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The outburst radial velocity curve of X-ray Nova Scorpii 1994 (= GRO J1655−40): a reduced mass for the black hole?

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ABSTRACT

We present a re-analysis of the outburst radial velocity data for X-ray Nova Scorpii 1994. Using a model based on X-ray heating of the secondary star, we suggest a more realistic treatment of the radial velocity data. Solutions are obtained in the (K_2, q) plane which, when combined with the published value for the binary mass ratio and inclination, constrain the mass of the black hole to within the region $4.1 < M_1 < 6.6$ M$_\odot$ (90 per cent confidence), which is significantly lower than the value obtained by Orosz & Bailyn. This reduced lower bound for the black hole mass, together with the high space velocity of the system, is consistent with the idea that it was formed by the post-supernova collapse of a neutron star.

Key words: accretion, accretion discs – binaries: close – stars: individual: X-ray Nova Sco 1994 (GRO J1655−40) – X-rays: stars.

1 INTRODUCTION

X-ray novae are low-mass binary systems in which a compact object undergoes unstable accretion from a late-type companion star, releasing energy in the form of X-rays. In a number of cases there is substantial evidence that the compact object is a black hole (see Tanaka & Shibazaki 1996 and van Paradijs & McClintock 1994 for reviews). Some of the best evidence for the presence of a black hole is obtained from the measurement of the orbital velocity of the companion star, leading to a determination of the mass function of the system and hence the minimum mass of the compact object. When this mass exceeds the maximum mass for a neutron star (~3.2 M$_\odot$; Rhoades & Ruffini 1974), a black hole seems the only remaining possibility.

The X-ray nova GRO J1655−40 is one such system, and was discovered on 1994 July 27 with BATSE on board the *Compton Gamma Ray Observatory* (Zhang et al. 1994). It has been studied extensively during the past two years in X-rays and at optical and radio wavelengths (Bailyn et al. 1995a,b; Zhang et al. 1995; van der Hooft et al. 1998). Strong evidence that the compact object in X-ray Nova Sco is a black hole was presented by Bailyn et al. (1995b) who initially established a spectroscopic period of 2.601 ± 0.027 d, and suggested a mass function $f(M) = 3.16 \pm 0.15$ M$_\odot$. An improved value of $f(M) = 3.24 \pm 0.09$ M$_\odot$ was presented by Orosz & Bailyn (1997), derived from a radial velocity semi-amplitude $K_2 = 228.2 \pm 2.2$ km s^{-1}. Their fitted values of inclination and the mass ratio then implied a black hole mass of $M_1 = 7.01 \pm 0.22$ M$_\odot$.

However, in calculating the radial velocity semi-amplitude, from which the mass function is derived, Orosz & Bailyn (1997) used both quiescent data (taken in 1996 February 24–25) *and* outburst data (taken in 1995 April 30–May 4), while Bailyn et al. (1996b) used just outburst data, and in both cases a sinusoidal fit was performed. We suggest that using outburst data in this way may lead to an incorrect result. The effect of substantial heating of the secondary can shift the 'effective centre' of the secondary, weighted by the strength of the absorption lines, from the centre of mass of the star, as described in Section 2 (below). This results in a significant distortion of the radial velocity curve and renders a sinusoidal fit clearly inadequate, leading to a spuriously high radial velocity semi-amplitude. The masses of the binary components derived from this will therefore be incorrect.

In this paper, we intend to consider only the outburst radial velocity data (from 1995 April 30–May 4). We use a model which incorporates the basic effects of X-ray heating of the secondary, and attempt to derive a more realistic range for the radial velocity semi-amplitude. Using the orbital period and the range of inclinations obtained by van der Hooft et al. (1998), we obtain (K_2, q) solutions. Using these solutions in conjunction with the mass ratio (Orosz & Bailyn 1997), we determine new limits on the masses of the secondary star and the black hole. Finally, we consider the implications of this on some current evolutionary scenarios for the black hole in X-ray Nova Scorpii 1994.

2 THE RADIAL VELOCITY CURVE

It is generally believed that any initial non-circularity in the orbit of the binary system would have been rapidly removed by tidal forces between the secondary star and the black hole, and that the present orbits are indeed circular. However, Davey & Smith (1992) argue that the radial velocity curves may still be distorted from a pure sine wave by geometrical distortion and heating of the secondary star by the compact object, causing the centre of light given by the strength of the absorption lines to differ from the centre of mass. The effects of this can be represented by allowing for a phase shift in the sine curve, or more generally by introducing a fictitious eccentricity. They describe a procedure for detecting any effects of heating on the radial velocity curve. First one must check for the significance of a fit with an eccentric orbit. If the fit is not significantly better than a purely sinusoidal fit, then the semi-amplitude of the curve measured from the absorption features represents a measure of the true semi-amplitude of the radial velocity curve of the secondary star, K_2. If an improved fit is obtained, this indicates the possible presence of asymmetric heating. In which case, the data should be treated using a model which includes the effects of heating.

We found that the fit to the outburst absorption line radial velocity data with an eccentric orbit is significantly better than that with a circular orbit. We obtained an eccentricity of 0.119 ± 0.023 (1σ errors) which is significant at the 99 per cent level. Therefore, the observed value of K_{obs} obtained from a sine wave fit to the absorption line radial velocity data cannot be taken to represent the true value of K_2.

3 X-RAY IRRADIATION OF THE SECONDARY STAR

According to BATSE measurements taken during 1995, the X-ray nova GRO J1655−40 continued to have major outburst events in hard X-rays long after its initial outburst. These include an event seen in 1995 late March (Wilson et al. 1995), and a further outburst in 1995 late July (Harmon et al. 1995). The source finally settled into true X-ray quiescence after 1995 late August, and was not detected by BATSE for the remainder of the year (BATSE occultation data). The observed X-ray luminosity of X-ray Nova Sco, as determined from the BATSE daily averages, varied between 1995 March 18 and March 25 within the range $5.7 \times 10^{36} \lesssim L_x \lesssim 2.3 \times 10^{37}$ erg s^{-1} (Orosz & Bailyn 1997). The outburst radial velocity data was obtained a little over one month later, during 1995 April and May.

In order to demonstrate the relative strength of the X-ray heating in X-ray Nova Scorpii, we will assume an X-ray luminosity of $L_x = 1.4 \times 10^{37}$ erg s^{-1}, the mean value of the range quoted above. The intrinsic luminosity of the secondary, computed from the observations made in the *V* band while the system was in quiescence (Orosz & Bailyn 1997), is approximately $L_{int} = 1.8 \times 10^{35}$ erg s^{-1}. Given the measured masses and orbital period of the system (Orosz & Bailyn 1997), we can use Kepler's Third Law to determine the separation, d, of the components to be approximately 16.8 $R_\odot$. Eggleton's (1983) expression for the effective radius of the Roche lobe then determines the radius of the secondary, R_2, to be about 4.9 $R_\odot$. The *maximum* ratio of the irradiating flux to the intrinsic flux at the surface of the secondary (in the limit of normal incidence) is therefore given by

$$\frac{L_x/4\pi d^2}{L_{int}/4\pi R_2^2} \sim 6.6. \qquad (1)$$

Thus, the incident X-ray flux may exceed the internal flux of the secondary star by almost a factor of 7, and will result in considerable heating of the region of the irradiated hemisphere beyond the shadow of the accretion disc. Additional evidence for the presence of irradiation comes from light curve fitting performed by Orosz & Bailyn (1997) using optical flux data in the *V* band taken from 1995 March 18–25 observations. The light curve exhibits two unequal minima at phases 0 and 0.5, the deepest being at phase 0, in contrast with the quiescent light curve (Orosz & Bailyn 1997). The shallow minimum at phase 0.5 can be explained by X-ray heating of the secondary hemisphere facing the compact object. A fitted value of $L_x = 3.7 \times 10^{36}$ erg s^{-1} is obtained for the X-ray luminosity, slightly lower than the range quoted above. (However, the discrepancy is not surprising given the large amount of scatter in the optical light curves around phase 0.5).

We suggest that heating of this magnitude will strongly affect the vertical temperature gradient in the irradiated atmosphere of the secondary, and may have significant consequences on the observed absorption line radial velocity curve. In order to correctly interpret the radial velocity data taken during outburst, it is therefore necessary to use a method which directly incorporates these heating effects.

4 THE X-RAY IRRADIATION MODEL

We modelled the secondary star as a Roche-lobe filling star of mean effective temperature 6500 K, consistent with its observed spectral type F3IV–F6IV. The black hole was assumed to act as a point source of radiation, emitting isotropically. The model includes an accretion disc with opening angle β, which shadows the region of the secondary near the inner Lagrangian point from X-rays. The secondary surface was then divided into grid elements, and an effective temperature was calculated for each point by combining intrinsic and incident fluxes (see Shahbaz, Naylor & Charles 1993; Orosz & Bailyn 1997; van der Hooft et al. 1998). We then specify the strength of the absorption lines over the secondary surface, and integrate to obtain the corresponding mean radial velocity.

Orosz & Bailyn (1997) used the absorption lines in the spectral region 5000–6000 Å to determine the radial velocity curve of the secondary star. Using stellar atmospheres (Jacoby, Hunter & Christian 1984), we obtained a fit to the total line flux of the absorption lines in the spectral region (5000–6000 Å) versus temperature (5000–15 000 K) relationship. The most obvious method would be simply to set the absorption line strength according to the effective temperature for each element. However, we must also consider the consequences of *external* heating. While we expect that the continuum fluxes are approximated by the star of the correct spectral type, the vertical temperature gradient in an atmosphere heated internally and externally is less than the value obtained when heated solely from within. This produces weaker absorption lines than expected from the effective temperature. As no satisfactory model exists for the effects of external heating in stars, we make the following crude approximation (see Billington, Marsh & Dhillon 1996). If the incident flux from the X-ray source exceeds 50 per cent of the unperturbed flux from the secondary, then we set the line flux for that element to zero; otherwise, the absorption line strength takes the value corresponding to the effective temperature of the element, using the stellar atmospheres described above.

In the case of X-ray Nova Sco, the incident flux can exceed the intrinsic flux by almost an order of magnitude, and results in a substantial region of the secondary having zero absorption strength. Fig. 1 shows the irradiated Roche lobe in the x–z plane, where the z-axis corresponds to the pole of the secondary and the compact object is at coordinates (1,0). An X-ray luminosity of $L_x = 1.4 \times 10^{37}$ erg s^{-1} is assumed, with a disc angle of 2°. The shaded areas represent the regions of the secondary where the absorption line flux has been set to zero because of irradiation. The region directly around the inner Lagrangian point is shielded by the accretion disc, and hence is unshaded.

This decrease in line flux over the irradiated hemisphere of the secondary leads to significant asymmetries in the radial velocity curves, and in particular, an increase in the gradient around phase

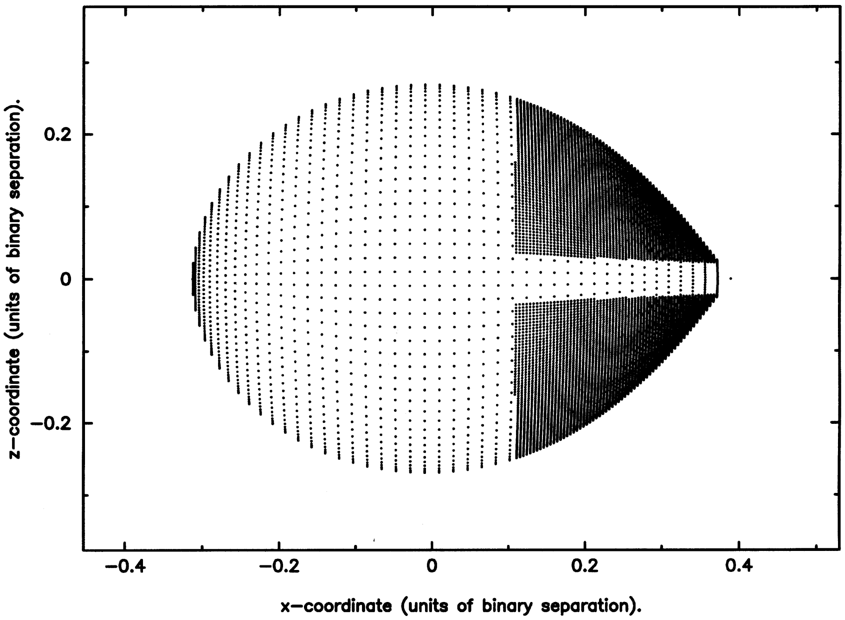

Figure 1. The irradiated Roche lobe in the x–z plane. The compact object is at coordinates (1,0). An X-ray luminosity of $L_x = 1.4\times10^{37}$ erg s^{-1} is assumed, with a disc angle of 2°. The shaded areas represent the regions of the secondary where the absorption line flux has been set to zero because of irradiation.

0.5. This appears to be consistent with observations. As the incident flux is so far in excess of the unperturbed flux, the results are not highly sensitive to the exact value of the X-ray luminosity, nor to the value of the cut-off point (i.e. the ratio of incident to unperturbed fluxes for which the absorption strength is set to zero). Although this is clearly a naive and crude model, it serves to illustrate the extreme effects of X-ray heating, and as we shall see, it provides a substantially better fit to the data.

Following Wade & Horne (1988), we may demonstrate the maximum magnitude of this effect by considering the extreme case of a uniform absorption line strength over the back hemisphere of the secondary and zero absorption over the heated front hemisphere. The 'effective centre' of absorption line strength will then be displaced from the centre of mass of the star away from the compact object by an amount $\Delta R_2/R_2 = 4/3\pi \sim 0.42$, where R_2 is the radius of the secondary. Therefore, the observed amplitude of the radial velocity variation, $K_{\rm obs}$, will be larger than the true (dynamical) amplitude, K_2, by an amount

$$\Delta K_2 = \frac{\Delta R_2}{a_2}K_2 = \frac{0.42R_2}{a}(1+q^{-1})K_2, \qquad (2)$$

where a and a_2 are the distances from the centre of mass of the secondary to the centres of mass of the primary and of the system, respectively. The mass ratio, q, is defined as the mass of the compact object divided by the mass of the secondary star. For X-ray Nova Sco, this leads to a maximum correction in $K_{\rm obs}$ of around 14 per cent, or ~32 km s^{-1}. The mass values derived from the uncorrected K velocity could thus be in error by as much as ~40 per cent.

5 FITTING THE OUTBURST RADIAL VELOCITY CURVE

Using the model described above we performed a least-squares fit to the outburst radial velocity data (note that each orbital phase was only covered once). The free parameters in the model were a phase shift (phase zero is defined as inferior conjunction of the secondary star) and the normalization of the light curve. We performed least-squares fits to the data using this model, grid searching K_2 in the range 180–240 km s^{-1}, q in the range 2.0–5.0 and β in the range 2°–14°. The effective temperature of 6500 K is appropriate for an F5IV star, so we used this as the polar temperature. We fixed the X-ray luminosity at $L_x = 1.4\times10^{37}$ erg s^{-1}, the mean value of the range quoted by Orosz & Bailyn (1997), and fitted the outburst radial velocity curve in the (K_2, q, β) coordinate space.

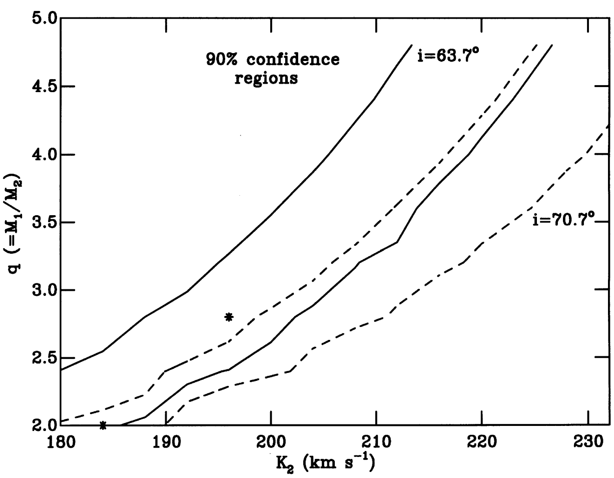

Figure 2. The 90 per cent confidence level solutions for model fits to the outburst radial velocity data of X-ray Nova Sco 1994 are shown. An X-ray luminosity of $L_x = 1.4\times10^{37}$ erg s^{-1} was used. The (K_2, q) solutions were obtained by collapsing the minimum χ^2 solutions along the β axis. The regions bounded by the solid and dashed lines contain fits using $i = 63.^\circ7$ and $70.^\circ7$, respectively. The stars show the best fitting solutions for the two inclination limits.

By fitting the quiescent multicolour optical light curves of X-ray Nova Sco 1994, van der Hooft et al. (1998) found a binary inclination in the range $63.^\circ7$–$70.^\circ7$. Fig. 2 shows the χ^2fit in the (K_2, q) plane for these upper and lower inclination limits. The solutions were obtained by collapsing the minimum χ^2solutions

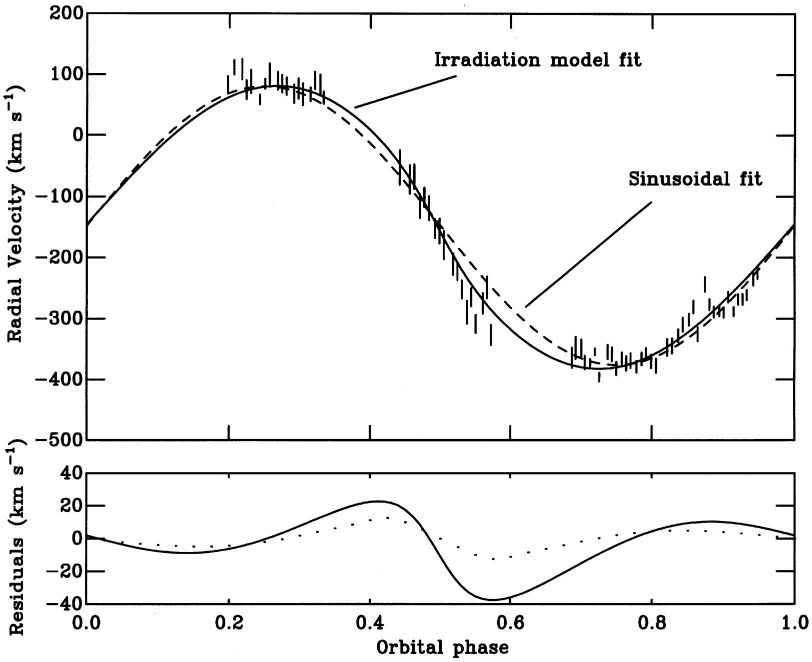

Figure 3. The outburst radial velocity curve of X-ray Nova Sco 1994 obtained from the absorption lines of the secondary star (Orosz & Bailyn 1997). Top panel: the data are fitted with a model that includes the effects of X-ray irradiation of the secondary star. The solid line shows the best model fit using $L_x = 1.4 \times 10^{37}$ erg s^{-1}, $i = 63\overset{\circ}{.}7$, $\beta = 2°$, $q = 2.8$ and $K_2 = 196$ km s^{-1}. The dashed line is a sinusoidal fit to the data. Bottom panel: the solid line shows the residual radial velocity obtained by subtracting the sine curve (shown in the top panel) from the irradiation model fit. The dotted line is the residual using a model that contains only the eclipse of the secondary by the accretion disc, with no irradiation effects, and again with the sine curve subtracted.

along the β axis on to the (K_2, q) plane. In effect, we have let β run as a free parameter. We obtained a minimum $\chi^2_\nu$of 3.3 at $K_2 = 196$ km s^{-1}, $q = 2.8$ and $\beta = 2\overset{\circ}{.}0$. The 90 per cent confidence regions are shown, calculated according to Lampton, Margon & Bowyer (1976) for two parameters, after the error bars had been scaled to give a minimum χ^2_ν of 1. (The high value of the minimum χ^2_ν is unsurprising given the large scatter in the radial velocity data, and suggests that the error bars have been under-estimated). Fig. 3 (top panel) shows our best fit to the outburst radial velocity data. A sinusoidal fit is also shown, as used by Bailyn et al. (1995b) and Orosz & Bailyn (1997).

We also investigated the effects of changing the level of X-ray heating on the secondary. The full range of observed X-ray luminosities was explored: $5.7 \times 10^{36} \lesssim L_x \lesssim 2.3 \times 10^{37}$ erg s^{-1}, as determined from the BATSE daily averages (see Section 3, above). However, it was found that the model was not sensitive to the irradiating luminosity in this range. For example, decreasing the X-ray luminosity by a factor of 2 (from 1.4×10^{37} to 7×10^{36} erg s^{-1}) only increases the (K_2, q) solutions by 0.6 km s^{-1}.

Finally, the effect of a grazing eclipse of the secondary by the accretion disc was considered in our model. A large disc was chosen, of opening angle 14° and a radius equal to 80 per cent of the Roche lobe radius of the primary, in order to emphasize the effects on the radial velocity curve. (Similar disc parameters were used by Orosz & Bailyn 1997 to model the outburst optical light curve from 1995 March). Fig. 3 (bottom panel, dotted line) shows the residual radial velocities obtained by subtracting the sine curve (shown in the top panel) from a model which contains only the eclipse of the secondary by the accretion disc, with no irradiation effects. Clearly, the residual curve has the right shape: it is positive just before phase 0.5 and negative just after. However, the maximum magnitude (about 13 km s^{-1}) is far smaller than the observed residual for the same phase (~80 km s^{-1}), and so the eclipse model provides a totally inadequate fit to the data. The residuals obtained from the irradiation model fit, with the same sine wave subtracted, are also shown (solid line). The amplitudes are much larger (up to ~40 km s^{-1}), and clearly give a far better agreement with the data.

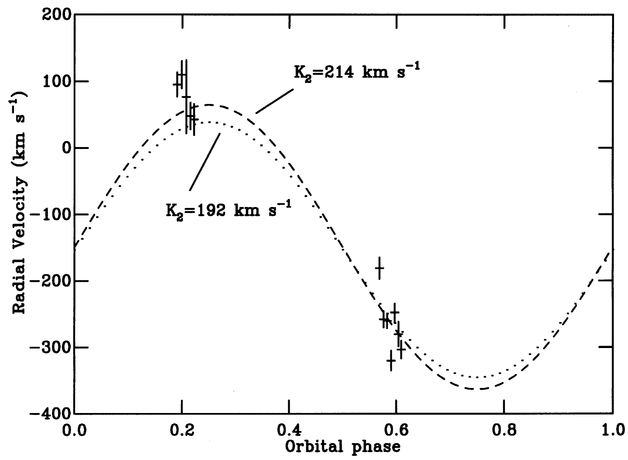

Figure 4. The poorly sampled quiescent radial velocity data of X-ray Nova Sco 1994 (Orosz & Bailyn 1997). The solid and dotted lines show the predicted sinusoidal radial velocity curves of the secondary star during quiescence, with $K_2 = 192$ and 214 km s^{-1}, respectively. These limits were obtained using our (K_2, q) fits and assuming $q = 3.0$ (see Section 5).

6 THE MASS OF THE COMPACT OBJECT

Although we have no reason to doubt the actual values obtained by Orosz & Bailyn (1997) for the binary inclination and mass ratio, it should be noted that the uncertainties quoted are probably optimistic given the fact that they have not fully taken into account systematic effects, which are most definitely present (see their fig. 7). Nevertheless, if we assume q to be 3.0, then this limits K_2 to within the range 192–214 km s^{-1} (90 per cent confidence), which then constrains the binary mass function to lie in the range 1.93–2.67 $M_{\odot}$. Note that this range is *much* lower than that derived by Orosz & Bailyn (1997) of 3.24 ± 0.09 $M_{\odot}$. (We also constrain the systemic velocity of the binary using the values for the normalization of the model fit to the data, obtaining the range −143 to −153 km s^{-1}.) Fig. 4 shows the current poorly sampled quiescent radial velocity data of X-ray Nova Sco 1994 (Orosz & Bailyn 1997). We also show the predicted sinusoidal radial velocity curves for our upper and lower limits on K_2. Note that the scatter in the quiescent data exceeds our range in K_2, and so cannot be used to restrict acceptable values.

Assuming $q = 3.0$, the inclination limits of $63\overset{\circ}{.}7$ and $70\overset{\circ}{.}7$ (van der Hooft et al. 1998) and the limits on the mass function obtained above, we can determine an allowed range for the masses of the black hole and the secondary star. We obtain 90 per cent confidence limits of $4.1 < M_1 < 6.6$ $M_{\odot}$ and $1.4 < M_2 < 2.2$ $M_{\odot}$ for the black hole and secondary star, respectively.

7 DISCUSSION

7.1 The accretion disc opening angle

The parameter ranges quoted above are derived from our optimum (K_2, q) solutions shown in Fig. 2. These are obtained by collapsing the minimum χ^2 solutions along the β axis. Although we could not constrain the disc angle, it should be noted that all of these solutions favoured small values of β, and our best-fitting solution is for $\beta = 2°$. Superficially, this appears inconsistent with a disc which is transferring enough mass to produce the outburst, and is below the range of disc angles obtained by several authors for other X-ray binaries. For example, Mason & Cordova (1982) analysed X-ray and optical eclipses of the ADC source 2A 1822−371, from which they deduced $\beta \sim 6$–14°; Motch et al. (1987) estimated $\beta \sim 9$–13° based on optical observations of 2S 1254−690. However, the above examples both concern stably accreting systems, whereas X-ray Nova Scorpii is a transient. We expect that the disc angle in such a system may vary dramatically over a dynamical or thermal time-scale, which is of the order of hours to days for typical disc parameters (Frank, King & Raine 1992). Given this variability, a disc angle which is close to the quiescent value of ∼2° (Orosz & Bailyn 1997), or at least towards the lower end of the ranges given above, does not seem unreasonable, despite later observations of the system which support larger values (e.g. Hynes et al. 1998).

In addition, we must also consider the effects of irradiation-driven circulation over the surface of the secondary. The transfer of heated material from the irradiated regions towards the inner Lagrangian point, and therefore within the shadow of the disc, would produce similar consequences for the radial velocity curve as for a small-angled disc. Furthermore, the obvious asymmetry of the data around orbital phase 0.5 (when the illuminated hemisphere is directed towards the line-of-sight) may possibly be explained by non-axially symmetric circulation induced by the Coriolis force. Although a detailed discussion is beyond the scope of this paper, it has been shown that such circulation effects are significant. For example, Schandl, Meyer-Hofmeister & Meyer (1997) used horizontal heat transfer in their modelling of the visual light curve of CAL 87; also, the analysis of the optical light curve of HZ Herculis, by Kippenhahn & Thomas (1979), required circulation to explain the shape of the light curve at minimum.

7.2 The heliocentric radial velocity of the system

Another unique feature in the radial velocity curve of X-ray Nova Sco 1994 is the high heliocentric radial velocity of approximately −150 km s^{-1}. After correction for the peculiar motion of the Sun and differential Galactic rotation, the magnitude of the space velocity of X-ray Nova Sco 1994 stands out as being much higher than any other dynamically identified Galactic black hole candidate. Brandt, Podsiadlowski & Sigurdsson (1995) give an explanation of the high space velocity of X-ray Nova Sco 1994 in terms of a delayed black hole creation, which appears to favour the production of a relatively low black hole mass. In this scenario, the initial collapse leads to the formation of a neutron star, allowing for a kick normally associated with a neutron star formation. The neutron star is then converted into a black hole as a result either of subsequent accretion of matter, or of a phase transition in the compact object.

According to the stripped-giant models for the companion star (King 1993; Brandt et al. 1995), the maximum mass of the secondary is 2.3 $M_{\odot}$. Our lower limit for the secondary star mass of $M_2 > 1.4$ $M_{\odot}$ implies that a maximum of ∼0.9 $M_{\odot}$ has therefore been available for accretion on to the black hole. Since in the phase transition scenario, the black hole would initially be formed with a relatively low mass (< 2 $M_{\odot}$, Brown & Bethe 1994), there is insufficient matter available to form the observed lower limit for the compact object of 4.1 $M_{\odot}$. The alternative hypothesis in which the black hole in X-ray Nova Sco is formed via an intermediate neutron star stage, and then converted into a black hole by subsequent accretion of supernova material, therefore appears more consistent with our mass limits.

However, other possible scenarios, such as a prompt black hole formation with an associated Blaauw–Boersma kick (see Brandt & Podsiadlowski 1995), cannot be ruled out at this stage.

8 CONCLUSIONS

We have re-analysed the published outburst absorption line radial velocity data of X-ray Nova Sco 1994. We find that as the X-ray source was active during the observations, one has to model the effects of X-ray irradiation of the secondary star when interpreting the radial velocity curve, since the irradiation will affect the strength of the absorption lines. The observed outburst radial velocity data is fitted using the X-ray heating model and 90 per cent confidence solutions are obtained in the (K_2, q) plane. Assuming a binary mass ratio of 3.0 and the inclination range of $63\overset{\circ}{.}7$ to $70\overset{\circ}{.}7$, we derive limits on the masses of the binary components: $4.1 < M_1 < 6.7$ $M_{\odot}$ and $1.4 < M_2 < 2.2$ $M_{\odot}$ for the black hole and secondary star, respectively (90 per cent confidence). This lower limit for the black hole mass is consistent with the idea that it was formed as the result of the post-supernova collapse of a neutron star.

We urge future spectroscopic observations of X-ray Nova Sco 1994 in *quiescence*, which will enable the true radial velocity of the secondary star and also the binary mass ratio to be determined directly. These parameters are crucial in establishing the true masses of the binary components.

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