BLACK-HOLE SYSTEMS: OPTICAL SPECTROSCOPY AND IR PHOTOMETRY

P.A. CHARLES
Oxford University
Nuclear & Astrophysics Laboratory,
Keble Road, Oxford OX1 3RH, United Kingdom

Abstract. The X-ray transient systems have provided the first opportunities for detailed studies of the mass losing star in low-mass X-ray binaries. During X-ray quiescence the cool star is the dominant light source in the red and near-IR. Optical spectroscopy yields the mass function (itself a lower limit to the compact-object mass), the rotational broadening leads to the mass ratio, q (assuming only that the star fills its Roche lobe), and the IR ellipsoidal light curve gives the system inclination (for high q). In such cases, a complete solution to the system parameters is possible, and this has been performed for A 0620–00 (V616 Mon) and GS 2023+338 (V404 Cyg), leading to the first accurate black-hole masses (which are in the range 10–12 $M_\odot$).

1. Introduction

Barely 10 years ago the only galactic black-hole candidates (BHCs) under consideration were Cyg X-1, LMC X-3 and A 0620–00 (McClintock 1986). Stemming initially from optical observations of the supergiant primary in Cyg X-1, the X-ray signature (spectrum and variability; see Tanaka & Lewin 1995) was then used as a guide to finding further candidates. But massive X-ray binaries such as Cyg X-1 and LMC X-3 are difficult objects for determining accurate masses since there is no velocity information associated with the compact object itself. The primaries are highly evolved and of uncertain mass, and hence only lower limits can then be derived to that of the compact object. (Nevertheless, this limit for Cyg X-1 exceeds 3 $M_\odot$, and it very likely is a black hole.) The low-mass X-ray binaries (LMXBs)

J. van Paradijs et al., (eds.), Compact Stars in Binaries, 341–350.

should be more straightforward for such measurements (as the companion star is much lighter), but they suffer from the major difficulty that the light is dominated by the much brighter X-ray irradiated accretion disc.

X-ray signatures alone are certainly not an unambiguous indicator of the presence of a black hole, as neutron stars can mimic such behaviour (see McClintock 1991). The signatures are merely indicators that the source is a BHC and that dynamical evidence should be obtained. Observationally, there is *no* evidence for any object with neutron star characteristics to have a mass above $2\,M_\odot$ (Thorsett *et al.* 1993), and $3\,M_\odot$ has been the dividing line, above which an object is declared to be a BHC. McClintock (1986) declared the ***holy grail*** in this field to be a source with a mass function $f(M) > 5\,M_\odot$ for which it could be unequivocally stated that the compact object was not a neutron star.

2. Soft X-ray Transients

In the last 10 years the field has been transformed by our ability to obtain optical spectra of the companions to the soft X-ray transients (SXTs).[1] They are LMXBs, but are X-ray luminous for only ~6 months in every 10–50 years. During the long X-ray quiescence the accretion disc becomes extremely faint, rendering the companion star visible. But even the brightest SXT only has $V \sim 18$, most are around 19–21, and so it is only recently that the equipment has existed on large telescopes to enable such studies to be made. SXTs now dominate the list of BHCs (see table 2 of White 1994).

With their low-mass secondaries (so far, all are K0–K7) this allows firm lower limits to be set to the compact-object mass on the basis of $f(M)$ alone, as the secondaries can be studied in detail during quiescence. In this class, GS 2023+338 (=V404 Cyg), has the highest $f(M)$ known at $6.1\,M_\odot$ (Casares *et al.* 1992; Casares & Charles 1994).

In this review I shall concentrate on the spectroscopic work on quiescent SXTs, but with some recent IR photometry in order to give a complete picture of the two most intensively studied objects. For a detailed discussion of the optical and IR photometry and the complexities of their behaviour see the accompanying review by Haswell.

[1]Note that even though several of the objects in this class do not exhibit the soft X-ray excess that gave SXTs their name, I shall still use the general term SXT to refer to them. This is so as to distinguish them from the "hard transients" that are associated with accreting neutron stars in Be systems, even though a hallmark of SXTs is a hard power law tail extending to very high energies. SXTs are also sometimes referred to as "X-ray novae", but they bear no relation to classical optical novae which are thermonuclear events on the surfaces of accreting white dwarfs.

3. Dynamical Mass Measurements

High spectral resolution observations were first performed on the SXT prototype A 0620–00 (=V616 Mon), which has a K5V secondary and 7.8 hr period (McClintock & Remillard 1986). With $f(M) = 2.9\,M_\odot$ it was immediately recognised as a strong BHC since, for any reasonable value of M_2, the secondary mass, the compact object significantly exceeds the maximum neutron star mass. In SXTs there is no emission from the black hole itself, although there is strong Hα emission from its surrounding disc. Attempts have been made to detect the orbital motion of the compact object from radial-velocity shifts in the wings of the line (which emanate from the inner disc). Whilst detected (although small, as expected), the disc behaviour is obviously complex as the phasing of this motion does not align with that of the secondary (Orosz *et al.* 1994).

To determine the masses in SXTs we therefore make use of: (i) the rotational broadening of the secondary star's spectral features; (ii) the ellipsoidal modulation of the secondary. These can be combined with $f(M)$ to yield a complete solution of the binary parameters with only minimal assumptions. With their late-type secondaries, the SXTs therefore provide the only method for obtaining accurate masses in BHCs. Indeed, only one SXT (Cen X-4) displays the properties of a neutron star (it bursts). Determining these masses provides a crucial challenge for understanding the late evolution of massive stars and the formation of supernova remnants (see, e.g., Verbunt & Van den Heuvel, 1995). Here I will summarise the results on the prime targets in this class. For more details on these objects see Van Paradijs & McClintock (1995).

3.1. THE NATURE OF THE COMPANION STAR

Since these stars must be (at least very close to) filling their Roche lobes (given their X-ray activity), their size is given by $R_2/a = 0.46(1+q)^{-1/3}$ where $q = M_X/M_2$. Combining this with Kepler's 3rd Law leads to the well-known result that the secondary's mean density $\rho = 110/P_{hr}^2\,\mathrm{g\,cm^{-3}}$ (see Table 1). As ρ for a MS star of this spectral type is $\sim 5\,\mathrm{g\,cm^{-3}}$ then only A 0620–00 and Nova Mus can contain (relatively) unevolved secondaries. It is on this basis that the luminosity classes are given above, since there are no suitable luminosity discriminants within existing spectra. Computations of the evolution of such a star lead to the concept of a "stripped-giant" and give $0.2\,M_\odot < M_2 < 1.3\,M_\odot$ (King 1993).

https://doi.org/10.1017/S0074180900055807 Published online by Cambridge University Press

TABLE 1. Optical and IR properties of soft X-ray transients

Source	P (hrs)	Sp. Type	$f(M)$ ($M_\odot$)	ρ ($g\,cm^{-3}$)	E_{B-V}	V	K	$v_{rot}\sin i$ ($km\,s^{-1}$)	K_2 ($km\,s^{-1}$)
A 0620–00	7.8	K5V	2.91	1.81	0.35	18.3	6	83	433
Nova Mus	10.4	K0–4V	2.86	1.02	0.29	20.5			399
Cen X-4	15.1	K7IV	0.20	0.48	0.1	18.4	15.0		146
V404 Cyg	155.3	K0IV	6.08	0.0046	1	18.4	12.5	39	208.5

from McClintock & Remillard 1986; Remillard *et al.* 1992; Orosz *et al.* 1994; McClintock & Remillard 1990; Casares & Charles 1994

3.2. ROTATIONAL BROADENING

With the size of the secondary restricted, then assuming co-rotation leads to a rotational velocity of $v_{rot}\sin i = K_2 \times 0.46\ (1+q)^{2/3}/q$ (Wade & Horne 1988), and hence yields q directly from the radial-velocity curve (K_2) and $v_{rot}\sin i$. This is technically challenging as typical values of v_{rot} are 30–80 $km\,s^{-1}$ and so high spectral resolution ($\leq$1 Å) is needed. Being faint ($V \geq 18$), then large telescopes are required even for the brightest SXTs. Casares & Charles (1994) used the 4.2 m WHT to determine $v_{rot}\sin i$ for V404 Cyg (Fig. 1) by subtracting different broadened versions (including the effects of rotation and limb darkening) of a K0IV template and performing a χ^2 test on the residuals. This gave $v_{rot}\sin i = 39\pm1\,km\,s^{-1}$ and hence $q = 16.7\pm1.4$. The absence of eclipses implies $i < 80°$ and hence $7\,M_\odot < M_X < 24\,M_\odot$ (Fig. 2). Clearly, further constraints on M_X, M_2 require knowledge of i. This is possible by exploiting the ellipsoidal modulation of the secondary. A similar study of A 0620–00 gave $v_{rot}\sin i = 83\pm5\,km\,s^{-1}$ and hence $q = 15 \pm 2$ (Marsh *et al.* 1994).

3.3. ELLIPSOIDAL MODULATION

The hallmark double-humped variation (resulting from the tidal distortion of the secondary) has been seen optically in all four SXTs of Table 1. However, there is clear contamination of these light curves, probably due to some combination of the accretion disc (e.g., the stream impact region), X-ray heating (although this should be small) and possible starspots on the secondary (cf. RS CVn systems). The principal contributor is probably the disc since veiling has been measured in all three and can be ~20–30%, and substantial (~20%) flickering on timescales $<P_{orb}$ is present in V404 Cyg.

Hence Shahbaz *et al.* (1993, 1994a,b) undertook a campaign of IR pho-

https://doi.org/10.1017/S0074180900055807 Published online by Cambridge University Press

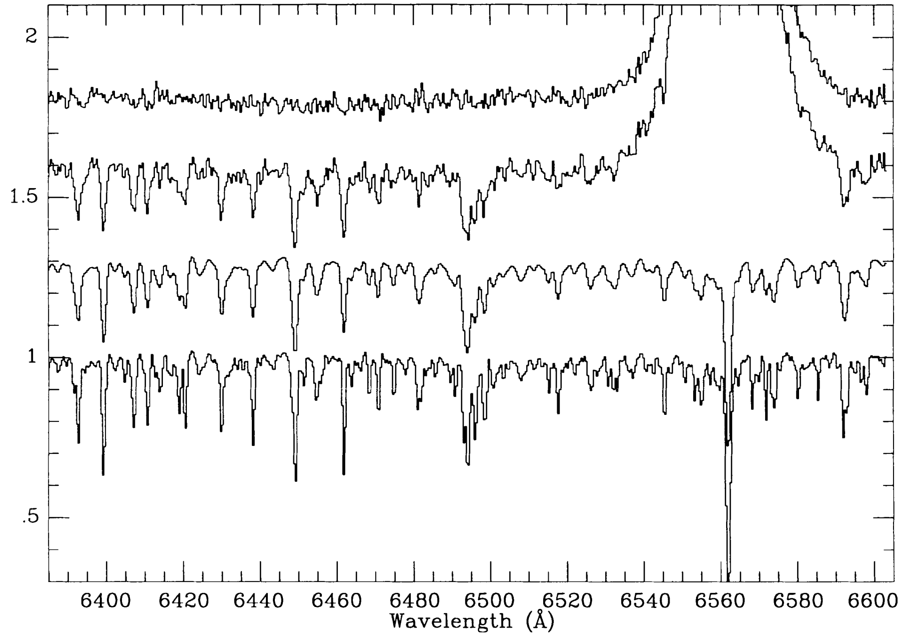

Figure 1. **Determining the rotational broadening in V404 Cyg. From bottom to top: the K0IV template star (HR 8857); the same spectrum broadened by 39 km s^{-1}; Doppler corrected sum of V404 Cyg (dominated by intense Hα emission from the disc); residual spectrum after subtraction of the broadened template (from Casares & Charles 1994).**

tometry, where the disc contamination would be less, and the limb- and gravity-darkening less affected by uncertainties in $T_{\rm eff}$. JHK photometry from UKIRT and the AAT yielded the first light curves for these objects (Fig. 3 shows A 0620–00).

Model calculations show that the shape and amplitude are a function of q and i, but they are insensitive to q if $q > 5$. The fits are summarised in Table 2.

TABLE 2. **System parameters for three soft X-ray transients**

Source	q	i	$R_2(R_\odot)$	$a(R_\odot)$	$M_X(M_\odot)$	$M_2(M_\odot)$
A 0620–00	15	37	0.8	4.3	10.0	0.6
Cen X-4	(1–30)	31–54	-	-	0.5–2	0.2–0.7
V404 Cyg	16.7	55	5.6	34	12	0.6

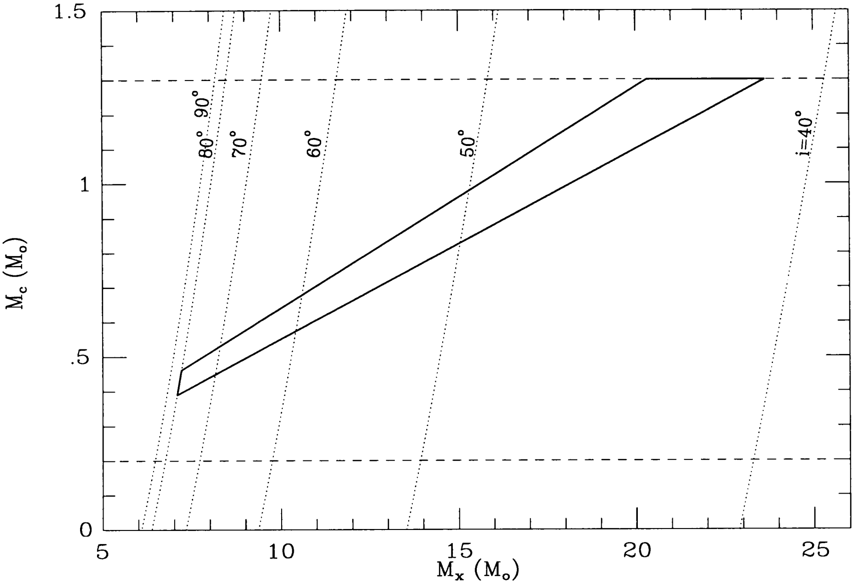

Figure 2. **Constraints on M_X and M_2 for a range of values of i in V404 Cyg based on the radial-velocity curve ($f(M)$) and determination of q (from the rotational broadening). It is the limited constraint on i (absence of eclipses) that leads to a wide range of M_X (from Casares & Charles 1994).**

The power of this technique is most clearly demonstrated for those systems (V404 Cyg and A 0620–00) in which the rotational broadening has been detected. This measures q directly, and then the ellipsoidal modulation tightly constrains i, giving the first direct mass measurements for black holes in our galaxy. Note that, even though we do not yet have an accurate q for Cen X-4, M_2 must be less than that of a main-sequence star of the same spectral type ($<0.7\,M_\odot$) and hence M_X must be in the range 0.5–$2\,M_\odot$. This is in excellent accord with that expected for a neutron star, and provides a useful confirmation of this basic approach.

4. Lithium in the Secondary Star

Perhaps the most surprising discovery in this field is that all three of the SXTs have high lithium abundances. Strong Li I λ6708 was discovered by Martín *et al.* (1992) in V404 Cyg when fitting with its K0IV template. This was a great surprise as Li is found with this abundance only in young stars, where the convective mixing (that leads to Li destruction) has not yet had time to substantially reduce the initial Li content. Li is an important element in galactic chemical abundances because galactic gas is enriched in

https://doi.org/10.1017/S0074180900055807 Published online by Cambridge University Press

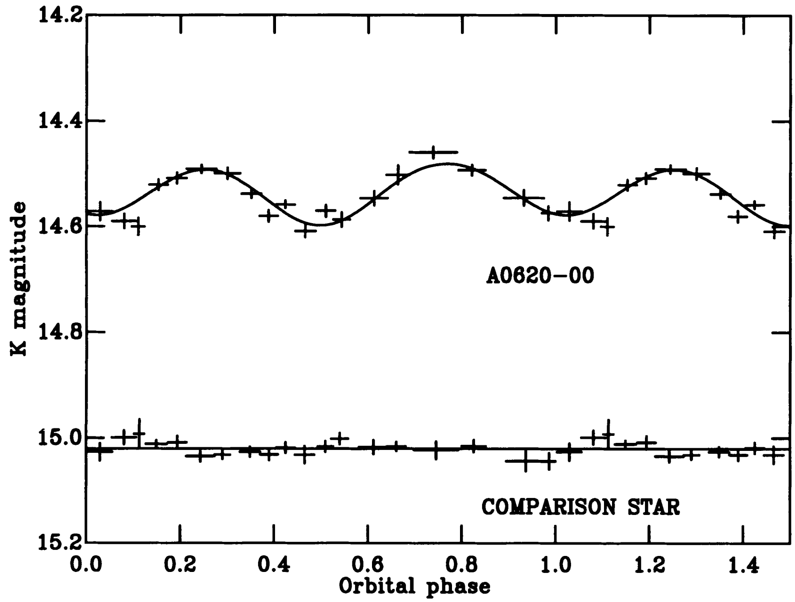

Figure 3. IR light curves of A 0620–00 (from Shahbaz *et al.* 1994a).

Li relative to the halo, and much effort has been put into locating the source of enrichment. Subsequently, Li was discovered in comparable spectra of A 0620–00 (Marsh *et al.* 1994) and Cen X-4 (Martín *et al.* 1994), with comparable abundances of log $N_{\mathrm{Li}} \simeq 2.0$–$3.3$ (see Fig. 4).

It is *very* unlikely that all three of these SXTs are young ($\leq 10^7$ yrs) and so the conclusion must be that Li is being created at these sites. They have a wide range of orbital periods (0.32–6.5 days), two are black holes while one is a neutron star, and the secondaries are of significantly different sizes. The *only* property they share is the huge X-ray outburst that recurs every few decades, and it has been proposed that spallation processes during these outbursts result in the production of Li (Martín *et al.* 1994). Large mass outflows seen during the outbursts transfer the Li to the secondary.

A possible test for this mechanism has been suggested that is related to the observed γ-ray line at 476 keV in Nova Mus 1991. This was originally interpreted as a gravitationally-redshifted $e^- - e^+$ annihilation line, double-peaked due to Keplerian rotation of the disc. Instead, it could be associated with the 478 keV line of ^{7}Li, which also provides a more natural explanation for the line width. If so, the temporal history of the feature

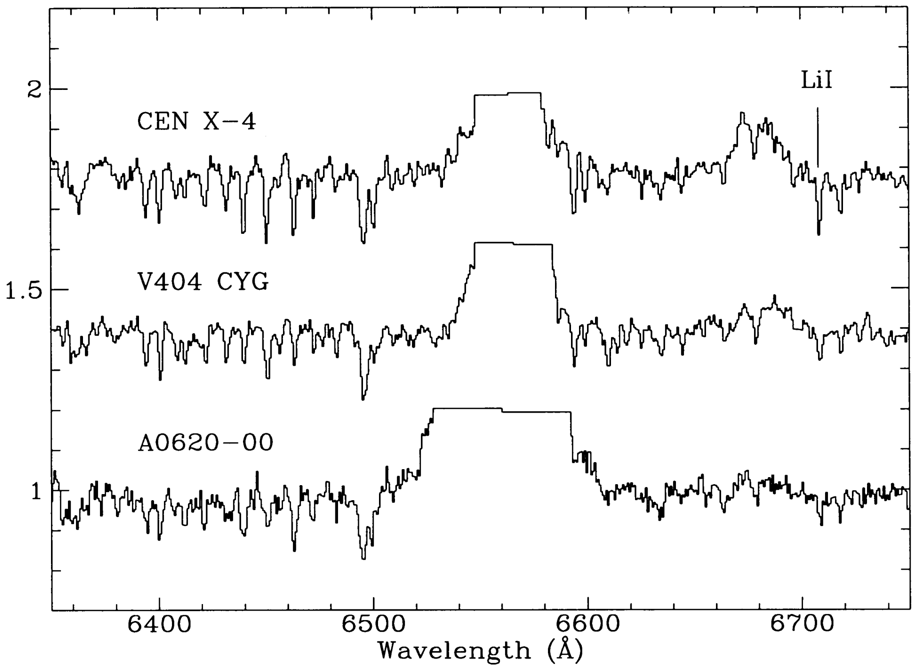

Figure 4. **AAT and WHT spectra of Cen X-4, V404 Cyg and A 0620–00 showing the presence of Li I λ6708 (from Charles *et al.* 1994).**

(it only lasted for ~1/2 day) will give information on the acceleration and spallation mechanisms that are taking place.

5. GRO J0422+32: an SXT exhibiting Mini-Outbursts

Nova Per 1992 (GRO J0422+32) was suggested as a BHC on the basis of its hard spectrum (similar to V404 Cyg) and 400–600 keV excess. It has a 5.1 hr optical period (Kato *et al.* 1992; Chevalier & Ilovaisky, 1993) and a slightly longer "superhump" period (see Haswell's review in these Proceedings). This has also been seen in GS 2000+25 (Charles *et al.* 1991) and Nova Mus 1991 (Bailyn 1992). GRO J0422+32 was thus considered as potentially an important system because it has low reddening ($E_{B-V} \sim 0.2$), the shortest period in the class, an unusually slow decline ($\sim 0^m.01\,d^{-1}$) and could also be the first high i SXT (dips in the light curve were reported by Kato *et al.* (1993).

It started declining rapidly 240 d after the peak but in August and December 1993 it exhibited two "mini-outbursts", behaviour that is unprecedented in this class. Spectroscopy with the WHT showed very broad

https://doi.org/10.1017/S0074180900055807 Published online by Cambridge University Press

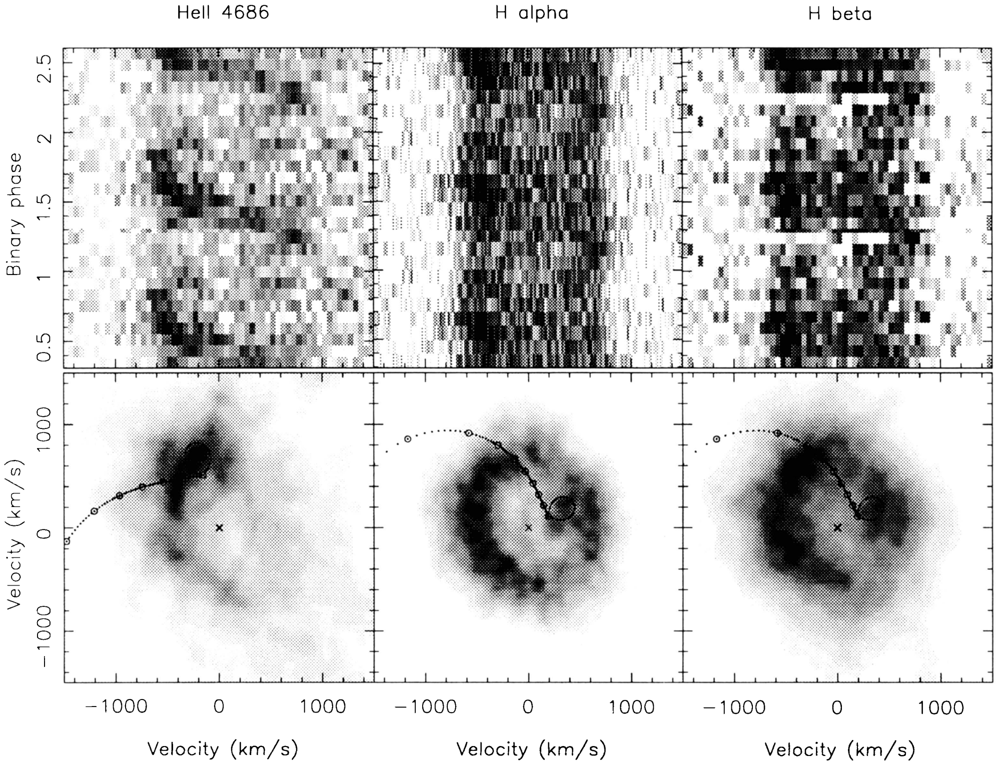

Figure 5. **Grey-scale representation of time-resolved spectra of GRO J0422+32 obtained of the He II λ4686, Hα and Hβ profiles. The bottom panels show the resulting Doppler tomograms for each profile in velocity space. The secondary star interpretation is shown for He II, while the disc location is indicated for the others (from Casares *et al.* 1995).**

($\pm \sim 3000\,\mathrm{km\,s^{-1}}$) Balmer absorption, and complex He II and Balmer emission components (Harlaftis *et al.* 1994). A grey-scale representation of the time-resolved spectra (Fig. 5) shows an S-wave component within He II that has semi-amplitude $\sim 750\,\mathrm{km\,s^{-1}}$ and a period of 5.1 hrs. This is the *first clear velocity modulation* observed in GRO J0422+32, and can be tentatively associated with the orbital period.

The time-resolved spectra can be used as input into a Doppler tomography analysis (Fig. 5). Without a detection of the secondary star, or an ellipsoidal modulation, the precise location of the sharp emission component is impossible to determine. It could be the X-ray heated face of the secondary star, or the hot spot where the stream impacts the disc. The former is favoured due to the correlation between He II λ4686 and the X-rays, but X-ray heating must be low and there is a complete absence of Bowen emission (which was strong during the main outburst). The two possible locations are shown in Fig. 5. If on the secondary star, then the velocities observed imply $f(M) \sim 9\,\mathrm{M_\odot}$, whereas the theoretical gas stream path to the hot spot gives $q \sim 5$. Conclusive evidence must await the secondary's radial-velocity curve now that the object seems to have reached true quiescence (Zhao *et al.* 1994). It is crucial to confirm the 5.1 hr period because, if real, then it means that in future SXT outbursts it will be possible to glean useful dynamical information from high resolution observations of the He II λ4686 line profiles.

Acknowledgments. I particularly thank Jorge Casares, Tim Naylor and Tariq Shahbaz for their help in preparing this manuscript.

References

Bailyn, C.D. 1992, ApJ 391, 298
Casares, J. & Charles, P.A. 1994, MNRAS (in press)
Casares, J., Charles, P.A. & Naylor, T. 1992, Nat 355, 614
Casares, J. *et al.* 1995, MNRAS (submitted)
Charles, P.A. *et al.* 1991, MNRAS 249, 567
Charles, P.A. *et al.* 1994, in *The Evolution of X-ray Binaries*, S.S. Holt & C.S. Day (Eds.), AIP Conference Proc. Vol. 308, p. 371
Chevalier, C. & Ilovaisky, S.A. 1993, IAU Circular 5692
Harlaftis, E.T. *et al.* 1994, in *The Evolution of X-ray Binaries*, S.S. Holt & C.S. Day (Eds.), AIP Conference Proc. Vol. 308, p. 91.
Kato, T., Mineshige, S. & Hirata, R. 1992, IAU Circ. 5676
Kato, T., Mineshige, S. & Hirata, R. 1993, IAU Circ. 5704
King, A.R. 1993 MNRAS 260, L5
Marsh, T.R., Robinson, E.L. & Wood, J.H. 1994, MNRAS 266, 137
Martín, E.L. *et al.* 1992, Nat 358, 129
Martín, E.L. *et al.* 1994, ApJ (in press)
McClintock, J.E. 1986, in *Physics of Accretion onto Compact Objects*, K.O. Mason, M.G. Watson & N.E. White (Eds.), Lecture Notes in Physics Vol. 266 (Springer), p. 211
McClintock, J.E. 1991, Ann. N.Y. Acad. Sci. 647, 495
McClintock, J.E. & Remillard, R.A. 1986, ApJ 308, 110
McClintock, J.E. & Remillard, R.A. 1990, ApJ 350, 386
Orosz, J.A. *et al.* 1994, ApJ (in press)
Remillard, R.A., McClintock, J.E. & Bailyn, C.D. 1992, ApJ 399, L145
Shahbaz, T., Naylor, T. & Charles, P.A. 1993, MNRAS 265, 655
Shahbaz, T., Naylor, T. & Charles, P.A. 1994a, MNRAS 268, 756
Shahbaz, T. *et al.* 1994b, MNRAS (in press)
Tanaka, Y. & Lewin, W.H.G. 1995, in *X-ray Binaries*, W.H.G. Lewin, J. van Paradijs & E.P.J. van den Heuvel (Eds.), Cambridge Univ. Press, (in press)
Thorsett, S.E. *et al.* 1993, ApJ 405, L29
van Paradijs, J. & McClintock, J.E. 1995, in *X-ray Binaries*, W.H.G. Lewin, J. van Paradijs & E.P.J. van den Heuvel (Eds.), Cambridge Univ. Press, (in press)
Verbunt, F., van den Heuvel, E.P.J. 1995, in *X-ray Binaries*, W.H.G. Lewin, J. van Paradijs & E.P.J. van den Heuvel (Eds.), Cambridge Univ. Press, (in press)
Wade, R.A. & Horne, K. 1988, ApJ 324, 411
White, N.E. 1994, in *The Evolution of X-ray Binaries*, AIP Conference Proc. 308, 371
Zhao, P. *et al.* 1994, IAU Circ. 6072