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Low-mass X-ray binaries

The connection between cosmic X-ray sources and compact stars is an old one: soon after the discovery of the first such source, Sco X-1 (Giacconi *et al*. 1962), it was proposed that these objects are young, hot neutron stars, formed in recent supernovae, which cool through thermal radiation from their surfaces (Chiu 1964, Chiu and Salpeter 1964, Finzi 1964). However, the finite extent of the X-ray source associated with the Crab Nebula (Bowyer *et al*. 1964), and the non-Planckian shape of the X-ray spectra of this source (Clark 1965) and of Sco X-1 (Giacconi *et al*. 1965) showed that this was not, in general, a good model for X-ray sources.

Accretion onto a compact star had meanwhile been suggested as a possible source of energy for quasars and X-ray sources (Salpeter 1964, Zel'dovich 1964, Zel'dovich and Guseinov 1966), and together with the peculiarities of the optical spectra of the counterparts of Sco X-1 (Sandage *et al*. 1966) and Cyg X-2 (Giacconi *et al*. 1967) this led to the idea that these sources are mass-exchanging binaries with a compact component (Shklovsky 1967; see also Burbidge 1972, Ginzburg 1990). The spectrum of Sco X-1 was similar to those of old novae and U Gem-type stars, which were by then known to be binary stars, in particular through the work of Crawford and Kraft in the 1950s and 1960s (Crawford and Kraft 1956; Kraft 1962, 1964). However, the single-most important characteristic of a binary star, that is, an orbital periodicity, was not found until many years later, in spite of substantial observational effort (see Hiltner and Mook (1970) and Kraft (1973) for discussions of early optical observations of X-ray sources, and references).

The discovery of the first X-ray binary, Cyg X-1, by Webster and Murdin (1972) and Bolton (1972) at the same time showed that this binary star contained an accreting object that is likely to be a black hole.

The idea that all bright galactic X-ray sources are mass-exchanging binary stars with a compact accretor became widely accepted with the observation, with the Uhuru satellite, of regular eclipses of the pulsating X-ray source Cen X-3 (Giacconi *et al*. 1971, Schreier *et al*. 1972). The variable delays of the pulse arrival times, in phase with the periodic (2.1 days) eclipses of the X-ray source, showed persuasively that in Cen X-3 the X-rays are generated by accretion onto a strongly magnetized neutron star, rotating at a 4.8 s pulse period, in orbit around a massive ($\gtrsim 10 M_{\odot}$) companion star. The discovery of the binary nature of Cen X-3 was soon followed by more observations of eclipsing X-ray sources, some of them pulsating, and by the identification of these X-ray sources with early-type stars. In addition, a general framework for the origin and evolution of a massive X-ray binary, as a rather normal episode in the life of a massive close binary star with successive stages of mass transfer between the two components, was readily accepted (Van den Heuvel and Heise 1972). Thus, within a few years the existence of a galactic population of high-mass X-ray binaries (HMXBs), with accreting neutron stars (or occasionally a black hole) was well established.

Already in the 1960s (e.g. Dolan 1970) it had become clear that there is a clustering of bright X-ray sources within $\sim 30°$ of the direction of the galactic center. This concentration was not accompanied by a strong background of unresolved sources, which showed that these sources are located in the central regions of the Galaxy (Ryter 1970, Setti and Woltjer 1970). It was, therefore, suspected that apart from the above-described HMXBs there is a class of low-mass X-ray binaries (LMXBs) with donor star masses of the order of a solar mass or less (e.g. Salpeter 1973), but proof for this idea was hard to obtain. Apart from the difficulty of finding orbital periods, the

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apparent heterogeneity of the properties of LMXBs may have played a role. Compared to the HMXBs the first handful of known systems now classified as LMXBs (Her X-1, Sco X-1, Cir X-1) show rather more diversity than similarity in their properties. As a result, only at the end of the 1970s did it become clear that there are such objects as LMXBs, which form a group with "family traits," distinct from the HMXBs with respect to their sky distributions, X-ray spectral characteristics, optical properties, and types of X-ray variability (e.g. Lewin and Clark 1980). The LMXBs comprise the globular-cluster X-ray sources, X-ray bursters, soft X-ray transients, and the bright galactic-bulge X-ray sources.

Roughly speaking, the reason for the bi-modal distribution of the masses of donor stars in X-ray binaries is that for stars less massive than $\sim 10 M_\odot$ the stellar wind is too weak to power a strong X-ray source; however, Roche lobe overflow is unstable for stars more massive than a neutron star, and proceeds on a very short timescale, as a consequence of which the accreting neutron star is completely engulfed and X-rays cannot escape.

The differences between the X-ray properties of LMXBs and HMXBs (with accreting neutron stars) may be linked to a difference in the strength of the magnetic fields of the neutron stars they harbor. The natural assumption that the difference in donor star masses corresponds to a difference in the ages of LMXBs and HMXBs has led to the idea that the magnetic fields of neutron stars decay with time.

Within the limits of this review it would be meaningless to strive for completeness. For detailed reviews on a variety of topics related to X-ray binaries we refer the interested reader to Lewin *et al*. 1995). Further background information can be found in Shapiro and Teukolsky (1983), Frank *et al*. (1992), Ögelman and Van den Heuvel (1989), Ventura and Pines (1991), Van den Heuvel and Rappaport (1992), Alpar *et al*. (1995), and Buccheri *et al*. (1998). References on individual sources can be found in Bradt and McClintock (1983) and Van Paradijs (1995). An extensive summary of X-ray satellite missions has been given by Bradt *et al*. (1992).

1 OPTICAL COUNTERPARTS

Whereas the optical properties of HMXBs are dominated by the emission of their very luminous mass-donor stars, the optical spectra of LMXBs (e.g. Shahbaz *et al*. 1996) show only a few emission lines, particularly Hα, Hβ, He II λ4686, and C III–N III λ4630–50, superposed on a rather flat (in frequency) continuum. In a few cases the signature of a companion star can be discerned. According to Motch and Pakull (1989) the relative strength of the C III–N III emission complex relative to the λ4686 emission provides a good measure of the heavy-element abundances in the accreted matter. Spectra of cataclysmic variables (CVs), in which the accretor is not a neutron star (or black hole) but a white dwarf, bear a general resemblance to those of LMXBs, showing emission lines superposed on a continuum (see Warner 1995 for a comprehensive review of CVs). However, the equivalent widths of these lines in LMXB spectra, in particular that of Hβ, tend to be much smaller than those in CV spectra (Van Paradijs and Verbunt 1984, Shahbaz *et al*. 1996).

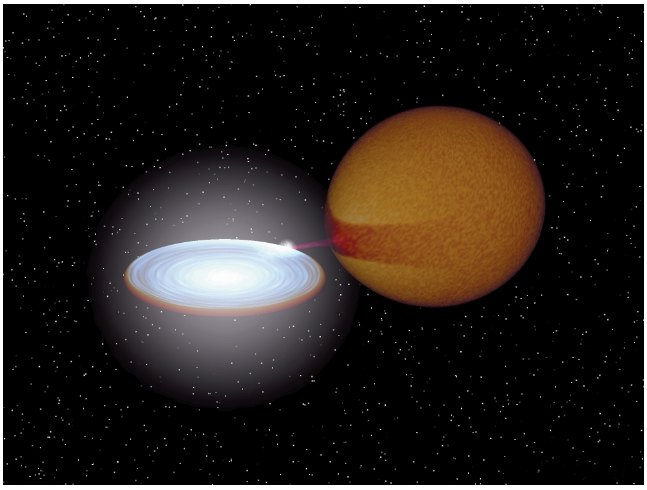

Figure 1 Artist's impression of an X-ray binary. (Credit: Rob Hynes).

In LMXBs the donor star transfers mass by Roche lobe overflow (Figure 1). This mass arrives at the compact star via a relatively flat rotating configuration, the accretion disk, in which it slowly spirals inward. Gravitational potential energy is converted into heat in this process. In the inner few tens of kilometers of this disk temperatures of $\sim 10^7$ K are attained, which leads to the emission of thermal X-rays. Part of these X-rays irradiate the disk further out. The optical emission of LMXBs originates primarily from these irradiated outer regions of the accretion disk, which produce their radiation mainly through reprocessing of incident X-rays into optical and UV photons. This reprocessing dominates the internal energy generation of the disk due to conversion of gravitational potential energy into heat, generally by a large factor (Van Paradijs and McClintock 1995). For internal energy generation alone, as occurs in accretion disks in CVs, the (local) effective temperature, T, in the disk varies with radial distance, r, from the central compact star approximately as $T(r) \propto r^{-3/4}$. In LMXB disks, where reprocessing of X-rays dominates the energy budget, one would expect $T(r) \propto r^{-1/2}$. Thus, the farther out in the disk, the more reprocessing dominates internal energy generation. According to the simplified, but self-consistent calculations of Vrtilek *et al*. (1990), in which also the effect of X-ray irradiation on the height of the disk is taken into account, $T(r) \propto r^{-3/7}$.

Many LMXBs show a regular orbital variation of their optical brightness, with one maximum and minimum per orbital cycle. Minimum light occurs at the superior conjunction of the X-ray source. These variations are caused by the changing visibility of the accretion disk and the X-ray heated side of the secondary, insofar as the latter is not in the X-ray shadow of the disk (see Van Paradijs 1991 and Van Paradijs and McClintock 1995 for reviews of the optical light curves of LMXBs).

For transient LMXBs ("soft X-ray transients") in quiescence, X-ray heating of the accretion disk and the companion star is not very important, and the optical emission of the system is dominated by the Roche lobe-filling secondary star. These systems then show ellipsoidal light curves, reflecting the tidal and rotational distortion of the secondary.

The (reddening-corrected) color indices $B-V$ and $U-B$ of LMXBs have average values of -0.09 ± 0.14 and -0.97 ± 0.17, respectively (errors are 1σ standard deviations), close to those expected for a flat continuum ($F_\nu=$ constant). The distribution of the ratio of X-ray to optical fluxes is rather sharply peaked. Expressed in terms of an "optical/X-ray color index" $B_0 + 2.5 \log F_X(\mu\text{Jy})$, the peak occurs near 21.5, corresponding to a ratio of fluxes emitted in X-rays (2–11 keV) and in optical light (3000–7000 Å) of $\sim$500 (Van Paradijs and McClintock 1995).

The optical luminosities of LMXBs are, in general, much higher than those of CVs (e.g. Warner 1987, 1995); this is because the gravitational potential well of a neutron star is much deeper than that of a white dwarf, and X-ray heating of the accretion disk is not important in CVs.

Absolute visual magnitudes M_V have been estimated for LMXBs with distance estimates: (i) LMXBs in stellar systems at a known distance; (ii) X-ray burst sources (Section 5) showing bursts with Eddington-limited photospheric radius expansion; (iii) Z sources (Section 6); when these are in the "normal-branch" state their X-ray luminosity is very close to the Eddington limit (e.g. Van der Klis 1995); (iv) soft X-ray transients, whose distance can be determined in quiescence from the spectral properties of the companion star. The absolute magnitudes of active LMXBs range between -5 and $+5$ (Van Paradijs and McClintock 1994). This large range is the consequence of the large range in X-ray luminosity, L_X, of the central source, and in the size of the accretion disk. For a simple model of reprocessing of X-rays the optical luminosity, L_V, of the disk is expected to scale with L_X and orbital period P as $L_V \propto L_X^{1/2}P^{2/3}$, in agreement with the values of M_V for LMXBs with known orbital periods. This is confirmed by numerical calculations of X-ray-heated accretion disks (De Jong *et al.* 1996).

2 ORBITAL PERIODS

Orbital periods are known for some three dozen LMXBs, mainly from regular X-ray eclipses and X-ray "dips" (White *et al.* 1995), and optical brightness variations (Van Paradijs and McClintock 1995). In several cases periodic radial velocity variations have been found for emission lines (originating from an accretion disk), or for absorption lines (secondary star of soft X-ray transients in quiescence). The known orbital periods of LMXBs range between 685 seconds and 16.6 days (Van Paradijs 1995, Liu *et al.* 2001). This large range indicates that LMXBs have a variety of mass donors (white dwarfs, main-sequence stars, giant stars). The orbital-period distributions of CVs and LMXBs (Figure 2) are different. Compared to the CVs a much larger fraction of LMXBs have periods above about half a day. A possible explanation for this difference is that for such long periods the companion star masses are expected to substantially exceed the mass of a typical white dwarf, but not that of a neutron star. This will make the mass transfer at long periods unstable for CVs, but not for LMXBs. The LMXB period distribution does not show the well-known period gap in the distribution for the CVs (e.g. Verbunt 1984, Spruit and Ritter 1983 for studies of the period gap); in fact, there are no LMXBs in the period range between 80 minutes and 2 hours (i.e., below the period gap), which is well populated by the CV. This may be the result of the high probability that LMXBs form at periods of about half a day or longer, whereas a large fraction of CVs form at periods below 2 hours (King and Kolb 1997). Perhaps evaporation of the LMXB secondaries plays a role after the LMXB has reached the upper edge of the period gap; mass transfer then stops, and the rapidly rotating neutron star (spun up by accretion torques) then becomes active as a millisecond radio pulsar (Ruderman

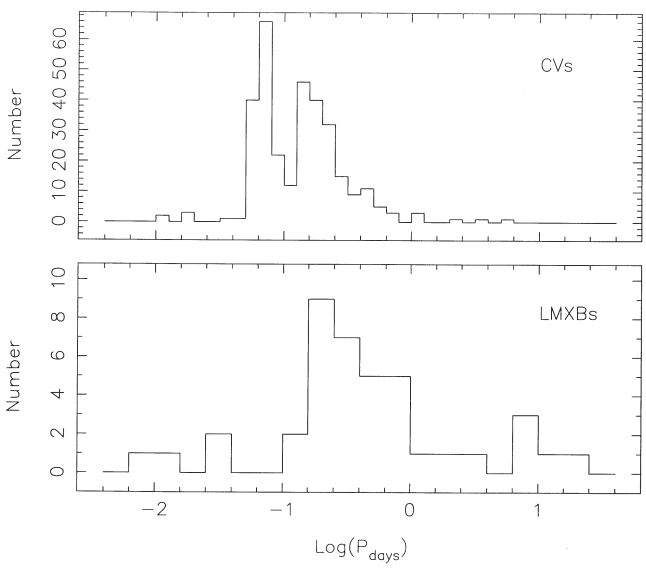

Figure 2 Distributions of orbital periods for LMXBs and CVs. Data have been taken from Van Paradijs (1995) and Ritter and Kolb (1998).

et al. 1989, Van den Heuvel and Van Paradijs 1988); however, whether or not complete evaporation of the secondary star occurs is a matter of debate.

3 GALACTIC DISTRIBUTION

The sky distributions of the HMXBs and LMXBs are quite different, as shown in Figure 3. The galactic HMXBs are distributed along the galactic plane, without an obvious concentration to the galactic center. They have an average latitude $< b^{\mathrm{II}} > = -0.8 \pm 6.9°$; if we leave out X Per and a few other nearby high-latitude Be/X-ray systems identified by Tuohy *et al.* (1988) we find $< b^{\mathrm{II}} > = 0.4 \pm 1.9°$. This fits the idea that HMXBs are young population I objects.

The galactic LMXBs (excluding the globular-cluster sources) have a wider latitude distribution ($< b^{\mathrm{II}} > = 0.4 \pm 9.1°$), and are also more concentrated to the direction of the galactic center. The scale height of the (assumed exponential) distribution of distances from the galactic plane, for LMXBs with neutron stars at known distances is 900 pc (Van Paradijs and White 1995). The z distribution of LMXBs with a black hole is substantially narrower (White and Van Paradijs 1996). The wide z dispersion of LMXBs with neutron stars requires that the neutron stars in these systems formed in an asymmetric supernova explosion which gave them an extra kick velocity (Brandt and Podsiadlowski 1995, Van Paradijs and White 1995, Ramachandran and Bhattacharya 1997); the kick velocity distribution is consistent with that of single radio pulsars (Lyne and Lorimer 1994, Hansen 1996, Hansen and Phinney 1997, Hartman *et al.* 1997).

There are $\sim 10^2$ persistent luminous LMXBs ($L_X > 10^{36}$ erg s^{-1}) in the Galaxy (Van Paradijs 1995). During the last decade it has become clear that in a large fraction of the transient LMXBs the compact star is a black hole; the number of such transient black-hole binaries in the Galaxy is estimated to be between a few hundred and a few thousand (Tanaka and Lewin 1995, White and Van Paradijs 1996).

The kinematic properties of LMXBs have been studied by Cowley *et al.* (1988) and Johnston (1992). Based on the large velocity dispersion and low galactic rotation velocity, Cowley *et al.* (1988) concluded that LMXBs are among the oldest objects in the Galaxy. However, since LMXBs get a kick velocity at the formation of the neutron star, such a direct interpretation of the kinematic properties of LMXBs in terms of their ages cannot be made.

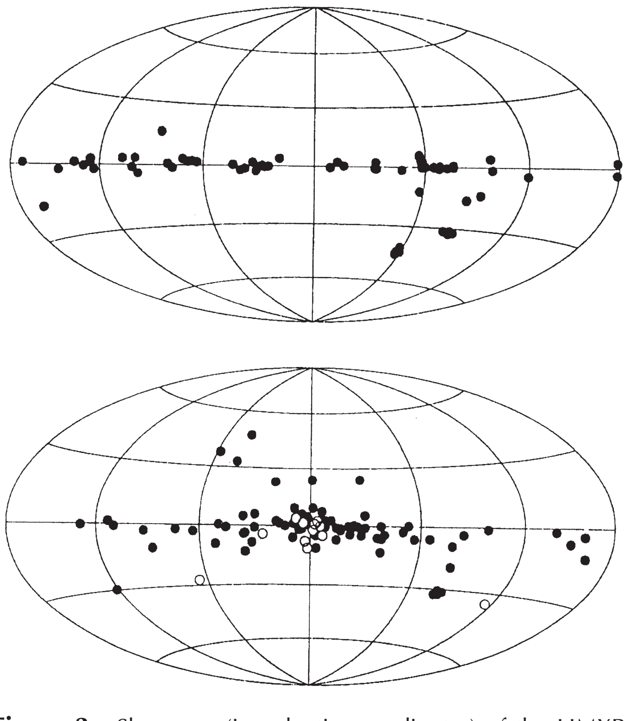

Figure 3 Sky maps (in galactic coordinates) of the HMXBs (top) and LMXBs (bottom); the latter also includes the globular-cluster sources (indicated by open circles). The 27 LMXBs within 2° of the galactic center have not been included to avoid congestion of the map. These maps are based on the catalog of Van Paradijs (1995).

4 X-RAY PULSATIONS

Almost all HMXBs show X-ray pulsations, which indicates that the accreting compact stars in these systems are strongly magnetized neutron stars (for reviews of various aspects of X-ray pulsars see, e.g. Joss and Rappaport 1984, Nagase 1989, White *et al.* 1995, Bildsten *et al.* 1997).

Pulse arrival time measurements for pulsating HMXBs, in combination with radial velocity observations of their massive companions, have provided information on the masses of accreting neutron stars.

X-ray pulsations in LMXBs are very rare. In spite of very sensitive searches (e.g. Vaughan *et al.* 1994) none of the bright LMXBs have shown the predicted millisecond pulsations, with upper limits to their amplitudes well below the 1% level. One case of a millisecond pulsar powered by accretion has recently been found. This pulsar, with a spin period of 2.5 ms, was discovered with the Rossi X-ray Timing Exporer (RXTE) in the faint transient LMXB SAX J1808.4-3658 (Wijnands and Van der Klis 1998). It has an orbital period of approximately two hours (Chakrabarty and Morgan 1998). In the last several years evidence for millisecond spin periods of the neutron stars in LMXBs has also been obtained from the "burst oscillations" seen in some X-ray bursts (Section 5); indirect evidence from aperiodic variability for millisecond spin periods also exists (Section 6).

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