MASSIVE X-RAY BINARIES

New developments in the INTEGRAL era

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Abstract The study of massive X-ray binaries provides important observational diagnostics for a number of fundamental astrophysical issues, such as the evolution of massive stars, the stellar winds of massive stars, the formation of compact objects and accretion processes. More than three decades of study have led to a coherent picture of their formation and evolution and some understanding of the physical mechanisms involved. As more and more systems are discovered, this picture grows in complexity. Over the last two years, INTEGRAL has discovered a new population of massive X-ray binaries, characterised by absorbed spectra, which challenges some of our previous assumptions and guarantees that this will be a major subject of research for the near future.

Keywords: binaries:close – pulsars:general – X-rays:binaries

1. Introduction

Massive X-ray binaries (MXBs) are X-ray sources composed of an early-type massive star and an accreting compact object (neutron star or black hole). These are objects of the highest astrophysical interest, as their study allows us to address a number of fundamental questions, from the masses of neutron stars to the structure of stellar winds (e.g., Kaper 1998). Moreover, because of their young age, when considered as a population, they can provide information on properties of galaxies, such as their star formation rates (cf. Grimm et al. 2003). Finally, they represent an important phase of massive binary evolution and, again considered as a whole, can provide strong constraints on binary evolution and the mechanisms for the formation of neutron stars and black holes. A relatively recent list of known MXBs is provided by Liu et al. (2000).
The vast majority of MXBs contain X-ray pulsars (magnetised neutron stars) and can be characterised by the pulse or spin period $P_s$. For a few MXBs, X-ray pulsations cannot be detected in spite of thorough searches. Some of them are considered good black hole candidates. The presence of an X-ray pulsar has allowed the determination of orbital parameters for a large number of systems via analysis of Doppler shifts in the pulse arrival times (e.g., Schreier et al. 1972; Rappaport et al. 1978). When no pulsations are detected, orbital solutions can only be obtained from analysis of radial velocity changes in the optical components, a method affected by many uncertainties (cf. Quaintrell et al. 2003).

For a significant fraction of MXBs, orbital periods ($P_{\text{orb}}$) are known through one of the methods described above or because of a clear periodicity in the X-ray lightcurve. For X-ray pulsars, Corbet (1986) found that the position of an object in the $P_{\text{orb}}/P_s$ diagram correlates well with other physical properties. Such a diagram is shown in Fig. 1 for a number of MXBs. Objects are observed to divide rather cleanly into three groups.

- MXBs with short $P_s$ (a few seconds) and short $P_{\text{orb}}$ (a few days) are observed as very bright ($L_X \sim 10^{38}\text{erg s}^{-1}$) persistent X-ray sources. It is believed that matter is being transferred through an accretion disk and that the mass donor is close to filling its Roche lobe, though mass is perhaps transferred through an enhanced wind.
  
  Only a few such systems are known, one in the Milky Way (Cen X-3), one in the SMC (SMC X-1) and one in the LMC (LMC X-4). Another system in the LMC (LMC X-1) is believed to be the black-hole equivalent. These objects are believed to be in a very short-lived phase immediately before catastrophic Roche-lobe overflow and so to be very rare. However, because of their brightness, these were among the first MXBs to be discovered and it is still customary to refer to them as “classical” MXBs.
  
  The mass donors in these systems have luminosity classes around III (except SMC X-1, which looks like a low-luminosity supergiant). Probably, they have been swollen by the gravitational pull of the compact companion.

- MXBs with long $P_s$ (hundreds of seconds) and relatively short $P_{\text{orb}}$ are observed as moderately bright ($L_X \sim 10^{36}\text{erg s}^{-1}$) persistent X-ray sources with a large degree of variability. The optical counterparts are always OB supergiants. The observed characteristics are believed to be due to direct accretion from the wind of the supergiant on to the neutron star, without a stable accretion disk.
There are 10 of these systems in the Galaxy, with a couple of unconfirmed further candidates. There is one candidate in the LMC and none in the SMC. Cyg X-1 would be the black hole equivalent. Because of their counterparts, these objects are called Supergiant X-ray Binaries (SXBs).

- MXBs with Be counterparts have relatively long $P_{\text{orb}}$. They populate a rather narrow region of the $P_{\text{orb}}/P_{s}$ diagram, in spite of the fact that their X-ray lightcurves show a huge diversity of behaviours. A substantial number of these objects are X-ray transients, showing very low X-ray fluxes in quiescence ($< 10^{33}$erg s$^{-1}$; e.g., Campana et al. 2002) and luminosities close to the Eddington limit for a neutron star ($\sim 10^{38}$erg s$^{-1}$) during bright outbursts. These systems are known as Be/X-ray binaries (BeXs).

Only a few among the well studied MXBs fail to fit into these categories: the microquasar 2E 0236.6+6101, whose counterpart is the B0 Ve star LS I +61°303 (Massi et al. 2004), the microquasar RX J1826.2−1450, whose counterpart is the O6.5 V((f)) star LS 5039 (Ribó et al. 2002), and the peculiar wind accretor 4U 2206+54, identified with the peculiar O-type star BD +53°2790 (Negueruela & Reig 2001).

Another peculiar system is XTE J0421+560, whose optical counterpart is the B[e] star CI Cam. Though B[e] stars are a motley grouping of objects in very different evolutionary stages, several lines of argument indicate that CI Cam is a supergiant (Hynes et al. 2002, and references therein). XTE J0421+560 would then be a MXB, even though a very peculiar one.

2. **The Be/X-ray binaries**

   The class of BeX binaries is generally simply defined by the fact that the mass donor is a Be star, i.e., a relatively massive star (sometimes) presenting emission lines because it is surrounded by a disk of material expelled from the star itself (see Porter & Rivinius 2003, for a recent review). In this general sense, the microquasar 2E 0236.6+6101 could also be a BeX (see Negueruela 2005, for a general discussion of the definition). However, BeXs defined in this way display such a huge variety of properties that one could doubt the physical reality of this grouping.

   Most BeX systems are transients displaying X-ray outbursts and long periods of quiescence. At present, we believe that we understand the physical mechanisms leading to this behaviour at the basic level, though the details are still too complex to allow accurate predictions. In several systems, we observe relatively quick (a few years) quasi-periodic cycles,
Figure 1. The $P_{\text{orb}}/P_{e}$ plot, a modern version of the diagram from Corbet (1986). Classical massive X-ray binaries are represented as stars, BeX systems are triangles and supergiant systems are squares. The filled square is the hypergiant binary GX 301–02. The filled triangle is SAX J2103.5+4545. The filled circle is the peculiar transient A 0538–66. See the text for discussion.
Table 1. Persistent BeX and candidates. The four objects in the top panel define the class (after Reig & Roche 1999). The first two objects in the second panel are SMC BeX binaries with slow pulsations, while the other three are Galactic objects with slow pulsations and no detected counterpart (and so an identification as cataclysmic variables is marginally possible).

| Object              | $P_s$ (s) |
|---------------------|-----------|
| X Per               | 835       |
| RX J0146.9+6121     | 1404      |
| RX J0440.9+4431     | 202       |
| RX J1037.5−5647     | 862       |
| AX J0049.5−7323     | 756       |
| AX J0103−722        | 345       |
| 1SAX J1452.8−5949   | 437       |
| AX J1749.2−2725     | 220       |
| AX J1700−419        | 715       |

during which the disk around the Be star forms, grows, gives rise to X-ray activity and then disappears (e.g., Negueruela et al. 2001; Reig et al. 2001). Such cycles are governed by a very complex interplay between the mass loss from the Be star, the dynamics of the Be disk and the gravitational interaction between the neutron star and the disk (Okazaki & Negueruela 2001).

A smaller group of BeX displays much less X-ray variability. Based on a sample of four pulsars (listed in the upper panel of Table 1), Reig & Roche (1999) propose the following characteristics differentiating “persistent” BeX binaries from BeX transients:

1. Persistent systems always display relatively long pulse periods, $P_s > 200$ s, while most transients have shorter periods.

2. Persistent sources always display low X-ray emission ($\lesssim 10^{35}$ erg s$^{-1}$) with small smooth fluctuations, compared to the outbursts of transients.

3. The X-ray spectra of persistent sources presents a low cut-off energy ($\sim 4$ keV, compared to $10 - 20$ keV in transients) and no dependence on intensity.

4. The X-ray spectra of persistent sources does not show the iron line at 6.4 keV that is generally seen in transients, or shows it very weakly.
Other X-ray pulsars have been proposed to be members of this class (second panel of Table 1). Among them, AX J0049.5−7323 and AX J0103−722 are BeX systems in the SMC sharing many of the defining characteristics. The three Galactic candidates are apparently persistent X-ray sources with long pulsations, but they have no optical counterpart and there is a small chance that they are really cataclysmic binaries.

The division between the two groups is not sharp and indeed there seem to be exceptions to the apparent rules. For instance, the source X 0726−260 behaves as a persistent source, but has $P_s = 103$s (Corbet & Peele 1997). A fundamental commonality would be indicated by the fact that both types of BeX systems occupy the same region of the $P_{\text{orb}}/P_s$ diagram. As first noticed by Corbet (1984), there is a clear correlation between $P_s$ and $P_{\text{orb}}$ for BeX binaries. The correlation is not tight, and a few systems do not seem to follow it, for example X 0726−260 and XTE J1946+274 (Wilson et al. 2003). However, Majid et al. (2004) have demonstrated a high degree of correlation between the maximum observed $L_X$ and $P_s$ for a large sample of SMC, LMC and Milky Way BeX systems, something that only makes sense if $P_s$ is directly correlated to the size of the orbit. The only persistent BeX binary for which the orbital period is known, X Persei, falls right between the transient BeX systems in the $P_{\text{orb}}/P_s$ diagram, and, because of the $L_X/P_s$ correlation found by Majid et al. (2004), we have good reason to expect all the other persistent sources to do the same.

The reasons for this correlation must lie in the fact that the neutron star is rotating at some kind of equilibrium spin (Corbet 1986). The issue was investigated by Waters & van Kerkwijk (1989), who concluded that the correlation was due to the neutron stars’ rotating at the equilibrium spin period when the corotation velocity at the magnetospheric radius equals the Keplerian velocity (see also Stella et al. 1986). They modelled the Be disk as an equatorial slow outflow and concluded that accretion of material from this wind could spin up the neutron star to this equilibrium period. Against this conclusion, King (1991) doubted that enough angular momentum could be supplied through this mechanism.

On the other hand, our current understanding of the Be disk is very different from the radial wind model used by Waters & van Kerkwijk (1989). We now believe that Be disks are quasi-Keplerian and held by viscosity (Okazaki & Negueruela 2001; Okazaki 2001). Such disks can probably transfer large amounts of angular momentum to the neutron star through an accretion disk (see detailed models in Okazaki et al. 2002; Hayasaki & Okazaki 2004), and indeed $P_s$ is observed to decrease strongly during BeX outbursts (e.g., Finger et al. 1999; Wilson et al.
Table 2. Be/X-ray transients with low eccentricities. The optical counterparts to XTE J1543−568 and 2S 1553−542 are actually not known, but they are believed to be BeX systems because of their transient behaviour.

| Object        | $P_{\text{orb}}$ (days) | $e$  |
|---------------|-------------------------|------|
| GS 0834−430   | 105.80 ± 0.40           | < 0.17 |
| XTE J1543−568 | 75.56 ± 0.25            | < 0.03 |
| KS 1947+300   | 40.42 ± 0.02            | 0.03  |
| 2S 1553−542   | 30.60 ± 2.20            | < 0.09 |

2003), suggesting effective transfer of angular momentum. Therefore it is likely that the correlation really stems from an equilibrium between the spin up caused by accretion of material with angular momentum and spin down during quiescence, perhaps caused by the propeller effect (Stella et al. 1986; but see also Rappaport et al. 2004).

Most BeX binaries have moderate or large orbital eccentricities, $e \gtrsim 0.3$. Evolutionary models have shown that these high eccentricities can only be explained if supernova explosions are not symmetric, but rather the neutron star receives a velocity kick when it is born (Habets 1987; Portegies Zwart 1995; van den Heuvel & van Paradijs 1997). However, the prototype persistent BeX system X Per was found to have $e = 0.11$ and $P_{\text{orb}} = 250$ d (Delgado-Martí et al. 2001). Based on this, Pfahl et al. (2002) argued that it was possible to define a new subclass of MXBs characterised by long ($P_{\text{orb}} > 30$ d) orbital periods and low eccentricities. As the long orbital periods imply that tidal circularisation cannot have occurred after the supernova explosion that created the neutron star, the low eccentricities are primordial: the systems must have formed in a supernova explosion not accompanied by a kick.

This class would be defined by X Per and the four low-eccentricity BeX transients listed in Table 2. As can be seen, the class (from now on, low-e BeX) cuts across the distinction between persistent and transient BeX, which is based on a different set of observational parameters. There are, however, strong reasons to believe that many BeX binaries for which there is not a good orbital determination may have low $e$, as the model by Okazaki & Negueruela (2001) suggests that the transient behaviour is intimately related to having a relatively high $e$. This suggests that all persistent BeX systems, and also some occasional transients (such as A 1118−615, $P_s = 407$ s), have wide orbits and low eccentricities.

A good counterexample, however, is provided by the BeX transient KS 1947+300, which has $P_{\text{orb}} = 40.4$ d, $P_s = 18.7$ s and $e = 0.03$ (Galloway et al. 2004). This object has shown a very high level of X-
Figure 2. Blue spectrum of the optical counterpart to the BeX transient KS 1947+300, taken on November 21st, 2002, with the 4.2-m WHT + ISIS, confirming the B0 Ve spectral type. The parameters of this system are rather difficult to explain within the current framework.

X-ray activity in recent years, in spite of its wide, almost circular orbit, against the predictions of the model by Okazaki & Negueruela (2001). Moreover, its low $e$, as well as that of XTE J1543−568, is very difficult to explain within current models for the formation of BeX binaries.

While the low-$e$ orbit of X Persei may be explained by a supernova explosion without kick (all the eccentricity induced is due to mass loss), XTE J1543−568 and KS 1947+300 must have been born with basically no eccentricity. Tidal circularisation in such wide orbits can only occur when the star enters the supergiant phase. The optical counterpart to KS 1947+300 was studied by Negueruela et al. (2003), who concluded that it was likely of spectral type B0 Ve. A classification spectrum of this object was obtained on November 21st, 2002, using the 4.2-m WHT (La Palma, Spain) and the ISIS spectrograph. The spectrum is displayed in Fig. 2 and confirms the spectral classification, which implies a mass of $\lesssim 16 M_\odot$. In order to explain the extremely low eccentricity of KS 1947+300, one would have to assume that the supernova explosion that gave birth to the neutron star occurred without a kick and that very little mass (close to none) was lost during it. The alternative possibility that the kick velocity exactly balanced the impulse due to mass loss can be ruled out by the existence of a second system, XTE J1543−568, with a similarly low $e$. Chance coincidences do not happen twice.
Podsiadlowski et al. (2004) have suggested that the existence of the class of low-e BeX can be naturally explained by a bimodal distribution in the velocity kicks, due to different modes of explosion, with neutron stars formed in an electron-capture supernova receiving a very small kick. Therefore the class of low-e BeX would be justified by a physical reason and hence a useful instrument for furthering our knowledge of MXB formation mechanisms.

3. The supergiant X-ray binaries

Because of the evolutionary timescales involved, SXBs are expected to be much less numerous than BeX binaries. Indeed, the numbers known are rather small and hence statistical work is unlikely to be very significant. The mass donors in these systems are OB supergiants, but they cover a wide range of stellar parameters.

The most massive donor known is probably HD 153919, the O6.5 Iaf+ counterpart to 4U 1700−37, with an estimated mass of $58 \pm 11 M_{\odot}$ (Clark et al. 2002). In comparison, the mass donor in Vela X-1, HD 77581, has spectral type B0.5 Ib and a mass in the $23 - 28 M_{\odot}$ range (Quaintrell et al. 2003). This means that HD 153919 is a much more massive star in a much earlier evolutionary stage (cf. Meynet & Maeder 2003). The X-ray luminosity of a SXB should depend strongly on the properties of the mass donor, as its evolutionary status determines the mass loss rate and wind structure. Because of this, it is a bit surprising that all the systems known display approximately the same X-ray luminosity, $L_X \sim 10^{36}$ erg s$^{-1}$.

Many of the SXBs show pulsations with long $P_s$, generally a few hundred seconds. In the $P_{\text{orb}}/P_s$ diagram (Fig. 1), they trace something close to a horizontal line, as the $P_s$ does not seem to be correlated to $P_{\text{orb}}$. In the standard scenario (Waters & van Kerkwijk 1989), it is believed that the neutron stars were born with shorter $P_s$, but during the main-sequence lifetime of the present donor (which must have originally been a main-sequence O-type star), no accretion took place, and the neutron stars were spun down to these present long $P_s$ because of the propeller effect. When the mass donors became supergiants, their mass loss rates increased sufficiently to permit effective accretion, but this accretion of matter is not accompanied by transfer of angular momentum, and so, the pulsars are not spun up back to low values of $P_s$.

This lack of effective angular momentum transfer is probably an intrinsic quality of the mass transfer mechanism. SXBs display episodes of both spin up and spin down, that look like random walks around a particular value (Anzer & Börner 1995). In the classical Bondi-Hoyle
formulation, accretion occurs directly from a relatively fast wind and material does not have enough angular momentum with respect to the accreting body to form a large and stable accretion disk that can provide the torque to spin up the neutron star. Early simulations showed the presence of a “flip-flop” instability that continuously changed the sign of the angular momentum accreted (Matsuda et al. 1992). More realistic simulations (Ruffert & Anzer 1995; Ruffert 1999; and references therein) are unable to provide a clear answer as to how much angular momentum is accreted from a wind.

In Fig. 1, we can see two systems which deviate strongly from the straight line traced by all the other SXBs. One is OAO 1657−415, with $P_{\text{orb}} = 10.44$ d and $P_s = 38$ s (Chakrabarty et al. 1993). This system has displayed long episodes of spin up, leading to the suggestion that it occupies an intermediate position between SXBs and classical MXBs. This behaviour could be perhaps explained if the mass donor is a late-B supergiant, as is suggested by the relatively low mass estimated for it, $M_\ast = 14−18M_\odot$ (Chakrabarty et al. 1993). In this case, the supergiant would be on the cool side of the bi-stability jump (cf. Vink et al. 2000), and its wind would be rather denser and slower than those of other SXBs, allowing the transfer of angular momentum. Unfortunately, the counterpart to OAO 1657−415 is very obscured and it has only recently been detected in the infrared (Chakrabarty et al. 2002).

The second system deviates in the opposite direction. It is 2S 0114+65, with $P_{\text{orb}} = 11.6$ d and $P_s = 10000$ s, the longest $P_s$ measured in a neutron star (Hall et al. 2000). The reasons for this extremely slow pulsation are not clear. It has been suggested that perhaps the neutron star was born with a very high magnetic field ($B \gtrsim 10^{14} \text{G}$, typical of a magnetar) and spun down by the propeller effect (Li & van den Heuvel 1999).

There is no obvious correlation between $P_{\text{orb}}$ and $L_X$ for SXBs, in contrast to what is observed for BeX systems. As noted above, this may simply be due to the number of SXBs being too small, as the evolutionary status of the mass donors has to be determinant for the $L_X$ expected, as well. It is, however, curious that no system with $P_{\text{orb}} > 15$ d is known, as one would in principle expect other systems to exist with broader orbits and lower X-ray luminosities. The notable exception is GX 301−02, marked in Fig. 1 as a filled square. This object has $P_{\text{orb}} = 41.5$ d, but it presents two singularities. First, its orbit is very eccentric $e = 0.46$, meaning that there is a very large variation in X-ray flux with the orbital phase (with the maximum happening shortly before periastron; cf. Leahy 2002). Second, the optical counterpart is a blue hypergiant, and must thus have a huge radius and a very high mass loss rate. As a matter of fact, episodes of rapid spin up have been observed in this system (Koh
et al. 1997), supporting the idea that a transient accretion disk forms. GX 301−02 is thus different in many senses from other SXBs, reinforcing the idea that general properties are difficult to define for this group.

4. Filling the gaps

The separation of MXBs into three distinct groups is not only very clear in the $P_{\text{orb}}/P_s$ diagram, but directly connected to the different physical mechanisms involved in the mass transfer process and the evolutionary status of the systems.

Among well-studied systems, only the position of the LMC transient A 0538−66 is unclear. This system has sometimes been classed as a BeX binary, as its optical counterpart is not very luminous (spectral type around B1III; cf. Negueruela & Coe 2002) and displays strong Hα emission in quiescence. However, A 0538−66 is an extremely bright (super-Eddington) transient X-ray source, displaying optical outbursts with a 16.6$d$ periodicity (McGowen & Charles 2003). When the source was active, X-ray outbursts occurred with the same periodicity, accompanied by the development of a complex emission spectrum, characterised by very strong P-Cygni profiles. This lead Charles et al. (1983) to propose that the source is likely a very eccentric binary in which the mass donor occasionally fills its Roche lobe when the compact object is at periastron. In this sense, as discussed by Corbet (1986), A 0538−66 could be a system evolving toward the classical MXB stage (via circularisation of its orbit).

The X-ray source SAX J2103.5+4545, discovered by BeppoSAX in 1997 was found to fall right among the SXBs in the $P_{\text{orb}}/P_s$ diagram in spite of being a transient source (Baykal et al. 2000). Recently, its optical counterpart has been identified as a B0 Ve mild Be star (Reig et al. 2004a). Its position in the diagram, marked by a filled triangle in Fig. 1, though certainly surprising, can perhaps be explained within the standard framework if we assume that the mass donor has only recently become a Be star or displays very sporadic activity. In this case, the spin evolution of the neutron star would have carried it to a value typical for a non-accreting system (as the spin periods of SXBs are believed to be) and BeX-like activity could not have been able to bring it back to a shorter spin yet. If this interpretation is correct, one can suspect that substantial numbers of binaries formed by a normal OB main-sequence star and a neutron star exist, but they are not detected, as they do not produce X-ray emission (LS 5039 is, for some reason, an exception, as the optical star is an O6.5 V star; its X-ray luminosity is, however, rather low). If the evolution of the OB star turns it into a Be star, accretion
will start, and it will move from a $P_s$ of several hundred seconds to the equilibrium position corresponding to its $P_{\text{orb}}$. If the OB star does not display Be characteristics, it will remain hidden until it begins to swell and evolve toward the supergiant stage.

Another system recently found that may represent an intermediate stage in the evolution of MXBs is IGR J00370+61226. This source, detected with INTEGRAL has been identified with 1RXS J003709.6+612131, a ROSAT source coincident with the catalogued OB star BD +60$^\circ$73. Observations with RXTE/ASM reveal a clear periodicity of 15.665 ± 0.006 d. The source is hardly detected during most of the time, and displays weak outbursts with this periodicity (den Hartog et al. 2004). Optical observations of BD +60$^\circ$73 reveal a spectral type BN0.5 II-III (Negueruela & Reig 2004; Reig et al. 2005), and no indications of emission lines. Therefore the optical counterpart is not a Be star and has a luminosity far too low to have a strong stellar wind. The source of the material accreted is not clear, but a likely hypothesis could be that a compact object in a very eccentric orbit comes very close to the surface of the B star. In this case, IGR J00370+61226 would represent an evolutionary stage previous to that of A 0538−66. Obviously, the determination of the orbital parameters of this system would be of high importance.

5. The new era

The INTEGRAL observatory, launched in October 2002, contains X-ray and $\gamma$-ray telescopes (see Winkler et al. 2003). For the last two years, it has detected several new X-ray sources, especially toward the inner regions of the Galaxy, which are monitored very frequently. Many of these new sources have rather hard spectra, with little or no emission in the soft X-rays. This lack of soft X-ray emission is probably the reason why they have not been detected by previous missions. An up-to-date list of the new sources is kept by J. Rodriguez at http://isdcu13.unige.ch/rodrigue/html/igrsources.html.

The first such system to be detected was IGR J16318−4848, which was observed to be hard because its soft flux was absorbed by intervening material. Observations with several satellites showed that the photoelectric absorption was variable and that the amount of absorbing material was much higher than the interstellar column density in that direction (Matt & Guainazzi 2003), leading to the suggestion that it was an X-ray binary immersed in a dense envelope of material associated with the donor star (Revnivtsev et al. 2003). The search for the counterpart led to the discovery of a very reddened object, undetectable in opti-
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cal bands, but rather strong in near infrared. Infrared spectra of this object reveal unprecedented characteristics, with a wealth of emission lines corresponding to both high and low excitation elements (Filliatre & Chaty 2004) that has not been observed in any other source known. There is, however, some similarity to CI Cam, the optical counterpart to XTE J0421+560, leading Filliatre & Chaty (2004) to the hypothesis that the counterpart may also be a sgB[e] star and that the high absorption is caused by a thick disk of material surrounding it.

Subsequently, INTEGRAL has discovered several other sources characterised by absorbed spectra. Many of them have later been found in archival observations obtained in the past with other satellites. Among them, IGR J16320−4751 had previously been observed with ASCA. Its X-ray spectrum was similar to that of accreting pulsars, leading Rodríguez et al. (2003) to suggest that it is an MXBs. Its nature has been confirmed by detection of pulsations in an XMM-Newton observation, with $P_s = 1300$ s (Lutovinov et al. 2004a).

Pulsations have also been detected from a few other absorbed INTEGRAL sources. IGR J16358−4726 displays pulsations with a period of almost 6000 s, the second longest $P_s$ known (Patel et al. 2004). Interestingly, these authors found that IGR J16358−4726 appears to be transient, as it was not detected during several BeppoSAX pointings of its field. As many of the other new sources appear to be rather variable, it is likely that the $\sim 10$ objects newly found represent only a small fraction of the population of absorbed sources.

So far, five of the new INTEGRAL sources have been confirmed to be X-ray pulsars. Based on the similarity between their hard spectra and those of other absorbed INTEGRAL sources, Lutovinov et al. (2004b) suggest that most of the new INTEGRAL sources are MXBs. This seems to be confirmed by their obvious concentration toward the Galactic arms (Lutovinov et al. 2004b).

In principle, the properties of these new sources do not appear to be extremely different from those of known MXBs, except for the higher absorption. The origin of this absorption is unclear. In the case of IGR J16318−4848, it seems to be associated with heavy mass loss from its peculiar companion. So far, the counterparts of most of these sources are unknown.

However, there are reasons to think that some of the sources have different characteristics from the three classes of MXB previously known. The INTEGRAL source IGR J17391−3021 was detected during two extremely short ($< 1$ d) outbursts in August 2003, and promptly identified with the already-known peculiar transient XTE J1739−302, which had displayed similar behaviour before (Smith et al. 1998). Recent Chandra
observations have allowed the identification of the optical counterpart to XTE J1739−302 (Smith et al. 2005), which turns out to be an O8Iaf supergiant (Negueruela et al. 2005).

Shortly afterwards, a second source was detected by INTEGRAL displaying the same sort of extremely short outbursts, IGR J17544−2619. XMM-Newton observations allowed the detection of a counterpart (González-Riestra et al. 2004), which also turns out to be an OB supergiant (Chaty et al. 2005). A third transient with very short outbursts, IGR J16465−4507, discovered in September 2004, also has a single candidate counterpart which could be an OB star (Smith 2004). IGR J16465−4507 is certainly a MXBs, as pulsations with $P_s = 228$ s have been discovered in XMM-Newton observations (Lutovinov et al. 2004b). Therefore there seems to be a new class of MXBs characterised by very short outbursts. In at least two cases, the counterparts are supergiants, clearly showing that not all MXBs with supergiant companions share the characteristics traditionally attributed to SXBs.

Some of the new INTEGRAL sources are likely to be similar to the previously known population of MXBs. For example, the transient IGR J01363+6610 has a Be star as optical counterpart (Reig et al. 2004b) and is almost certain to be a BcX transient. However, the unprecedented characteristics of many of them, such as the very high absorption the short outbursts or the transient behaviour from supergiant systems rise the suspicion that we are finding objects mostly belonging to new classes. The fact that many of them appear transients opens the possibility that a large population of MXBs remains still undetected.

6. Conclusions

The traditional division of MXBs into three separate classes stems naturally from their physical characteristics and has indeed provided valuable insights that have allowed us to further our understanding of such systems. However, as new MXBs are being discovered, we are finding more and more systems that are basically impossible to fit into any of these divisions.

On the one hand, the subclasses correspond to well-defined evolutionary stages, and some objects have been found that may be evolving toward or between some of these subclasses. On the other hand, the capability of INTEGRAL to detect sources strongly affected by photoelectric absorption results in the discovery of objects surrounded by denser environments. On both accounts, the discovery of new systems outside the classical classification appears only natural.
These discoveries, however, could have strong implications for our understanding of MXBs. Until now, there has been the widespread impression that the total Galactic population of SXBs could not be very large. As these are persistent, relatively bright sources, they can be seen to large distances (many of the known sources are at distances of $\sim 5$ kpc) and hence we could expect the sample of objects known to probe a significant fraction of the Galaxy. If many new sources turn out now to be transient, the size of the population could have been severely underestimated.

We can expect INTEGRAL to discover several new MXBs in the near future and XMM-Newton to provide error circles small enough for the discovery of counterparts, allowing further characterisation of this interesting class of objects.

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