Session 1

Key source categories in our Galaxy

LOC members making a preparatory visit to Dublin Castle. From right: Cóilín Ó Maoiléidigh, Laura Norci, Evert Meurs. Photo courtesy of C. Woods.

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Key Source Categories in the Galaxy

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Abstract. The proliferation of X-ray astronomy missions over the last 10 years has had a major impact on our knowledge of Galactic X-ray binaries. More recently, Chandra and XMM-Newton have provided a dramatically improved census of extra-galactic X-ray binaries. In this talk I will provide an overview of the various populations and observational properties of X-ray binaries in our Galaxy, in an effort to "set the scene" for a comparison with their extra-galactic counterparts.

Keywords. X-rays: binaries, binaries: close, stars: neutron, black hole physics.

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1. Introduction

"A round tower of fire was seen in the air over Ros Ela on Sunday the feast of St. George for five hours of the day" – Irish monks record the Crab supernova in 1054 AD.

The appearance of the Crab Supernova in 1054 was a propitious moment in astronomy – a mysterious harbinger of discoveries to come (the quotation above comes from observations made by monks in Tullamore in Ireland, one of the very few written European accounts of this event: see Polcaro in these proceedings for a detailed discussion of similar historical records). However, it took more than 900 years before X-ray astronomy could finally provide the tool required to comprehensively study the formation and evolution of such compact objects in our Galaxy and beyond. Currently, astronomers inhabit a "golden age" of multiwavelength astronomy – an astronomy that is problem driven, rather than its modus operandi of the past, dominated by observations at a fixed (e.g. optical) wavelength range.

X-ray astronomers currently find themselves with a multitude of observatories at their disposal, including Chandra, XMM-Newton, INTEGRAL, Swift, RXTE, etc. Of all the objects in the menagerie of sources accessible to X-ray astronomy, Galactic X-ray binaries have led to particular insights into the formation and evolution of compact objects in accreting binaries. Here I give a brief overview of some of the salient properties of these binaries in our Galaxy: whilst a review of this type will be, by necessity, no-where near complete, hopefully it can still serve to "set the scene" for the extra-galactic (X-ray binary) discussions to follow in the rest of these proceedings.

2. The View from Afar: a very brief overview

Currently, there are almost 300 X-ray binaries known in our Galaxy, including both the persistently bright and the quiescent systems (e.g. see Fig. 1). These systems have traditionally been divided into the so-called High Mass X-ray Binaries (HMXBs), with a secondary mass $M_2 > 10$ $M_\odot$, and Low Mass X-ray Binaries (LMXBs), with $M_2 \leqslant 1$ $M_\odot$ – which, for the purpose of this review, also includes the so-called Intermediate Mass X-ray Binaries (e.g. Pfahl *et al.* 2003). Accretion generally occurs via either a stellar

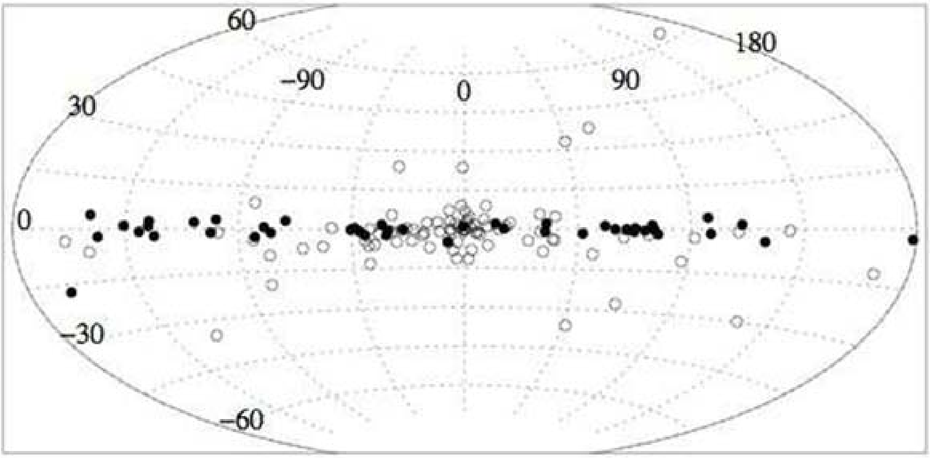

Figure 1. The Galactic distribution of X-ray sources: from Grimm *et al.* (2002). The open circles denote LMXBs, and the filled ones HMXBs.

wind or circumstellar disk for the HMXBs, and via Roche Lobe overflow for the LMXBs. A large fraction of both types of X-ray binary consists of transient sources: whereas the recurrence timescale of the LMXB transients is highly irregular, many of the HMXB transients recur periodically.

The X-ray emission of our Galaxy is dominated by the LMXBs in the bulge: Grimm *et al.* (2002) find that the (average) total LMXB X-ray luminosity (L_x) of our Galaxy is $\sim$2–3 × 10^{39} ergs s^{-1}, compared to $\sim$2–3 × 10^{38} ergs s^{-1} for the HMXBs.

For our Galaxy and others, it has also been shown that a universal (X-ray) luminosity function exists for both LMXBs (scaling with galaxy mass) and HMXBs (scaling with star formation rate), see Grimm *et al.* (2002, 2003 and these proceedings). This seems remarkable, considering the transient nature of many LMXBs and HMXBs as observed in our Galaxy and others, and the fact that the appearance of our Galaxy is dominated by only the 5–10 most luminous sources.

Nearer the Galactic Centre, a large fraction of the observed “diffuse” X-ray emission is likely due to quiescent X-ray transients, absorbed HMXBs and magnetic cataclysmic variables (CVs), in addition to genuinely diffuse emission (e.g. Muno *et al.* 2003, Hands *et al.* 2004).

Finally, some 13 LMXBs, both persistently bright and transient, are known to exist in Galactic globular clusters, in addition to fainter populations of sources including CVs, millisecond pulsars, magnetically active binaries, etc. (e.g. Verbunt and Lewin, 2006). Uniquely amongst all the binaries we discuss here, many of these globular cluster systems are thought to be created by 2 and 3-body tidal interactions between stars in the dense cluster cores (e.g. Pooley *et al.* 2003).

We will now discuss each of these key types of compact binary in more detail.

3. The High Mass Systems

The majority (some $\sim$96) of the 130 known HMXBs pulsate, with spin periods ranging from 69 msec to 1400 s. Their X-ray spectra are characterised by a flat power-law with an energy index 0–1, and a high energy cut-off of 10–20 keV. A soft excess is often seen below 1 keV (see White, Nagase and Parmar 1995 for more details).

Grimm *et al.* (2002) suggested that HMXBs tend to avoid the inner 3–4 kpc of the Galactic disk, although Kuulkers (2005) suggests that many of the recently discovered, highly absorbed Integral sources sources may be obscured HMXBs and hence closer to the Galactic Centre.

The SMC contains a disproportionately large population of HMXBs: this is probably due to tidal interactions between the SMC and the LMC in the past (see e.g. Corbet, these proceedings).

There are two main categories:

3.1. *Systems with Supergiant Secondaries (Of, or earlier than B2)*

These comprise ∼25% of all known Galactic HMXBs (Charles and Coe, 2006). With mass loss dominated by stellar wind from the secondary (although Roche lobe overflow can also play a role), L_x, although persistent, is low, $\sim 10^{34}$–10^{35} ergs s^{-1}, and hence the optical flux is completely dominated by the secondary star. Many of these systems exhibit an ellipsoidal modulation, and five undergo X-ray eclipses, and as such are ideal for accurately measuring neutron star masses – if sufficiently high resolution optical spectra can be obtained (e.g. van der Meer *et al.* 2005).

3.2. *Systems with Be Star Secondaries*

These constitute some 60% of all known Galactic HMXBs. Accretion occurs via an equatorial region of material generated by anisotropic wind loss from the (rapidly rotating) secondary star. Combined with the eccentric orbit of the compact object, this results in a highly variable X-ray luminosity, often showing periodic X-ray outbursts (recurring with the orbital period), with L_x 10^{37}–10^{38} ergs s^{-1} (at maximum). Typical quiescent X-ray luminosities range between 10^{33}–10^{34} ergs s^{-1}. An IR excess due to emission from circumstellar disk is often observed (e.g. Charles and Coe, 2006). Finally, we note that a strong correlation exists between orbital and spin periods for the Be systems (Corbet, 1984).

With their relatively bright secondary stars, the optical counterparts to HMXBs should be identifiable in nearby galaxies: whilst several such systems have been found, relatively few HMXB transients appear to have been identified so far (e.g. Williams *et al.* 2006).

4. The Low Mass Systems

More than half of all known Galactic X-ray binaries are LMXBs, with orbital periods ranging from 11 mins to 16.5 days. For those systems that are persistently bright, $L_x \sim 10^{36}$–10^{38} ergs s^{-1}. LMXB X-ray spectra can be crudely characterised by power-law/bremsstrahlung emission (e.g. due to Comptonization), with a black body component for the more luminous ($L_x > 10^{37}$ ergs s^{-1}) sources. Lower luminosity sources often exhibit thermonuclear (Type-I) X-ray bursts, and harder, power-law spectra with an energy index ∼1 and an exponential high energy cut-off (again, see White, Nagase and Parmar, 1995 for more details).

Many of the techniques used to study CVs have been successfully applied to LMXBs (e.g. Doppler tomography), particularly those LMXBs in a quiescent state – e.g. radial velocity and ellipsoidal studies of the secondary star. It has been found, for example, that the shorter period LMXBs have accretion geometries comparable to those found in CVs – e.g. Roche-lobe overflow mediated accretion, relatively high mass ratios ($= M_1/M_2$, where M_1 is the compact object mass), outer disk "bulges" where the accretion stream

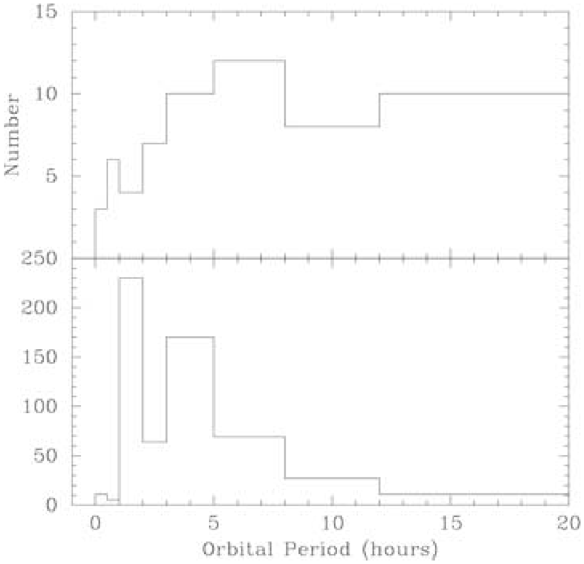

Figure 2. The CV (lower) and LMXB (upper) orbital period distribution.

meets the disk, precessing accretion disks, etc. In addition, the accretion disk instability that drives the outbursts of so many CVs is also thought to be responsible for LMXB transient behaviour (see next section, and Charles and Coe, 2006 for more details).

In Fig. 2, we plot the orbital period distribution for 596 CVs and 81 LMXBs, from the most recent catalogue of Ritter and Kolb (2005) over the range 0–20 hrs. The orbital period bins are rather wide, in an attempt to improve on the statistics for the LMXB distribution. Although the LMXB numbers are low, the distributions are clearly quite different. The data suggest that the CV period gap (at 2–3 hrs) is not present in the LMXB orbital distribution, perhaps because of the effect of X-ray irradiation on the orbital evolution of these systems. The relative fraction of longer period LMXBs (in comparison to CVs) should also be noted: this may be due again to the effect of X-ray irradiation on the secondary star, enabling it to fill its Roche lobe and maintain mass-transfer for the longer period systems.

A quite spectacular Type-I bursting phenomenon has recently been discovered – the “superbursts” (e.g. Kuulkers, 2005). Lasting several hours and with total fluences of $\sim 10^{42}$ ergs, such bursts (some of which may be due to C burning) should be observable from extragalactic (i.e. beyond SMC/LMC) distances.

4.1. *X-ray Novae (aka Soft X-ray Transients)*

Approximately half of all known LMXBs are transient, with typical recurrence times 10–50 years. In outburst, these are the brightest sources in the X-ray sky, with $L_x \geqslant 10^{39}$ ergs s^{-1} for the more extreme examples. Their quiescent luminosities, on the other hand, are equally dramatic, reaching values as low as 10^{30} ergs s^{-1} in some cases. Quiescent neutron star systems appear to be systematically brighter than this, strongly suggesting that the fainter black hole systems possess an event horizon across which material is accreted before it can radiate (e.g. Garcia *et al.* 2001).

With orbital periods ∼4 hrs – 33.5 days, and secondary stars that can be spectroscopically studied in quiescence, these systems have yielded 15 binaries for which strongest evidence exists for the presence of stellar mass black holes in our Galaxy (see Charles and Coe, 2006 for more details).

4.2. *Accreting Binary Millisecond Pulsars*

Of all the X-ray binaries discussed in this review, this is the class of object that is expanding at the fastest rate. Since the discovery of the prototypical system in 1996, SAX J1808.4-3658 – the all-singing, all-dancing, bursting and pulsating X-ray binary – 6 more systems have been discovered at the time of writing (see Wijnands, 2005). With orbital periods ranging from 40 mins to 4.3 hours, and spin periods from 1.67-5.4 msec, these systems finally provide firm confirmation of the link between accreting LMXBs and millisecond pulsars. Many of these transients would have escaped detection in the past, as they have relatively meagre maximum outburst luminosities, $\sim 10^{36}$ ergs s^{-1}. Why X-ray pulsations can be so easily observed for this class of system, and so much harder to see directly for the vast majority of LMXBs, is still unclear (although it may be due to the lower accretion rates present in these short period transients: e.g. Wijnands, 2005).

The best studied of these systems in quiescence remains SAX J1808.4-3658: interestingly, Campana *et al.* (2004) suggest that strong heating of the secondary star is maintained even in this state, caused by irradiation due to the spin-down luminosity of the neutron star, similar to the case of the "black-widow" binary millisecond pulsar PSR B1957+20 (e.g. Callanan *et al.* 1995).

Between these and the burst oscillations observed in some LMXBs (and, of course, the persistently bright pulsators), some 20 LMXBs now exist for which the spin period of the neutron star is known.

4.3. *X-ray Reprocessing*

In contrast to the HMXBs, the optical flux of most LMXBs (except those with the longest orbital periods) is dominated by X-ray processing. As discussed by van Paradijs and McClintock (1994), this allows us constrain the orbital period of a given system, if we know the X-ray luminosity and absolute magnitude (M_V): this is particularly useful in the case of extragalactic LMXBs (see e.g. Williams *et al.* 2005). It is interesting to investigate the effect of the nature of the compact object on this correlation: for example, systems with a higher mass ratio ($q = M_1/M_2$) might be expected to have larger, and hence brighter, accretion disks (e.g. Garcia 2005). Indeed, taking two values of $q = 10$ and 1 – corresponding to a 1 $M_\odot$ secondary with a black hole and neutron star primary respectively – we expect a difference in Roche-lobe radius of the primary star of $\sim$2 (for the same orbital period and X-ray luminosity).

In Fig. 3, we plot the relationship derived by van Paradijs and McClintock (1994) between M_V and $\log\Sigma$, where $\Sigma = P^{2/3}(L_x/L_{Edd})^{1/2}$ (with P the orbital period and L_{Edd} the Eddington luminosity), for some 12 LMXBs for which these parameters can be measured with reasonable confidence. In addition to their best fit, we superimpose a line $\sim$1 mag higher, corresponding to the offset we expect between neutron star and black hole systems (of comparable X-ray luminosity and orbital period). It can be seen that this offset is perilously close to the scatter in the data, indicating that M_V, L_X and P measurements alone do not appear to provide sufficient discrimination between black hole and neutron star systems in the case of our Galaxy. However, as some of the scatter in this plot is undoubtedly due to uncertainty in the distance to the systems, longer term monitoring of extragalactic LMXBs (i.e. systems at known distance) may reveal a systematic difference in M_V between the black hole and neutron star systems.

4.4. *Globular Cluster Sources*

Of the 13 luminous LMXBs in Galactic globular clusters, 5 are transient. Furthermore, 4–5 are likely to have ultrashort ($\leqslant$ 1 hr) orbital periods, as inferred either from direct measurement, from the L_x M_V relationship discussed above, or other properties (e.g.

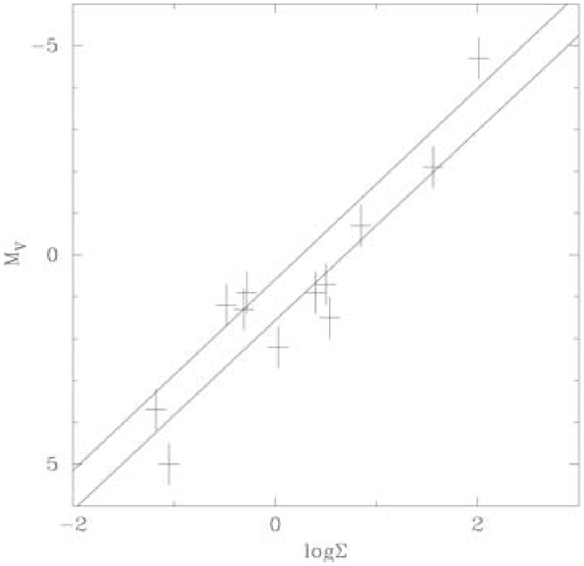

Figure 3. The absolute magnitude vs Σ, from van Paradijs and McClintock (1994); see Section 4.3 for the meaning of the two lines.

Deutsch *et al.* 2000, Verbunt & Lewin, 2005). These compact binaries are important for the overall evolution of the host cluster (e.g. providing it with energy against collapse), and suggest that clusters not only make binaries via 2 and 3-body interactions (see Fig. 4), but also create ultra-compact systems. Many other types of binaries are also present in globular clusters (CVs, millisecond pulsars, magnetically active binaries, etc). Bildsten and Deloye (2004) suggest that most cluster LMXBs are ultracompact, with lifetimes of a few $\times 10^6$ yrs: this has the effect of increasing the overall birthrate of binaries in globular clusters, bringing it into agreement with the observed population of the (descendent) millisecond pulsars.

Have globular clusters made most, if not all, of the Galactic LMXBs we see today? This has been suggested by, for example, Grindlay (1984), and more recently by White, Sarazin and Kulkarni (2002). As pointed out by Verbunt and Lewin (2005), in our Galaxy and M31 there are 10 disk LMXBs for each cluster LMXB, whereas for elliptical galaxies this ratio of cluster to non-cluster LMXBs is 1:1: this suggests that most Galactic LMXBs formed in the disk. However, the argument is not clearcut: Gnedin and Ostriker (1996) raise the possibility that the current population of Galactic globular clusters are but a very small fraction of the initial population, with many clusters in the past completely disrupted as they orbit through the plane of the Galaxy. On the other hand, elliptical galaxies, or course, do not have the same perturbing influence on their clusters. This issue appears to have been resolved by Irwin (2005), who provides strong arguments for the creation of the majority of "field" LMXBs in the field itself, rather than through cluster disruption or destruction.

5. X-ray Population of the Galactic Centre

Finally, we briefly discuss the population of X-ray sources recently uncovered near the Galactic Centre. Muno *et al.* (2003) discovered some ∼2000 point-like sources within ∼20 pc of Galactic Centre, with $L_x \sim 10^{31} - 10^{33}$ ergs s^{-1}. As many of these have relatively hard X-ray spectra (kT>8 keV), they are similar to magnetic CVs – as postulated,

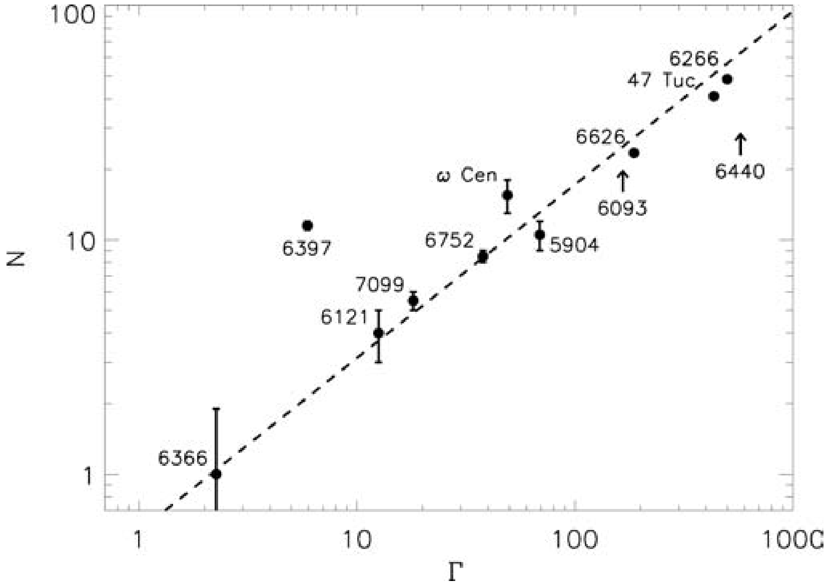

Figure 4. The number of faint globular cluster sources vs encounter rate Γ ($\propto$ (central density)$^{1.5}$(core radius)^2) for a sample of globular clusters. See Pooley *et al.* (2003) for more details.

for example, by Watson (1999). These sources may contribute to a large fraction of the diffuse emission near the Galactic Centre. In addition, Muno *et al.* (2005) report 7 transients, some of which vary by a factor of $\sim$10, with L_x (maximum) $> 5 \times 10^{33}$ ergs s^{-1}: 4 of these lie within 1 pc of Sgr A*. These could be HMXBs, or, intriguingly, LMXBs produced by 3 body interactions (in the environment near the Galactic Center where the stellar density is $\sim$240–900 M$_\odot$ pc^{-3}: see e.g. Muno *et al.* 2003, 2004).

6. Conclusions

In summary, we note that:

(1) The combination of RXTE Galactic monitoring, and high resolution imaging of Chandra and XMM, has finally allowed us (at least attempt) to unite the Galactic and extragalactic populations of X-ray binaries.

(2) Optical observations are an essential tool in the study of X-ray binary populations in our Galaxy and others. We note, however, that once the demise of the HST occurs, and its successor launched, the kind of imaging previously possible with the HST will only be available in the near and far IR, where its successor will be optimised. Hence more effort spent now on characterising the IR properties of Galactic X-ray binaries, for comparison with future IR observations of their extra-galactic cousins, will be time well spent.

(3) Whatever about the need for a future space based optical facility, there is an obvious and pressing need for a future imaging X-ray astronomy mission with larger throughput/effective area than either Chandra or XMM (e.g. White, 2005). However, there is also a very strong case for (cheaper !) lower resolution, but wider field monitoring missions. The expanding number of Galactic black hole X-ray binaries, and the even more rapidly increasing number of accreting binary millisecond pulsars are but a foretaste of what could be delivered by such a mission.

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Discussion

Eracleous: Do we know any example in our Galaxy of systems that are HMXBs accreting via genuine RLOF (i.e. $L_x \sim 10^{38}$ erg/s and a supergiant companion)?

Callanan: We know of a number of RLOF systems of this type but their L_x are several orders of magnitude lower.

Mirabel: GRS 1915 is one such example.

Callanan: Yes, that is the exception to many rules.

The Symposium audience listening. How many are sleeping? Notice the bouncer at the door.