MASSES OF COMPACT X-RAY SOURCES

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1. INTRODUCTION

The presence of compact x-ray sources in binary systems provides an opportunity to determine observationally the masses of neutron stars and possibly of black holes. These masses are important for equations of state at nuclear densities, for theories of gravitation, and for late stages of stellar evolution. A mass range for each source is determined by finding the sets of orbital elements that are consistent with the available x-ray and optical data. As such analyses are subject to various uncertainties, the resulting mass ranges are rather wide. Nevertheless, significant mass estimates are obtained, accompanied by interesting results on other system parameters.

In this concise review we present the observational ingredients used in mass determinations, discuss their uncertainties, and list new results obtained recently (Section 2). We then summarize the derived mass ranges for the identified x-ray binaries, and other important conclusions (Section 3).

Due to the limited space available, we can neither discuss all important details nor list all significant references. Both may be found in the more recent references which we do quote, and in the following reviews: Tananbaum and Hutchings (1975), Avni (1976a), Avni and Bahcall (1976a), Joss and Rappaport (1976). As new observational material becomes available quite frequently, we wish to emphasize that this review is based on data available at its time of writing (August 1976).

2. DATA: USE, UNCERTAINTIES AND RECENT RESULTS

2.1 X-ray Velocity Curves

These are available for the x-ray pulsars, and yield the x-ray mass function f(x;M) and the size of the x-ray orbit a(x) sin i. f(x;M) determines the masses M(x) and M(opt) as functions of the mass-

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ratio Q=M(x)/M(opt) and of the inclination angle i. a(x) sin i helps to determine the radius of the primary R for comparison with independent estimates.

The velocity amplitudes K(x) are known very accurately, except for an uncertainty of a few percent in slow pulsars (such as 3U0900-40) due to reflection of x-ray pulses from the primary (Milgrom and Avni 1976) and due to accretion torques (Fabian and Pringle 1976).

New results: K(x) measured for 3U0900-40 (Rappaport, Joss and McClintock 1976) and for SMC X-1 (Primini et al. 1976).

2.2 Optical Velocity Curves

The absorption-line velocity amplitude K(ab), which is basically associated with the orbital motion of the optical primary, yields f(opt;M) and a(opt) sin i. These are used like the x-ray values. If K(x) is also known, then Q is determined. The emission line velocities K(em) can be used if their origin is known or assumed. If the lines are emitted near the x-ray source, K(em) can replace K(x). If the lines are emitted from a part of the surface of the primary, K(em) can replace K(ab) with further geometrical assumptions on the shape of that surface (see below).

Distortion and variability of the absorption line data are common, and are caused by several effects: (a) material motions in the system and contamination by emission components, typical of mass-transfer binaries in general (see e.g. Batten 1973); (b) tidal distortion of the primary (van Paradijs, Takens and Zuiderwijk 1976); (c) large surface-temperature gradients in systems with a large ratio of x-ray to optical luminosities (L(x)/L(opt)) (Crampton and Hutchings 1974, Bahcall, Joss and Avni 1974, Milgrom 1976a); (d) filling-in of absorption lines in systems with a small ratio L(x)/L(opt) (Milgrom 1976b). The interpretation of emission line velocities is frequently ambiguous since they could either form in the accretion disk, or in the stream that hits the disk, or on the x-ray heated primary (Basko, Sunyaev and Titarchuk 1974, Milgrom 1976c).

New results: K(ab) was measured for 3U0900-40 by excluding the hydrogen lines (van Paradijs et al. 1976, van Paradijs 1976) but theoretical calculations of the effect of tidal distortion (van Paradijs, Takens and Zuiderwijk 1976) indicate a possible difficulty with the association of the observed K(ab) with the orbital motion alone. Based on these results we estimate a maximum uncertainty of 30% in the lower limit for the orbital velocity. K(ab) was measured for Cyg X-2 (Crampton and Cowley 1976). K(em) was measured for Sco X-1 (Cowley and Crampton 1975, Crampton et al. 1976).

2.3 X-Ray Eclipse Durations

The x-ray eclipse half angle θ gives a relation between the orbital separation, i and R. With the additional geometrical assumption that the primary fills an equipotential surface (e.g., a Roche equipotential), θ gives a relation between i, Q, and the ratio of R to its critical value R(c) for that potential. These relations are used to constrain the allowed values of the orbital elements.

Uncertainties in the measurement of θ are due to x-ray absorption by a stellar wind, or due to coincidences of absorption dips with eclipse edges. Upper mass limits are numerically very sensitive to θ (Avni and Bahcall 1974a).

New results: The effect of the apparent eccentricity on the calculation of θ was calculated to first order for 3U0900-40 (Avni 1976b). Smaller values of θ (better approximations for the photospheric eclipse) were measured for Cen X-3 (Pounds et al. 1976), Her X-1 (Joss 1976) and 3U1700-37 (Mason, Branduardi and Sanford 1976).

2.4 Optical Light Curves

In systems with a small ratio L(x)/L(opt) the optical light curves are ellipsoidal, and caused by the tidal deformation of the primary. When the atmospheric properties of the primary are known from observations, the two amplitudes that characterize the light curve depend on the orbital parameters Q, i and R/R(c), and can therefore be used to constrain their values. When L(x)/L(opt) is large, x-ray heating dominates the light curve, which then depends also on the intensity, spectrum and spatial distribution of the impinging flux. If the latter are known or assumed, the orbital elements can be constrained. When L(x)/L(opt)~1, both effects must be taken into account.

The analysis of the ellipsoidal light curves is subject to two types of uncertainties. Observationally the data exhibits erratic variations that complicate the extraction of the underlying amplitude (see discussion by Avni and Bahcall 1976b). Theoretically, the analysis is based on a set of assumptions, some of which have no direct observational confirmation (see discussion of the "standard model" by Avni 1976a). The calculational scheme must therefore be tested observationally (Avni and Bahcall 1975). Optical light curves that are dominated by x-ray heating are very sensitive to the properties of the illuminating x-rays, which may be different from those observed at earth due to beaming or obscuration. In such systems additional sources of optical light may be present, e.g., accretion disks heated by x-rays (Lyuty and Sunyaev 1976, Avni and Milgrom 1976). No complete studies of such systems were attempted.

New results: Light curve of 3U0900-40 analyzed by Avni and Bahcall (1975), Bochkarev, Karitskaya and Shakura (1975) and Zuiderwijk et al. (1976); of SMC X-1 by Avni and Milgrom (1976). Light curve of Cyg X-2 measured by Wright et al. (1976), but their period probably inconsistent with that of Crampton and Cowley (1976); for a preliminary analysis see Milgrom (1976d). Light curve of Sco X-1 shown to be inconsistent with simple interpretations of K(em) (Crampton et al. 1976).

2.5 Mass and Radius of Primary

These can sometimes be estimated, within limits, from considerations of the spectral type, luminosity, distance and visual absorption. Such estimates constrain the orbital elements by requiring consistency.

Mass and radius estimates must be done with care because the evolutionary state of the primary is not well known and may be affected by mass transfer, thus enabling anomalous masses and radii for the spectral type. Also, uncertainties in the distance and visual absorption must be taken into account.

2.6 Optical Pulsations

Optical pulsations were observed from Her X-1. Part of them result from the pulsed x-ray heating of the primary. Their small modulation is due to pulse-smearing by travel-time and by reprocessing time (Avni and Bahcall 1974b). From the systematics, amplitude and frequency of the pulsations a narrow range of masses was deduced by Middleditch and Nelson (1976). While their method is potentially powerful, that narrow range is presently unjustified. This is so mainly because the reprocessing effect was calculated using only one special response function, thus the parameter search done is incomplete. Also, the sensitivity to several assumptions is unknown, and the calculations did not use realistic x-ray heated model atmospheres. The importance of reprocessing time was established by showing that the pulsations are present throughout the optical continuum (Margon, Davidsen and Bowyer 1976, Nelson, Chanan and Middleditch 1976).

3. SUMMARY: MASSES AND RELATED RESULTS

The ranges of masses of compact x-ray sources in identified binary systems, that are consistent with data available at present, are summarized in Table 1. The "strong" limits were derived using a conservative interpretation of the data. The "weak" limits correspond to "reasonable" interpretations of the data by current thinking. Most of the numerical entries in the table are new results, which we have obtained while preparing this review. The data available for 3U1700-37, Cyg X-2 and Sco X-1 are very meager, and the limits given for the first two are suggestive only. For completeness and comparison we also list the masses derived for Taylor's binary pulsar assuming that the unseen component is compact (Taylor et al. 1976).

Source	Lower Limit		Upper Limit	
	"Strong"	"Weak"	"Weak"	"Strong"
3U0900-40	1.0	1.5	2.6	3.2
Cen X-3	0.8	-	3.1	4.4
SMC X-1	0.8	2.0	3.5	5.0
Her X-1	0.3	0.6	1.6	2.3
3U1700-37	-	0.5	3.0	-
Cyg X-2	-	0.6	4.7	-
Sco X-1	-	-	-	-
Cyg X-1	3	8	15	-
PSR1913+16	$M(\text{pulsar}) \leq 1.78$, $1.05 \leq M(\text{other}) \leq 2.83$, one is > 1.41, one is < 1.42			

Table 1: Mass Estimates for Compact Objects (in $M_\odot$).

From the values given in the table the following consequences emerge:

(a) The masses of x-ray pulsars, probably neutron stars, are consistent with theoretical models of neutron star structure.

(b) There is no conclusive evidence for any neutron star mass being significantly lower than 1 $M_\odot$. This could be partly due to selection effects (e.g., a low-mass x-ray pulsar may escape optical identification if K(ab) and the ellipsoidal light variations are too small to be observed).

(c) There is no conclusive evidence for any neutron star mass being higher than 1.5 $M_\odot$, but there is a suggestion that SMC X-1 is heavier than 2 $M_\odot$.

(d) Cyg X-1 still stands out alone as a serious candidate for a black hole because of the estimated large mass.

(e) X-ray velocity curves are very helpful in deriving reliable mass limits.

The analyses of the observational data that led to the above mass estimates also yielded the following general conclusions:

(i) The optical primaries in 4 out of the 5 systems with early type primaries cannot underfill their critical lobes by more than a few percent (possible exception: Cyg X-1). Apparently even stellar wind accretion, if operable, produces observable high-luminosity x-ray sources only when the critical lobe is approximately filled.

(ii) The x-rays that heat the primary in 3 out of the 4 systems with appreciable x-ray heating do not correspond to the same x-ray flux as observed at earth (possible exception: Cyg X-2). This could indicate anisotropic or beamed x-ray emission, or the existence of obscuring material either in our line of sight or between the two binary components.

The ingredients which are presently most important for narrowing the ranges of estimated masses are:
(1) 3U0900-40: Understanding the possible causes of distortion of the x-ray and optical velocity curves (in particular, tidal distortion); calculating the effect of the apparent eccentricity on the optical velocity and light curves.
(2) Cen X-3: Measuring K(ab) or an upper limit for it.
(3) SMC X-1: Simultaneous spectroscopic and photometric (and preferably also x-ray) observations, in order to isolate the effects of x-ray heating on the optical data; search for a source of optical light close to the neutron star (line profiles, optical pulsations).
(4) Her X-1: A more complete analysis of optical pulsations; continuous monitoring to catch transition to extended off state; measuring K(ab) and light curve in off state.
(5) 3U1700-37: More accurately measured eclipse duration and optical light curves.
(6) Cyg X-2: Reconciliation of spectroscopic and photometric periods.
(7) Sco X-1: Study of emission line profiles to understand their origin.
(8) Cyg X-1: Further observational studies of the shape of the light curves and the possibility of long time-scale variations of them.

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