. The rate of decline of the X-ray lightcurve suggests a rather low–mass primary, while a lower limit of 1.6 $M_\odot$ is indicated by the superhump period. In turn this implies that the secondary might then be a late K type dwarf, as suggested by Della Valle et al. (1996). However, we notice that the approach proposed by Mineshige et al. (1992) to estimate the mass of the compact object, which was originally intended for dwarf novae, should be applied to SXTs with some degree of caution. In fact, its extension to these systems might be sometimes questionable since, for example, the large X-ray irradiation could modify the structure of the disk. Thus, the analogy with dwarf novae might not be fully justified.

Spectroscopic observations confirm the presence of Balmer absorption lines with emission cores, as indicated by Bailyn & Orosz (1995) and Della Valle et al. (1996), and the presence of interstellar absorption lines.

We measured the V magnitude and estimated the spectral type of the neighbor star: the results indicate a late G–type star, which will make difficult the observations of the quiescent nova.

We tentatively classified GRS 1009–45 as a 'hybrid' SXT, because during the outburst it exhibits characteristics which are typical of both Type I and Type II SXTs. Several hints actually play in favour of the presence of a low–mass black hole: primarily, its similarity with the BHXN V 518 Per (=GRO J0422+32; Chevalier & Ilovaisky 1995, Callanan et al. 1995), supported by the presence of superhumps, minioutbursts, emission cores inside the Balmer absorption lines. This behaviour is not typical of neutron–star SXTs. In all cases, the occurrence of the secondary optical maximum $\sim$ 90 days after the X-ray outburst and the soft X-ray spectrum with a hard power–law tail at maximum light are interpreted as signature for a black hole candidate in SXTs (see e.g. Tanaka & Lewin 1995). In addition, the optical decay rate of GRS 1009–45 is quite similar to those shown by other BHXNe. On the other hand, we have also found some indications in favour of a neutron star candidate (i.e. Type I SXT) like: (a) the orbital period, which appears to be the shortest among the SXTs and which, in the hypothesis of a Roche–lobe filling main–sequence secondary, would lead, according to the prescription of Mineshige et al. (1992), to a lower limit of the mass of the primary of only 1.6 $M_{\odot}$ (this case is different from the Type I SXTs Cen X-4 and Aql X-1 because these systems have longer orbital period but secondaries which are stripped giants and not main–sequence stars); (b) the short *e*–folding decay time of the X-ray lightcurve; and (c) the short recurrence time between the outbursts. As a final remark, we mention the fact that the X-ray plateau shown by GRS 1009–45 is a rather unusual feature for both Type I and II SXTs.

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