X-RAY BINARIES AND RELATED SYSTEMS

VIRGINIA TRIMBLE
Astronomy Department
University of Maryland
College Park MD 20742 USA

and

Physics Department
University of California
Irvine CA 92717 USA

ABSTRACT. Neutron stars and a few black holes in binaries reveal their presence by emitting X-rays when they accrete gas from their companions via a wind or disk. Related objects include SS 433, Geminga, gamma ray bursters, TeV/PeV sources, and the source in CTB 108. Systems with secondaries $\gtrsim 8\ M_o$ are the natural descendents of main sequence OB binaries. Those with secondaries $\lesssim 1\ M_o$ arguably form some other way. These systems display a wealth of structure in both wavelength and time domains, much of which is reasonably well understood. Among the things we would like to know more about are the masses and rotation periods of the neutron stars in the two main kinds of systems.

1. SYSTEMS AND SYSTEMATICS

A neutron star or stellar-mass black hole, accreting gas from its surroundings, will radiate, mostly in X-rays, a luminosity given by

$$L_{36} = 6.71\ M_{1.5}\ (dM/dt)_{15}\ /\ R_{10} \tag{1}$$

where L_{36} is the luminosity in units of 10^{36} erg/sec, $M_{1.5}$ is the mass of the accreter in units of 1.5 M_o, $(dM/dt)_{15}$ is the accretion rate in units of 10^{15} g/sec (= 1.5×10^{-11} M_o/yr), R_{10} is the accretion radius in units of 10 km, and the numerical factor incorporates the constant of gravity and a correction factor (0.745) for gravitational redshift.

Such accretion rates can be achieved (a) from the wind of a massive star or the beginning of Roche lobe overflow by such a star and (b) from fully-developed Roche lobe overflow by a solar-type star. Full RLOF by a massive star transfers gas far in excess of the maximum (Eddington) rate at which the neutron star can accept it and chokes the X-rays; while the wind of a solar-type star provides too little gas for detectable accretion X-rays. For further details, see Bhattacharya and van den Heuvel (1991), who also give an excellant overview of many other aspects of the origin, evolution, and fate of X-ray binaries.

Y. Kondo et al. (eds.), Evolutionary Processes in Interacting Binary Stars, 91–101.

TABLE 1: X-RAY BINARIES AND RELATED OBJECTS

TYPE	NUMBER KNOWN	EVIDENCE FOR CBS	EVIDENCE FOR HIGH B	ROTN PER	ORBIT PER	EXAMPLE
MXRB	30	Yes	Yes	$0.7\text{-}850^{s}$	$16\text{-}188^{d}$	Vela X-1
BeXRB	70	Yes	Yes	$0.06\text{-}835^{s}$	$1.4\text{-}41^{d}$	GX 304-1
BH Cands.	4-6	Yes	No	none	$0.3\text{-}5^{d}$	Cyg X-1
LMXRB	100					
opt. data	36	Yes	No	$0.13\text{-}122^{s}$	$11^{m}\text{-}12.5^{d}$	Sco X-1
gl. clust	12	Yes?	No	msec?	$11^{m}\text{-}8.5^{h}$	4U2121+12 = AC 211(M15)
bulge	50	Yes	No	msec?	hr-days	GX 17+2
QPOs	10	Yes	No	msec	$11^{m}\text{-}10^{d}$	Cyg X-2
very soft	5	Yes	No	?	hr-days	RX 05278 -6954
SS 433	1	Yes	No	?	13.1^{d}	SS 433
XRB in SNR	1?	No	Yes?	6.98^{s}	----	1E 2259+586 = CTB 108
γ bursters	100's	No	Yes	?	----	1979 Mar 5
TeV/PeV sources	few?	some	some	various	various	Cyg X-3
Geminga	1	No	No	60^{s}?	----	Geminga

Table 1 lists the major types of X-ray binaries and some systems and objects that may be related to them (apart from the binary and millisecond pulsars that I discuss elsewhere in these proceedings). The abbreviations are: XRB = X-ray binary; M = massive (optical identification with star $\gtrsim$ 8 $M_{\odot}$); Be = emission line B star as optical identification (always well inside Roche lobe, but surrounded by stray gas); LM = low mass (optical identification with star $\lesssim$ 1.5 $M_{\odot}$); QPO = source of quasi-periodic oscillations; CBS = close (interacting) binary system nature reasonably well established; high B = magnetic field of 10^{12-13} G revealed by cyclotron resonances and/or rotationally modulated accretion. The black hole candidate transient sources discovered by Ginga and described by Y. Tanaka elsewhere in this volume may be a new separate class.

Several conferences and books have been devoted primarily to X-ray binaries in recent years. Recommended for further reading are Lewin and van den Heuvel (1983), Lamb and Patterson (1985), Mason et al. (1986), Truemper et al.(1986), Tanaka (1988), and Hunt and Battrick (1990). Trimble (1991) is a more extended version of my own views on the subject.

2. SPECIFICS

This section can be regarded as a series of extended footnotes to Table 1. It deals with how we know the properties listed there, current interpretations of the underlying physical processes, and some residual puzzles, many connected with the one-of-a-kind objects. No complete catalogue of X-ray binaries is currently in print, But Bhattacharya and van den Heuvel (1991) give tables of most members or representative members of the main classes, and Cherepashchuk et al. (1989) tabulate very extensive references as well as many of the known objects.

2.1. Massive X-ray Binaries

The clean division between the two main categories of MXRB (including Be systems) and LMXRB remains in my mind a major puzzle. Either systems consisting of, e.g., NS + 5 M_o main sequence star never form, or accretion in them is never at the right level (Eqn. 1) to radiate X-rays. Neither is obviously true, and the issue has not been much addressed in recent discussions of evolutionary processes (Bhattacharya and van den Heuvel 1991).

Other interesting aspects of MXRBs include the slowness of their rotation periods; changes in their orbit periods; their spectra; masses and magnetic fields of the neutron stars; and various luminosity changes. The general idea on rotation periods is that the neutron stars spin down early on when they are accreting from winds and back up toward the end while accreting from the beginnings of Roche lobe overflow (Bhattacharya and van den Heuvel 1991; Bisnovatyi-Kogan 1991; Illarimov and Kompaneets 1990). This fits, in the sense that the fastest-rotating MXRB (0538-66) and the fastest recycled pulsar with a neutron star companion (1913+16) both have periods near 0.06 sec, but I remain surprised at the very slow average rotation period of the MXRB population (median about 75 sec.).

Statistically significant changes in orbit period have been found for five MXRB and Her X-1 (Nagase 1991). Four periods are getting smaller, and two are increasing, all on time scales near 10^6 yr, except for Her X-1 whose $P/\dot{P} = -1.3 \times 10^{-8}$ yr. The time scale is about right for secular changes in the massive donors, but there is no obvious correlation of, for instance, sign of the change with wind vs. Roche lobe overflow accretion.

About seven MXRBs definitely have magnetic fields in the expected range 10^{12-13} G, on the basis of cyclotron features confirmed or detected by Ginga (Makishima 1991). Some experience bursts, which do not cool as they fade and which can be attributed to accretion instabilities (Angelinit et al. 1991); and all display complex X-ray spectra, which, however do not apparently present any fundamental difficulties in their interpretation (Burnard et al. 1991).

Because Doppler shifts can be determined both from spectral lines of the donors and from timing of the rotationally modulated flux of the neutron stars, mass determinations for the latter are, in principle, possible. Most have error bars spanning nearly a factor of two, and none is as precise as those for binary pulsars. All are marginally consistent with 1.5 M_o, though the best value for Her X-1 is nearer 1.2 M_o and for Vela X-1 near 1.8 M_o (Inoue 1991). Values with 10% or better accuracy would be of great interest for testing evolutionary scenaries, but await a better understanding of just how the line velocities relate to stellar center of mass velocities.

2.2. Emission Line B Star (Be) and Transient Systems

Our inventories of these sources are guaranteed not to be complete, for transients because they are on for weeks to months and off for months to years, and we may not be looking at the right time; and for Be star systems because nearly all of those with optical identifications are within a couple of kpc of us. Most of the Be star systems are transients, but not all transients are Be stars.

For thoses that are, X-ray outbursts are sometimes periodic and at periastron (meaning that the neutron star has come in close enough to cross through equatorial gas around the donor, Makishima et al. 1990) and sometimes erratic and due, presumably, to episodic equatorial shedding by the Be star. If the non-equilibrium spin periods of many Be systems (King 1991) really indicate ages near 10^5 yr, then the birthrate must be comparable with the galactic supernova rate.

The mechanism for low mass transients is different and probably associated with disk instabilities, perhaps resembling those that produce superhumps in cataclysmic variables (Charles et al. 1991). These can also recur: A0620-00 was seen as a nova in 1917, and GX 2023+338 as Nova Cygni 1938. The accreting star in the former seems to be a black hole, and it can be argued that the same is true for many of the other low mass transients (Y. Tanaka, elsewhere in these proceedings).

2.3. Low Mass X-Ray Binaries

The first compact galactic X-ray source seen, Sco X-1, belongs to this class (and is, like all prototypes, untypical). The binary nature was initially somewhat difficult to establish, since most neither eclipse nor display regular pulsations that can be timed for Doppler shifts. About three dozen now have established orbit parameters (Parmar and White 1988: Ritter 1990). This includes only two of the globular cluster sources, but the binary nature of the others is no longer in doubt. Companions include main sequence, red giant, and white dwarf stars. The distinction between LMXRBs and cataclysmic variables is made from the ratio L_x/L_{opt} (larger for neutron star accretors) and from short term variability (CVs flicker; LMXRBs burst).

Phenomena connected with LMXRBs that seem to be reasonably well understood include the spectra and the X-ray bursts. The spectra are complex but can be modelled (White 1988; Ponman et al. 1990) in terms of the components you would expect -- radiation directly from the neutron star surface, from its boundary layer with the disk, and from the disk, with a good deal of reprocessing of photons from inner regions by gas in outer regions (approximately describable as Comptonization). The bursts occur when accreted hydrogen burns steadily to helium but the helium ignites degenerately (Lewin and Joss 1983). A residual problem is that bursts sometimes recur sooner than another helium layer could be built up, and stars must somehow either burn helium incompletely or ignite hydrogen explosively.

The bursts look nearly thermal and cool as they fade, suggesting the potential for calculating radii of the neutron stars. Sadly, the actual spectra are always different enough from black bodies that no useful constraints on neutron star equations of state result (Madej 1991; van Paradijs et al. 1990).

Items connected with LMXRBs that I think require further thought and/or data include the masses and rotation periods of the neutron stars, the driver for mass transfer, and the cause of changes in orbit periods. Because none of the (normal) LMXRBs reveal their rotation periods, we cannot use Doppler shifts to extract orbit parameters or masses. The rotation periods are believed to be short, corresponding to the results of prolonged accretion and to the "best buy" model of QPOs (Sect. 2.6), but precision searches for modulation of the X-rays at such periods have yielded only upper limits around 1% (Y. Tanaka in van den Heuvel and Rappaport 1991). Accretion over the lifetimes of the low-mass donors leads us also to expect that some of the neutron stars could be quite massive and so tell us about the equation of state of nuclear matter. No data support this hope.

Measured orbit period changes for LMXRBs include two positive and two negative values, all with time scales near 10^7 years, about 100 times faster than you expect from nuclear evolution of the donor (Tavani 1991). The solution to this puzzle may also cast light on what drives mass transfer in those systems where it is not self sustaining (that is, transfer makes the Roche lobe grow not shrink) and not explicable by gradual expansion of the donor, magnetic wind braking, or gravitationa radiation. The proposed solution (Tavani 1991; Podsiadlowski 1991) is radiation driving. That is, radiation from the neutron star (both pulsar-type and accretion powered) sigificantly changes the structure of the donor, leading to loss of mass and/or angular momentum on the time scales seen.

2.4. The Black Hole Candidates

Perhaps the most important property of these systems is their existence as the best evidence we have for objects that have collapsed beyond neutron star densities. Although a number of XRB display what may be X-ray signatures of black hole accretors (Miyamoto and Kitamoto 1991), I regard as persuasive only the four (or so) systems for which optical line velocities yield a mass function inconsistent with the accretor being a neutron star. With this definition, the official candidates are Cyg X-1 (Sokolov 1988; Dolan and Tapia 1989), which has been with us since 1972, A0620-00 (Haswell and Shafter 1990), and two Magellanic Cloud sources LMC X-1 and LMC X-3 (White 1989). It is a surprise, though one of low statistical significance, that half the candidates should be in the LMC. Indulekha (1990) has suggested that all the systems have had line profiles distorted by winds, and none contains an accretor more massive than the maximum possible for a stable neutron star.

2.5. Hercules X-1

Identified with a 2 $M_{\odot}$ A type star (whose features are detectable in the optical spectrum) Her X-1 is either the heaviest LMXRB or the lightest MXRB. It has in common with massive systems rotational modulation (P =

1.24 s) and a magnetic field near 10^{12} G (Makishima 1991) and in common with the low mass systems dominant light output from an accretion disk. Additional periodicities occur at 1.7 days (the orbit) and 35 days, interpreted as precession of either the neutron star (Truemper et al. 1986) or the disk (Bisnovatyi-Kogan et al. 1990).

Some systems that may be related are 4U0614+09 with a 10 day period interpretable as disk precession (Machin et al 1991) and three other LMXRB with pulsational modulation, 4U1627-67 (7.98 s), GX 1+4 (tentatively 122 s), and 1E2259+59 (6.98 s, of which more in Sect. 2.9).

2.6. Accretion Disks and Quasi-Periodic Oscillations

All LMXRBs and black hole systems and some of the massive neutron star systems convey gas from the companion onto the compact star via accretion disks somewhat similar to those found in cataclysmic variables and (probably) in active galactic nuclei. Whole books (Treves et al. 1989) and conferences (Meyer et al. 1989) have been devoted to these disks, which are responsible for most of the optical continuum and line emission we see from XRBs (hence the difficulty sometimes in deciding whether emission line velocities really track the center of mass of the accretor). They can both obscure X-ray flux and, in ionized coronae, scatter it into our line of sight, so that the absence of true eclipses is primarily an orientation effect (Milgrom 1978). The brightening of the XRB in M15 above 10^{38} erg/s, assuming isotropic, unobscured emission (Dotani et al. 1990) casts some doubts on this picture.

Accretion disks are generally also held responsible for channelling material out into extended radio-emitting regions (Achterberg 1989) and for producing irregular variability on time scales from minutes up to years (Priedhorsky and Holt 1987) via many different kinds of instability in disk structure and mass transport process.

EXOSAT discovered a new category of LMXRB variability, the quasi-periodic oscillations (QPOs), also arising from disk processes. Most have frequencies of 5-60 Hz, widths in the power spectrum of about half the central frequency, amplitudes of 1-10%, and remarkably complex correlations of their properties with source brightnesses and color temperatures, with some correlations also occurring in their ultraviolet, optical, and radio fluxes. Co-discoverer van der Klis (1989) has reviewed the phenomenology and models. One well-defined QPO mode (found in Cyg X-2, Sco X-1, and a handful of other sources) is well explained by a beat frequency between the rotation periods of the inner edge of the accretion disk and of the magnetosphere of the neutron star, at the point where pressures in the two are equal.

An important implication is that LMXRB neutron stars rotate at millisecond periods, as expected from prolonged accretion-driven spin up. Other modes require other models, some analogous to the disk instability that triggers dwarf nova outbursts. Some MXRB and black hole candidates display related sorts of variability (Miyamoto and Kitamoto 1991). GX 2030+375 is particularly instructive. Assuming a beat model, the QPO frequency (0.2 Hz) and NS rotation period (42 s) permit one to calculate the size of the magnetosphere, which turns out to imply a surface dipole field of 10^{12-13} G, just as you would have expected (Angelini et al. 1989).

2.7. The Very Soft Sources

This new and possibly heavily populated category identified by the ROSAT team so far includes four sources in the Magellanic Clouds and only one in the Milky Way (Truemper et al. 1991; Greiner et al. 1991). This seems to be an observational selection effect, and the galactic counterparts could make up a major fraction of the progenitors of binary and millisecond pulsars (J. Truemper in van den Heuvel and Rappaport 1991).

2.8. SS 433

The optical counterpart of this X-ray source was "prediscovered" as an emission line object by Stephenson and Sanduleak. A set of narrow H and He emission lines shift through an amplitude ± 195 km/s with a stable 13.1 day period (Margon and Anderson 1989) revealing its binary nature. It is not possible to reconstruct the geometry of the system accurately enough to be sure whether this amplitude is consistent with a neutron star emitter or requires a black hole (Zwitter et al, elsewhere in this volume). There is no periodicity suggestive of rotation.

The uniqueness lies in a second broader set of emission lines, with a period of 164 days and amplitude of ±40,000 km/s. This velocity behavior was quickly modeled as a pair of oppositely directed jets, moving at 0.26 c, in directions that precess every 164 days around an axis tilted 79^{o} to the plane of the sky (Fabian and Rees 1979; Milgrom 1979). The velocity suggests line locking, because (1216-912)/1216 = 0.26.

Many important points remain obscure. These include the cause of the 164 d precession (wobbling disk? neutron star? something else?); the relationship between SS 433 and the (presumed) supernova remnant W50 around it (remnant left from event that made NS? mostly powered by relativistic beam input from current binary?); just what accelerates the jet; are the collimated, moving radio jet and the optical emission line one the same gas, different gas at same velocity, or largely unrelated; and why is only one of them known, even though there are a number of similar X-ray binaries with collimated radio structure and precession-like periodicities? These puzzlements are further discussed by Zwitter et al. (1989), Kochanek and Hawley (1990), and Brown et al. (1991). Kundt (1991) proposes a definite set of answers (jets unrelated; neutron star precession driven by disk; etc.) that leaves a different set of puzzles.

2.9. 1E 2259+586, an X-ray Binary in a Supernova Remnant?

Otherwise known as the Fahlman-Gregory object, this compact X-ray source with a 6.98 s pulsation period is located within the supernova remnant CTB 108, although its physical association with the remnant has been doubted (Davis and Coe 1991). Its spin down time of 3 X 10^{5} yr is too long for rotational kinetic energy to power the X-ray emission, leading to interpretation as an X-ray binary. There is, however, neither dynamical (Koyama et al. 1989) nor optical (Davis and Coe 1991) evidence for a companion. Alternative models include a millisecond pulsar precessing at the 7 s period (Carlini and Treves 1989) and pulsar-type emission from a highly magnetized, rotating, massive white dwarf produced by a recent merger (Paczyński 1990a). In both caases, the object would be the product of an interacting binary and so belong in this conference. The former model is also consistent with the tentative detection of cyclotron resonance features (Makishima1991); the latter is not.

2.10. Gamma Ray Bursters

These events (fully described by Higdon and Lingenfelter 1990) continue to defy efforts at identification with steady sources in any wavelength band (Ho et al 1991). Their near isotropy on the sky means that they must be either within a few hundred parsecs or at cosmological distances. In the former case, absence of X-ray reflection effects precludes the presence of a binary companion (Dermer et al. 1991) and the sources must be old, single neutron stars, retaining fields near 10^{12} G (at least for those with cyclotron resonance features (Murakami 1991). In the latter case, they could result from mergers of binary neutron stars in distant galaxies (Paczyński 1990b) and so be part of our subject matter.

2.11. TeV and PeV Gamma Ray Sources

Detections with rather low statistical significance of very high energy gamma rays from an assortment of pulsars, X-ray binaries, and related objects go back more than a decade. The Crab Nebula (Vacanti et al 1991) is the most persuasive of the detections, but not relevant here. Of the X-ray binaries, Cyg X-3 has been most frequently and consistently reported (Muraki et al. 1991). Doubts have been cast on the reality of many detections (Lewis et al 1991), but this has not prevented theorists from modeling, apparently successfully, the production of TeV and PeV photons (Eichler and Ko 1988; Gnedin and Ikhsanov 1990; and many others). Part of ones lingering doubts come from the detected events acting like particles somewhere between photons and hadrons (Dingus et al. 1988).

2.12. Geminga

The Gemini gamma ray source (the name also means "it is not there" in Milanese dialect) has a uniquely high ratio ($\gtrdot$ 1000) of gamma ray flux to that in X-ray, optical, or other bands. The rotation period is somewhat tentative, and there is no direct evidence for a binary companion, thus the system may well not belong in this book at all (Bignami et al 1988). If by any chance Geminga is the nearest, youngest millisecond pulsar, (Srinivasan 1990), then it is, at any rate, the descendent of an interacting binary!

3. FORMATION MECHANISMS

Stars that start out with more than 5-9 $M_{\odot}$ leave neutron star remnants rather than white dwarfs and some still more massive ones perhaps black holes. Half or so of the dots of light in the sky are really binaries, and while mass transfer will increase the initial mass required to produce the more compact remnants, it also means that an isotropic supernova explosion of the first star will not unbind the system (Trimble and Rees 1971).

The initial system must, however, be wide enough that the primary can evolve a helium core of at least 2.2 $M_{\odot}$ before the onset of transfer if core collapse to a neutron star or black hole is to occur.

Thus about a third of the neutron stars and black holes that form will do so in close binaries. This straightforward picture accounts for both the numbers and the properties of massive and Be star XRBs provided that their lifetimes are not too much shorter than those of the donor stars (Bhattacharya and van den Heuvel 1991). If the galactic population of assorted MXRBs is 10^{2-3} and they live for the 10^5 yr during which the secondary experiences a strong wind or marginal RLOF, then the birthrate must be 1-10 per millenium, and most of the compact objects born in binaries must experience an XRB phase.

Allowing for loss of mass and angular momentum permits a wider range of initial systems to produce a wider range of final ones, optionally accomodating Her X-1 within this scenario (van den Heuvel and Habets 1985). Such losses occur primarily during a common envelope phase (Paczyński 1976) when the primary (or, later, the secondary) is shedding material faster than its companion can accrete. Both analytical approximations and numerical calculations for this process exist (Taam and Bodenheimer 1989), but the amount of mass lost and the extent to which the accretor spirals in remain somewhat adjustable parameters. Thus even LMXRBs could form this way (Joss and Rappaport 1979), though there are alternatives.

The LMXRB formation process is entitled to be a rare one, if the 100 or so systems in the Milky Way persist for the 10^9 yr permitted by the lifetimes of their companions. That they are, at any rate mostly old follows from their distribution in the galactic bulge population and globular clusters, where they are over-represented relative to the rest of the galaxy by about 100 to 1 (Katz 1975). It has, as a result, been suggested that LMXRBs form only in globular clusters, the field population having been ejected from their parent clusters by encounters or liberated by cluster dissolution (Grindlay 1988).

If all or most LMXRBs start out in clusters, then they could have formed through a variety of stellar encounter processes in the dense cluster cores (especially in globulars that have been through core collapse). The possibilities include two body tidal capture (Clark 1975; Fabian et al. 1975), three body captures (where two stars are left bound because a third carries away excess energy), and star exchanges between primordial binaries and neutron stars left in the clusters from core collapse supernovae long ago (Hut et al. 1991; Phinney and Kulkarni 1991). Head on collisions of neutron stars with less compact objects are also possible but probably result in total distruction of the extended star. Some recycled pulsars may be made this way.

Finally, a process called accretion induced collapse (AIC: Canal et al. 1990) has been associated with the formation of globular cluster XRB (Grindlay 1988) but can also occur in the field (van den Heuvel 1981). The original motivation, to account for neutron stars with magnetic fields up to 10^{10} G in dyamically old binary systems, has largely disappeared -- we do not understand the time evolution of NS magnetic fields, but they are no longer thought to decay exponentially without limit. For a white dwarf to be driven above the Chandrasekhar limit by accretion from a companion and so to collapse to a neutron star sounds, a priori, quite probable. The catch is that, for this to happen in preference to a series of nova explosions or a single carbon burning deflagration (which destroys the star), the white dwarf has to be quite massive to start with and the accretion rate must fall within a fairly narrow range. The recurrent novae are possible progenitors of AIC (R.E. Webbink in van den Heuvel and Rappaport 1991). Admittedly, recurrent novae are rare, but so is the formation of LMXRBs, unless they are required to give rise to all the binary and millisecond pulsars we see (elsewhere in this volume).

4. UNANSWERED QUESTIONS

Several dozens of these appear in the preceeding pages, but if a canonical genie limited me to three they would be: (a) What are the masses and rotation periods of neutron stars in LMXRBs? (b) Which formation processes dominate in and out of globular clusters? and (c) How does a core collapse decide when to form a black hole? A second genie would be asked to explain (a) the energy source in 1E2259+586, (b) the absence of donor stars between 2 and 8 $M_{\odot}$, and (c) the uniqueness of SS 433 and Geminga.

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