The radio luminosity of persistent X-ray binaries

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ABSTRACT

We summarise all the reported detections of, and upper limits to, the radio emission from persistent (i.e. non-transient) X-ray binaries. A striking result is a common mean observed radio luminosity from the black hole candidates (BHCs) in the Low/Hard X-ray state and the neutron-star Z sources on the horizontal X-ray branch. This implies a common mean intrinsic radio luminosity to within a factor of twenty five (or less, if there is significant Doppler boosting of the radio emission). Unless coincidental, these results imply a physical mechanism for jet formation which requires neither a black hole event horizon or a neutron star surface. As a whole the populations of Atoll and X-ray pulsar systems are less luminous by factors of $\sim 5$ and $\sim 10$ at radio wavelengths than the BHCs and Z sources (while some Atoll sources have been detected, no high-field X-ray pulsar has ever been reliably detected as a radio source). We suggest that all of the persistent BHCs and the Z sources generate, at least sporadically, an outflow with physical dimensions $\geq 10^{12}$ cm, i.e. significantly larger than the binary separations of most of the systems. We compare the physical conditions of accretion in each of the types of persistent X-ray binary and conclude that a relatively low ($\leq 10^{10}$ G) magnetic field associated with the accreting object, and a high ($\geq 0.1$ Eddington) accretion rate and/or dramatic physical change in the accretion flow, are required for formation of a radio-emitting outflow or jet.

Key words: binaries : close — ISM : jets and outflows — radio continuum : stars

1 INTRODUCTION

Radio synchrotron emission is observed from $\sim 20\%$ of X-ray binaries (e.g. Hjellming & Han 1995). In several cases the radio emission has been resolved into jet-like outflows reminiscent of the jet/lobe structures in AGN (e.g. Fender, Bell Burnell & Waltman 1997; Mirabel & Rodriguez 1999, Fender 2000). Much recent work, both theoretical and observational, e.g. Hjellming & Johnston (1988), Penninx (1989), Hjellming & Han (1995), Falcke & Biermann (1996) and Livio (1997), has discussed not only these clearly-resolved relativistic outflows, but also weaker unresolved radio emission from X-ray binaries. It seems increasingly possible that all radio emission from X-ray binaries could arise in such outflows.

However, little serious study has been made of the properties of radio emission from the persistent sources to see whether it is consistent with this wide-ranging model. In this paper we consider the radio luminosity of the persistently accreting BHC, Z-type and Atoll-type X-ray binaries and discuss whether observations are compatible with the generic jet picture.

2 THE SAMPLE : TYPES OF X-RAY binary

In this work we are interested in the radio emission from persistently accreting X-ray binaries, i.e. X-ray binary systems in which we infer from their continual and reliable detection by X-ray satellite missions that they are in a quasi-steady state of stable accretion. Van Paradijs (1995; hereafter vP95), lists 193 X-ray binaries in the most up to date catalogue available. More than 70 of these systems are transients with unstable accretion and are not considered here. In addition, more than 15 new X-ray binaries have been discovered since the publication of the catalogue, but again they are all transient, and not under study in this work.

We shall ignore the distinction between low- and high-
Table 1. Observed mean radio flux and estimated distances for the persistent BHCs Refs 1: Pooley, Fender & Brocksopp (1998), 2: Gies & Bolton (1986), 3: Han (1993) 4: Sood et al. (1997), 5: Fender et al. (1997a), 6: Callanan et al. (1992), 7: Hannikainen et al. (1998), 8: Mirabel (1994), 9: Martí (priv. comm.), 10: Martí (1993), 11: Anantharamaiah et al. (1993), 12: Fender, Southwell & Tzioumis (1998).

| Name          | Mean cm radio flux density (mJy) | distance (kpc) | Refs |
|---------------|----------------------------------|----------------|------|
| Cyg X-1       | 12.9 ± 0.4                       | 2.5 ± 0.5      | 1,2,3|
| GX 339-4      | 5.0 ± 2.2                        | 3.0 ± 1.5      | 4,5,6,7|
| 1E1740.7-2942 | ∼ 0.5                            | 8.5 ± 1.5      | 8,9,10,11|
| GRS 1758-258  | ∼ 0.5                            | 8.5 ± 1.5      | 8,9,10|
| LMC X-1       | < 1.5                            | 55 ± 5         | 12   |
| LMC X-3       | < 0.12                           | 55 ± 5         | 12   |

In addition, the majority of systems in the vP95 catalogue are unclassified beyond being indicated as Bursters and/or Dippers. However, advances in our knowledge and understanding of the properties of the neutron-star X-ray binaries indicate that the majority of the unclassified systems are likely to be Atoll-like, although a small subclass of lower-luminosity sources is possible (Ford, van der Klis and van Paradijs, private communication). So, the majority of the persistently detected X-ray binaries are likely to be Atoll-type neutron star low-mass binaries. X-ray transients are generally low-mass BHCs, although a small number are Atoll-like. The sample of persistent BHCs (four plus two in the LMC) and Z-type sources (six), both intrinsically very luminous, is likely to be more or less complete for our Galaxy and the Magellanic Clouds. We note that Smale & Kuulkers (1999) have recently claimed that LMC X-2 may be a Z source but do not consider it as such in this work and their interpretation has yet to be confirmed.

Below we shall discuss the state of our knowledge about the radio emission in these four classes of system.

2.1 Black hole candidates

Four binary systems in our Galaxy (Cyg X-1, GX 339-4, 1E1740.7-2942 and GRS 1758-258) and two in the LMC (LMC X-1 and LMC X-3) are considered to contain persistently accreting stellar mass black holes. The majority of other BHCs are X-ray transient systems which spend most of the time in the ‘off’ state in which the accretion rate is very low and the associated X-ray emission very weak. Two of the persistent sources (Cyg X-1 and GX 339-4) also undergo state changes, typically being observed in the ‘low/hard’ state but occasionally switching to the ‘high/soft’ state, sometimes via ‘intermediate’ states (e.g. Zhang et al. 1997; Mendez & van der Klis 1997) but the dynamic range in observed luminosity is less than that of the transient systems and they can (almost) always be detected by X-ray satellite missions. An ‘off’ state, corresponding to very low X-ray flux levels, has also been observed from GX 339-4.

The radio emission from Cyg X-1 and GX 339-4 in the low/hard X-ray state is relatively well studied, being observed to be weak (in comparison to more extreme systems like Cyg X-3) and steady, and roughly correlated with the X-ray emission (Pooley, Fender & Brocksopp 1999; Brocksopp et al. 1999; Hannikainen et al. 1998; Corbel et al. 2000). In addition, the radio emission is observed to drop below detectable levels during transitions to intermediate or high/soft X-ray states (e.g. Tananbaum et al. 1972; Fender et al. 1999a). The radio spectra of these two systems are approximately flat between 2 – 15 GHz (Pooley et al. 1999; Fender et al. 1997, Corbel et al. 1997), with no observed cut-off at high or low frequencies. Recent mm-wavelength observations have shown that this flat spectrum continues to at least 220 GHz in Cyg X-1 (Fender et al. 1999b). The first imaging of a compact jet from Cyg X-1 has recently been reported (Stirling, Spencer & Garrett 1998).

Fewer observations have been made of the Galactic Centre systems 1E1740.7-2942 and GRS 1758-258, but they too appear to be weak and steady, with approximately flat radio spectra, (Martí 1993; Mirabel 1994) similar to Cyg X-1 and GX 339-4. In addition, both have associated weak arcmin-scale radio
established the distance and verified the existence of radio-
recently Bradshaw, Fomalont & Geldzahler (1999) have es-
shaw, Geldzahler & Fomalont (1997) have found evidence
which time an optically thin component is superposed. Brad-
casional flaring events (most prominent in Sco X-1) during
They show generally flat radio spectra except during oc-
and radio emission appears to be ‘off’ during the ‘Flaring
sion appears to be associated with the ‘Normal Branch’,
the ‘Horizontal Branch’ of the X-ray emission; weaker emis-
above, the most persistent radio emission is associated wit h
≥
man 1991; Penninx et al. 1993).
Klis (1995). Following his suggestion, the remaining two Z-
sources had been detected at radio wavelengths, and sug-
ery when on the ‘Horizontal Branch’ of the X-ray colour-
ized by their X-ray timing properties (e.g. van der Klis
characteristic pattern they trace out in X-ray colour-colour and
hardness-intensity diagrams and they are further characterised by their X-ray timing properties (e.g. van der Klis 1995, 1999). Their name arises from a charac-
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hardness-intensity diagrams – see e.g. van der Klis (1995).
2.2 Z-type X-ray binaries
The six Z-type X-ray binaries (Z-sources) are believed to be low magnetic field neutron stars accreting at, or just
below, the Eddington limit, and as such are amongst the most luminous persistent X-ray sources in our Galaxy (e.g.
van der Klis 1995, 1999). Their name arises from a charac-
teristic pattern they trace out in X-ray colour-colour and
hardness-intensity diagrams and they are further characterised by their X-ray timing properties (e.g. van der Klis 1995, 1999). Penninx (1989) reported that four of the six Z-
sources had been detected at radio wavelengths, and sug-
gested that they all had approximately the same radio lumi-
nosity when on the ‘Horizontal Branch’ of the X-ray colour-
colour or hardness-intensity diagrams – see e.g. van der Klis (1995). Following his suggestion, the remaining two Z-
sources were detected at the predicted levels (Cooke & Pon-
man 1991; Penninx et al. 1993).
These systems are usually, but not always, detected by
radio observations with a sensitivity of ≥ 0.1 mJy. As noted
above, the most persistent radio emission is associated with the ‘Horizontal Branch’ of the X-ray emission; weaker emis-
ion appears to be associated with the ‘Normal Branch’,
radio emission appears to be ‘off’ during the ‘Flaring Branch’ (Hjellming & Han 1995 and references therein).
They show generally flat radio spectra except during oc-
casional flaring events (most prominent in Sco X-1) during
which time an optically thin component is superposed. Brad-
shaw, Geldzahler & Fomalont (1997) have found evidence for periodic flux density variations from Sco X-1, and more recently Bradshaw, Fomalont & Geldzahler (1999) have established the distance and verified the existence of radio-
emitting outflows from the system. The radio flux densities

and distance estimates of the Z-sources are summarised in
table 2.

2.3 Atoll-type X-ray binaries
The Atoll-type X-ray binaries (‘Atoll sources’), like the Z-
sources, are low mass X-ray binaries containing low mag-
etic field accreting neutron stars. However, they are believed to be accreting at around an order of magnitude lower rate than the Z sources (see e.g. van der Klis 1995). As dis-
cussed above, while vP95 listed only 11 Atoll sources, it now
seems likely that the majority of other low-luminosity X-ray
binaries classified as Bursters and/or Dippers (and/or occasion-
ally Transient) are also Atoll sources. Only a very small
number of these systems have reported detections at radio
wavelengths (Hjellming & Han 1995). Grindlay & Seaquist
(1986) report the detection of a weak (0.49±0.12 mJy) radio
signal from 4U 1820-30, which has not been confirmed. Martí
et al. (1998) report the possible detection of variable radio
emission from GX 354+0 which peaks at a level of ∼ 0.5
mJy but which is undetected to ≤ 0.3 mJy in the majority of their observations. Gaensler, Stappers & Getts (1999)
also report a transient radio detection of the Atoll-like mil-
isecond X-ray pulsar SAX 1808.4-3658. The only convincing and repeated detection of persistent radio emission from an
Atoll source is that of GX 13+1, an unusual system sharing
some of the properties of both Atoll and Z sources (Penninx
1990; Homan et al. 1998).
As already stated, the majority of other, unclassified X-ray binaries are also likely to be Atoll sources. The X-ray binary radio surveys of Nelson & Spencer (1988 – northern hemisphere) and McKie (1997; see also Spencer et al. 1997 – southern hemisphere) typically reached flux density detection limits of 2.0 and 0.2 mJy respectively. Without doubt some of the ‘miscellaneous’ X-ray binaries observed (but not detected) were unclassified low-luminosity Atoll
sources; none were detected as radio sources. In addition,
more than 30 X-ray pulsar systems, containing a high mag-
etic field neutron star which disrupts the inner accretion
disc and channels the accretion flow onto its magnetic poles
(White, Nagase & Parmar 1995; Bildsten et al. 1997), are
known. Many of these systems are in high mass X-ray bina-
ries, suggesting that the neutron stars are relatively young.
Not one of the high-field X-ray pulsars has ever been con-
vincingly detected as a synchrotron radio source (Fender et
al. 1997). Martí et al. (1997) report a marginal radio detec-
tion of the X-ray pulsar system GX 1+4 but this has yet to
be confirmed, and in any case may be consistent with ther-
mal free-free emission from the red giant wind in this system. Fender et al. (1997) showed that there was a significant an-
ticorrelation between the properties of radio emission and X-ray pulsations from X-ray binaries, which they suggested

| Name      | Mean cm radio flux density (mJy) | Distance (kpc) | Refs |
|-----------|----------------------------------|----------------|------|
| GX 1+4    | < 0.2                            | 6 ± 1          | 1    |
| X Per     | < 2.2                            | 0.7 ± 0.3      | 2    |
| Her X-1   | < 1.3                            | 6.6 ± 1        | 2,3  |
| SMC X-1   | < 0.2                            | 55 ± 5         | 4    |
| LMC X-4   | < 0.2                            | 45 ± 5         | 4    |
| Vela X-1  | < 0.2                            | 1.9 ± 0.1      | 4,5  |
| IE 1048.1-5937 | < 0.2                           | ?              | 4    |
| Cen X-3   | < 0.2                            | 8 ± 1          | 4    |
| IE 1145-614 | < 0.2                         | 8 ± 1          | 4, 6 |
| GX 301-2  | < 0.2                            | 5 ± 1          | 4, 5 |
| 3A 1229-599 | < 0.2                         | ?              | 4    |
| 4U 1626-67 | < 0.2                            | 8 ± 1          | 4, 7 |
| OAO 1657-41 | < 0.2                         | ≤ 10           | 4    |
arose because of the disruption of the inner accretion disc preventing the formation of an outflow from the system.

Table 4 lists ten persistent X-ray pulsar systems for which there are good limits to the radio flux density and reasonable distance estimates. None of the systems are detected as radio sources. It is worth noting that (at least) an additional six transient X-ray pulsars (4U 0115+63, GS 0834-430, A 0535-66, A 1118-616, 4U 1145-619, 4U 1416-62) have not been detected to comparable limits (Fender et al. 1997; McKie 1997; some distance estimates in Negueruela 1998).

As noted above, there is a reported detection of transient radio emission from the accretion-powered millisecond X-ray pulsar SAX 1808.4-3658 (Gaensler et al. 1999). However, in nearly all its properties this system is more like an Atoll source than an X-ray pulsar, due to the low ($\leq 10^{30}$G, c.f. $\geq 10^{31}$G for other X-ray pulsars) magnetic field.

2.5 Other, peculiar, systems

In addition to the classes of system described above, there are several systems which are persistently detected by X-ray missions but which are not easily classified. These include Cyg X-3, Cir X-1 and, for the past 5 years, GRS 1915+105, although this last source was almost certainly ‘off’ prior to 1994. Several of these systems, notably those mentioned above, are bright and variable radio sources. However, while the quiescent state of their radio emission is relatively weak with a flat spectrum, their radio emission is often dominated by the superposition of many components which evolve from optically thick to optically thin. It seems that radio jet production in these systems is more sporadic and violent than in the persistent sources, and it is not within the scope of this paper to try and identify in detail areas of common astrophysics between the production of radio emission in persistent and transient sources.

3 A COMMON RADIO LUMINOSITY FOR PERSISTENT BHC AND Z SOURCES

Fig 1 plots the mean radio flux densities and best distance estimates for the persistent BHC and Z sources, plus the anomalous Atoll source GX 13+1, from the data listed in Tables 1-4. The limits on radio emission from the other Atoll sources and the persistent X-ray pulsar systems are also indicated. The weakness of the radio emission from the X-ray pulsar and Atoll sources compared to the persistent BHC and Z sources is immediately apparent. In fact the data suggest a common mean radio luminosity for the persistent BHC and Z sources, which is far above that of the other persistent X-ray binaries. It is worth stressing that this radio luminosity is still orders of magnitude below that of the more extreme and poorly classified systems such as Cyg X-3; SS 433 etc.

In order to test the goodness of fit of a common observed radio luminosity for all the sources, a straight line was fitted to the relationship between the (base ten) logarithm of centimetre radio flux density, $S_{cm}$ (in mJy) and estimated distance, $d$ (in kpc). Both the intercept and gradient were treated as free parameters and our least squares fitting procedure allowed for errors on both flux and distance – the appropriate errors on the log quantities having been derived from the tabulated flux and distance errors using Monte Carlo simulations. We included only the ten galactic sources in our fits, since the two LMC sources had only upper limits on the observed flux. The resulting best fit relation was

$$\log_{10} S_{cm} = (2.03 \pm 0.40) - (2.46 \pm 0.51) \log_{10} d$$

(1)

($\chi^2_{red} = 0.514$) which is clearly consistent with a $d^{-2}$ relation and therefore a common luminosity. Fixing the slope of the relation to be equal to $-2$ produced a similar fit, although now with a smaller error on the intercept:

$$\log_{10} S_{cm} = (1.71 \pm 0.10) - 2 \log_{10} d$$

(2)

($\chi^2_{red} = 0.527$) which is shown by the dotted line on Fig 1. Expressed in terms of flux and distance (in kpc) this relation corresponds to

$$S_{cm} = \frac{55 \pm 13}{d^2} \text{ mJy}$$

(3)

A possible explanation for the low values of $\chi^2_{red}$ may be that some of the flux and distance errors tabulated in Tables 1 & 2 have been over-estimated: if the quoted errors – particularly those in distance – were correct then the data would be unlikely to lie so close to the best fit straight line shown in Fig 1. We discuss this point further below, but remark for the moment that the agreement of the data with an inverse square relation between flux and distance is clearly convincing. This is a surprising result given that both different accretion structures and outflow velocities (see below) in the neutron star and black hole systems might be expected.

For a flat spectrum from 30 to 2 cm (1 to 15 GHz), this corresponds to an observed radio synchrotron luminosity of $10^{36}$ erg s$^{-1}$ ($10^{23}$ W) for these sources. It should be stressed however that a high-frequency cut-off in synchrotron emission has yet to be found in any of these sources, and the total (ie. radio – mm – infrared) synchrotron luminosity is likely to be orders of magnitude higher (see for example Fender et al. 1997c and Mirabel et al. 1998 where a synchrotron luminosity $\geq 10^{36}$ erg s$^{-1}$ is inferred for GRS 1915+105 from the observation of the flat spectral component to 2 $\mu$m).

3.1 The sample and selection effects

As discussed in the introduction, the sources under discussion, the neutron star Z-sources and persistent BHCs, are unique in their relatively steady, bright X-ray emission, implying steady accretion at high luminosity. Given the number and sensitivity of X-ray missions over the past 30+ yr, the sample is likely to be more or less complete for the entire Galaxy, LMC and SMC.

The sample is clearly dominated by sources in the vicinity of the Galactic centre, with distances between 7 – 10 kpc. This clustering of data points is suggestive of selection effects dominating the fit to the data, as a result of small numbers in the sample. However, as discussed above, the sample is effectively volume-limited and cannot be expanded. One selection effect which could significantly bias the fit would be if the Galactic centre systems were being detected only when they came up above the detection limits of typical radio observations. In this case, a mean flux density calculated from
Figure 1. A plot of the mean radio emission against distance estimate for the persistent BHC and Z-source X-ray binaries, using the values listed in Tables 1 and 2. In addition the upper limits to radio emission from the Atoll (except GX 13+1, see text) and X-ray pulsar systems are indicated, using the values in Tables 3 & 4. A single function, described in the text, and indicated on the figure by the dashed line, can be reasonably fitted to all the persistent BHCs and Z sources, implying a similar centimetric radio luminosity for all the sources.

an unrepresentative sample of positive detections could be very similar for all the sources, regardless of their true mean radio flux. However, this does not appear to be the case: comprehensive high-sensitivity observations of Cyg X-2 and GX 17+2 (Hjellming et al. 1990; Penninx et al. 1988), among the most distant sources in the sample, consistently detect these sources and accurately measure the mean flux density.

4 BEAMING AND THE LUMINOSITY FUNCTION

It has been speculated that low-level radio emission from the persistent BHC and Z-source X-ray binaries could arise in a continuous jet (e.g. Hjellming & Han 1995). It has also been suggested that the velocities of jets from accretion discs should approximately reflect the escape velocity of the central object, i.e. jets from black holes will have velocities \( \geq 0.9c \), those from neutron stars \( \sim 0.3c \) etc. (e.g. Livio 1997).

Combining these ideas, a scenario can be envisaged whereby the low-level radio emission from persistent BHCs and Z-sources originates in compact jets of velocities \( \sim 0.9c \) and \( \sim 0.3c \) respectively. In the light of our result that all persistent BHC and Z-source X-ray binaries have the same mean radio luminosity at centimetre wavelengths, however, there are problems with this interpretation, based upon the Doppler boosting associated with a relativistic jet.

Relativistic jets are significantly Doppler boosted; for a continuous jet at a given angle to the line of sight, \( \theta \), the rest-frame flux of the source, \( S \), is boosted to an apparent value,

\[
S' = SD^{2-\alpha}
\]

where \( \alpha \) is the spectral index of the radio emission, and the relativistic Doppler factor \( D \) is defined as

\[
D = \left[ \gamma(1 \mp \beta \cos \theta) \right]^{-1}
\]

(\( \mp \) for approaching and receding components respectively) and \( \gamma \) is the Lorentz factor

\[
\gamma = (1 - \beta^2)^{-1/2}
\]

where \( \beta \) is the velocity of the jet expressed as a fraction of \( c \). As an example, at an angle to the line of sight of 30 degrees, a flat-spectrum (\( \alpha = 0 \)) symmetric jet of velocity 0.9c would appear 2.4 times brighter than the same jet at a
velocity of 0.3c, and 3.9 times brighter than in the rest frame. The total flux observed will be a sum of the approaching and receding jets. Note that for jets near to the plane of the sky both approaching and receding jets can be de-boosted (as is the case for GRS 1915+105; Mirabel & Rodríguez 1994; Fender et al. 1999b). Figure 2 illustrates the ratio of observed to intrinsic flux expected from symmetric jets at 0.3c and 0.9c for all inclinations.

Assuming naively that any jet is approximately perpendicular to the orbital plane of the system, then the angle, $\theta$, of the jet to the line of sight would be equal to the inclination, $i$, of the orbital plane to the line of sight. Estimates of the orbital inclinations of the systems in question are very limited. A survey of the literature does not reveal any particular bias in inclination estimates for any of the classes of source, so we will assume that the inclinations are uniformly distributed in $\cos i$. It certainly appears likely that the systems show a significant spread in inclination. This immediately presents a problem for the hypothesis that the radio emission from these systems originates in Doppler boosted jets. The problem may be stated qualitatively as follows.

If the ten galactic systems are viewed at a range of different inclinations, their observed fluxes will be boosted by a range of different Doppler factors. Thus, if their observed fluxes obey the inverse-square relationship with distance given by Eq. (6), their intrinsic fluxes will not in general obey this relationship. It would, therefore, seem unlikely that one should obtain such a relation between distance and observed flux by chance, since it would require a series of fortunate coincidences in order that the intrinsic fluxes and inclinations yield observed fluxes in agreement with the fitted relation.

One resolution of this problem would be if all the systems were observed at approximately the same inclination, since the sources would then all be Doppler boosted by the same factor. As we have already remarked, however, this possibility appears incompatible with the inclination estimates reported in the literature. Even if we choose to regard these estimates as unreliable, it seems reasonable to suppose that the orbital planes of the ten systems should be randomly sampled from a uniform distribution over all possible orientations. It is then straightforward to show that the probability of drawing a sample of ten sources, with inclinations all lying within, say, an interval of 5 degrees, is less than $10^{-10}$.

Is it possible that the inclinations of the observed systems are selected to lie within a narrow range? One plausible mechanism for such a selection effect might be if their intrinsic fluxes were too faint to be detected, but there exists a critical inclination at which the Doppler boosting factor is sufficient to raise the observed fluxes above the detection limits of typical radio observations. As remarked above, however, our sample is not dominated by systems whose flux lies close to the detection limit. The observed fluxes listed in Tables 1 & 2 span a range of more than a factor of 20, arguing in favour of a wide range of different inclinations consistent with the estimated limits.

### 4.1 Monte Carlo simulations

We have used extensive Monte Carlo simulations to investigate the effect of beaming and the width of the intrinsic radio luminosity function (LF) of the persistent BHC and Z sources. The width is defined such that the LF is uniform in log $L$ between log ($L/\text{width}$) and log ($L \times \text{width}$). We have defined a critical width for which, after running $10^4$ simulations, 90% of the sample have $\chi^2_{\text{red}} > 3$. Not surprisingly, the higher values of $\beta$ we consider for the jets, the narrower the intrinsic LF must be in order to produce the observed inverse square relationship. The results of the simulations are presented in Table 5. In addition to considering the same value of $\beta$ for both jets from black hole and neutron star systems, we also consider what may be considered the ‘canonical’ model, where jets from black hole systems have $\beta = 0.9$ and jets from neutron star systems have $\beta = 0.3$.

It is clear from the results of the MC simulations presented in table 5 that for jet velocities in the range $0 - 0.7c$ the intrinsic radio luminosity of the BHC and Z-sources must be the same to within a factor of 25 or so. This is a result of the relative unimportance of Doppler boosting at these velocities. For higher jet velocities the intrinsic luminosities need to be even closer together; for jets in both types of systems with velocities of $0.9c$ they must be intrinsically within a factor of 15 in radio luminosity in order to produce the observed $d^{-2}$ relation. Thus we can conclude that the classes of BHC (in the low/hard X-ray state) and Z sources have a common intrinsic radio luminosity within an order of magnitude or so.

We can also use the MC simulations to quantify how much weaker radio sources the Atoll and X-ray pulsar systems are, as a class, compared to the BHC and Z-sources. We use the observed upper limits on radio emission and distance estimates given in tables 3 & 4. The maximum mean luminosities of these two classes, compared to that obtained for the combined BHC and Z-sources, are given in table 6. From this we can assert that, as a class, the mean radio luminosity of Atoll sources is more than a factor of five below that of the BHC and Z sources. For the X-ray pulsar systems the limits are even stronger; they are at least an order
The Atoll sources are of 15–25, depending on the velocity of the inferred outflows. We have found that the BHC and Z-source X-ray binaries share a common mean radio luminosity to within a factor of 5–10, as radio sources, than the BHC and Z sources.

5 DISCUSSION

We have found that the BHC and Z-source X-ray binaries share a common mean radio luminosity to within a factor of 15–25, depending on the velocity of the inferred outflows. The Atoll sources are ≥5 times fainter; the X-ray pulsar systems ≥10 times so. One reason that these results are surprising is the different inferred accretion modes for the BHCs and Z-sources. In BHCs in the low/hard X-ray state the ‘standard’ (thin, cold, optically thick) accretion disc is believed to be truncated many Schwarzschild radii from the central black hole and replaced in the inner regions by an optically thin, radiatively inefficient quasi-spherical flow (Advection-dominated accretion flows; see Svensson 1998 and references therein). However in Z and Atoll sources the ‘standard’ accretion disc is believed to reach to almost the surface of the neutron star (e.g. van der Klis 1999).

| Source type | Compact object | $S_v/(\text{kpc}^2$) (mJy) | Inferred physical characteristics | Source type | $S_v/(\text{kpc}^2$) (mJy) | Inferred physical characteristics |
|-------------|----------------|-----------------------------|---------------------------------|-------------|-----------------------------|---------------------------------|
| BHC (low/hard state) | BH | $55 \pm 13$ | $\leq 0.1$ | BH | $0.1 - 1.0$ | $10^9 - 10^{10}$ | few x100 |
| Z (horizontal branch) | NS | $0.7 \pm 0.7$ | $10^{22}$ | NS | $\leq 10.0 \pm 2.4$ | $0.01 - 0.1$ | few x10 |
| Atoll | NS | $6.6 \pm 2.4$ | $\leq 1.0$ | NS | $\leq 6.6 \pm 2.4$ | $\geq 10^{22}$ | $\geq 1000$ |
| X-ray pulsar | NS | $1.0 \pm 0.7$ | $10^{22}$ | NS | $0.0 \pm 0.0$ | $10^{12}$ | few x100 |

Table 6. Comparison of derived mean intrinsic radio luminosities for the BHC/Z, Atoll and X-ray pulsar classes of X-ray binary, plus simple interpretations of their physical differences

| $\beta$ (BHC) | $\beta$ (Z) | Critical width of Luminosity Function |
|--------------|------------|-------------------------------------|
| 0.0          | 0.0        | 26.1                                |
| 0.5          | 0.0        | 26.0                                |
| 0.1          | 0.0        | 25.8                                |
| 0.3          | 0.0        | 25.7                                |
| 0.5          | 0.0        | 25.5                                |
| 0.7          | 0.0        | 24.5                                |
| 0.1          | 0.0        | 24.4                                |
| 0.3          | 0.0        | 24.3                                |
| 0.5          | 0.0        | 24.0                                |
| 0.7          | 0.0        | 23.5                                |
| 0.9          | 0.0        | 22.9                                |
| 0.1          | 0.0        | 22.7                                |
| 0.3          | 0.0        | 22.0                                |
| 0.5          | 0.0        | 21.5                                |
| 0.7          | 0.0        | 21.0                                |
| 0.9          | 0.0        | 15.0                                |

Table 5. Critical width of radio luminosity function for different values of $\beta (= v/c)$ for the population of persistent BHC and Z source X-ray binaries

5.1 Jets?

We have established that Doppler boosting is unlikely to affect the observed radio luminosities of the BHC and Z sources by more than an order of magnitude. Thus, assuming the emission is incoherent, we can apply the limiting brightness temperature of $10^{12}$ K which results from second-order inverse Compton losses. As a result we find that the emission at 2 GHz must arise in a region $\geq 10^{12}$ cm (for a spherical emitting region). This is a significant size scale, larger than the inferred binary separations of most, maybe all, of the systems (e.g. $\sim 3 \times 10^{11}$ cm for the Z source Sco X-1). A cone of opening half-angle 10 degrees in the plane of the sky would require a length of $10^{13}$ cm to produce the same observed surface area; angling the jet more towards the line of sight or making the opening angle smaller only increases this dimension. Similarly, attributing at least some of the observed radio flux to optically thin emission, less efficient than optically thick, also increasing the required emitting volume. Coupled with the recent imaging of collimated outflows from both Sco X-1 (Bradshaw et al. 1999) and Cyg X-1 (Stirling et al. 1998; de la Force et al. in prep) the observational evidence seems to point to extended radio-emitting outflows in all BHCs, Z sources and GX 13+1.

5.2 Why not Atoll sources?

Why are Z sources so much brighter radio emitters than the Atoll sources? the inferred differences between the two classes are a stronger magnetic field and higher accretion rate in the Z sources. We do not believe that the magnetic field plays much of a role in this difference:

- The inferred magnetic field in Z sources lie between those of the Atoll sources and the X-ray pulsars, both of which we shown to be significantly less luminous radio sources.
- The presence of kilohertz quasi-periodic oscillations in both Z and Atoll sources (van der Klis 1999 and references therein) implies that the accretion flow in both classes is not truncated by the magnetic field and instead reached almost to the surface of the neutron star.

Instead, it seems likely that it is the accretion rate which is the origin of the difference. This is supported by the radio detections of the Atoll source GX 13+1 at a similar level to the Z sources; this system is believed to be accreting at a higher rate ($\sim 10^{17}$ g s$^{-1} \equiv 0.1$ Eddington) than the other Atoll sources. In addition, we can imagine that the occasional detections of Atoll-type sources at radio wavelengths...
are associated with transient periods of high accretion rates comparable to those continuously occuring in the Z sources.

Alternatively, or perhaps additionally, transient radio emission seems to be produced at points of change in the X-ray ‘state’ of a system. Perhaps GX 13+1 and the Z sources change X-ray ‘state’ more often, or physically in a more dramatic way, than the other Atoll sources, and hence are more prone to significant mass ejections.

5.3 Why not X-ray pulsars?

As mentioned in section 2.4, no X-ray pulsar has ever been detected as a synchrotron radio source. As originally suggested by Fender et al. (1997b) we believe this is due to the truncation of the inner accretion flow by strong neutron star magnetic fields which force the accreting material to flow along the field lines towards the magnetic poles. We can now definitively state that the X-ray pulsars are at least one order of magnitude fainter than the BHC and Z sources as a population of radio emitters.

The apparent exception to this rule is the recent detection of transient radio emission from SAX 1808.4-3658 (Gaensler et al. 1999). In fact, this observations seems to confirm, rather than violate the above hypothesis, as in SAX 1808.4-3658 the magnetic field appears to be so weak ($\lesssim 10^9$ G) as to allow the nearly-Keplerian flow of material almost to the neutron star surface (Wijnands & van der Klis 1998). In this case the source is in nearly all respects Atoll-like and the detection of transient, weak, radio emission is consistent with this picture. It appears that somewhere in the range $10^9 - 10^{11}$ G, the magnetic field of a neutron star becomes so strong that its affect on the inner disc structure is enough to prevent the formation of a radio-emitting outflow.

6 CONCLUSIONS

We have investigated the radio detections and upper limits on the radio emission from persistent (i.e. non transient) X-ray binaries. Whilst always bearing in mind that the sample is not large, our conclusions are summarised in Table 6, and are:

- The BHCs (in the low/hard state) and the Z sources (on the horizontal branch) share a common mean observed radio luminosity corresponding to $(55 \pm 13)/d^2$ mJy, where $d$ is the distance to the source in kpc.
- Depending on the degree of Doppler boosting of the radio emission, this implies a common intrinsic radio luminosity to within a factor of 25 (decreasing as Doppler boosting becomes more important to e.g. a factor of 15 if both BHCs and Z sources have jets with $v = 0.9c$).
- Upper limits on radio emission from Atoll and X-ray pulsar populations as a whole show that they are in general at least 5 and 10 times fainter, respectively, than the BHC/Z systems.
- Assuming that the radio emission from BHC/Z systems arised in jets for which Doppler boosting is not very significant, we find that all these systems are likely to be generating radio-emitting outflows or jets whose physical scales are significantly larger than the binary orbits.

Combining these results with knowledge of the nature of accretion in different types of X-ray binaries, we can surmise that the following physical conditions are required for formation of a radio jet:

- A dipole magnetic field of $\lesssim 10^{10}$ G associated with the accreting compact object, allowing the formation of an accretion flow to $\lesssim 1000$ km which is not channeled onto the magnetic poles of the neutron star.
- A high accretion rate ($\gtrsim 0.1$ Eddington) and/or dramatic physical changes in the accretion mode which result in the ejection of disc material.

and further that the coupling between accretion and outflow in persistent systems (excluding X-ray pulsars) is comparable for both neutron stars and black holes, and therefore probably does not require the presence of either a surface or an event horizon.

Observation of exactly what causes the Atoll sources to occasionally produce radio emission, and determination of the high-frequency spectrum of the radio emission from the Z sources (to see if they, like the BHCs, possess a flat spectrum through mm wavelengths) are amongst the many important future observations to be made in this field.

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