X-ray and optical studies of black-hole X-ray transients

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An ellipsoidal modulation in X-ray Nova Velorum 1993 (= GRS 1009-45)

T. Shahbaz, F. van der Hooft, P.A. Charles, J. Casares & J. van Paradijs


Abstract

We present the first optical observations of the soft X-ray transient Nova Velorum 1993, taken during quiescence in 1995 and 1996. From the R-band photometry with a magnitude of 20.6, we find an orbital, ellipsoidal modulation with an amplitude of 0.23 mag at a period of 6.86 ± 0.12 hr. The optical spectra show only broad double-peaked Hα emission presumably arising from the accretion disk. We estimate the spectral type for the secondary to be late-G/early-K, which is consistent with the value for the mean density of the Roche lobe filling secondary star, obtained using the orbital period. By modeling the optical ellipsoidal modulations of the secondary star we determine a firm 95 per cent lower limit to the binary inclination of 37°.

5.1 Introduction

The X-ray transient Nova Velorum 1993 (GRS 1009–45) was discovered by the WATCH instrument on board GRANAT (Lapshov, Sazonov & Sunyaev 1993; Lapshov et al. 1994) and confirmed by the BATSE instrument on board of the Compton Gamma Ray Observatory (Harmon et al. 1993a) on 1993 September 12. The 2–200 keV X-ray spectrum of GRS 1009–45 was similar to the X-ray spectra of the soft X-ray transient (SXT) sources GS 2000+25 and GS 1124–68 (Kaniovsky, Borozdin & Sunyaev 1993), which are both dynamically proven black-hole candidates (Casares, Charles & Marsh 1995; Remillard, McClintock & Bailyn 1992). The X-ray spectrum of GRS 1009–45 consisted of a soft component which could be approximated by a blackbody temperature of 0.5 keV, and a power law with spectral index −2.5 at 10–100 keV (Kaniovsky et al. 1993). The primary X-ray outburst of GRS 1009–45 was similar
to GS 1124–68; however, two later maxima in the hard X-ray flux of GRS 1009–45 occurred at \( \sim 30 \) and \( \sim 85 \) days after the primary maximum, both of them occurring sooner than the secondary maximum observed in GS 1124–68 (Paciesas et al. 1995).

The optical counterpart of GRS 1009–45 was discovered in 1993 November as a blue object with \( V = 14.6 \) and broad H\( \alpha \) emission (FWHM \( \sim 30 \) Å) (Della Valle & Benetti 1993). Bailyn & Orosz (1995) observed the source between 150 and 200 days after the primary outburst in the V-band and found evidence for a secondary optical outburst and repeated mini-outbursts similar to those observed from the SXT Nova Persei 1992 (GRO J0422+32). The brightness of Nova Vel 1993 during these observations varied between \( V \sim 16 \) and \( V \sim 20 \). We report here on optical observations of Nova Vel 1993 during quiescence, from which we present a finding chart showing the source to be well resolved from its close neighbor star and also a medium-resolution red spectrum.

### 5.2 Spectroscopy

#### 5.2.1 Observations and data reduction

Optical spectra of Nova Vel 1993 were obtained in 1995 June 3 and 1996 March 25–26 with the 3.5m New Technology Telescope at the European Southern Observatory (ESO) in Chile using the ESO Multi Mode Instrument (EMMI). We used the red arm in medium dispersion mode, order-separating filter OG 530 and grating #8 with a dispersion of \( \sim 1.3 \) Å pixel\(^{-1} \) covering 6010–8575 and 6150–8720 Å for the 1995 and 1996 runs. The TEK 2048 × 2048 pixel CCD was used, binned with a factor of two in the spatial direction in order to reduce the readout noise. The dispersion direction was not binned. A slit width of 0\('\)8 was used which resulted in a resolution of 3.5 Å.

The seeing stayed below 1\('\) most of the time and conditions were photometric in both runs. The integration time of the spectra was 1800 sec in all cases. The CCD frames were corrected for the bias and flat-fielded in the standard way. For the data of each night an average bias frame (obtained using more than 10 bias frames) was subtracted from all data. The data were then flat-fielded using an average flat field. The stellar spectra were extracted from the CCD frames using an optimal extraction algorithm similar to that of Horne (1986) and wavelength-calibrated using Ar–Ne exposures taken at the same telescope position close in time to the object exposures. Spectra of the flux standards Feige 56 and HD 60778 were taken during the 1995 and 1996 observations, respectively, to obtain the relative flux calibration. Also, spectra of several bright F, G, K and M stars were taken as spectral type standards.

### 5.3 Photometry

#### 5.3.1 Observations

We obtained optical CCD photometry of Nova Vel 1993 on the Danish 1.54m telescope at ESO during two observation runs on 1995 May 8–10 and 1996 February 17–21. For the 1995 run the Tektronix TK1024M CCD was used giving a 6\(')7 × 6\(')7 field of view whereas for the 1996 run the Ford-Loral 2052 CCD was used giving a 13\(')3 × 13\(')3 field of view. The platescale for
Table 5.1: Magnitude of local field stars. The mean magnitude and scatter is quoted for Nova Vel 1993.

<table>
<thead>
<tr>
<th>Star number</th>
<th>$R$ (mag)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Star 001</td>
<td>20.600 ± 0.100</td>
<td>Nova Vel 1993</td>
</tr>
<tr>
<td>Star 002</td>
<td>17.431 ± 0.002</td>
<td>Bright companion</td>
</tr>
<tr>
<td>Star 003</td>
<td>20.566 ± 0.005</td>
<td>Comparison star</td>
</tr>
<tr>
<td>Star 004</td>
<td>20.895 ± 0.008</td>
<td>Comparison star</td>
</tr>
<tr>
<td>Star 005</td>
<td>20.723 ± 0.007</td>
<td></td>
</tr>
<tr>
<td>Star 006</td>
<td>16.904 ± 0.004</td>
<td></td>
</tr>
<tr>
<td>Star 007</td>
<td>18.357 ± 0.005</td>
<td></td>
</tr>
<tr>
<td>Star 008</td>
<td>18.225 ± 0.001</td>
<td></td>
</tr>
<tr>
<td>Star 009</td>
<td>17.332 ± 0.002</td>
<td>Local Standard</td>
</tr>
<tr>
<td>Star 010</td>
<td>18.030 ± 0.001</td>
<td></td>
</tr>
</tbody>
</table>

Figure 5.1: Finding chart for Nova Vel 1993 (GRS 1009–45) taken on 1995 May 9 at the Danish 1.54m telescope at ESO. An exposure time of 600 sec was used with a $R$-band filter. Nova Vel 1993 is marked as star 1 and has a mean magnitude of $R = 20.6$. Other field stars are also labeled (see Table 5.1). North is at the top and east is to the left. The field of view is $30'' \times 30''$. 
both runs was 0''39 pixel$^{-1}$. All the observations were taken with the Gunn R-band filter. The median seeing for the 1995 and 1996 runs was 1''1 and 1''2, respectively. We obtained a total of 246 images of Nova Vel 1993, of which 73 were from the 1995 run and 173 from 1996. The median exposure time used for both runs was 600 sec. Photometric standards were also observed during the 1995 observing run which we used to calibrate the data.

5.3.2 Data reduction

First, both sets were debiased and flat-fielded in the standard way. The bias level, obtained from the overscan region of the CCD, was subtracted from all data and the data were then flat-fielded using images of flat fields taken during each observing run. The crowded nature of the field and the faintness of Nova Vel 1993 implied that simple aperture photometry could not be used to separate the target from its bright companion 1''4 South-East. Instead we used the point spread function fitting algorithm DAOPHOT (Stetson 1987) in an ARK-compatible version.

We performed relative photometry on Nova Vel 1993 and stars 3 and 4 (which are of similar brightness to the target) using star 9 as a local standard. Figure 5.1 shows a finding chart in which Nova Vel 1993 is labeled as star 1 along with other stars in the field which we used as comparison stars and local standards. The data were calibrated using four Landolt standard fields (Landolt 1992): PG 0918 (five stars), PG 1323 (three stars), Mark A (four stars) and SA 110 (four stars), observed during photometric conditions in the 1995 observing run. The local standard was then calibrated, yielding a mean magnitude of $R = 17.332$. Observations of local field stars within one night showed that the photometric calibration was stable to within 0.06 mag. Table 5.1 lists the $R$ magnitudes of the comparison stars used as well as various field stars.

5.4 The optical spectrum

For the spectrum of Nova Vel 1993 obtained on 1995 June 3 we rotated the slit such that the close neighbor star with $R = 17.4$ (star 2; see Fig. 5.1, located 1''3 South and 0''6 East of the source) was also in the slit. Although the observing conditions were excellent during this night, extraction of the spectrum of Nova Vel 1993 from the CCD frame was difficult since it was partly blended with the spectrum of this bright neighboring star. The spectrum of this star is blue and shows H$\alpha$ in absorption. The partly extracted spectrum of Nova Vel 1993, i.e., the part of the spectrum farthest from the contaminating star, is red and featureless, apart from a broad, double-peaked H$\alpha$ emission line. However, we were not certain of the level of contamination by the neighboring star and decided to obtain more spectra of Nova Vel 1993 during the 1996 March observations.

This time we applied a rotation to the slit such that is was placed across Nova Vel 1993 and the star located 2''1 North and 3''1 East of the source (star 7; see Fig. 5.1). One spectrum of Nova Vel 1993 was obtained at 1996 March 25, and two additional spectra were taken during the next night. These last two spectra are of poorer quality owing to poorer seeing conditions and are possible contaminated by the bright neighbor star; the spectra show a blue excess, the H$\alpha$ emission is weaker and the overall flux level is increased by a factor $\sim 3$ with respect to the spectrum taken one night before. Therefore, we excluded these last two spectra of Nova Vel 1993 from our analysis.
Figure 5.2: The top section shows the smoothed spectra of Nova Vel 1993 taken in 1995 June and 1996 March. The 1995 spectrum has been shifted by 0.1 mJy for clarity. In the lower section we show the spectra of a G6, K0 and M2 star.

The 1995 and 1996 spectra of Nova Vel 1993 are displayed in Figure 5.2. The flux level of the 1995 spectrum is reduced by a factor ~ 2 with respect to the 1996 spectrum since it could only be extracted partly due to the blending with the spectrum of the neighboring star. Nevertheless, both spectra are very similar, showing a broad Hα emission line superimposed on a red featureless continuum. In the 1995 spectrum the Hα emission is clearly double-peaked with a separation between both components of 1020 ± 51 km s\(^{-1}\) (as derived from fitting Gaussian profiles). The evidence for the presence of a double-peaked structure in the spectrum taken in 1996 is less compelling. The zero-intensity full width at the base of the Hα emission line is 2850 ± 600 and 2700 ± 320 km s\(^{-1}\) for the 1995 and 1996 data, respectively.

Fig. 5.2 shows the 1995 and 1996 spectra of Nova Vel 1993 along with a G6, K0 and M2 star. No obvious molecular features are present in the Nova Vel 1993 spectra, thus making it difficult to determine the spectral type of the secondary star. Also, the continuum slope could be misleading because of reddening and disk contamination. However, if the disk contamination is similar to that in the other SXTs, then one would still expect to see some molecular features in the Nova Vel 1993 spectra, if the secondary star were a late-K/M star. Since we do not see any molecular features, the secondary star most probably has a spectral type of an early-K star or even earlier. High-quality spectra are clearly needed in order to determine the spectral type of the secondary accurately.
Figure 5.3: The resolved R-band photometry of Nova Vel 1993 taken during 1995 May 8 and 9 and 1996 February 17–21. Comparison stars 3 and 4 of similar brightness to Nova Vel 1993 are shown in the upper panel.

5.5 The orbital period

In order to find any periodicities present in the data, we first removed data points where the seeing was such that the target and star 2 were blended into one, i.e., when the seeing was greater than about 1"4. In these images the profile-fitting algorithm could not find the target. A total of 20 images were removed by this procedure. Figure 5.3 shows the data for Nova Vel 1993 and two comparison stars of similar brightness to Nova Vel 1993.

Like the other SXTs, we expect the quiescent optical modulation of Nova Vel 1993 to be primarily caused by the ellipsoidal variations of the secondary star. These variations arise since the observer views differing aspects of the gravitationally distorted star as it orbits the compact object (van Paradijs & McClintock 1995). In theory, the modulations should have two maxima and two minima. The two minima may be unequal depending on the binary inclination, but the maxima should be equal. In practice, however, the light from the accretion disk contaminates the ellipsoidal variations of the secondary star, making detailed interpretations of the optical light curves difficult (see Shahbaz, Naylor & Charles 1993).
Figure 5.4: Results of the period search using the combined 1995 and 1996 data of Nova Vel 1993 during quiescence. Top: phase dispersion minimization (PDM) spectrum. The deepest minimum is found at 3.5 cycle day$^{-1}$ (indicated by the star). All the other minima correspond to twice this frequency or a simple fraction (2/3, 1/3) of it (shown by white circles and their sidelobes. Middle: Lomb-Scargle power spectrum. The strongest peak is found at a period of 7.0 cycle day$^{-1}$. Similarly to the PDM spectrum, all other peaks correspond to a multiple of this frequency. The orbital period is half the strongest peak, and is indicated by the star. Bottom: a Bayesian probability spectrum obtained using a priori knowledge of the expected double-humped modulation. The strongest peak is found at 3.5 cycle day$^{-1}$, and represents the orbital period.
Therefore, we first analyzed the optical light curve of Nova Vel 1993 using the phase dispersion minimization (PDM) algorithm (Stellingwerf 1978). This technique is insensitive to the shape of the modulation, but does not remove the effects of the window function. The method groups the data in phase bins and seeks to minimize the dispersion within the bins. The true period corresponds to the deepest minimum of the statistic. The PDM spectrum was computed in the frequency range 2 to 10 cycle day\(^{-1}\) at a resolution of \(8.6 \times 10^{-4}\) cycle day\(^{-1}\) with 25 phase bins. The deepest minimum is found at 3.50 cycle day\(^{-1}\) or 6.86 hr (indicated by the star). All the other minima present in this spectrum are either a multiple (2\(f\)) or submultiple (2\(f/3, f/2\)) of this frequency. All main minima are accompanied by the corresponding sidelobes, which are separated by intervals of 1, 1/2, 1/3 and 1/4 cycle day\(^{-1}\) (see Figure 5.4, top panel).

The common method of computing a discrete Fourier transform (DFT) and halving the estimate of the period is equivalent to assuming that the minima are of equal depths. This may not be the case, as other observed ellipsoidal modulation may contain unequal minima depending on the binary inclination and the contamination by the accretion disk. A Lomb-Scargle periodogram (Lomb 1976; Scargle 1982) of the combined 1995 and 1996 data sets was then computed with the same resolution and frequency range as was used for the PDM technique. The strongest peak was found at a period of 3.41 hr (see Fig. 5.4, middle panel), i.e., about half the period obtained using the PDM method.

Using Bayesian methods (Bretthorst 1988) to analyze the data it is possible to include any a priori knowledge about the expected modulation. The results can then be analyzed using probability analysis. The Bayesian periodogram can, in principle, give an accuracy which is an order of magnitude better than the DFT methods (Martin 1995). The ellipsoidal modulation is equivalent to a sinusoid of frequency \(2f\) which lags by 90° in phase relative to a sinusoid at a frequency \(f\). The difference between the minima is usually small, which means that the amplitude of the sinusoid at a frequency \(f\) will be smaller than that at \(2f\). This information can be used in a Bayesian two-frequency model to constrain the frequency and phase of the two sinusoids relative to one another.

We performed such a two-frequency Bayesian analysis on the combined 1995 and 1996 data. Fig. 5.4 (bottom panel) shows the Bayesian spectrum computed in the frequency range 2 to 10 cycle day\(^{-1}\) at a resolution of 0.001 cycle day\(^{-1}\), along with the periodograms obtained using the PDM and Lomb-Scargle methods. The strongest peak in the Bayesian analysis is at 3.505 cycle day\(^{-1}\), with a probability of \(10^{37}\). The next strongest peak is at 7.010 cycle day\(^{-1}\) with a probability \(10^{11}\) smaller than the 3.505 cycle day\(^{-1}\) peak. Thus we conclude that the data can be described best by a modulation at a frequency of 3.505 cycle day\(^{-1}\).

The alias pattern from the two data sets can be clearly seen in Fig. 5.5. Rather than being a single line, the plot in the PDM spectrum shows an envelope of power, which is filled in with fine structure. This fine structure is the alias pattern from the two data sets due to their 10 months’ separation. Also shown in Fig. 5.5 as a solid line is the PDM spectrum for the 1996 February data alone, where, as expected this alias pattern is not present. However, the line is still broad because of the quality and short baseline of the 1996 February data set being used alone. We thus take the orbital period to be 3.50 ± 0.06 cycle day\(^{-1}\) or 6.86 ± 0.12 hr, where the uncertainty quoted is the 1\(\sigma\) width of the line obtained by fitting the line with a Gaussian function.
**Figure 5.5:** This figure shows part of the PDM spectrum around the orbital period at high resolution. The thin weighted line is the combined 1995 and 1996 data of Nova Vel 1993, and the heavy weighted line is the 1996 data set alone. One can clearly see the 0.0035 cycle day$^{-1}$ alias pattern between the 1995 and 1996 data sets taken about 10 months apart.

### 5.6 The ellipsoidal light curve

From the orbital period of 6.86 hr we can calculate the mean density of the secondary star, assuming that it fills its Roche Lobe (Frank, King & Raine 1992). This gives \( \rho = 2.4 \text{ g cm}^{-3} \), which is similar to the value of the mean density of a K5 V star. By comparison with the other SXTs, however, the secondary star could be undermassive for its spectral type (Chevalier et al. 1989; McClintock & Remillard 1990; Shahbaz, Naylor & Charles 1994a), and so this estimate for the spectral type should be used with caution. It should be noted that all the SXTs with a similar orbital period to Nova Vel 1993 have secondary stars with early-K spectral types. The optical spectra presented in Section 2.2 also suggests that the spectrum of the secondary star is an early-type K star.

We can describe the observed 0.23 mag R-band modulation as being due to the ellipsoidal variations of the secondary star. The expected modulation is a double-humped modulation with two maxima and two minima per cycle, the minima being centered on phases 0.0 and 0.5, where phase 0.0 is defined as the superior conjunction of the secondary star. By comparing the amplitude of the optical modulation (~0.25 mag) with other SXTs in quiescence, e.g., A0620−00 (McClintock & Remillard 1986), Cen X-4 (McClintock & Remillard 1990) and GS 2000+25 (Chevalier & Ilovaisky 1993) one can conclude that the binary inclination must be relatively high. For this to be true the deepest minimum must correspond to phase 0.5, since the difference between the minima is only evident when the system is at high inclinations, and is a result of the larger gravity darkening at the inner Lagrangian point. It should be noted
that the observed optical modulation is most probably contaminated by flux arising from the accretion disk, similar to other SXTs. The effect this would have on the optical light is that the true ellipsoidal modulation would be underestimated, implying that the value obtained for the binary inclination will also be underestimated.

Using the data obtained on the night of 1996 February 18, where we observed Nova Vel 1993 for the longest period of time, we can estimate the time of phase 0.0. This estimate was found by fitting the brightest minimum with a Gaussian function in order to determine the epoch of minimum light. We thus obtain the orbital ephemeris to be HJD 245 0132.7973(32) + 0.286(5) × N, where 1σ errors are quoted.

The data were then folded on this ephemeris and binned into 20 phase bins. Ellipsoidal model fits were performed using $T_{\text{eff}} = 4500$ K: the appropriate limb-darkening coefficient was taken from Al-Naimy (1978) and a gravity-darkening exponent of 0.08 was used, appropriate for a convective star. Since the compact object in Nova Vel 1993 is likely to be a black hole, and for a given inclination the ellipsoidal amplitude changes little for $q > 5$ (Shahbaz et al. 1993, 1994a, 1994b) and therefore depends almost entirely on inclination alone, we have assumed $q = 15$, typical of the black-hole SXTs. Folding the data on the orbital ephemeris and fitting it with the ellipsoidal model, we find the binary inclination to be $44^\circ \pm 6^\circ$ (90 per cent confidence). The uncertainty quoted here was calculated according to Lampton, Margon & Bowyer (1976) after the error bars had been rescaled to give a minimum $\chi^2_\nu$ of 1.
Figure 5.6 shows the best ellipsoidal fit to the Nova Vel 1993 data. The fit yielded a minimum $\chi^2_r$ of 3.2. Also shown are linear fits to the comparison stars. The $\chi^2_r$ for these fits were 0.7 and 2.3 for stars 3 and 4, respectively. Changing $T_{\text{eff}}$ by 500 K and using $q = 5$ introduces an extra uncertainty in the inclination of $3^\circ$. Therefore, we estimate the total uncertainty in the binary inclination to be $7^\circ$, implying $i = 44^\circ \pm 7^\circ$.

In light of the effects the accretion disk will have on the amplitude of the light curve, the value we obtain for the binary inclination should be used as a lower limit. Thus we find the 95 per cent lower limit to the binary inclination to be $37^\circ$. A firm upper limit to the binary inclination arises from the absence of X-ray eclipses. This implies $i < 80^\circ$. We thus constrain the binary inclination to lie in the range $37^\circ \leq i \leq 80^\circ$.

## 5.7 Conclusion

The similarity of the X-ray behavior of Nova Vel 1993 during outburst to that of other SXT black-hole candidates, and the absence of any type-i X-ray bursts, suggests that Nova Vel 1993 is a promising black-hole candidate. We have obtained quiescent optical light curves, which show the ellipsoidal variations of the secondary star. We have determined the orbital period to be $6.86 \pm 0.12$ hr, implying that Nova Vel 1993 is one of the shortest period black-hole candidates. By modeling the ellipsoidal variations we place a firm 95 per cent lower limit to the binary inclination of $37^\circ$. From optical spectroscopy we estimate the secondary to be an early-type K star. Unfortunately, it is not possible to derive a mass function for the system as yet, as there is no currently available radial velocity curve for the secondary star. This will be the subject of future studies.

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