High proper motion X-ray binaries from the Yale Southern Proper Motion Survey

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ABSTRACT

We discuss the results of cross-correlating catalogs of bright X-ray binaries with the Yale Southern Proper Motion catalog (version 4.0). Several objects already known to have large proper motions from Hipparcos are recovered. Two additional objects are found which show substantial proper motions, both of which are unusual in their X-ray properties. One is IGR J17544-2619, one of the supergiant fast X-ray transients. Assuming the quoted distances in the literature for this source of about 3 kpc are correct, this system has a peculiar velocity of about 275 km/sec – greater than the velocity of a Keplerian orbit at its location of the Galaxy, and in line with the expectations formed from suggestions that the supergiant fast X-ray transients should be highly eccentric. We discuss the possibility that these objects may help explain the existence of short gamma-ray bursts outside the central regions of galaxies. The other is the source 2A 1822-371, which is a member of the small class of objects which are low mass X-ray binaries and long (i.e. > 100 millisecond) X-ray pulsars. This system also shows both an anomalously high X-ray luminosity and a large orbital period derivative for a system with its orbital period, and some possible indications of an eccentric orbit. A coherent picture can be developed by adding in the proper motion information in which this system formed in the Perseus spiral arm of the Galaxy about 3 Myr ago, and retains a slightly eccentric orbit which leads to enhanced mass transfer.

Key words: proper motions, X-rays: binaries

1 INTRODUCTION

The mechanisms by which supernovae explode have been a topic of recent debate (e.g. Belczynski et al. 2012). X-ray binaries represent one of the few classes of systems in the Universe in which the end results of supernova explosions can be explored, and the mass distribution of compact objects has been proposed as a key test of the supernova mechanism. The systems can be readily identified from their X-ray emission, allowing them to be selected easily for further study. The masses of the compact objects can be estimated from the radial velocity motions of the donor stars, along with estimates of their inclination angles from eclipses, in an ideal case, or ellipsoidal modulations (see Cantrell et al. 2010 for the state of the art) or polarimetry (Brown et al. 1978; e.g. Dolan & Tapia 1989). Astrometric wobble has been seen in Cygnus X-1 (Reid et al. 2011), but not yet at a level where it could be used to make precise measurements of a system inclination angle. Spaced-based astrometric surveys such as Gaia or the proposed SIM mission do have the potential to measure the inclination angles of wide, nearby X-ray binaries (e.g. Tomsick et al. 2009; Tomsick & Muterspaugh 2010).

Along with the mass distribution of compact objects, it is interesting to understand their space velocity distribution. A few different mechanisms have been proposed for giving X-ray binaries (and, indeed, isolated neutron stars) space velocities far in excess of those of their massive star progenitors. The loss of mass in supernovae on timescales fast compared with the orbital period means that the mass lost in the supernova will carry away linear momentum relative to the center of mass of
the binary system, meaning that the binary itself will receive an equal an opposite momentum kick (see e.g. Blaauw 1961). These kicks are sometimes referred to as Blaauw kicks, or as symmetric kicks, since they are symmetric about the supernova progenitor’s center of mass.

A different class of supernova kicks have also been proposed – asymmetric kicks, which are, as suggested from the name, asymmetric about the center of mass of the supernova progenitor. A variety of theoretical mechanisms exist for producing such kicks – hydrodynamic kicks, due to actual asymmetries in the mass ejection (e.g. Burrows & Hayes 1996), interactions between neutrinos and a strong magnetic field (e.g. Arras & Lai 1999), and electromagnetic (e.g. Harrison & Tademaru 1975) – see Lai et al. (2000) for a review.

From relatively early on in the study of pulsars, it was found that they had typical space velocities of order 100 km/sec or more (Trimble & Rees 1971; Lyne et al. 1982) - much larger than the space velocities of the OB stars which are their progenitors. In some cases, these high space velocities might be explained as a “Blaauw kick”. A variety of lines of evidence, mostly from observations of X-ray binaries, indicate that some additional kick component is likely to be present (see Podsiadlowski et al. 2005 for a discussion of the array of evidence). In principle, hypervelocity stars can also be produced in dynamical interactions – for example with the supermassive black hole in the Galactic Center (e.g. Hills 1988; Brown et al. 2006; Rossi et al. 2013), although the velocities will then always be radial, away from the Galactic Center.

Understanding the space velocities of X-ray binaries gives one route to estimating the kick distribution of neutron stars at birth. Understanding the kick velocities in X-ray binaries is important for understanding their formation and evolution, the retention of neutron stars in globular clusters (e.g. Pfahl et al. 2002; Smits et al. 2006), and for making connections between the populations of high mass X-ray binaries and gravitational wave sources (e.g. Belczynski et al. 2011, 2013).

In this paper, we report on the discovery of large proper motions from two X-ray binaries, the low mass X-ray binary 2A 1822-371, and the supergiant fast X-ray transient IGR J17544-2619. In both cases, the high energy properties of the systems are unusual, and large space velocities may help to understand the systems.

2 THE DATA

We work here with several public catalogs, the Yale Southern Proper Motion (SPM) Catalog, version 4.0 (Girard et al. 2011), and the catalogs of low mass X-ray binaries (these can come from burst oscillations – Strohmayer et al. 1996; or from accreting millisecond pulsars – Wijnands et al. 1998; see Liu et al. 2007 for a compilation) and high mass X-ray binaries (Liu et al. 2006) which represent the updates to the van Paradijs catalog (van Paradijs et al. 1995). We use the CDS X-match facility to cross-correlate the catalogs, taking all matches within 5” in order to allow for the fact that some of the X-ray positions for some sources will be of poor quality, while also not taking such a large search radius that the matches will be heavily dominated by chance superpositions. In many cases, the positions in the Liu catalog are not accurate to the sub-arcsecond level, because the source positions were not known to high precision at the time of publications of the catalogs – for this reason we begin by including some sources whose positions are separated by more than the positional accuracies of the sources in the SPM catalog, and then filter out the sources which in hindsight appear to be chance superpositions by making use of additional information from SIMBAD. As an extra check on the accuracy of the proper motions we report here, we have also considered the same sources’ proper motions in the fourth UCAC catalog (Zacharias et al. 2013), and the cross-calibration between proper motions in Hipparcos (Perryman et al. 1997) and SPM within 1 degree of our sources of interest.

2.1 High mass X-ray binaries

There are 27 matches within 5” between the SPM catalog and the HMXB catalog. Of these, 22 are within 1” and 24 are within 1.5”, with the uncertainties in the catalogued X-ray positions likely to dominate for many of the objects. One is a double match with 1H 1555-552, and we remove the false match before presenting the table. The objects are listed in Table 1.

The other matches are believed to be real, given that the magnitudes in the SPM catalog match well to the magnitudes in the HMXB catalog, and that the space density of such bright stars, and of X-ray sources is small. For the two key objects of interest, we discuss the robustness of the matches to the SPM data.

We have cross-checked the proper motions for the brightest objects against the Hipparcos catalog (Perryman et al. 1997; see also Chevalier & Ilovaisky 1998 who have already presented the Hipparcos results for the high mass X-ray binaries). Seven objects match within 0.5” in the two proper motion catalogs, and for five of them, the proper motions in both directions agree within 1σ, while one (1H 1255-567) disagrees by 3.5 σ in declination, and one (4U 1700-37) disagrees by 2.8σ in declination. These are two extremely bright stars (B=4.99 and 6.74, respectively in the SPM photometry), and saturation may have affected their positional measurements.

The only high proper motion object which had not previously been identified as such is IGR J17544-2619. In the SPM data, it is seen to have a proper motion of $-13.86 \pm 1.34$ masec/year in right ascension, and $+7.31 \pm 1.41$ in declination. The UCAC4 proper motions are consistent with these values, but with larger errors: $-17.1 \pm 5.5$ and $+10.7 \pm 1.9$ masec/yr in RA.
Table 1. The proper motions of High Mass X-ray binaries in SPM 4.0. The columns are: (1) Name of the object, from the L07 catalog (2) right ascension, from SPM 4.0 (3) declination from SPM 4.0 (4) proper motion in right ascension, in milliarcseconds per year, from SPM 4.0 (5) proper motion in declination in milliarcseconds per year from SPM 4.0 (6) uncertainty on column 4 (7) uncertainty on column 5 (8) SPM 4.0 source catalog number (9) orbital period in days from L07 (10) spectral type of the donor star from L07 (11) the Galactic longitude of the source rounded to the nearest degree and (12) the Galactic latitude of the source rounded to the nearest degree. The Galactic coordinates are given to allow the reader an idea of the location within the Galaxy, and should not be used for matching with other catalogs. Daggers indicate sources with more precise measurements from Hipparcos (Chevalier & Ilovaisky 1998). The source 1WGA J0648.0-4419 has a proper motion from Hipparcos, but is most likely an accreting white dwarf, rather than a high mass X-ray binary (e.g. Mereghetti et al. 2013).

and Dec, respectively. Finally we have inspected the Hipparcos versus SPM 4.0 data within 1 degree of this star, and have found a mean offset of +2.1 mas/year between the two fields in declination. We take this to be an estimate of the systematic errors of the SPM 4.0 data within this crowded region near the Galactic Center, and take 2.5 mas/yr as an uncertainty in both the RA and Dec directions – it is likely that the same effects of crowding led to the discrepancies in the proper motions of the two sources discussed above for which we did not see good agreement between SPM 4.0 and Hipparcos.

We note that the probability that IGR J17544-2619 is a chance superposition is tiny. The positions in Liu et al. (1997) and SPM match to within 0.05". Additionally, the source displays the X-ray source properties of the supergiant fast X-ray transients, and supergiant stars are both rare and bright. The counterpart has also been verified to be a supergiant and SPM match to within 0.05". Additionally, the source displays the X-ray source properties of the supergiant fast X-ray transients, and supergiant stars are both rare and bright. The counterpart has also been verified to be a supergiant.

2.2 Low mass X-ray binaries

We next consider the matches between low mass X-ray binaries from Liu et al. (2006) and the SPM catalog. A number of the globular cluster X-ray sources match the SPM positions to within 2", but these cannot be considered reliable matches because of the high density of stars in globular clusters. Among the field stars, there are matches within 2" of an X-ray source. For the matches with separations between 2" and 5", we check whether coordinate round-off may have led to a larger separation in our matching process than the real separation, but we find that these objects are all likely to be chance superpositions. As a result, we focus on the three matches that are within 2":

The three matching sources are GRO J1655-40, GX 1+4 and 2A 1822-371. The former two sources have proper motions consistent with zero in the SPM data. The proper motion of GRO J1655-40 has been measured with HST (Mirabel et al. 2002), and is statistically significantly different from zero, but given the large measurement errors in the SPM data for this object, the two results are consistent with one another.

The final object, 2A 1822-371, is of interest. It shows a proper motion in right ascension of $-12.11 \pm 2.18$ mas/year and in
declination of $8.55 \pm 2.14$ mas/year. The data values are consistent with the values of $-6 \pm 4$ and $14 \pm 4$, respectively from the UCAC4 catalog (Zacharias et al. 2012), but since the uncertainties are smaller for the SPM catalog, we use the SPM values throughout the paper. No systematic offsets were found between the Hipparcos and SPM measurements of nearby stars, and 2A 1822-371 itself is too faint (roughly 15.2 in all filters from B through K) to have been detected by Hipparcos.

The offset between the SPM and Liu et al (2006) positions for this object is 0.5", consistent with roundoff to the nearest 0.1" in RA and nearest 1.0" in Declination. The match is further understood to be correct on the basis of the fact that the optical star and the X-ray source show the same periodicity (the orbital period of the binary). An image of the field from 2MASS in $J$ band is shown in figure 1.

3 DISCUSSION: IGR J17544-2619

The source IGR J17544-2619 was first detected with INTEGRAL in a burst of emission that lasted about two hours (Sunyaev et al. 2003), and is a member of the class of objects called supergiant fast X-ray transients (SFXTs). The SFXTs are a class of objects discovered mostly with INTEGRAL (Sguera et al. 2005) which show extremely bright flares in the hard X-rays on timescales of minutes. For an excellent review on the topic, we refer the reader to Sidoli (2013), but we briefly summarize some of the key properties of these systems. About half of the SFXTs show rapid periodicities consistent with the rotation period of a neutron star (Sidoli 2013), and, by definition, all members of the class have supergiant donor stars (e.g. Chaty 2010). Many of the systems show modulation on the apparent orbital periods of the systems (e.g. Sidoli et al. 2007). In the Corbet diagram of spin period plotted versus orbital period, the SFXTs share parameter space with both the Be X-ray binaries and the traditional persistent supergiant wind-fed systems (Sidoli 2013). There remains debate about whether the systems have stellar winds with strong equatorial components (e.g. Sidoli et al. 2007), are clumpy (e.g. in ’t Zand 2005; Oskinova et al. 2012), or perhaps both. Gated accretion due to high magnetic fields and slow rotation periods is an additional possibility (e.g. Grebenev & Sunyaev 2007; Bozzo et al. 2008).

1 The 2MASS data offer the best digital optical/infrared data from Skyview.
The full set of system parameters of IGR J17544-2619 are well described in Drave et al. (2012). It has been shown to be associated with the infrared counterpart 2MASS J17542527-2619526 (in ’t Zand 2005). Optical and infrared studies have further found that its donor star is an O9Ib star, with a mass of 25-28 $M_{\odot}$ (Pellizza et al. 2006) at a distance of about 3.6 kpc (Rahoui et al. 2008). Its orbital period has been identified by Clark et al. (2009) on the basis of INTEGRAL timing to be 4.926±0.001 d, and its pulse period has been found by Drave et al. (2012) to be 71.49±0.02 s. Drave et al. (2012) show that the system lies near the supergiant persistent X-ray binaries in the Corbet diagram, and that the chief difference relative to those systems is likely to be a higher eccentricity for the binaries (see also in ’t Zand 2005).

In light of the expectation that these systems might have large eccentricities, measurements of their proper motions is especially interesting, as the same processes that induce eccentricity in previously circular binaries will tend to impart momentum to the binary’s center of mass. These processes can include the loss of a substantial amount of mass during the supernova explosion – the Blauuw kick – and an asymmetric kick applied to the compact object during or very shortly after the supernova explosion.

At least one runaway high mass X-ray binary is known, LS 5039 (Ribó et al. 2002). That system has a short orbital period, and a high measured eccentricity, so it is quite similar in system parameters to IGR J17544-2619. On the other hand, it is thought to have a more rapidly rotating neutron star, such that the radio pulsar mechanism works in that system, and its high energy emission is produced by a shock between the stellar wind and the pulsar wind in the system (e.g. Dubus 2006).

A useful starting point in understanding an X-ray binary system is to determine whether its observed kinematical properties could be explained only as the result of a Blauuw kick. Nelemans et al. (1999) work out the system velocity expected due to symmetric mass loss in a supernovae explosion as:

$$v_{sys} = 213 \left( \frac{\Delta M}{M_{\odot}} \right) \left( \frac{m}{M_{\odot}} \right) \left( \frac{P_{\text{postSN}}}{\text{day}} \right)^{-1} \left( \frac{m + M_{\text{rem}}}{M_{\odot}} \right)^{-\frac{1}{2}} \text{ km/sec},$$

(1)

in a form which is convenient, but appropriate only for low mass X-ray binaries where there is sufficient time for the system to re-circularize. They had already derived that $P_{\text{recirc}} = P_{\text{postSN}}(1 - e^2)^{3/2}$, which is more appropriate to the case of a high mass X-ray binary. We can then re-write equation (1) as:

$$v_{sys} = 213 \left( \frac{\Delta M}{M_{\odot}} \right) \left( \frac{m}{M_{\odot}} \right) \left( \frac{P_{\text{postSN}}}{\text{day}} \right)^{-1/2} (1 - e^2)^{-\frac{1}{2}} \left( \frac{m + M_{\text{rem}}}{M_{\odot}} \right)^{\frac{1}{2}} \text{ km/sec}$$

(2)

Furthermore, $e = \frac{\Delta M}{m + M_{\text{rem}}}$ so it can be seen immediately that for increasing $\Delta M$, both $e$ and $v_{sys}$ increase monotonically. Furthermore, we can rewrite the equation now to remove $e$, getting:

$$v_{sys} = 213 \left( \frac{\Delta M}{M_{\odot}} \right) \left( \frac{m}{M_{\odot}} \right) \left( \frac{P_{\text{postSN}}}{\text{day}} \right)^{\frac{1}{2}} \left( \frac{M_0}{M_{\odot}} \right)^{\frac{1}{2}} \left( \frac{m + M_{\text{rem}}}{M_{\odot}} \right) \text{ km/sec}$$

(3)

where $M_0$, is the initial total mass of the system. In the case of asymmetric kicks, the situation can be more complicated, since they can counter-act the symmetric kicks (e.g. Kalogera 1998), but generally speaking, large eccentricities and large space velocities are expected to be seen in the same systems.

Starting from equation (3) we can estimate the amount of mass loss that must have taken place. If we take the donor star mass to be 25 $M_{\odot}$, and the accretor to be a 1.4$M_{\odot}$ neutron star, we find that the systemic velocity will be about $13 \frac{\Delta M}{M_{\odot}}(1 - e^2)^{-1/2}$ km/sec. If the system is assumed to be at a distance of 3.6 kpc, then its tangential velocity relative to its Local Standard of Rest is about 275 km/sec out of the Galactic Plane, with a range of 160-320 km/sec for the range of possible distances from 2.1-4.2 kpc given in Rahoui et al. (2008). The distance uncertainties dominate over the proper motion uncertainties. Its mean systemic radial velocity is about 47 km/sec (Nikolaeva et al. 2013).

The system is thus just within the bounds possible for producing a neutron star from a red supergiant without an asymmetric kick being required (see e.g. Woosley et al. 2002). The eccentricity, at least before any tidal circularization processes have taken place, would be about 13/39.4, or about 1/3. At the present time, no concrete measurement exists for the eccentricity of this system. If the eccentricity is small, it may be because the binary has become partly circularized. Both in ’t Zand (2005) and Drave et al. (2012) have suggested that the major difference between SFXTs and the more traditional

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2 Nikolaeva et al. (2013) also suggest that the orbital period may be about 12 days for this source, on the basis of 27 spectra. This analysis gives a minimum mass for the compact object of 2.8 $M_{\odot}$, suggesting either that the neutron star is, by far, the heaviest neutron star measured to date, or, more likely, that the radial velocity curve has not yet been sampled well enough, given that fitting an eccentric orbit requires 6 free parameters. We prefer the latter interpretation, largely on the basis of the very convincing X-ray modulation from the source found by Clark et al. (2009), and the finding that the masses of the neutron stars in high mass X-ray binaries tend to be well-clustered around 1.4 $M_{\odot}$ (Thorsett & Chakrabarty 1999). The mean radial velocity should be robust to uncertainties in the orbital solution.

3 If the Nikolaeva et al. (2013) results are taken at face value then the eccentricity is about 0.44.
persistent supergiant X-ray binaries is that the SFXTs have higher orbital eccentricities. We thus do expect that the binary will not have been completely circularized.

Some models of stellar evolution suggest that neutron stars can be produced from progenitors with quite high initial masses that lose a lot of mass in a Wolf-Rayet phase (Woosley et al. 2002). If the neutron star were produced from a massive star progenitor, which underwent considerable mass loss in a Wolf-Rayet phase, then it is likely that the progenitor was less than $14M_\odot$ before the supernova (Woosley et al. 2002), and that an asymmetric kick was needed to give the system its observed proper motion. Given the considerable uncertainties, in mass loss rates from massive stars, supernova explosions, and whether this system has mass transfer from the progenitor star of the neutron star to the current donor star, it is difficult to determine without detailed calculations that go beyond the scope of this paper whether the system must have had a natal kick, or whether all its properties can be explained by a simple impulsive mass loss.

The essential point is that the large proper motion is in agreement with the idea that the system at least formed with a large eccentricity. We can now look at circularization timescales of X-ray binaries to make some estimate of for how long the eccentricity is likely to have remained. The theory of circularization of binaries is generally tested by observations of open clusters (see e.g. Verbunt & Phinney 1995). However, if, as suggested by Mathieu et al. (1992) that binaries with such short orbital periods ordinarily circularize on the pre-main sequence, then there is no empirical handle on how quickly such systems should circularize. Most theoretical work has focused on the circularization of binaries with cooler stars (e.g. Zahn 1977; Claret & Cunha 1997; Goodman & Dickson 1998), so there is not currently even much theoretical work to use to test whether significant circularization should take place in a mass transferring binary with a supergiant donor star.

We can attempt to bound the system’s age in a few ways. First, we can see if we can trace its motion back to any of the star forming regions nearby in the catalog of Avedisova (2002). The position matches up well with that of region 3.270-0.102 but the distance for that star forming region is given by Downes et al. (1980) to be 18 kpc, so the association is unlikely. In the absence of a birth site, we can make a crude estimate of the age, on the basis that the system is moving away from the Galactic Plane at about 10 msec/year, and is unlikely to have formed more than about 50 pc from the Galactic Plane. This yields an age of a few hundred thousand years, so if substantial circularization has taken place, then we immediately learn something interesting about circularization of supergiant binaries. On the other hand, if we take its high eccentricity as a given based on its SFXT nature, we can use it as a probe of circularization in binaries. Then we can see that it is moving toward the nearest supernova remnant, and is located several degrees from the next nearest supernova remnant (Green 2009), making an association with a supernova remnant unlikely and thus making the system age likely to be larger than the typical lifetimes of supernova remnants. It is thus unlikely to be much younger than about $10^4$ years. Further searches for associations (e.g. from the Vista Variables in the Via Lactea project – Minniti et al. 2010) with young star associations may potential help locate the birth site of this X-ray binary.

### 3.1 Runaway high mass X-ray binaries and the short GRB problem

The short gamma-ray bursts are thought to be produced by mergers of compact objects, either between two neutron stars or between a neutron star and a black hole (e.g. Paczynski 1986). As such, high mass X-ray binaries represent excellent candidate progenitors for these events. Furthermore, many of these short gamma-ray bursts have been located not in the centers of galaxies, near the location of maximum star formation, but rather in the outskirts of galaxies (e.g. Gehrels et al. 2005). The discovery of at least one such object with a peculiar velocity of the same order as the velocity of the Galactic rotation curve helps point the way toward finding the actual progenitors of the subclass of short GRBs taking place outside of the main bodies of galaxies. In particular, the second velocity kick that will be applied at the time of the second supernova explosion could easily be large enough to unbind the system from the Galaxy without unbinding the binary itself.

The cleanest sample of high mass X-ray binaries whose kinematic properties are well understood is the Hipparcos sample (Chevalier & Ilovasik 1999 – CI99). Hipparcos made measurements of 17 HMXBs, including 4 with supergiant donor stars and 13 with Be donor stars (CI 99). The four supergiant systems are all found to have peculiar tangential velocities of less than 100 km/sec. The largest quoted tangential velocity is that of Cygnus X-1; the proper motion of Cyg X-1, is, in fact, very similar to that of the Cygnus OB3 association, so that it is unlikely to have formed with a large velocity kick (Mirabel & Rodrigues 2003). The other high mass X-ray binaries studied with Hipparcos have tangential velocities that are larger than the typical velocity dispersion of massive stars, but considerably smaller than the Galactic escape velocity, or even the Galactic rotational velocity. The Be X-ray binaries measured by Hipparcos have even lower system tangential velocities – typically about 10 km/sec. That the Be X-ray binaries were formed with relatively small velocity kicks is not surprising given that very large kicks would have unbound most of them.

Developing an understanding of these objects is important, as well, for understanding where gravitational wave source are likely to be located and determining strategies for conducting electromagnetic follow-up of them. At the present time, it is not clear what will be the eventual fate of IGR J17544-2619 – but with continued improvement in understanding its orbital parameters it should be possible to conduct binary evolution simulations (e.g. Belczynski et al. 2006;2008) of it to estimate the probability it will eventually turn into a double neutron star which merges in less than a Hubble time.
3.2 Linear momentum

The linear momentum of the system has a large uncertainty due to the distance uncertainty. Taking the best estimate distance and the best estimate for the systemic radial velocity, the space velocity of the system is about 280 km/sec. The donor star mass has been estimated to be 25 $M_\odot$ (Rahoui et al. 2008), so the systemic mass should be about 26-27 $M_\odot$. The total momentum is then equivalent to that of a pulsar with a 5300 km/sec space velocity. This value is far in excess of the largest space velocities seen from isolated pulsars (Hobbs et al. 2005). It thus requires that either there is a population of pulsars which has not been detected because pulsars born with such a high velocity quickly escape the Galaxy, or, more likely, that the kick comes primarily from the Biauw mechanism. If the kick comes primarily from the Blauuw mechanism, then we can establish that there must have been dramatic mass loss during the supernova that produced the neutron star. Given that the system must also be quite young, an interesting implication is that the donor star may still be polluted with supernova ejecta. Abundance studies of the donor stars in SFXTs may thus be an interesting topic for future research.

4 DISCUSSION: 2A 1822-371

The source 2A 1822-371 differs from the bulk of low mass X-ray binaries in several ways. First, it is a slow pulsar, with a pulse period of 0.59 seconds (Jonker et al. 2001). Nearly all the low mass X-ray binaries in the Galaxy with known spin periods have spin periods less than 10 milliseconds (see Liu et al. 2007). The ones which have longer measured spin periods are the ultracompact X-ray binary 4U 1626-67 (Middleitch et al. 1981), the symbiotic X-ray binary GX 1+4, the intermediate mass X-ray binary Her X-1 (Tananbaum et al. 1972; Crampton 1974) and the “Bursting Pulsar” (Finger et al. 1996). None of these systems is a traditional low mass X-ray binary with a main sequence (or mildly evolved) donor star of less than 1 $M_\odot$ except 2A 1822-371.

That so few X-ray binaries are seen with slow pulsations, main sequence donors and orbital periods of 3-10 hours is not surprising. Standard theories of the evolution of neutron stars’ spin periods and magnetic fields predict that only a small fraction of the donor star’s mass much be accreted in order to spin up the neutron star into a millisecond pulsar (e.g. Alpar & Shaham 1985). The slow pulsar phase of an X-ray binary’s lifetime is therefore expected to be a short one.

4.1 Position in the Galaxy

A variety of approaches have been used to estimate the distance to 2A 1822-371. Because the system is persistent, one cannot use the standard method of estimating the flux and temperature of the donor star in quiescence. Because the system is a pulsar and does not show Type I bursts, the bursts cannot be used as standard candles. Instead, we rely on the work of Mason & Cordova (1982), who modelled the disk rim emission from this nearly edge-on system, and found that the system’s distance is in the 1-5 kpc range, depending on the exact assumptions used.

The position of 2A 1822-371 is 18:25:46.81 -37:06:18.6 (Cutri et al. 2003) – in Galactic coordinates, this corresponds to 356.8502, -11.2908. If we trace the proper motion backwards from the present time, it intersects the Galactic Plane in about 3.2 Myrs, at almost exactly the projected location of the Galactic Center. As a result, given that the Galaxy has a nearly constant rotational velocity as a function of Galactocentric radius outside the very inner Bulge, one can take its proper motion to be the same as its initial velocity kick. We note that the object could not have formed in the Galactic Center region 3.2 Myr ago unless its distance has been badly mis-estimated – Jonker et al. (2003) find a mean radial velocity of only about 54±24 km/sec, so that in 3.2 Myrs, the distance travelled, ignoring acceleration, would be only a few hundred pc, not enough to bring a source from the Galactic Center to the upper bound distance of 5 kpc.

Finally, we estimate the space velocities for the source, in Galactic coordinates, where $U$ is the velocity in the direction of the Galactic anti-center, $V$ is the velocity along the direction of the Galactic rotation curve, and $W$ is the velocity in the direction toward the North Galactic Pole. These total velocity is about 100 km/sec if the source is at a distance of 1 kpc, and about 365 km/sec if the source is at a distance of 5 kpc; these distances represent the range of possible distances given in Mason & Cordova (1982). In either case, the tangential motion is directly away from the Galactic Center.

4.2 Age and eccentricity connection?

A coherent picture can be developed based on the idea that 2A 1822-371 is only about 3.2 Myrs old. In such a case, the system may still be a mildly eccentric binary in Roche lobe contact. Hut & Paczynski (1984) showed that even very small eccentricities of Roche lobe overflowing systems could lead to large changes in the mass accretion rate – essentially, because

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Given the very large uncertainties on the system’s distance and the substantial uncertainties on the proper motions, we simplify the calculations to ignore its acceleration in the Galactic potential, which will, in any even have a small effect in a few Myrs.
the scale height of a stellar atmosphere for a typical main sequence star is about $10^{-4}$ times its radius, a change of a factor of a few in mass transfer rate should result from an eccentricity of order $10^{-4}$. Such changes would be nearly impossible to measure from X-ray binaries except possibly through careful pulse timing. For 2A 1822-371, the best observational constraint on the eccentricity requires only that it be less than 0.03 (Jonker & van der Klis 2001).

It is generally expected that X-ray binaries (and cataclysmic variables) with orbital periods less than about 4 hours will have their orbital evolution, and hence their mass transfer rate, determined mostly by the effects of gravitational radiation (Kraft et al. 1962). Interestingly, 2A 1822-371 shows two separate lines of evidence that its mass transfer rate is much higher than would be expected from gravitational radiation. It is luminous in the X-rays, despite being an accretion disk corona source, in which one expects only about 1% of the emission to be scattered into the observer’s line of sight; and it shows a large, positive orbital period derivative from eclipse timing, suggesting super-Eddington, non-conservative mass transfer, where a mass transfer rate about $10^3$ times lower would be expected for a circular orbit at that period (Burderi et al. 2010). Invoking an eccentricity of order $10^{-3}$ would allow for the high mass transfer rate, while also not producing any directly detectable signature of the eccentricity. An eccentricity that large should be produced in a low mass X-ray binary at birth in all cases – even in the extreme case of an accretion induced collapse of a white dwarf would result in a large enough loss of mass-energy as the difference in binding energy of the compact object. This would not give the $\sim 100 – 500$ km/sec space velocity we observe for 2A 1822-371, but the mass loss from a pre-SN core of about $3M_\odot$ would.

Maccarone (2005) summarized a range of literature on the circularization of close binaries. Because short period binaries in open clusters appear to be circularized on the pre-main sequence (Mathieu et al. 1992), it is difficult to approach empirically the problem of the circularization of binaries which reach short periods as the result of common envelope evolution and then become eccentric as the result of supernovae. Goodman & Dickson (1998) estimate the circularization timescale for solar-like binaries to be about 150 Myr $P_{\text{orb}}^3$, with $P_{\text{orb}}$ being the orbital period in days. In such a case, the circularization timescale would be about 1 Myr for 2A 1822-371. Since the inferred eccentricity at formation would be $\sim 0.3$ if $\sim 1/3$ of the mass of the progenitor binary were lost, the system could be $\sim 10$ circularization timescales old, and still have $10^{-3}$ as its current eccentricity. If resonant effects (Witte & Savnoije 2002) and mass transfer (e.g. Claret & Cunha 1997) speed up the circularization process dramatically, even the $10^{-3}$ eccentricity we have invoked may be too large, but at the present time, the scenario seems reasonable, albeit not proved beyond doubt by the present data. Better timing of the pulsar, as may be possible with LOFT (Feroci et al. 2012) could provide better constraints on the eccentricity of the orbit.

### 4.3 An asymmetric kick versus a Blaauw kick?

In some cases, the combination of the three-dimensional velocity of a system and its inclination angle can give information about the relative strengths of the Blaauw kick versus an asymmetric impulse. This is most clear in the case of a face-on binary, for which any large radial velocity offset from the local standard of rest must be due to an asymmetric kick. In the case of 2A 1822-371, the system is nearly edge on, and the velocity difference from the local standard of rest is mostly in the tangential direction (Jonker et al. 2003). In this case, the possibility that the kick is dominated by the Blaauw mechanism cannot be discarded out of hand, but does require a fine tuning of the orbital phase at the time of the supernova explosion. With a single system, no definitive statements can be made; however, if Gaia measures large proper motions relative to the local standard of rest for a large sample of nearly edge-on X-ray binaries, it would be possible to make a statistical statement from such a result.

### 4.4 Linear momentum

The linear momentum of the system has a large uncertainty due to the distance uncertainty. Taking the best estimate distance and the best estimate for the systemic radial velocity, the space velocity of the system is about 100 km/sec. The donor star mass has been estimated to be 0.4 $M_\odot$ (Cowley et al. 2003), so the systemic mass should be about 1.8 $M_\odot$. The total momentum is then equivalent to that of a pulsar with a 150 km/sec space velocity. This value is well within the range of values for isolated radio pulsars (see e.g. Hobbs et al. 2005, who find that a 265 km/sec Maxwellian is a good description of the space velocity distribution of pulsars).

### 5 SUMMARY

We have discussed the matches between the catalogs of bright X-ray binaries and the Yale Southern Proper Motion Survey 4.0 catalog. We have found two interesting binaries which are both unusual in their X-ray properties, and show large proper motions away from the Galactic Plane, and we have tabulated their three-space velocities in Table 2. In both cases, the X-ray data are suggestive of eccentricities created at the same time the systems received their large peculiar velocities.
Table 2. The space velocities, in km/sec, in Galactic coordinate components for the two sources with newly identified large proper motions. The values for 2A 1822-371 are given for distances of 1 and 5 kpc, and the values for IGR J17544-2619 are given for distances of 3.6, 2.1 and 4.2 kpc.

| Source               | U  | V  | W  |
|----------------------|----|----|----|
| 2A 1822-371 (1 kpc)  | -76| 21 | 64 |
| 2A 1822-371 (5 kpc)  | -132| 65 | 335|
| IGR J17544-2619 (3.6 kpc) | -57| 4  | 273|
| IGR J17544-2619 (2.1 kpc) | -57| 9  | 162|
| IGR J17544-2619 (4.2 kpc) | -58| 2  | 317|

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