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NICHOLAS E. WHITE*

High-mass X-ray binaries

High-mass X-ray binary (HMXB) systems were first identified in the early 1970s amongst the handful of mysterious bright X-ray sources found in the 1960s from brief sounding rocket and balloon flights. The launch of NASA's Uhuru (SAS 1) satellite, which made the first all-sky X-ray survey, established the class. One of the first results from this mission was the discovery by Giacconi *et al*. (1971) of 4.8 s X-ray pulsation from Cen X-3 (Figure 1). Precise pulse timing and the observation of an eclipse of the pulsar showed that Cen X-3 is in a 2.1-day orbit around a massive early-type star (Schreier *et al*. 1972). Within the Uhuru error box of Cen X-3 Krzeminski (1974) identified the optical counterpart as a 13th magnitude highly reddened early OB-type star. It is ironic to note that if the radio astronomers had not discovered radio pulsars in 1967, then X-ray astronomy would surely have found them a few years later. Around the time of the launch of Uhuru, Bolton (1972) and Webster and Murdin (1972) identified the optical counterpart to the then anonymous X-ray source Cyg X-1 (discovered by Bowyer *et al*. 1965) with an OB supergiant HD226868. For a brief time it was thought that Cyg X-1 was also a pulsar (Oda *et al*. 1971), but it turned out the pulses were not coherent but rather a manifestation of "shot noise" (Terrell 1972), caused by chaotic energy release in the accretion disk around the black hole. The mass function of the HD226868/Cyg X-1 system suggested that the X-ray source was too heavy to be a neutron star, and might be a black hole with a mass of 10 or more solar masses. This caused headline news at the time, as it provided the first direct evidence that these enigmatic objects might exist in nature. Over the course of time the black hole candidacy of Cyg X-1 has strengthened and it is now widely accepted. While this was one of the first HMXBs to be found, it is a relatively unique system in containing a black hole.

Following these initial discoveries several more HMXBs similar to Cen X-3 were found, primarily from the identification of other Uhuru sources. These included Vela X-1 (Ulmer *et al*. 1972; Forman *et al*. 1973), SMC X-1 (Webster and Murdin 1972; Schreier *et al*. 1972), 4U1700-37 (Jones *et al*. 1973), and GX 301-2 (Vidal 1973; Jones *et al*. 1974).These discoveries stimulated a flood of theoretical papers. Pringle and Rees (1972), Davidson and Ostriker (1973), Lamb *et al*. (1973), and Shakura and Sunyaev (1973) all proposed and discussed variants on the basic model that successfully explained the broad observational properties of Cyg X-1 and Cen X-3. The X-rays are driven by material captured from a relatively normal star, falling into the deep gravitational potential well of a neutron star in the case of Cen X-3 and a black hole in Cyg X-1 (Figure 2). The strong wind of the OB star provides a natural source of material to be captured by the pulsar or black hole. The wind may be enhanced due to the fact that the OB star is close to filling its critical Roche potential lobe, so that material spills through the inner Lagrangian point onto the compact object.

These early results provided the first direct confirmation of the earlier suggestion by Shklovsky (1967) and Pendergast and Burbidge (1968) that the mysterious bright X-ray sources were binary systems containing a compact object. These earlier models were based on the identification of Sco X-1 and Cyg X-2 with nova-like objects. These eventually became the class of low-mass X-ray binaries (LMXBs) where the mass donor is a late-type star. But it was the HMXB systems that provided the first direct proof

* NASA – Goddard Space Flight Center, Greenbelt, MD, USA

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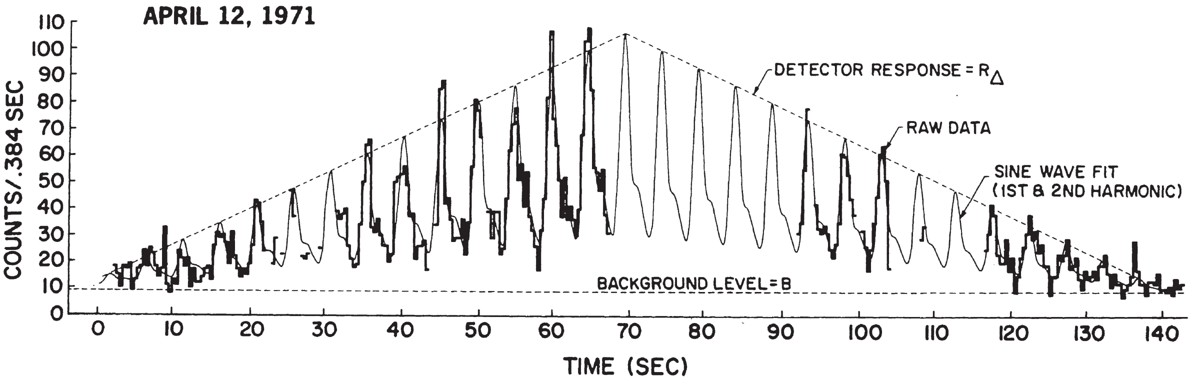

Figure 1 The discovery of X-ray pulsations from Cen X-3 made by Giacconi *et al.* (1971). The 4.8 s pulsations are seen as the Uhuru satellite scanned across the source.

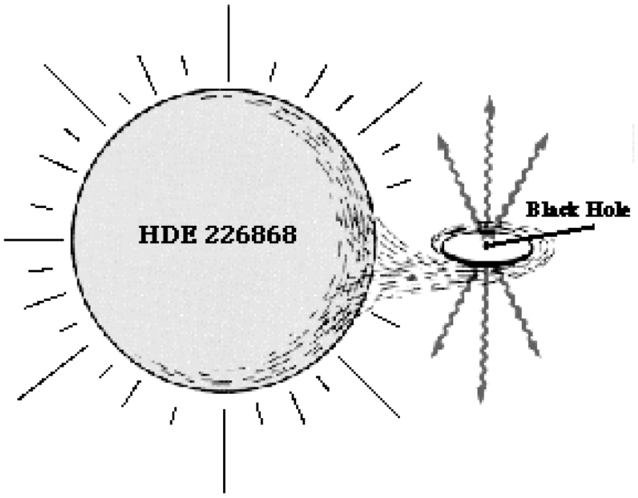

Figure 2 An artist's impression of the HMXB Cyg X-1, which has an orbital period of 5.6 days. This system contains a black hole accreting from the wind of a massive OB star.

for both the presence of accretion onto a neutron star and for the binary orbit.

The OB star companion has a substantial stellar wind, removing between 10^{-6} and 10^{-10} solar masses per year with a terminal velocity up to $2000\,\mathrm{km\,s^{-1}}$. Roche lobe overflow has also been discussed as a supplement to the mass transfer rate in some of the supergiant HMXBs. But full Roche lobe overflow is not likely to be the case because when the mass ratio of the compact object to its companion is greater than unity, then mass transfer via Roche lobe will become unstable $\sim 10^5$ yr after it starts (Savonije 1983). As the supergiant approaches its Roche lobe, the reduced gravity and/or X-ray illumination can cause a focusing of the wind towards the compact object (Friend and Castor 1982; Day and Stevens 1993).

The newly launched Ariel V observatory detected transient X-ray pulsars that brightened quickly, and then faded away over several tens of day (Ives *et al.* 1975). Several were identified with Be star optical counterparts. Maraschi *et al.* (1976) suggested they formed a distinct class of HMXB object, with the X-ray outburst driven by mass-loss episodes from the Be star. This idea was subsequently confirmed with the determination by Rappaport *et al.* (1978) using the SAS 3 satellite of a 24-day orbital period for one of these transients, 4U0115+63. The Be X-ray binaries are much more widely separated than the supergiant systems. Their typical X-ray luminosity is many orders of magnitudes lower, both because the wind is less strong and the neutron star is further out. The Be stars are well known as a class of star that is rotating close to breakup velocity. They are thought to have a disk in the equatorial plane and to undergo mass-ejection episodes. Most are only seen as X-ray sources when the Be star undergoes such a mass-ejection episode, so that the X-ray luminosity increases dramatically (Stella *et al.* 1986).

Not all the Be systems are transients. The Uhuru error box of the persistent, relatively faint source 4U0352+52 contained X Per, a bright Be star that up until then had been assumed to be a single star. White *et al.* (1976a) using the small X-ray telescope on the Copernicus observatory discovered a coherent 13.9-minute pulsation from the X-ray source associated with X Per. The luminosity of this system is $10^{33}\,\mathrm{erg\,s^{-1}}$, 1000 to 1 million times fainter than the other members of the HMXB class. The Be star systems are by the far the most populous members of the HMXB class. They tend to be nearer by (by virtue of their higher space density) and have a lower luminosity.

The term "high-mass X-ray binary" did not enter the vernacular until the early 1980s. By then the systematic studies using the X-ray observatories of the 1970s (Uhuru, Ariel V, SAS 3 and HEAO 1) had resulted in the identification of $\sim$25 systems associated with OB stars (Bradt and McClintock 1983). By that time it was clear that the overall properties of an X-ray binary were dictated by the nature of the mass donor. The spectral type of the mass donor in an

LMXB is K or later and does not have a strong wind – Roche lobe overflow drives the X-ray emission. In an HMXB the wind of the OB star provides a ready source of fuel for the X-ray source, and also attenuates the X-ray source. This natural division also means that HMXBs are younger systems, where the neutron star has been relatively recently formed.

PULSE AND ORBITAL PERIODS

Orbital periods

The orbital period and eccentricity of a representative selection of HMXB systems are listed in Table 1. The orbital periods range between 4.8 h and 250 d. The supergiant systems typically are eclipsing and show extreme intensity and absorption variability on all timescales. The longer orbital period systems are more eccentric. This eccentricity is to be expected from the "kick" imparted during the supernova explosion that created the neutron star. Tidal effects will tend to circularize the orbit, and will be more important in the shorter orbital period systems. All but one of the supergiant systems have orbital periods less than 15 d, and dominate this part of the period distribution. Most Be star systems have longer periods of several tens or hundreds of days. The orbital periods of the Be X-ray binaries are not so well known, except that they must be long to avoid any tidal modulation of the optical star or variations of the pulsar arrival times. For these systems it can take many years of observations to reveal the orbital period. For example the orbital period of X Per remained elusive for many years until very recently the Rossi XTE, by monitoring the pulse timing over several years, revealed a 250-day period (Delgado-Martí *et al.* 2001).

As the baseline of the pulsar timing measurements increased it became possible to search for changes in HMXB orbital periods. Kelley *et al.* (1983) determined that the orbital period of Cen X-3 is decreasing on a timescale of $\sim$500,000 yr. This decrease is the result of tidal torque between the neutron star and the outer layers of the

Table 1 The parameters of some well-known HMXBs

Name	Alternative name	Orbital period (day)	Pulse period* (s)	Eccentricity	Type†
Gamma Cas	4U 0053+604	?	?		Be
A 1118-61	He3-640	?	405		Be transient
Cyg X-3	V1521 Cyg	0.20	—		WR
LMC X-4	Sk-Ph	1.4	13.5		SG
LMC X-3	—	1.7	BHC		Be
Cen X-3	Kra	2.1	4.8	0.0008	SG
4U 1700-37	HD 153919	3.41	—		SG
4U 1538-522	QV Nor	3.73	529		SG
SMC X-1	Sk 160	3.89	0.71	<0.0007	SG
Cyg X-1	HD226868	5.60	BHC		SG
4U 1907+097		8.38	438	0.22	SG
Vela X-1	HD77581	8.96	283	0.092	SG
OAO 1657-415		10.4	38		SG
4U 0115+63	LS I+65 010	11.6	850	0.34	Be
SS433	4U 1909+048	13.1	—		SG
1E 1145.1-6141	V830 Cen	?	298		SG
A 0535-668		16.7	0.069		Be transient
4U 0115+634	V662 Cas	24.3	3.6		Be transient
4U 1553-542		30.6	9.3		Be?
V 0332+53	BQ Cam	34.25	4.4	0.31	Be transient
GX 301-2	Wra 977	41.5	696		SG
EXO 2030+375		46.0	41.8		Be
A 0535+262	HD 245770	111	104		Be transient
GX 304-1	V850 Cen	133	272	0.47	Be
4U 1145-619	Hen 715	187.5	292		Be
X Per	4U 0352+30	250	835		Be

*BHC, black hole candidate.
†SG, supergiant; WR, Wolf Rayet.

supergiant. A similar decay in the orbit of SMC X-1 has been measured by Levine *et al.* (1993). There are several other HMXBs where marginal evidence for a change in period has been reported, including LMC X-4, Vela X-1, and X0115+634 (Nagase 1992, and references therein).

Neutron star orbit and mass determination

The X-ray pulsar can be used as a precise clock to determine the orbital parameters of the neutron star and to obtain a mass function (Figure 3). A mass function can also be obtained for the OB star using optical spectroscopy. These can be combined with other constraints to determine the orbital inclination, such as the duration of the eclipse, to yield the mass of the neutron star. These measurements also give the overall system parameters.

The neutron star mass has now been determined in seven X-ray binary systems and three radio pulsar binaries. The uncertainties for the X-ray pulsars are dominated by those in the optical mass function (which can be difficult to measure) and the system inclination. Within the uncertainties, the neutron star masses obtained are consistent with 1.4 solar masses, the canonical Chandrasekhar mass.

Pulse periods

HMXB pulse periods are also given in Table 1. They range from 60 ms to 850 s. Many of the HMXBs have long pulse periods of the order of minutes, the slowest rotating neutron stars known. During the mid-1970s many of these long-period X-ray pulsars were found using a combination of Ariel V, SAS 3, and Copernicus. These missions provided the first pointed capability where observations lasting many hours to days were possible (as opposed to Uhuru which scanned a narrow field of view across the sky). Many of these long-period pulsars were discovered in quick succession (e.g. McClintock *et al.* 1976, 1977; White *et al.* 1976b). A striking example of how common these long-period pulsars are was the discovery of the "twin pulsars" by White *et al.* (1978) using Ariel V. The field of view of the instrument being used for the search was 3.75°. In one field containing the Uhuru source 4U1145-61 a power spectrum of the time series revealed two peaks at 292 and 298 s. This suggested there were two pulsars within 1° of each other, with very similar pulse periods. This result was confirmed a year later when the Einstein Observatory took the first images of the region to reveal two separate sources, pulsing at the two periods found by Ariel V (Lamb *et al.* 1980). The original 4U1145-61 source is in a widely separated Be system with an orbital period of 292 days (Watson *et al.* 1982).

The longer pulse periods were an unexpected discovery. While there was no reason to exclude such a population, the radio pulsars cuts off at about 10 s because they cross a "death line" where the dipole radiation is no longer efficient. These newly found long-period X-ray pulsars were dubbed "slow rotators" (e.g. Fabian 1975; Lea 1976) and provided a new view on the evolution of neutron star spin periods.

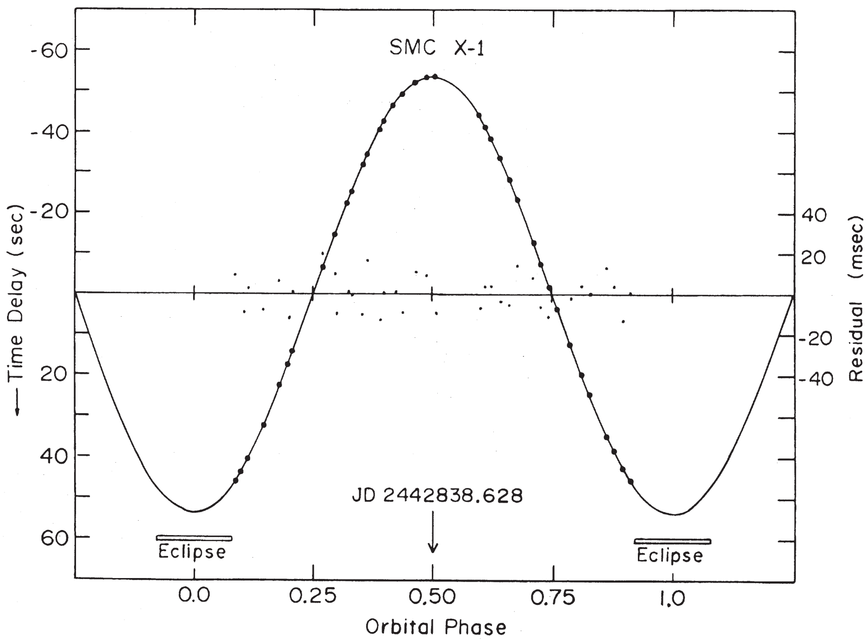

Figure 3 The orbit of SMC X-1 determined from an arrival time analysis of the 0.7 s pulsations. (Taken from Primini *et al.* 1977).

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