Black-Hole Candidates in X-ray Binaries

X-ray binaries are short-period (hours to days) interacting binaries in which one component is an (almost) normal star transferring material onto its compact companion via an ACCRETION DISK around the compact object. Matter spirals in the intense gravitational field, eventually falling onto the surface of the compact companion, which can be a white dwarf, neutron star or black hole. However, the x-ray luminosities generated in this accretion process are so high (sometimes $>10^{38}$erg s^{-1}) that a white dwarf can (usually) be excluded. Also while the presence of regular pulsations (usually $\sim$ seconds) indicates that the compact object must be a neutron star (a PULSAR), the absence of this signature does not automatically mean it must be a black hole. Only direct measurement of the compact object mass (from the normal star's orbital motion around the unseen compact object) can determine this. By simple application of Kepler's laws it is possible, with minimal assumptions, to infer the minimum mass of the compact object. If it exceeds a certain value (theory suggests this maximum to be $3.2M_\odot$, while observationally no confirmed neutron star exceeds $2M_\odot$) then it is declared to be a black-hole candidate on the grounds that a neutron star cannot then support itself without collapsing. Also if general relativity (GR) is the correct physical description of gravity, then such an object can only be a BLACK HOLE (see also GENERAL RELATIVITY TESTS: BINARY PULSARS). Determining the *maximum* mass of a neutron star accurately therefore has important repercussions for the nature of matter at nuclear densities.

If the mass-losing star is significantly *less* massive than the compact object (the so-called *low-mass x-ray binaries* or LMXBs), then these mass estimates provide a firm *lower* limit to the compact object's mass which is of great importance. Effectively the companion is being used as a test particle in orbit about the compact object, analogous to the (extremely low mass) planets orbiting our Sun. All-sky monitors on space-borne x-ray observatories have led to the discovery of soft x-ray transients (SXTs, so called because of their low x-ray temperatures), a class of object which produces rare, dramatic x-ray outbursts (typically separated by decades), followed by an extended period of x-ray inactivity (see also X-RAY BINARY STARS). It is only during this time that their mass-losing companions are visible, making them virtually the only class of LMXB for which dynamical mass studies are possible. More than two dozen SXTs are known, of which $\sim$10 have produced accurate mass determinations, the heaviest of which (V404 Cyg) is $12M_\odot$.

Dynamical mass measurements

A detailed knowledge of binary parameters for many of the high-mass x-ray binaries (HMXBs) (which have easily identified early-type, massive companions) is due to their pulsating neutron star compact objects. They are effectively *double-lined spectroscopic binaries*, in which each component produces a radial velocity curve (the neutron star pulsation period is also modulated by the Doppler effect). The amplitudes of these curves are K_X and K_2 (for the compact object and secondary star respectively), the ratio of which is their mass ratio, q. With an orbital period of P then Kepler's third law allows $f(M)$, the *mass function*, to be determined for each component:

$$f(M_X) = \frac{PK_2^3}{2\pi G} = \frac{M_X^3 \sin^3 i}{(M_X + M_2)^2} \tag{1}$$

$$f(M_2) = \frac{PK_X^3}{2\pi G} = \frac{M_2^3 \sin^3 i}{(M_X + M_2)^2} \tag{2}$$

where i is the orbital inclination. If the systems are eclipsing (which constrains i) then M_X and M_2 can be determined. Such work has produced the detailed dynamical mass measurements of neutron stars that are summarized in figure 1 together with the mass measurements from binary radio pulsars. All these masses are consistent with a mass of $(1.35 \pm 0.04)M_\odot$.

However, when HMXBs are suspected of harboring black holes (as in Cyg X-1 and LMC X-3), the mass measurement process is less straightforward. By definition, there will be no dynamic features (such as pulsations) observable from the compact object, and so these are *single-lined spectroscopic binaries* with only K_2, and hence $f(M_X)$, being measurable. Also, since $M_2 > M_X$, then M_X cannot be accurately determined without constraints on the value of M_2. Unfortunately, there is usually a wide range of uncertainty in M_2 ($\sim$12–20 $M_\odot$ for Cyg X-1) because of the (necessarily) unusual evolutionary history of the binary. Nevertheless the compact object in Cyg X-1 almost certainly is a black hole, since the available data constrain it to be $>3.8M_\odot$, which is just above the canonical maximum mass of a neutron star.

Low-mass x-ray binaries

However, when the mass-losing star is of low mass (the LMXBs), then the situation is very different. Such short-period x-ray binaries will have very faint companion stars, which leads to the major observational problem that the observed optical light will be dominated by reprocessed x-radiation from the accretion disk (or heated face of the companion star). This is why the optical spectra of LMXBs are hot, blue continua (U–B typically -1) with superposed (usually weak) broad hydrogen and helium emission lines, the velocities of which indicate that they largely arise in the inner disk region. This normally prevents the observation of any useful dynamical information associated with either component in the binary. Hence, the evidence for the nature of the compact object in most LMXBs has come indirectly, usually from the detection of x-ray bursts (as few are x-ray pulsars; see X-RAY BURSTERS) or the fast flickering first seen in Cyg X-1 (and hence frequently used as a black-hole 'indicator', although it too is also seen in NEUTRON STAR systems).

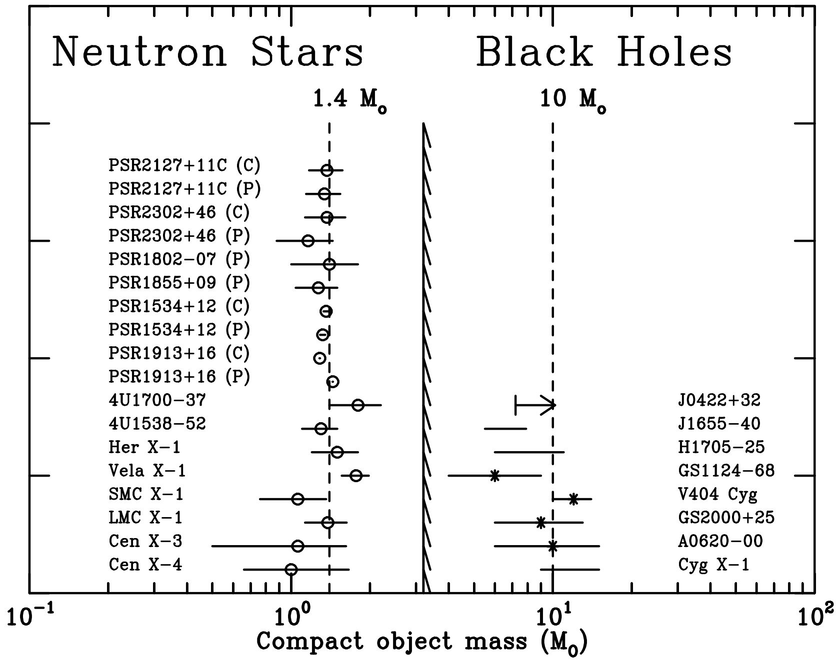

Figure 1. The distribution of neutron star and black-hole masses in binary systems.

Soft x-ray transients

It is therefore necessary to find sources where the x-ray emission switches off for some reason, so that the companion star can become visible. This is the basis of the new field of study of the SXTs (sometimes referred to as x-ray novae), which contain a remarkably high fraction (∼75%) of black-hole candidates. Only six SXTs are confirmed neutron star systems in that they display type I x-ray bursts. The observed properties of SXTs are summarized as follows.

- *X-ray transient outbursts*, reaching a typical peak x-ray luminosity of $\sim 10^{37-39}$erg s^{-1}. Erratic variability on short timescales is often present. Several new transients are found each year.
- *Fast-rise, exponential decay light curves*, with timescales ∼few days and ∼30 days respectively, recurring typically every 10–50 yr. However, linear decays are possible, especially for lower peak luminosities.
- *Variable optical counterpart* that brightens by ~ 4–7^{m} depending on orbital period (a longer period implies a larger and hence brighter secondary star which correspondingly reduces the observed outburst amplitude). Such a large brightness increase at outburst shows that the SXTs are LMXBs, and are *not* similar to Cyg X-1 or the harder Be x-ray transients.
- Lithium has been detected in absorption in five SXTs, and may be created by spallation processes during the intense x-ray outbursts.
- Mini-outbursts sometimes occur within ∼1 yr of the main outburst.
- Superluminal radio jets analogous to those seen in QSOs and other AGN have been seen.
- Residual accretion disks seen in quiescence through the presence of strong, broad Hα emission. Usually exhibiting a double-peaked profile, this implies a disk size ∼0.4–0.7 of the primary ROCHE LOBE. Velocity studies of the emission lines have revealed small phase offsets with respect to that expected if the lines are only associated dynamically with the compact object.
- Galactic distribution of SXTs is consistent with that of population I objects, suggesting that they evolved from massive progenitor stars. There are estimated to be ∼500 in our galaxy.

Black-hole diagnostics?

X-ray spectrum

X-ray properties similar to those of Cyg X-1 are, not surprisingly, frequently used as diagnostics that lead to black-hole candidacy. In addition to a (very stable) power-law component extending to very high energies (∼MeV) which is usually attributed to Comptonization, Cyg X-1 also (occasionally) exhibits a high, soft state which has an additional (multicolor or 'disk') black-body spectrum at a temperature of $kT \sim 1$ keV. Assuming that the inner accretion disk can be represented as a set of rings of decreasing temperature with increasing radius, x-ray spectra suggest that sources suspected (on other grounds) of being black-hole candidates had inner disk radii of $\sim 3r_S$, appropriate for stellar mass black holes (where r_S is the Schwarzschild radius, and $\sim 3r_S$ is the location of the last stable orbit for matter in its vicinity). While the continuum spectrum is unaffected by including the effects of GR, they are important for the profiles of spectral lines formed in the inner disk. Only x-ray lines can be formed at such high temperatures, and the effects of GR are believed to have been seen in certain AGN spectra, but not yet in x-ray binaries.

The low-temperature black-body ('soft') component in SXTs has widely varying properties from source to source. Indeed, even though they are classified as SXTs, the two transients GS2023 + 338 and GRO J0422 + 32 do not show such components in their bright state (and nor do Cyg X-1 and GX339-4 when in their hard (low) states). At the other extreme, GRO J1655-40 and GRS1915+10 have the highest temperature and most luminous soft component, and are also the only SXTs to display superluminal radio ejections (see the section below on population size and distribution). This has led to the speculative suggestion that the soft component is related to the spin of the black hole, as this property is considered to be important in extragalactic radio jets.

Temporal behavior

A simultaneous analysis of the x-ray spectral and temporal variability is necessary in order to map out these source 'states'. Building on the two-state behavior of Cyg X-1, interesting correlations between their x-ray spectra and temporal variability have been found in the black-hole x-ray binaries. The presence of quasi-periodic oscillations (QPOs, as seen in neutron star systems) also reinforces their interpretation as a property of the inner accretion disk rather than the compact object. The SXT outbursts, when studied from peak to quiescence, cover a very large range in accretion rate onto the compact object, and the x-ray spectral and temporal behavior appears related to the mass accretion rate (table 1).

Furthermore, even faster QPOs (67 Hz, 184 Hz, 300 Hz) have been seen during bright phases of the transients GRS1915 + 105, XTE J1550-564 and GRO J1655-40 respectively. Such short-timescale variability must be associated with the region close to the last stable orbit of the inner accretion disk, and hence has potential importance as a property that arises very close to the black-hole primary. Various models have been proposed to account for the details of this behavior, and all include effects of GR which relate to the mass and spin of the black hole.

Quiescent flux levels

Quiescent SXT x-ray fluxes are much lower than those expected from the mass transfer rate implied by the continuing strong Hα emission, and in particular are lower than in corresponding neutron star systems. This may be due to advection-dominated accretion flows (ADAFs) in which, at low mass transfer rates, the high temperature and low density of gas in the inner disk region combine to produce a cooling time for the gas that exceeds the time to fall onto the compact object. Hence the thermal energy of the gas would be advected into the black hole and 'lost'. While similar flows would occur in neutron star systems, the thermal energy would eventually have to be radiated from the neutron star's solid surface, hence producing an apparently much higher x-ray flux from the same amount of accreted matter.

Mass measurements

Radial velocity curves

Once they reach quiescence SXTs become valuable resources for research into the nature of LMXBs. Optically fainter now by a factor of 100 or more, (they have quiescent magnitudes in the range 17–23), their emission is dominated by the companion star and, while technically challenging, their spectral type, period and radial velocity curve (whose amplitude is the K velocity) can be determined. From the latter two the mass function (equation (1)) can be calculated (table 2), and these represent the absolute minimum values for M_X, since (for all of them) $i < 90^\circ$ and $M_2 > 0$. Changing either of these parameters serves only to *increase* the implied value of M_X. However, to determine the actual value of M_X, additional constraints must be applied, so as to infer values for M_2 and i.

Rotational broadening

In short-period interacting binaries the secondary must be corotating (at velocity v_{rot}) with the primary, and since its size R_2 is given by

$$R_2/a = 0.46(1+q)^{-1/3} \quad (3)$$

then

$$v_{rot} \sin i = \frac{2\pi R_2}{P} \sin i = K_2 \times 0.46 \frac{(1+q)^{2/3}}{q} \quad (4)$$

from which q can be derived if v_{rot} is measurable. Typical values are in the range 40–100 km s^{-1}.

Figure 2 shows the summed spectrum of V404 Cyg (Doppler corrected into the secondary's rest frame) and that of a template star, which clearly has much narrower absorption lines. A range of broadening velocities (together with the effects of limb-darkening) are applied to the template for comparison with the target, yielding $v_{rot} \sin i = 39 \pm 1$ km s^{-1}, from which $q = 16.7 \pm 1.4$. Note also that, while the accretion disk around the compact object might be expected to provide some velocity information, the breadth of the Hα line ($\geq$ 1000 km s^{-1}) makes this extremely difficult as the compact object's motion in such high-q systems will be very small (typically $\leq$ 30 km s^{-1}). Nevertheless such motions have been seen, but their interpretation is not straightforward as there is a small phase offset relative to the motion of the companion star.

Having determined q, the only remaining unknown is the orbital inclination i. To date, none of the SXTs is eclipsing (although GRO J1655-40 shows evidence for a grazing eclipse), and so it is the determination of i that leads to the greatest uncertainty in the final mass measurement.

Table 1. X-ray spectral and temporal properties of SXTs.

Source state	X-ray spectrum	Temporal characteristics
Low (LS)	No ultrasoft (US) component	Power-law PDS, substantial variability
Intermediate (IS)	US + steeper power law at high E	Lorentzian noise
High (HS)	US dominates (MCD model), very weak power-law component	Very little variability
Very high (VHS)	Strong US + PL component	Strong QPOs at ~10 Hz, Lorentzian noise

Table 2. Derived parameters and dynamical mass measurements of SXTs.

Source	$f(M)$ ($M_\odot$)	q ($=M_X/M_2$)	i (deg)	M_X ($M_\odot$)	M_2 ($M_\odot$)
V404 Cyg	6.08±0.06	17±1	55±4	12±2	0.6
G2000+25	5.01±0.12	24±10	56±15	10±4	0.5
N Oph 77	4.86±0.13	>19	60±10	6±2	0.3
N Mus 91	3.01±0.15	8±2	54^{+20}_{-15}	6^{+5}_{-2}	0.8
A0620-00	2.91±0.08	15±1	37±5	10±5	0.6
J0422+32	1.21±0.06	>12	20–40	10±5	0.3
J1655-40	3.24±0.14	3.6±0.9	67±3	6.9±1	2.1
4U1543-47	0.22±0.02	—	20–40	5.0±2.5	2.5
Cen X-4	0.21±0.08	5±1	43±11	1.3±0.6	0.4

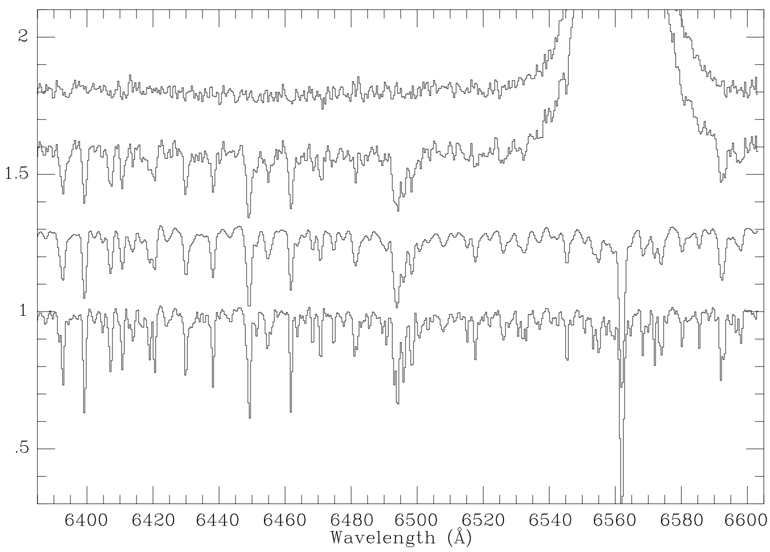

Figure 2. Determining the rotational broadening in V404 Cyg. From bottom to top: a K0IV template star; the same spectrum broadened by 39 km s^{-1}; Doppler-corrected sum of V404 Cyg (dominated by intense Hα emission from the disk); residual spectrum after subtraction of the broadened template.

Ellipsoidal modulation

The distorted shape of the secondary (the Roche lobe) produces a so-called *ellipsoidal modulation* as the projected area of the secondary varies around the orbit (figure 3). The form of the Roche lobe is theoretically well determined, and so the observed light curve depends on only two parameters, q and i (note that the modulation will disappear if i=0). Usually q is already determined (previous section), but in practice the ellipsoidal modulation is largely insensitive to q for q >5. This assumes that the secondary is actually filling the Roche lobe, which is reasonable given that mass loss from the secondary is observed via Doppler tomography even during quiescence. Results for i determined in this way are given in table 2 (and the masses in figure 1).

However, the principal uncertainty in this final stage is the problem of any other contaminating light sources, especially the accretion disk, as this will lead to i being underestimated and the compact object mass being overestimated. The disk component has already been measured in the optical (figure 2) and is typically $\leq$ 10%. To further reduce this effect, ellipsoidal studies

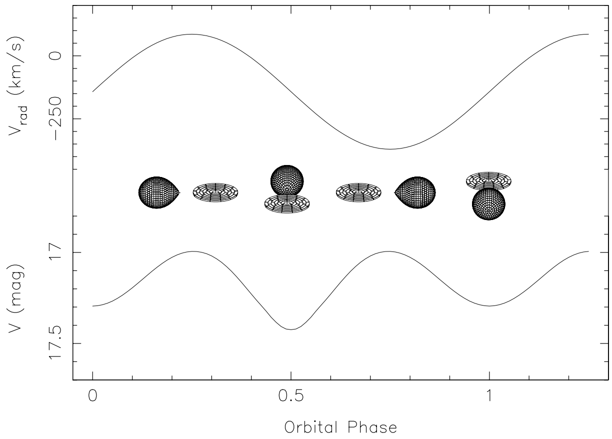

Figure 3. Schematic of the SXT (center) as a function of binary orbital phase, together with (upper) the observed radial velocity of the secondary, and (lower) the ellipsoidal light curve resulting from the distorted (Roche-lobe) shape of the secondary which produces a double-humped modulation.

are performed in the infrared whenever possible (as the disk should be blue in color). Application of this method to the neutron star SXT Cen X-4 yields a value of $1.3M_{\odot}$, in excellent accord with that expected.

The superluminal transients

The discovery, in 1994, of GRS1915 + 105 and GRO J1655-40 brought an entirely new type of behavior to this field. Although other transients were strong radio sources, VLA and VLBI observations showed that these new objects exhibited ejection events that were 'superluminal', the first time that such phenomena had been observed within the Galaxy. Furthermore, both these objects displayed continuing and extremely variable x-ray activity that is totally unlike any of the 'classical' SXTs. Combined with the extremely high interstellar extinction ($A_V \sim 26$) to GRS1915 + 105, dynamical studies of its variable, $K \sim 14$ IR counterpart are currently not possible.

GRO J1655-40 (N Sco 1994) is optically the brightest in quiescence of all the SXTs, with one of the earliest spectral types (mid-F). It also exhibits a high γ velocity which suggests that it might have been formed from a neutron star that had suffered accretion-induced collapse. A subsequent optical rebrightening was found to have begun ~6 days before the x-rays, indicating an 'outside-in' outburst of the accretion disk. This substantial delay is explained by the inner disk needing to be re-filled before accretion onto the compact object can take place.

The brightness of GRO J1655-40 allows high-quality photometric light curves to be obtained, from which the orbital system parameters can be derived. With such an early spectral type, it has a low mass ratio ($q \sim 3$) which means that the ellipsoidal modulation is sensitive to both q and i (the latter being constrained by the observed grazing eclipse). The normal star appears to be crossing the Hertzsprung gap and about to ascend the giant branch, hence driving the much higher mass transfer rate. Temporary drops in $\dot{M}$ then return it to the transient domain.

Population size and distribution

The locations of ~90% of SXTs within a galactic longitude range of ±80° implies that they lie within 8 kpc of the galactic centre. However, distance estimates for the current sample suggest they are all < 5 kpc away, and so only ~10% of the transients occuring in our Galaxy are being detected (owing to a combination of interstellar absorption and sensitivity). Hence the total number of SXTs is ~200–1000 for a recurrence time range of 10–50 yr. The narrower dispersion in z of the SXTs, compared with neutron star LMXBs, implies that their black holes are not formed by accretion-induced collapse of a neutron star (except possibly GRO J1655-40), but more likely as the end-product of evolution of a very massive progenitor.

Nature of the compact object

With the secure observation of compact objects with masses $\geq 10M_{\odot}$, their interpretation as black holes depends on a knowledge of the maximum mass of a neutron star. This is usually quoted as $3.2M_{\odot}$, but this is based on an assumption of causality (i.e. the sound speed is $<c$) and a knowledge of the density up to which the equation of state is well understood. Relaxing these can increase the limit.

Alternative suggestions for the nature of compact objects include Q stars, where the strong force confines neutrons and protons at densities below nuclear density, leading to a very different equation of state (in which the Q stands for conserved quantity, the baryon number). They can be very compact and hence consistent with the properties of neutron stars. However, the mass of V404 Cyg shows that it cannot be a Q star as it would be inconsistent with current experimental results. In which case, it must be concluded that V404 Cyg and related objects contain black holes.

Bibliography

Charles P 1998 Black holes in our galaxy: observations *Theory of Black Hole Accretion Disks* ed Abramowicz, Bjornsson and Pringle (Cambridge: Cambridge University Press) p 1

McClintock J E 1991 *Ann. NY Acad. Sci.* **647** 495

Mirabel I F and Rodríguez L F 1994 *Nature* **371** 46

Tanaka Y and Shibazaki N 1996 *Ann. Rev. Astron. Astrophys.* **34** 607

Van Paradijs J and McClintock J E 1995, *X-Ray Binaries* (Cambridge: Cambridge University Press) p 58

Philip A Charles