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

van der Hooft, F.

Citation for published version (APA):
vander Hooft, F. (1998). X-ray and optical studies of black-hole X-ray transients

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The black-hole transient Nova Scorpii 1994 (= GRO J1655–40): Orbital ephemeris and optical light curve


Abstract

We have measured the brightness of the optical counterpart of the black-hole X-ray binary Nova Sco 1994 (GRO J1655–40) during 40 nights between 1995 May 3 and July 27. From our observations and data from the literature we refine the orbital period to be $2.62040 \pm 0.00098$ days. We model the $R$-band light curve as primarily being due to an X-ray heated secondary, using a model that includes a Roche lobe filling secondary star, the effects of X-ray heating on both the concave accretion disk and the X-ray illuminated surface of the secondary, shadowing of the secondary and disk, and mutual eclipses of the disk and the secondary star. From the shape of the light curve we constrain the inclination of the system to lie in the range $65^\circ$–76$^\circ$ and constrain the mass ratio $q = M_1/M_2$ to lie in the range 3.8–5.5. This implies a mass range for the secondary star and compact object of $0.95$–1.8 $M_\odot$ and 4.9–6.8 $M_\odot$, respectively. The $(V-R)$ and $(R-i)$ color curves do not show evidence of significant variability with orbital phase during 1995 June–July, their average values being $1.06(3)$ and $0.86(2)$ mag, respectively.

6.1 Introduction

THE SOFT X-RAY transient (SXT) Nova Sco 1994 (GRO J1655–40) was discovered with the Burst And Transient Source Experiment (BATSE) on board the Compton Gamma Ray Observatory on 1994 July 27 (Zhang et al. 1994). After its initial three week long outburst, in which a peak intensity of 0.7 Crab (20–100 keV) was reached (Crary et al. 1996b), it remained...

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active, showing repeated outbursts separated by about 120 days (Zhang et al. 1995) each typically lasting many weeks (Harmon et al. 1995a; Harmon et al. 1995b; Wilson et al. 1995). Radio observations have shown that Nova Sco 1994 exhibits radio outbursts which generally lag the X-ray outbursts by an interval of several days to two weeks (Harmon et al. 1995b; see also Paciesas et al. 1996). During radio outbursts material is ejected from the central source in opposite directions at superluminal speeds (Tingay et al. 1995; Hjellming & Rupen 1995). Models for the radio jets (Hjellming & Rupen 1995) suggest an orbital inclination of ~85°, indicating that Nova Sco 1994 may be an eclipsing binary.

Bailyn et al. (1995a) identified the optical counterpart of Nova Sco 1994, its visual brightness having increased by about 3 mag to V = 14.4 during the initial X-ray outburst. The optical light curve of Nova Sco 1994 shows a primary and secondary minimum, possibly caused by mutual eclipses of the accretion disk and the F3-F6 type secondary star (Bailyn et al. 1995b). This is the earliest spectral type of any of the SXTs known (van Paradijs & McClintock 1995). The optical brightness of Nova Sco 1994 showed a sharp reduction in its optical brightness on 1994 August 17, interpreted by Bailyn et al. (1995a) as a possible eclipse. From radial-velocity variations Bailyn et al. (1995b) established a spectroscopic period of 2.601 ± 0.027 days and a mass function f(M) = 3.16 ± 0.15 M⊙. The observed mass function and the possible high orbital inclination leads to the conclusion that the compact object in Nova Sco 1994 is a black hole with a maximum mass of 5.4 ± 0.2 M⊙ for secondary masses less than 1.5 M⊙ and inclination ≥ 80° (Bailyn et al. 1995b). It is thus of particular interest as a low-mass black hole (compared to, e.g., V404 Cyg, Casares & Charles 1994) which might have been produced by the accretion-induced collapse of a neutron star (Brandt, Podsiadlowski & Sigurdsson 1995).

We have conducted an extensive optical photometry campaign to study the light curve of Nova Sco 1994 using telescopes in Tasmania and Chile. In Section 2 we describe the observations and the photometric analysis. Average orbital light and color curves, an improved orbital ephemeris and model fitting are presented in Section 3 and our results are discussed in Section 4.
6.2 Observations and data analysis

We observed Nova Sco 1994 during the period 1995 May–July with the 1.0m telescope of the University of Tasmania near Hobart, and the Dutch 0.91m and Danish 1.54m telescopes at the European Southern Observatory (ESO) in Chile. All telescopes were equipped with CCD cameras and standard B, V and R filters, and a Gunn i filter. Integration times ranged from 1 to 10 min, depending on the filter, telescope and atmospheric conditions. A log of the observations is given in Table 6.1. All images were corrected for the bias and flat-fielded in the standard way.

We applied aperture photometry to Nova Sco 1994 and several nearby comparison stars within the field of view, using MIDAS and additionally written software operating in the MIDAS environment. We selected 3 comparison stars which were checked for variability during each night separately, and over the entire data set. From the distribution of the relative magnitudes between the comparison stars over the entire data set we conclude that they are stable within 0.02 mag. We estimate the accuracy of a single measurement of the differential magnitude of Nova Sco 1994 (relative to the average of the 3 comparison stars) to be 0.002 mag in the different bands. The differential magnitudes obtained in Tasmania have a small offset (< 0.03 mag) with respect to the data obtained at ESO. Also, the accuracy of these data is less (0.015 mag in R and i, 0.03 mag in V) due to poorer observing conditions and a lower signal-to-noise ratio.

Calibration of data obtained with the Danish and Dutch telescopes was performed using four different Landolt standard fields (Landolt 1992), PG 0918 (five stars), PG 1323 (three stars), Mark A (four stars), and SA 110 (four stars), during photometric nights that had 1″ seeing or better. Observations of different standard fields within one night showed that the accuracy of the photometric calibration was better than 0.05 mag. The differential magnitudes of Nova Sco 1994 measured with the Tasmanian telescope were given an offset such that they overlapped the data obtained contemporaneously at the Danish and Dutch telescopes.

6.3 Results

A history of the brightness variations of Nova Sco 1994 is given in Figure 6.1. During the period 1995 May–July the optical brightness increased (apparently steadily) by about 0.9 mag in V and R to 15.7 and 14.7, respectively; in the same period the i magnitude increased to 13.8.

We removed this long-term trend from the differential magnitudes by applying linear fits to the two extended data sets (June–July Dutch data, Tasmanian data, respectively) independently, and subtracting the mean from each of the remaining smaller data sets. Due to the uniform (orbital phase) sampling of the data, the detrend could be applied satisfactorily to each data set.

6.3.1 Orbital ephemeris

A Lomb-Scargle periodogram (Press & Rybicki 1989) of the detrended R-band data (483 data points) is shown in Figure 6.2. The periodogram has a distinct maximum corresponding to 1.3106 days; the second maximum occurs at 2.6246 days, very close to twice this period. When a temporally contiguous subset of the R-band data (i.e., excluding the data taken during the start of 1995 May and the end of 1995 July; 244 remaining data points) is subjected to a periodicity analysis we find a maximum corresponding to a period of 1.3123 days, close to the period found in the analysis of all available R-band data.
Figure 6.1: $R$-band magnitudes of Nova Sco 1994 (*bottom*) and one of the comparison stars (*top*) during the period 1995 May–July. Apart from a long-term trend, Nova Sco 1994 is clearly variable on a time scale of hours. The differential magnitude of one of the three reference stars (relative to the remaining two) shown in the top panel is stable within 0.01 mag. The start of the hard X-ray outburst on 1995 July 22 detected by BATSE is indicated by an arrow.

The periodogram of the $V$-band data (158 data points, excluding the 1995 May $V$-band data since they were taken in a single night during which Nova Sco 1994 was constant within 0.01 mag) shows a maximum at a period of 1.3038 days. The period search in the $i$-band data (99 data points during 1995 June–July) results in a period of 1.3039 days. Given the long baseline (85 days), and the largest number of data points (483) we consider the period of 1.3106 days derived from the $R$-band data as the most reliable.
Figure 6.2: Lomb-Scargle periodogram of the complete set of detrended (see text) R-band data. The distinct maximum corresponds to a period of 1.3106 days. The inset shows an enlargement of the same periodogram for periods longer than one day.

We calculated sinusoidal fits with a fixed period of 1.3106 days to the R-band data of each set of observations separately, having the extensive data set obtained at the Dutch telescope split further into two subsets. The accuracy of the arrival times of minimum light was estimated to be 0.05 days. From a least-squares fit to these arrival times and the respective cycle numbers we derive a photometric ephemeris for Nova Sco 1994 with $\chi^2 = 4.20$ for 4 degrees of freedom. Following the results obtained by Bailyn et al. (1995b) and further supported by the difference in the two minima of the light curve, we assume that the light curve has 2 minima per orbital cycle. Hence, the implied orbital period of Nova Sco 1994 is twice the value obtained from the least-squares fit, i.e., 2.6212 days. The times of the primary (deeper) minima are described by the following photometric ephemeris:

$$T_{\text{min}(\HJD)} = 2449885.592(21) + 2.6212(16) \times N$$

where N denotes the number of cycles. The detrended R-band light curve, folded at this photometric ephemeris, is shown in Figure 6.3. The light curve shows two clear minima, differing by about 0.1 mag in depth, and two maxima of equal brightness. The peak-to-peak modulation of the light curve is $\sim 0.35$ mag. We have determined the relative phasing of the four extremes by fitting parabolae. The maxima occur at phase 0.30(1) and 0.69(1), the minima occur at 0.0 (by definition) and 0.51(1), with the first value corresponding to the deepest minimum. The detrended R-band light curve, folded at the photometric ephemeris and binned into 20 phase bins, is shown in the bottom panel of Figure 6.4. To prevent possible distortion of the binned light curve due to the detrending, we excluded in this figure the data taken during 1995 May which covered less than one orbital cycle.
We calculated the $(V-R)$ and $(R-i)$ color curves of Nova Sco 1994 from the 1995 June–July observations using consecutive $V$, $R$ and $i$ measurements taken close in time. The $(V-R)$ and $(R-i)$ color curves folded at the photometric ephemeris and binned into 20 phase bins, are displayed in the top panels of Fig. 6.4. These color curves do not show evidence of significant variability with orbital phase. The average values for the $(V-R)$ and $(R-i)$ colors during this period were 1.06(3) and 0.86(2) mag, respectively. The average $(B-V)$ and $(V-R)$ colors derived during the night of 1995 May 4 were 1.480(8) and 1.026(5) mag.

### 6.3.2 Orbital inclination

We observed Nova Sco 1994 while it was $\sim 1$ mag brighter in the $R$-band than its quiescent brightness, the extra light probably arising from the accretion disk. Although the optical light curves of Nova Sco 1994 are reminiscent of the ellipsoidal variations of the secondary star (Shahbaz, Naylor & Charles 1993), one must take into account the effects of X-ray heating of the secondary star and accretion disk, which will alter the shape of the light curve (van Paradijs & McClintock 1995).

In order to interpret the optical light curves, we used a model that includes a Roche lobe filling secondary star, the effects of X-ray heating on the secondary and a concave accretion disk, shadowing of the secondary star and the disk, and mutual eclipses of the disk and the secondary star. The intensity distribution on the secondary star is calculated using Kurucz model atmospheres and the concave accretion disk is assumed to radiate as a blackbody. The temperature distribution of the accretion disk is calculated according to Vrtilek et al. (1990). This model is similar to the models described by Tjemkes, Zuiderwijk & van Paradijs (1986) and de Jong, van Paradijs & Augusteijn (1996), which have been applied to 1254–690 and 1755–338 (de Jong et al. 1996).
Figure 6.4: Detrended R-band light curve of Nova Sco 1994 (bottom) and $(V-R)$ and $(R-i)$ color curves (top), folded at the photometric ephemeris $T_{\text{min}}(\text{HJD}) = 2449885.592(21) + 2.6212(16) \times N$ and binned into 20 phase bins. Each bin of the binned R-band light curve and the binned $(V-R)$ and $(R-i)$ color curves contain on average 15, 10 and 7 data points, respectively. The error bars show the rms fluctuations about the mean. All curves are shown twice for clarity.
Figure 6.5: The 90 percent confidence regions for fits to the R-band light curve in the $(i, q)$ plane, obtained by collapsing the solutions along the $R_{\text{disk}}$ axis. Results of fits using $L_X = 1$ and $3 \times 10^{36} \text{ erg s}^{-1}$ are shown as solid and dashed lines, respectively. Also shown are the bounds to the allowed solutions obtained from the absence of the compact object eclipse and the tidal eclipse limit to the size of the accretion disk.

We performed least-squares fits to the R-band light curve using the model described above. The model parameters are the binary mass ratio, $q = M_1/M_2$, inclination, $i$, the mass of the secondary star, $M_2$, the X-ray luminosity, $L_X$, the size of the accretion disk, $R_{\text{disk}}$ (as a fraction of the distance to the inner Lagrangian point $R_{L1}$) and the flaring angle of the accretion disk, $\alpha$. The albedo of the accretion disk and secondary star were taken to be 0.95 and 0.40 respectively (see results obtained by de Jong et al. 1996).

We used two values for $L_X$, $1 \times 10^{36} \text{ erg s}^{-1}$ and $3 \times 10^{36} \text{ erg s}^{-1}$ (the 3$\sigma$ BATSE upper limit during the period of our observations, Harmon, private communication), and searched for solutions in the $(i, q, R_{\text{disk}})$ plane, using only parameter combinations that satisfied the mass function, i.e., given each set of $(i, q)$ values we determined $M_2$, which was subsequently used in the model fit. We searched $i$ in the range 40$^\circ$–90$^\circ$, $q$ in the range 3–10, and $R_{\text{disk}}$ in the range 0.4–0.7 $R_{L1}$.

Figure 6.5 shows the solutions in the $(i, q)$ plane, obtained by collapsing the solutions along the $R_{\text{disk}}$ axis onto the $(i, q)$ plane. The 90 percent confidence regions are shown, calculated according to Lampton, Margon & Bowyer (1976) with 5 interesting parameters $(i, q, R_{\text{disk}}, \alpha,$ and the normalization), after the error bars had been scaled to give a minimum $\chi^2$ of 1. We
find that the best fits are those with a small accretion disk, $R_{\text{disk}} = 0.4 \ R_{L1}$. The solid and dotted lines in Fig. 6.5 mark the contours for fits using $L_X = 1 \times 10^{36} \text{ erg s}^{-1}$ and $3 \times 10^{36} \text{ erg s}^{-1}$, respectively. We also show the physical bounds placed on the geometry of the system: the absence of X-ray eclipses implies $i < 76^\circ$ and the maximum size allowed for the accretion disk (i.e., the tidal radius $0.75 \ R_{L1}$) implies $i > 65^\circ$. Therefore, we constrain the system to lie at an inclination between $65^\circ$–$76^\circ$. From Fig. 6.5 it follows that we can constrain the mass ratio $q$ to lie in the range 3.8–5.5 at the 90 percent confidence level. Figure 6.6 shows the R-band light curve with model fits for $i = 68^\circ$, $R_{\text{disk}} = 0.4$ and 0.7 $R_{L1}$ and $L_X = 1$ and 3 $\times 10^{36} \text{ erg s}^{-1}$, respectively.

### 6.4 Discussion

During the period of our observations the optical brightness of Nova Sco 1994 increased (apparently steadily) by 0.9 mag to $V = 15.7$. Bailyn et al. (1995b) found the average brightness of Nova Sco 1994 to be $V = 16.5$ (1995 March 18–25) and $V = 16.7$ (1995 April 5–24), close to the quiescent brightness of $V = 17.3$ (Bailyn et al. 1995a). Between 1995 June 26 and July 3, and during 1995 August 4–7, Orosz, Schaefer & Barnes (1995) measured $V = 15.9$ consistent with the observations discussed here.

On 1995 July 22 the onset of an outburst of hard X-rays ($> 20$ keV) from Nova Sco 1994 was detected with BATSE which reached a maximum intensity of $650 \pm 30 \text{ mCrab}$ (20–100
keV) on August 1 (Harmon et al. 1995c; Harmon, Paciesas & Fishman 1995). Our measurements show that the optical brightness of Nova Sco 1994 increased long before and during the onset of this X-ray outburst. The maximum of the X-ray outburst was not covered by our observations, but those performed by Orosz et al. (1995) during the decay of the X-ray outburst in early August, showed that the optical brightness of Nova Sco 1994 decreased as well. The \((V-R)\) and \((R-i)\) color curves of Nova Sco 1994 did not show variability with the orbital period and had average values of 1.06(3) and 0.86(2) mag, respectively. However, Bailyn et al. (1995b) detected a color variation in the light curves of Nova Sco 1994 through orbital phase during their observations in 1995 March and April, with the source being redder during inferior conjunction of the secondary and bluer at the other conjunction.

The analysis of our photometric observations leads to an orbital period of 2.6212(16) days. The accuracy of this measurement can be improved by combining our results with those published in other investigations. Bailyn et al. (1995b) determined the moment of maximum redshift of the velocities for the secondary star in Nova Sco 1994 to occur at Heliocentric Julian Day (HJD) 244 9839.083(3). This epoch corresponds to photometric phase 0.257(13) (calculated with respect to the ephemeris given above), indicating that the photometric minimum at phase 0.0 corresponds to inferior conjunction of the secondary star. The change of blue-to-redshift of the velocities for the secondary star, as determined by Casares (private communication) occurred at HJD 244 9885.589(19). This corresponds to photometric phase 0.001(11). Adding the corresponding two spectroscopic epochs of minimum light to our photometric epochs leads to the following ephemeris:

\[
T_{\text{min}}(\text{HJD}) = 244 9838.4277(89) + 2.62040(98) \times N
\]

where the errors in the zeropoint and period were calculated by requiring \(\chi^2 = 1.0\) for 6 degrees of freedom.

Bailyn et al. (1995b) observed a fiducial minimum in the V-band light curve of Nova Sco 1994 on 1995 April 2 (HJD 244 9809.70) which they used to improve their spectroscopic ephemeris. However, they could not phase all photometric and spectroscopic data with this ephemeris and suggest that activity in the disk may be responsible for the apparent phase offset. The April 2 minimum occurs at phase 0.04 (calculated with respect to the refined ephemeris given above), close to the expected photometric minimum at phase 0.0. In view of the different shape of this narrow minimum compared to the light curve observed on all other occasions, we choose not to use this epoch in our effort to improve the orbital period of Nova Sco 1994. The possible eclipse event on 1994 August 17 reported by Bailyn et al. (1995a) occurred at HJD 244 9581.62(5) (according to their Fig. 4) and corresponds to photometric phase 0.997(27) when using the refined ephemeris given above. However, since this possible eclipse event did not recur and given the lack of data during this particular minimum and the strong photometric variability of Nova Sco 1994 at that time, we choose not to include this epoch either.

The folded light curve of Nova Sco 1994 (after removal of the long-term trend) shows two equally bright maxima, occurring at phases 0.302 and 0.691, and two unequal minima at phases 0.0 (by definition) and 0.505, when fitted by parabolae. Within one orbital cycle the light curve is smooth. Cycle-to-cycle variations in the shape of the light curve of ±0.1 mag occur as well. During our observations the average V-band brightness of Nova Sco 1994 was about ~1 mag brighter than in quiescence. As a result, ellipsoidal variations contribute at most a minor part of the observed brightness modulations. The light curve of Nova Sco 1994 is fairly similar to those of high inclination systems such as CAL 87, 2A 1822–371 and Her X-1.
Figure 6.7: The $(M_2, M_1)$ plane together with the limits placed on the mass of the secondary from evolutionary arguments ($0.23 \leq M_2 \leq 2.3 M_\odot$) and the limits obtained from calculating model fits to the $R$-band data. The mass of the compact object is restricted to lie in the range $4.94-6.79 M_\odot$ and the mass of the secondary star in the range $0.95-1.78 M_\odot$.

(van Paradijs & McClintock 1995). The light curves of these systems are dominated by X-ray heating of the secondary star, and by mutual eclipses of the secondary star and the accretion disk. The luminous accretion disk provides an independent source of light, which, in the absence of mutual eclipses, will decrease the amplitude of the light curve, and may cast an X-ray shadow on the secondary, decreasing the effect of X-ray heating substantially. Haswell (1996) has shown recently that small brightness variations of an accretion disk can affect the detailed shape of the double-waved optical light curves of quiescent SXTs. The optical contribution of a bright accretion disk will change in the different pass bands and is expected to be least in the red. Superhump variations may affect the detailed shape of the light curve as well (King 1995; O'Donoghue & Charles 1996).

From a special-relativistic kinematic model of the superluminal radio source in Nova Sco 1994, Hjellming & Rupen (1995) have derived an inclination angle of $85^\circ$. At this inclination regular eclipses of the compact X-ray source by the secondary should occur. These are not observed (Harmon et al. 1995b) and our modeling of the $R$-band light curve constrains the inclination of Nova Sco 1994 to lie between $65^\circ-76^\circ$. The absence of X-ray eclipses while viewing the binary system at a high orbital inclination can possibly be explained by a model in which the X-rays are generated in a region much larger than the secondary; for $R_2 \sim R_\odot$ this would imply that the size
of the X-ray source may be as large as \( \sim 10^{12} \text{ cm} \). This is much larger than the size of accretion disk coronae (ADC) seen in some high inclination low-mass X-ray binaries which scatter a few percent of the primary X-rays generated near the compact star (White, Nagase & Parmar 1995). In the case that the observed X-rays all originate from an ADC with no direct view of the compact star, then the real X-ray luminosity of Nova Sco 1994 is likely to be one or two orders of magnitude higher than the observed value of \( \sim 10^{36} \text{ erg s}^{-1} \), i.e., close to the Eddington luminosity for a black-hole mass of \( \sim 5 \, M_\odot \). We therefore conclude that our results are inconsistent with an inclination angle of \( i = 85^\circ \).

### 6.5 Conclusion

Since Nova Sco 1994 was clearly not in quiescence during the period of our observations, we included the effects of X-ray heating on the secondary star and the concave accretion disk in calculating model fits to the R-band data, using values for the X-ray luminosity consistent with the BATSE upper limit. For these model fits we constrain the inclination and the mass ratio of Nova Sco 1994 to lie in the range 65°–76° and 3.8–5.5, respectively. From evolutionary arguments, Brandt et al. (1995) restrict the mass of the secondary star to lie in the range 0.23–2.3 \( M_\odot \). These limits are shown in the \((M_2, M_1)\) plane (Figure 6.7) along with the limits placed on the mass of each of the binary components obtained from the fitting procedure. We thus limit the mass of the compact object in Nova Sco 1994 to lie in the range 4.94–6.79 \( M_\odot \) and the mass of the secondary star in the range 0.95–1.78 \( M_\odot \).

### Acknowledgments

The authors thank Paul Vreeswijk and Martin Zwaan for their help in obtaining observations. We thank V.S. Dhillon for supplying the 'PERIOD' package, which we used for part of our data analysis. FvdH acknowledges support by the Netherlands Foundation for Research in Astronomy (NFRA) with financial aid from the Netherlands Organisation for Scientific Research (NWO) under contract number 782-376-011. This work is partly based on observations made at the European Southern Observatory, La Silla, Chile.