CHAPTER 5

X-RAY NOVA VELORUM 1993
(=GRS 1009-45, MM Vel)

Far away, away, fading distant lights
Leaving us all behind,
Lost in a changing world.
(Genesis 1991)

5.1. INTRODUCTION

Many times, in the previous Chapters, it has been remarked that the study of optical counterparts of SXTs is of great interest because, in a handful of cases such as V616 Mon (McClintock and Remillard 1986), GU Mus (Remillard et al. 1992), V404 Cyg (Casares et al. 1992), QZ Vul (Casares et al. 1995), GRO J1655-40 (Bailyn 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 NS, thus pointing out SXTs among the most suitable targets to probe the existence of BHs. These systems were described in Sect. 3.4 and called Type II SXTs or BHXNe.

There are however at least 5 other cases (see Ch. 8 of this Thesis), that is, Aql X-1 (Koyama et al. 1981), Cen X-4 (Matsuoka et al. 1980, Cowley et al. 1988), QX Nor (Penninx et al. 1989), KS 1731-260 (Sunyaev et al. 1990) and A1742-289 (Maeda et al. 1996) for which the detection of X-ray bursts (due, as already said in Ch. 3.1, to helium thermonuclear runaway burning episodes on the surface of the primary), would indicate that the accreting object is a NS(1). These systems are then labelled as Type I SXTs.

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(1) This result seems to be questioned by Kinnea & Skinner (1996; PASJ, 48, L117) who reanalysed the archival outburst data of A1742-289 and concluded that the observation by Maeda et al. (1996) likely refers to a different and previously undetected object.

This short introduction is necessary as the SXT which this Chapter is devoted to showed, during the outburst phase, some characteristics which are typical of Type I SXTs and some other typical of Type II SXTs. That's why this object has been defined a 'hybrid' SXT.

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). Lapshov et al. (1994) reported an X-ray flux maximum of ~0.8 Crab in the 8÷20 keV and the 20÷60 keV bands; the X-ray light curves (Fig. 5.1a,b) in these two bands show a fast rise (few days), a decay time of about 10 days and a quite scattered *plateau* which lasted at least one month.

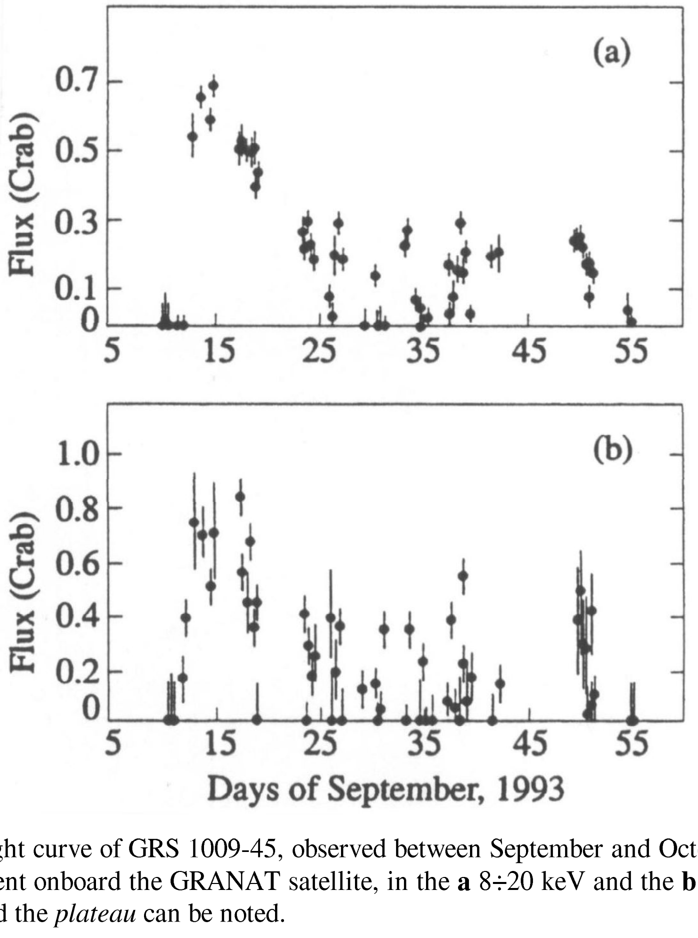

Fig. 5.1. X-ray light curve of GRS 1009-45, observed between September and October 1993 with the WATCH instrument onboard the GRANAT satellite, in the **a** 8÷20 keV and the **b** 20÷60 keV bands. The fast decay and the *plateau* can be noted.

The X-ray emission (Sunyaev et al. 1994) was blackbody-like with a temperature of $kT = 0.52 \pm 0.03$ keV and thus considerably soft, with a hard power-law tail of spectral index $\alpha = 2.53 \pm 0.05$ and extending to at least 500 keV. So, this object showed the typical X-ray behaviour of SXTs at maximum. The X-ray spectrum at maximum was reported by these authors in their Fig. 1, where one can note that the soft emission component is dominant over the hard one. Again Sunyaev et al. (1994) noted that, during the X-ray decline, the main responsible for the decrease in brightness was the soft component, while the hard one remained practically unaltered (their Fig. 6). The X-ray spectrrum of the object became harder toward the end of the outburst, thus following another common behaviour for SXTs (Tanaka & Lewin 1995). Instead, no radio emission has been reported. Paciesas et al. (1995) found the presence of two secondary maxima in the hard X-ray band about 30 and 85 days after the main X-ray peak.

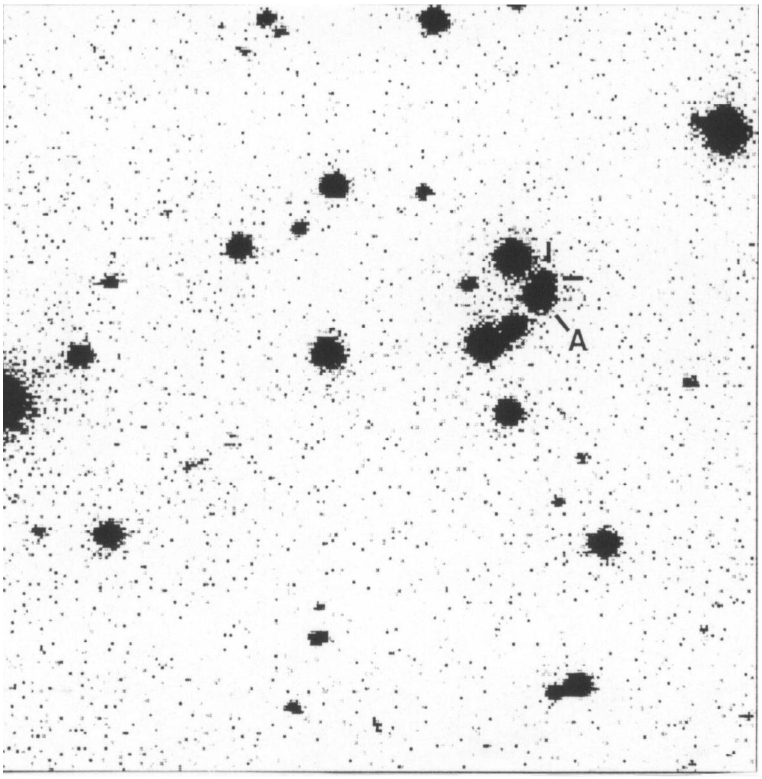

Fig. 5.2. *R*-band image of the field of MM Vel taken on March 3, 1995 (exposure time: 40 seconds). North is at top, East is to the left. The field is about 1′ × 1′. The X-ray Nova, practically returned to quiescence, is indicated by the dashes, while the 'neighbor' star, prospectically superimposed to MM Vel, is labelled with the 'A' letter.

The optical counterpart, called MM Vel, was discovered by Della Valle & Benetti (1993) on November 17, that is more than 2 months after the X-ray outburst, thanks to more accurate coordinates for the X-ray position given by the ASCA satellite (Tanaka 1993). At that epoch, the object was detected at a magnitude $V = 14.71$; it was also rather blue, having optical color indices B-V = 0.13 and V-R = 0.06 (Della Valle et al. 1997).

The same authors, assuming an optical decline rate similar to those found for other SXTs, estimated that this X-ray nova reached at optical maximum light the magnitude V = 13.8 ± 0.3 and evaluated a luminosity jump in the optical, with respect to quiescence, of at least 6 - 7 magnitudes. They also reported the possible presence of a modulation with a period of about 4 hours and a possible previous outburst occurred in February 1982.

Spectroscopic observations, again made by Della Valle et al. (1997) at the time of the discovery of the optical counterpart, showed that the optical continuum was modeled with a blackbody energy distribution with temperature T ~ 25000 K. They also reported the presence of a double-peaked (with separation of about 800 km s^{-1}) H_{α} line in emission (EW = 2.1 Å), and of He II, N III and O II, in emission as well. These authors also detected several interstellar absorption lines in the optical specrtum of MM Vel; from these lines they estimated a color excess $E(B$-$V)$ = 0.2 for the X-ray Nova. One more spectrum, acquired by Della Valle et al. (1997) during the late decline phase (July 15, 1994), showed wide Balmer absorption lines, with FWHM of ~3000 km s^{-1}, and an emission produced by the superposition of He I e C II at ~5870 Å.

These same authors also estimated the distance to the X-ray Nova to be between 1.5 and 4.5 kpc and suggested that the companion star is a low-mass secondary of spectral type G5-K0 or later.

Further photometric observations performed by Bailyn & Orosz (1995) showed in the decline light curve the presence of minioutbursts, similar to the ones observed in V518 Per (=GRO J0422+32) by Chevalier & Ilovaisky (1995) and by Callanan et al. (1995), on February, June and July 1994 (that is, about 5 and 10 - 11 months after the main optical and X-ray outburst) with amplitudes of 2 - 3 magnitudes. Bailyn & Orosz (1995) also reported a double-peaked H_{α} emission line on a spectrum acquired on January 15, 1994 and observed an oscillation of 1.6 hours in their V-band observations of 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 a spectrum taken on July 5, 1994.

Lately, Shahbaz et al. (1996) reported the discovery of the orbital period of the object at quiescence by means of the ellipsoidal variation of the secondary. Such value is 6.86 ± 0.12 hours and, on this basis, these authors estimated that the spectral type of the secondary should be between late G and early K.

In this Chapter the results of a spectrophotometric monitoring of MM Vel spanning, though fragmentary, from the optical discovery until March 3, 1995, will be presented. In the next Section the spectrophotometric CCD observations and their reduction will be described. Photometry, in particular, showed the presence of a clear modulation with a period **different** from that found in quiescence by Shahbaz et al. (1996). With the assumption that the periodicity found here during the outburst is a superhump modulation, an estimate of M_1 will also be given.

5.2. THE OBSERVATIONS

5.2.1. Photometry

B, *V* and *R* images of the X-ray 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 3.6-meter telescope plus EFOSC1 spectrophotometer, the 2.2-meter ESO/MPI telescope plus EFOSC2 spectrophotometer and the 0.92-meter Dutch telescope, all located in La Silla (Chile).

Further multicolor photometry was performed with the 3.58-meter ESO NTT telescope equipped with EMMI spectrophotometer on March 3, 1995 in La Silla. Unfortunately, due to poor seeing conditions and to the disturbing presence of a ‘neighbor’ star prospectically superimposed (see Fig. 5.2), only the *R* magnitude could be measured (R = 20.6) for MM Vel, while only lower limits (fainter than magnitude 22) could be given for the *B* and *V* bands.

Here 106 *V*, 12 *B* and 3 *R* measurements are presented and analyzed. The upper part of Table 5.I reports the journal of these photometric observations.

The frames were corrected for bias and flat fields and reduced with the *DAOPHOT II* package (Stetson 1987) and the *ALLSTAR* procedure inside *MIDAS*, which makes use of PSF-fitting algorithms. This was necessary because of the presence of the 'neighbor' star located 1″.5 NW of the nova (Fig. 5.2; see also Bailyn & Orosz 1995), which discourages the use of aperture photometry for an accurate measurement of the MM Vel magnitudes.

Table 5.I. Journal of the observations presented in this Chapter: imaging (upper part) and spectra (lower part) sequences are reported.

Date	Telescope	Filter or passband	Number of frames	Exposure times (minutes)
		IMAGING		
November 17, 1993	2.2 m.	*B; R*	1; 1	2; 2
November 18, 1993	Dutch	*B; V; R*	1; 33; 1	3; 2; 2
November 19, 1993	3.6 m.	*B; V*	2; 1	0.66; 0.16
November 20, 1993	3.6 m.	*B; V*	1; 2	0.16; 0.5
December 1, 1993	3.6 m.	*B; V*	1; 2	2; 1
December 2, 1993	3.6 m.	*B; V*	1; 1	3; 1
December 3, 1993	3.6 m.	*B; V*	1; 1	3; 1
December 4, 1993	3.6 m.	*B; V*	1; 1	3; 1
December 5, 1993	3.6 m.	*B; V*	1; 1	3; 1
December 6, 1993	3.6 m.	*B; V*	1; 1	3; 1
December 11, 1993	Dutch	*B; V*	1; 62	3; 3
March 3, 1995	NTT	*B; V; R*	1; 1; 1	1.5; 0.83; 0.66
		SPECTRA		
July 5, 1994	3.6 m.	Grism *B300*	2	15

Within the field of MM Vel three comparison stars were then selected among the photometric secondary standards reported by Bailyn & Orosz (1995) and by Della Valle et al. (1997), in order to calibrate the magnitude of the object. The choice has been made once again on the basis of their *B-V* colors, and the stars for which this parameter was as much as possible close to that of the X-ray Nova in the November-December 1993 period were selected.

The analysis of the internal magnitude differences among the comparison stars showed that these were practically constant within 0.02 mag. This confirms that, within the errors, only the X-ray Nova is responsible for the observed variability. Again, as done in the previous Chapter, the time at mid-exposure of each image has been expressed in HJDs in order to make the study of time series easier and most of all to eliminate the effects induced by the motion of the Earth around the Sun.

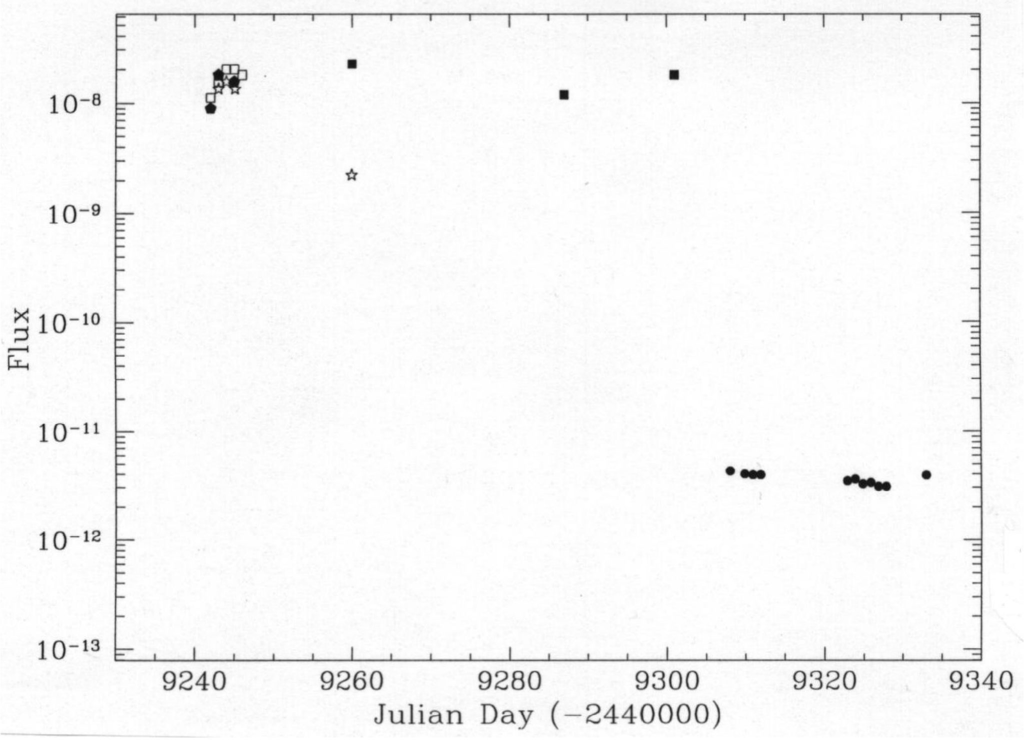

Fig. 5.3. The observed X-ray and *V* light curves of GRS 1009-45/MM Vel. Different symbols indicate different energy bands: 1÷10 keV (filled squares), 8÷20 keV (stars), 20÷60 keV (filled pentangles), 20÷500 keV (open squares), and the October-November nightly averaged *V* data reported in this Chapter (dots). Fluxes are in units of erg 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), and Tanaka (1993).

5.2.2. Spectroscopy

Spectroscopic observations were performed with the 3.6-meter telescope plus EFOSC1 on July 5, 1994 during the late decline of the X-ray Nova (see Fig. 5.8). Two spectra with exposure times of 15 minutes each were taken using a slit width of 1″.5, which gave a dispersion of 6.3 Å pixel^{-1}. The journal of these observations is reported in the lower part of Table 5.I.

After correcting for bias and flat field, 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 spectroscopic standard Feige 110.

The spectra were then dereddened for interstellar absorption by using a color excess $E(B\text{-}V) = 0.2$, as estimated by Della Valle et al. (1997), and following the prescription of Cardelli et al. (1989); finally, they have been stacked using as wavelength reference the interstellar absorption lines.

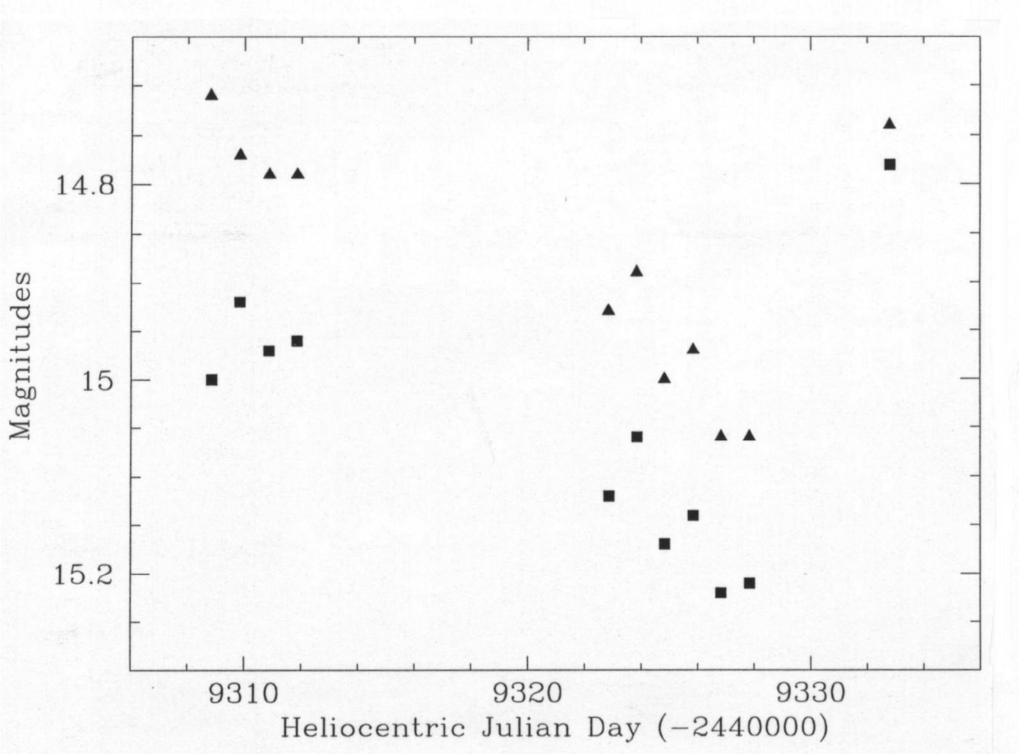

Fig. 5.4. *B* (filled squares) and *V* (filled triangles) light curves of MM Vel. One can note the decay trend and the secondary maximum around HJD 2449330.

5.3. DATA ANALYSIS

5.3.1. The light curve and the search for light modulations

Figure 5.3 shows an X-ray-to-optical luminosity ratio $L_X/L_{ott} \approx 10^3$, which is quite typical for persistent LMXBs and for SXTs at maximum (see Tanaka & Lewin 1995 and Chs. 3 and 8 of this Thesis), thus confirming the estimate given to this ratio by Sunyaev et al. (1994). Figure 5.4 instead reports the November-December 1993 *B* and *V* light curves of MM Vel. When more measurements in the same color were available during the same night, their mean value was plotted.

The *B*-*V* color index seems to remain practically constant and equal to 0.17 ± 0.02 mag between November 18 and December 6, 1993. The *V*-*R* color, on the night of November 18, 1993, is 0.06 ± 0.01. This is in agreement with the measurements made by Della Valle et al. (1997).

One can also note in Fig. 5.4 the presence of a secondary maximum or reflare in the light curve 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 about ~0.4 mag in *B*, thus decreasing the *B*-*V* color up to 0.04 mag.

The search for light modulations has been carried out by using a DFT algorithm. Firstly, the best-fitted linear decay trend was subtracted from the *V* data. This procedure will eliminate biasing due to the decline toward quiescence phenomenon on the DFT power spectrum. Then, the 62 magnitudes obtained on December 11, 1993 were further corrected by subtracting the amplitude of the flare with respect to the extrapolated linear decay trend. This procedure could appear somewhat arbitrary, but is strongly suggested by the sinusoidal shape of the light curve of that night (Fig. 5.5).

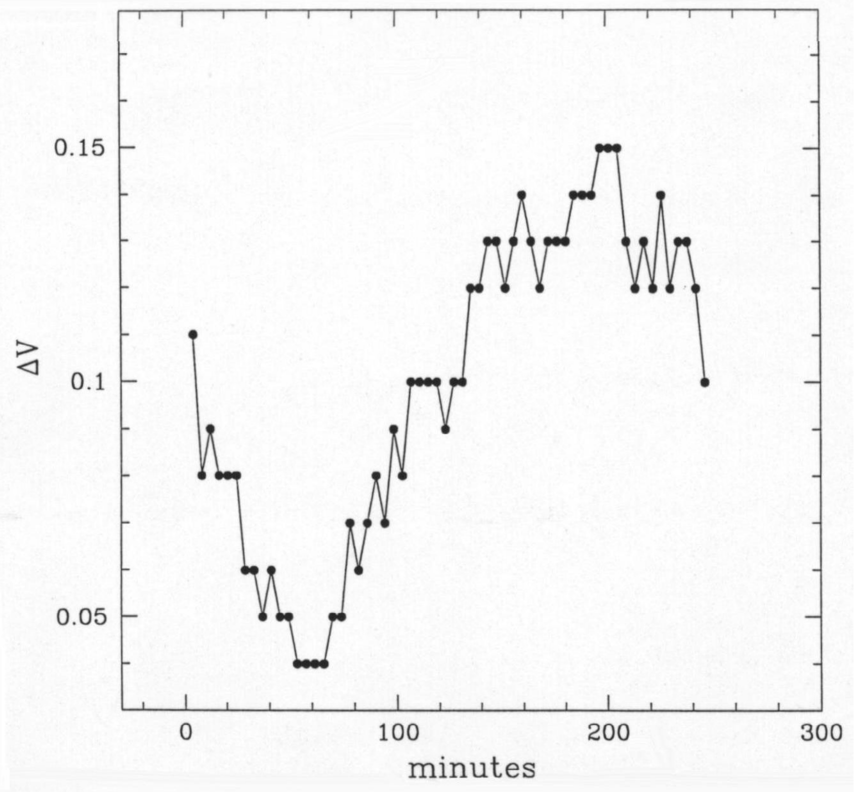

Fig. 5.5. Observations of MM Vel in the *V* band obtained on December 11, 1993 at the Dutch Telescope. The temporal resolution is about 3 minutes.

The DFT power spectrum of the *V* data set, shown in Fig. 5.6a, strongly indicates the presence of a signal at ~5 cycles day^{-1}. 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. Nevertheless, the *CLEAN* approach (Roberts et al. 1987) confirms, as shown in Fig. 5.6b, the 0.1996-day (=4.79 hours) periodicity suggested by the DFT as the far more probable modulation of the MM Vel *V* light curve.

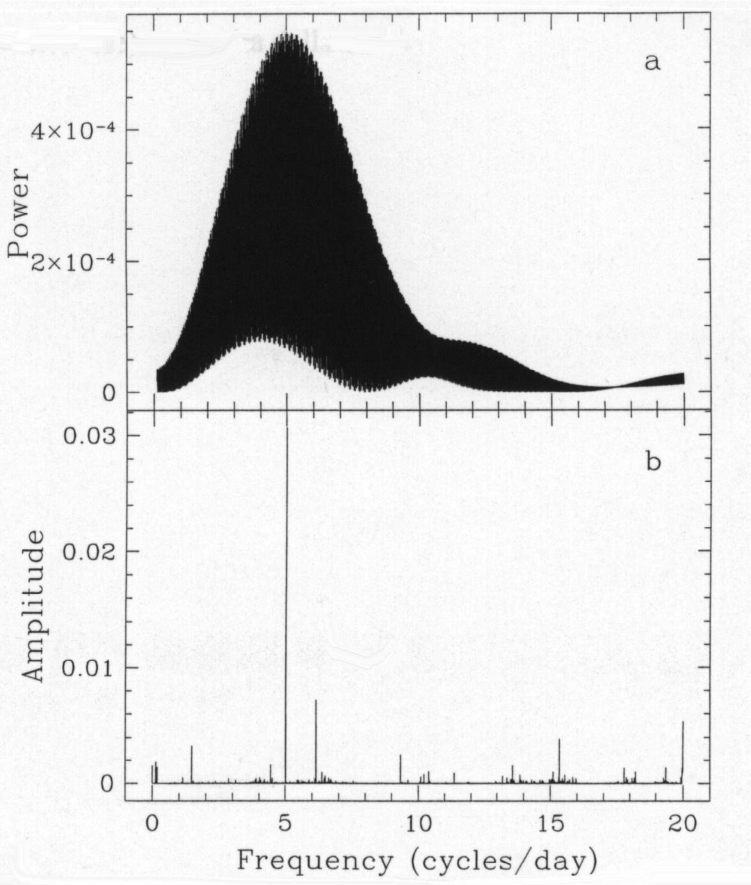

Fig. 5.6. **a** DFT and **b** *CLEAN*ed power spectra of the *V* data set. The strongest peak falls in correspondence of the 0.1996 days periodicity.

In order to confirm this result, two best-fit methods for the search of periodicities were also applied to the *V* data: Sterken's (1977) method and Schoeneich-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 bins and performs the fit on each one of them (see Appendix C of this Thesis). 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* light curve folded with the 0.1996-day period is presented in Fig. 4.7. The asymmetry in this light curve will be discussed later in Sect. 5.4.1.

Instead, it is not possible to speculate over any modulation of the *B*-*V* color index as the avaliable data are very few (10 in total, and no more than one per night in the time span November 18 - December 6, 1993); in any case, it never appreciably departs from the mean value of 0.17 given above, with the only exception of the night of December 11, 1993 (as said above).

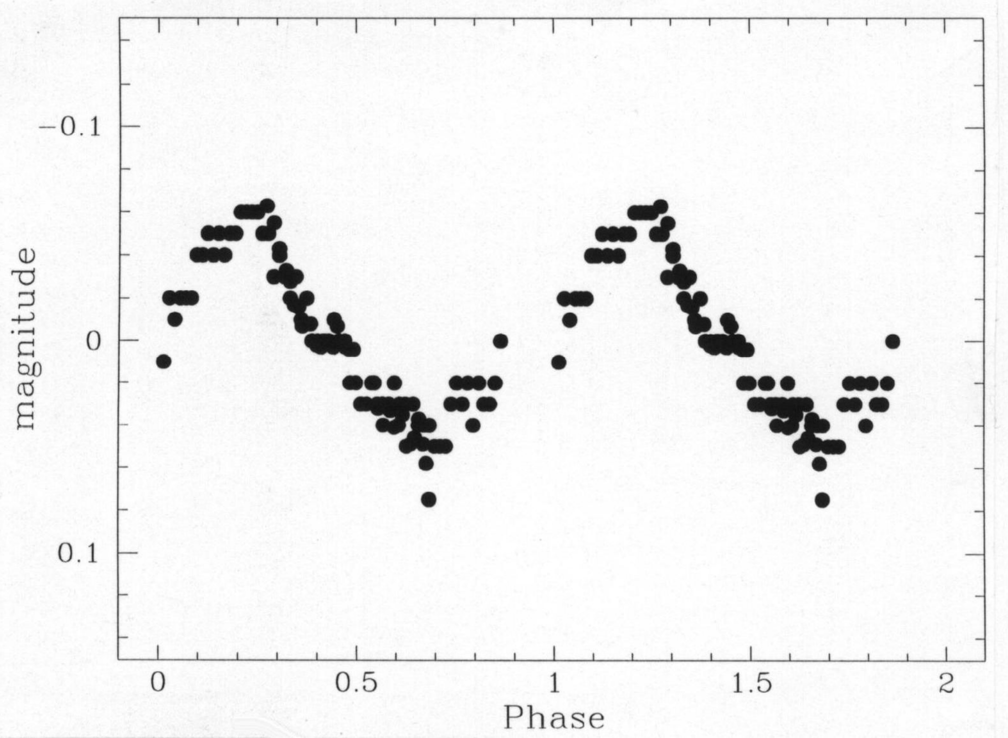

Fig. 5.7. *V* data folded with period *P* = 0.1996 days. Data points have been rescaled to a common zero magnitude level. Phases were arbitrarily referred to HJD = 0.00.

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

5.3.2. The spectra

The mean spectrum of MM Vel, taken about 300 days after the X-ray maximum (see Table 5.I), is shown in Fig. 5.8. The continuum appears slightly less steep than that displayed 60 days after the outburst (Della Valle et al. 1997, their Fig. 6), although it is difficult to exclude that it could be contaminated by the 'neighbor' 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 absorption is likely filled in by the corresponding emission. A faint emission core is also observed in the H_β absorption, as already noticed by Bailyn & Orosz (1995) and by Della Valle et al. (1997). This behaviour is similar to that displayed by V518 Per (=GRO J0422+32; Callanan et al. 1995), GRO J1655-40 (Bianchini et al. 1997; see also Ch. 6) e GU Mus (Della Valle et al. 1998; see also Ch. 7).

The measurements of the EWs of the Balmer absorption lines are reported in Table 5.II.

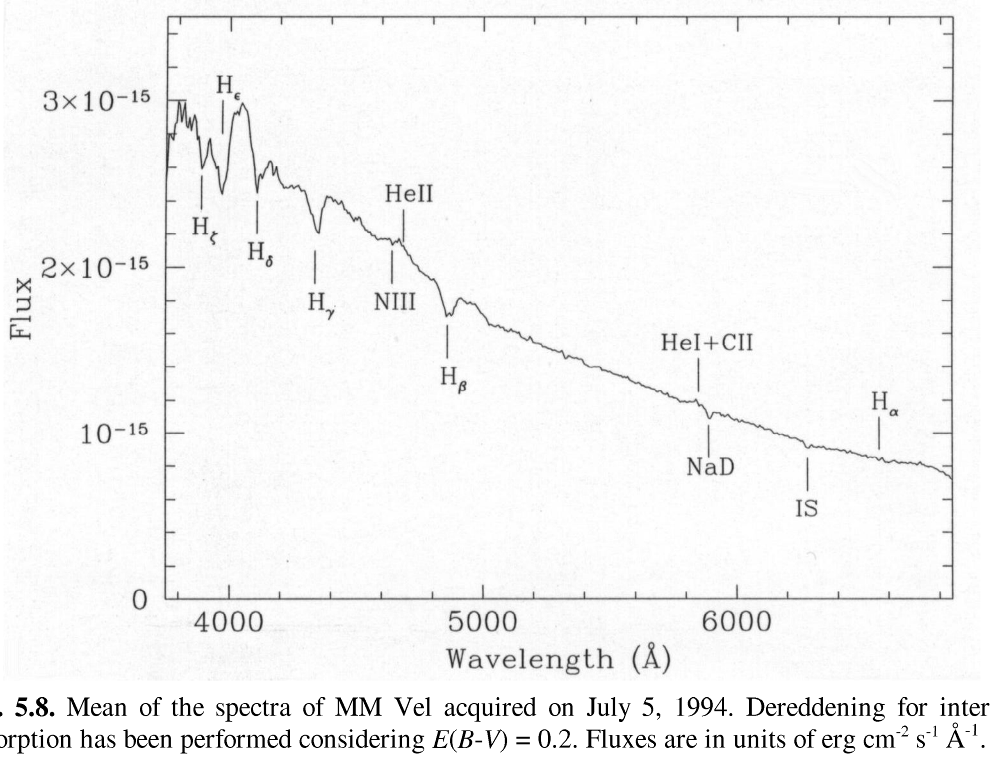

Fig. 5.8. Mean of the spectra of MM Vel acquired on July 5, 1994. Dereddening for interstellar absorption has been performed considering $E(B\text{-}V) = 0.2$. Fluxes are in units of erg cm^{-2} s^{-1} Å^{-1}.

The N III+He II emission bump at 4640-4686 Å is also detected. The N III, in particular, might have a double-peaked profile. Another noticeable feature is a broad bump at 5870 Å, probably due to a blend of He I and C II emissions. All this is in agreement with the features observed by Della Valle et al. (1997) in the spectrum they acquired 9 days after this one. Interstellar absorption lines are present at 5890 Å (the NaD doublet, with 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 spectroscopic features are clearly seen.

Table 5.II. EWs of Balmer absorption lines in the spectrum of MM Vel reported in Fig. 5.8. $H\varepsilon$ may be blended with C II and O II.

Balmer line	EW (in Å)
$H\beta$	5.07
$H\gamma$	4.61
$H\delta$	5.31
$H\varepsilon$	11.1
$H\zeta$	4.92

Then, the V magnitude and the B-V color index of the 'neighbor' star have been measured, in order to estimate its contamination on the spectra of MM Vel, which may become particularly important when the X-ray Nova will be observed at quiescence. It is found that $V \approx 17.9$ and $(B\text{-}V)_0 \approx 0.7$ (the last value is corrected for interstellar absorption). This indicates that the 'neighbor' is a star of mid or late G spectral type, depending on its luminosity class.

5.4. DISCUSSION

5.4.1. The superhump phemonenon and the optical light curve

As already said in the previous Chapters, 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 MM Vel 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), V518 Per (Kato et al. 1995) and, perhaps, also V2293 Oph (Masetti et al. 1996; see also Ch. 4 of this Thesis), have shown real superhump phenomena during the outburst, one may hypothesize that this is the general behaviour of all BHXNe. If this is the case, one can tentatively interpret the modulated light curve of Fig. 5.7 as due to the superhump mechanism.

One must however note that the folded light curve of Fig. 5.7 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, one 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 outburst decline (Bailyn 1992; his Figs. 4 and 5), whereas in V2293 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 light curves observed in SXTs probably remains in the many uncertainties involved in the superhump model calculations.

The ~1.6-hour modulation of the V light curve observed by Bailyn & Orosz (1995) does not appear in the data shown here; therefore, it should be regarded as a different phenomenon. One should note that these authors performed their observations six months after the November-December 1993 run reported here, and the star had faded down to $V \sim 18.5$ mag and was undergoing a small minioutburst.

One possibility is that the ~1.6-hour modulation was produced by one or more blobs of material orbiting in the inner parts of the disk, similarly to what observed in V2293 Oph after the outburst maximum (Masetti et al. 1996). One might perhaps suggest that, in general, the smoothness of a superhump light curve depends on the lack of orbiting blobs in the inner disk.

It is known from observations that superhump periods exceed the orbital ones by a few percent not only in SU UMa-type DNe but also in SXTs (Chevalier & Ilovaisky 1993 for QZ Vul, Remillard et al. 1992 for GU Mus and Chevalier & Ilovaisky 1995 for V518 Per); therefore, in the hypothesis that the observed modulation is a superhump, MM Vel might have the shortest orbital period ever found for a SXT.

The result by Shahbaz et al. (1996) seems to cast some doubt on the superhump interpretation for the periodicity found here during the outburst, as the value they found in quescence for the orbital period, 6.86 hours, is much longer than the modulation reported here. Actually, given the larger data set by those authors (more than 200 data points against about 100 of the present work), their uncertainty is indeed smaller; anyway, the object was observed by Shahbaz et al. (1996) at a luminosity level which was much lower than that of the November-December 1993 observations shown in this Chapter, and thus the error on their measurements is 0.1 mag (which, on the modulation of amplitude 0.23 mag found by them, is not negligible at all) against the 0.02 mag of uncertainty on the present photometric data. The presence of the 'neighbor' star, which in quiescence overwhelms the luminosity of the X-ray Nova and then introduces further uncertainties, should also be added to the above considerations. Moreover, it may be added that the photometry of the orbital period at quiescence should always be confirmed by spectroscopic observations(2): several cases are reported in literature of wrong measurements (e.g. Shahbaz et al. 1994 in the case of QZ Vul and Martin et al. 1995 in the case of V2107 Oph) later corrected by other works (Casares et al. 1995 in the first case and Remillard et al. 1996 in the second).

One should however note that the ratio between the superhump period presented here and the orbital one detected by Shahbaz et al. (1996) for MM Vel is about 2/3: this might lead to the conclusion that the superhump value is in fact a lower order harmonic of the *real* superhump period, or alternatively that the value reported by Shahbaz et al. (1996) is an upper order harmonic of the *real* orbital period value.

Finally, one more hypothesis is that the modulation observed during the outburst and presented in this Chapter is anything but a superhump and that it might be due to

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(2) Actually, the observations by Filippenko et al. (1999, PASP, 111, 969) seem to substantially confirm the results by Shahbaz et al. (1996) for the orbital period of MM Vel.

other transient disk effects, as in the case of short-term periodicities seen in V2293 Oph (Masetti et al. 1996).

From the observations taken from November 17 to December 6, 1993 it can be noticed that the optical light curve exhibited a decay rate of 0.0147 mag d^{-1} in both B and V bands between those dates. This seems a quite common trend for SXTs containing a BH, such as GU Mus (Della Valle et al. 1991), QZ Vul (Pavlenko et al. 1990) and V616 Mon (Tsunemi et al. 1977).

Therefore, by using this decline rate and extrapolating back to the date of the X-ray outburst, one obtains $V_{\rm max} = 13.85 \pm 0.15$ e $B_{\rm max} = 14.00 \pm 0.15$, in agreement with the estimate by Della Valle et al. (1997); from these values, one also gets an outburst amplitude of about 8 mag both in B and V, as usually seen in SXTs (van Paradijs & McClintock 1995; see also Sect. 3.4). Moreover, the presence of an optical secondary maximum $\approx$90 days after the X-ray outburst sholud be stressed: as already said in Sect. 3.4 of this Thesis, this behaviour is also typical for SXTs, which generally show an optical reflare at about 70-100 days after the onset of the X-ray outburst (Tanaka & Lewin 1995). This secondary maximum for MM Vel is very likely the optical counterpart of the X-ray maximum observed by Paciesas et al. (1995) ~85 days after the X-ray luminosity peak. Unfortunately, the poor observational coverage during that phase does not allow determining whether the restart of the activity firstly occurred in X-rays or in the optical.

5.4.2. The X-ray light curve

As already remarked in Section 5.1, the 8÷20 keV light curve of Fig. 5.1a given by Lapshov et al. (1994) shows a rather steep first decline with an *e*-folding time of 10 days; Then, ten days after maximum, the X-ray light curve presents a sort of *plateau* lasting not less than one month. The harder (20÷60 keV; Fig. 5.1b) X-ray light curve from the same authors has a similar behaviour, but with larger flickering. The presence of strong flickering in both light curves could be an indication of a low inclination for the system, since in this case one would see almost directly the central X-ray source.

Even admittedly the scanty statistics, the rapid decay and the presence of a long *plateau* are quite unusual for BHXNe, since their X-ray light curves decay with an *e*-folding time of ~30 days and no *plateau* is generally seen either before or after the secondary X-ray maximum (Fig. 3.6a). On the contrary, SXTs containing a NS show a more rapid X-ray decay: ≈3 days for Cen X-4 (Fig. 1 of Kaluzienski et al. 1980) ~10 days for both QX Nor (Lochner & Roussel-Dupré 1994) and KS 1731-260 (Fig. 2 of Sunyaev et al. 1990), ~12 days for A1742-289 (Murdin et al. 1980), and 20 days for Aql X-1 (Fig. 1 of Charles et al. 1980). The *plateau*, however, is absent also in the X-ray light curves of these objects with perhaps the only exception of A1742-289, for which Branduardi et al. (1976) indicate the possible, but not clear, presence of such a structure in the X-ray light curve.

Fourier analysis of the X-ray data points (Table 1 of Lapshov et al. 1994) reveals rather weak periodicity signals at 4.6 and 2.8 hours. The first one is close to the optical period found here; anyway, the X-ray light curves with both periods are quite noisy.

5.4.3. The mass of the compact object

If the observed modulation is a superhump, one can use Eq. (2.7) to determine the lower limit for the mass of the compact object in the system MM Vel.

The obtained value of ~1.6 $M_{\odot}$ is substantially below the maximum mass allowed for a rotating NS (i.e. 3 $M_{\odot}$: Rhodes & Ruffini 1974); nevertheless, one can not exclude that this system might contain a small mass BH like the SXT V518 Per (=GRO J0422+32). Indeed this object exhibited superhumps during outburst, 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 the modulation found here for MM Vel. Its optical light curve and its spectral behaviour during the decline also bear some similarities with MM Vel (although the X-ray light curve of V518 Per has a much slower decline, as reported by Vikhlinin et al. 1992).

On the other hand, as pointed out by Della Valle et al. (1997), it might be that MM Vel undergoes outbursts with recurrence times of ≈10 years, that is, shorter than those of the BHXNe, whose outbursts recur on a timescale of ≈50-100 years (Tanaka & Lewin 1995). In this sense, the behaviour of this SXTs is thus more similar to that of Aql X-1, Cen X-4, KS 1731-260 and QX Nor which, as stated above, are known to contain a NS.

The X-ray *e*-folding time also suggests an intermediate or low mass compact object. Indeed, according to Eq. (3.10), the rate of decay of the X-ray light curve, $\tau_{1/e}$, 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 $\tau_{1/e}$ observed in MM Vel is at least three times shorter than that seen in BHXNe, one can argue that in this system the mass of the compact object can override the NS stability limit only if the viscosity of the disk is considerably higher than that assumed for the other SXTs containing a BH.

Finally, it is known from theoretical models (Whitehurst & King 1991) that the superhump phenomenon takes place only if the mass ratio q is less than 0.25-0.33; from this, one can estimate the mass of the secondary. Assuming $q = 0.33$ and $M_1 \approx 1.6\ M_\odot$, it is found that M_2 is $\approx 0.5\ M_\odot$. Moreover, considering $P_{\rm orb} \approx P_{\rm sh}$, the Roche lobe of the secondary is ~0.5 $R_\odot$.

Both these values are consistent with a late-type K Main Sequence star.

5.5. CONCLUSIONS

The observations of MM Vel presented in this Chapter show the presence of a ~4.8-hour modulation of which may be likely due to a superhump phenomenon. No ~1.6-hour variations as those reported by Bailyn & Orosz (1995) have instead been detected in our data. The rate of decline of the X-ray light curve suggests a rather low-mass primary, while a lower limit for it of 1.6 $M_\odot$ is indicated by the superhump period. This in turn implies that the secondary might then be a late K type dwarf, as suggested by Della Valle et al. (1997), or at the very least an early K dwarf (Shahbaz et al. 1996). Of course, it should be kept in mind that the approach proposed by Mineshige et al. (1992) and expressed by Eq. (2.7) for the estimate of the mass of the compact object, which was originally intended for DNe, should be applied to SXTs with some degree of caution, as said in Sect. 3.4.

Spectroscopic observations confirm the presence of Balmer absorption lines with emission cores, as indicated by Bailyn & Orosz (1995) and by Della Valle et al. (1997), and the presence of interstellar absorption lines.

The *V* magnitude and the spectral type of the 'neighbor star' were measured and estimated, respectively: the results indicate a that this star is probably a late G-type star, which will make difficult the observations of the quiescent X-ray Nova.

It was then chosen to tentatively classify MM Vel, in absence of further observations, as a 'hybrid' SXT, because during the outburst it exhibited 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 BH: primarily, its similarity with the BHXN V518 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, and a periodic modulation of similar duration. This behaviour is not typical of SXTs harboring a NS. In all cases, the occurrence of the secondary optical maximum ~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 BHC (see Sect. 3.4). In addition, the optical decay rate of MM Vel is quite similar to those shown by other BHXNe.

On the other hand, we have also found some indications in favour of a NS candidate (i.e. a Type I SXT) like:

- the orbital period, which appears to be the shortest (or one of the shortest) among 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);

- the short *e*-folding decay time of the X-ray light curve;
- the short recurrence time between the outbursts.

As a final remark, we mention the fact that the X-ray *plateau* shown by MM Vel is a rather unusual feature (with perhaps the single exception of A1742-289) for both Type I and II SXTs.

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