A COMPARISON OF RADIO EMISSION FROM NEUTRON STAR AND BLACK HOLE X-RAY BINARIES

R. P. FENDER
Astronomical Institute ‘Anton Pannekoek’
and Center for High Energy Astrophysics,
University of Amsterdam, Kruislaan 403,
1098 SJ Amsterdam, The Netherlands

1. Introduction: radio emission from X-ray binaries

Radio emission has now been detected from $\sim 20\%$ of all X-ray binaries. In nearly all cases it has been found to be variable and to display a nonthermal\(^1\) spectrum, and synchrotron emission has been established as the most likely emission mechanism.

Radio outbursts from X-ray binaries generally follow a pattern of fast rise and power law and/or exponential decay, with an evolution of the spectral index ($\alpha = \Delta \log S_\nu / \Delta \log \nu$) from ‘inverted’ ($\alpha \geq 0$), probably arising in (partially) optically thick emission, to optically thin ($\alpha \leq -0.5$), with a corresponding shift in the peak of emission to lower frequencies. This is in qualitative agreement with models of an expanding, synchrotron-emitting cloud, as proposed by van der Laan (1966) for outbursts of active galactic nuclei. Furthermore, in recent years the time evolution of several outbursts have been imaged at high angular resolution with arrays such as VLA, MERLIN and VLBA, and these images reveal the outflow of radio-emitting matter along more or less collimated paths at relativistic velocities. More recently relatively stable radio emission from at least one persistent X-ray binary has also been resolved into a jet-like structure. As a result it has become widely, if not universally, accepted that radio emission from X-ray binaries arises in synchrotron-emitting jets. For detailed reviews and references, see e.g. Hjellming & Han (1995), Mirabel & Rodríguez (2000), Fender (2000a).

\(^1\)Here ‘nonthermal’ is taken to mean arising from a non-Maxwellian particle distribution which cannot be described by a single temperature
In this paper I compare, briefly, the properties of radio emission from both transient and persistent neutron-star and black-hole(-candidate) X-ray binaries.

2. Transients

Bright X-ray transients are generally accompanied by transient radio emission which follows the pattern outlined in the introduction. Bright transients can contain both neutron stars (e.g. Aql X-1) and black holes (e.g. GS 1124-684); do the radio properties of these two populations differ?

The answer is yes and no. Firstly, it is clear that, excluding bright, exotic objects for which classification of the compact object type has proved impossible to date (e.g. Cyg X-3, SS 433, LS 1 +61° 303), the black hole transients are, at the peak of outburst, the brightest radio sources associated with X-ray binaries. However, this is also the case for their X-ray emission – i.e. the brightest transients in the X-ray band are also the black holes. It is unclear at present whether this simply reflects the larger average masses of the black holes, or differences in the accretion flows onto
the two types of compact accretor. On the other hand, the ratio of radio to X-ray peak fluxes is comparable for both neutron star and black hole X-ray binaries. As an example, the neutron star transient Cen X-4 reached peak fluxes of $\sim 4$ Crab and $\sim 10$ mJy at soft X-ray and radio wavelengths respectively during its 1979 outburst. For comparison, the black hole transient A 0620-00 reached peak fluxes of $\sim 45$ Crab and $\sim 200$ mJy during its 1975 outburst. While the ratios are not exactly the same (but bear in mind there is likely to be a large scatter in observed radio fluxes due to beaming – see Kuulkers et al. 1999), their order-of-magnitude correspondence indicates that in both neutron star and black hole systems the ratio of X-ray to radio luminosities is comparable. Furthermore, the ratio is similar for most other systems (Fender & Kuulkers, in prep). This in turn implies that the accretion and jet formation mechanisms are broadly the same, during outburst, for both types of system.

Cir X-1 stands out as an example of a neutron-star X-ray binary which undergoes transient radio-bright outbursts every 16.6 days (Fig 1). The outbursts are believed to occur at periastron passage of a neutron star in a highly eccentric orbit with a main sequence or slightly evolved mass donor. The system displays a number of unique characteristics including a radio jets which connect to a radio-bright synchrotron nebula (Fender et al. 1998 and references therein), rapidly evolving X-ray and radio light curves, and the highest measured radial velocity ($\sim 400$ km s$^{-1}$) of any X-ray binary (Johnston, Fender & Wu 1999). Given its relative brightness (core + jets are typically $\geq 10$ mJy) and the predictability of its radio outbursts, Cir X-1 may be the best source in which to study the formation of jets by a neutron-star accretor.

3. Persistent sources

Only four persistently bright X-ray sources in our Galaxy are believed to contain black holes: Cyg X-1, GX 339-9, 1E 1740.7-2942 and GRS 1758-258. The latter two are too faint for regular monitoring, however for Cyg X-1 and, especially, GX 339-4, we have a good idea of how radio emission is related to X-ray state. This is explored in detail in Fender (2000b), and is summarised in table 1. Discrete, bright, outbursts correspond to major state transitions and/or the Very High State; the formation of a steady outflow seems to occur in the Low/Hard and, more weakly, Off states.

Neutron star systems do not display analogs of the black hole states, but can nonetheless be classified into different groups. These are the ‘Z’ and ‘atoll’ X-ray binaries (believed to contain low magnetic field neutron stars), and the high-field X-ray pulsars. Thus the population of neutron star X-ray binaries allows us to explore the effects of mass accretion rate and
accretor magnetic field on the production of radio jets. The Z sources (and the unusual atoll source GX 13+1) are all regularly detected as variable radio source.

Penninx et al. (1988), in observations of the Z-source GX 17+2 established a link between radio emission and location on the Z track (corresponding to the soft X-ray colours, and hence presumably the state of the accretion disc, at the time of observation – see e.g. van der Klis 1995), such that radio emission is strongest on the ‘horizontal branch’, weak on
### Radio Emission from X-ray Binaries

State & Radio properties
---
Very High & Bright ejections with spectral evolution from absorbed $\rightarrow$ optically thin
High/Soft & Radio suppressed by factor $\geq 25$
Intermediate & Weak?
Low/Hard & Low level, steady, flat spectrum extending to at least sub-mm
Off & Weak; similar to Low/Hard but reduced by a factor $\geq 10$

**TABLE 1.** The relation of radio emission to black hole X-ray state. From Fender (2000b).

| Source type       | $S_\nu/(\text{kpc}^2)$ (mJy) | $\dot{m}/\dot{m}_{\text{Edd}}$ | $B$ (Gauss) | inner disc radius (km) |
|-------------------|-------------------------------|---------------------------------|-------------|------------------------|
| BHC (low/hard state) | $55 \pm 13$                  | $\leq 0.1$                      | -           | few $\times 100$       |
| Z (horizontal branch) | "                             | $0.1 - 1.0$                     | $10^9 - 10^{10}$ | few $\times 10$       |
| Atoll             | $\leq 10 \pm 2$               | $0.01 - 0.1$                    | $10^9 - 10^{10}$ | few $\times 10$       |
| X-ray pulsar      | $\leq 6 \pm 2$                | $\leq 1.0$                      | $\geq 10^{12}$ | $\geq 1000$            |

**TABLE 2.** Comparison of derived mean intrinsic radio luminosities for the BHC/Z, Atoll and X-ray pulsar classes of persistent X-ray binary, plus simple interpretations of their physical differences. From Fender & Hendry (2000).

The ‘normal branch’ and absent on the ‘flaring branch’. This relation is in agreement with (most) subsequent studies, and at face value appears to demonstrate an anti-correlation between radio emission and accretion rate in these sources, but this is almost certainly an oversimplification.

The atoll sources are in general not detected except during outbursts (e.g. Aql X-1 is an atoll source and a transient, which had a radio outburst) and/or at very high mass accretion rates (which may be the cause in the case of GX 13+1). No X-ray pulsar has ever been detected as a radio source.

These results, and their inferences, are summarised in table 2 (adapted from Fender & Hendry 2000). It seems clear that an inner ($\leq 1000$ km) accretion disc, as a result of a low ($\leq 10^{10}$ G) accretor magnetic field and, most importantly and intuitively, a high mass accretion rate, are required for jet formation. In addition, it is demonstrated in table 1 that the Z sources (plus GX 13+1) have approximately the same radio luminosity as the persistent black hole candidates when in the Low/Hard X-ray state. Once again we are forced to conclude that the accretion and jet formation processes in neutron star and black hole X-ray binaries are similar (although it is noted that the Z sources are apparently a little more luminous in X-rays on average than the black holes in the Low/Hard state).
4. Conclusions

This comparison of the radio properties of the neutron-star and black-hole X-ray binaries has revealed that whether the systems are transient, as a result (in most cases) of low average accretion rates and disc instability mechanisms, or persistent, as a result of high average accretion rates, the coupling between radio jet formation and accretion luminosity is similar for both classes of accretor. It appears that the disc : jet coupling does not really care too much about the nature of the accretor (as long as the magnetic field is not strong enough to disrupt the accretion disc, as in the case of the X-ray pulsars).

However, this is an oversimplification of the situation, and many important questions remain. For example, it is the atoll sources, amongst the neutron star X-ray binaries which appear to show the strongest X-ray spectral evidence for Comptonising coronae, yet they are weak radio sources ... while in the black holes the presence of the corona is (nearly) always associated with observable radio emission. Is it just a question of accretion rate, or is another factor allowing only one of the classes to form jets ? This and other questions will only be resolved by future coordinated radio and X-ray observations of neutron-star, as well as black-hole, X-ray binaries.

References

Fender R.P., 1997, ‘New radio observations of Circinus X-1’, In: Proceedings of 4th Compton Symposium, 1997, AIP Conf. Proc. 410, Eds. Dermer C.D., Strickman M.S., Kurfess J.D., p.798
Fender R.P., 2000a, ‘Relativistic Jets from X-ray binaries’, In: Astrophysics and Cosmology : A collection of critical thoughts’, Springer Lecture Notes in Physics, in press (astro-ph/9907050)
Fender R.P., 2000b, ‘Black hole states and radio jet formation’, In: L. Kaper, E.P.J. van den Heuvel, P.A. Woudt (Eds), ‘Black holes in binaries and galactic nuclei’, ESO workshop, Springer-Verlag, in press
Fender R.P., Hendry M.A., 2000, MNRAS, submitted
Fender, R., Spencer, R., Tzioumis, T., Wu, K., van der Klis, M., van Paradijs J., Johnston H., 1998, ApJ, 506, L21
Fender, R. P., Garrington, S. T., McKay, D. J., Muxlow, T. W. B., Pooley, G. G., Spencer, R. E., Stirling, A. M., Waltman, E. B., 1999, MNRAS, 304, 865
Hjellming R.M., Han X.H., 1995, ‘Radio properties of X-ray binaries’, In: Lewin W.H.G., van Paradijs J., van den Heuvel E.P.J., eds., X-ray binaries, CUP, p. 308
Johnston H.M., Fender R.P., Wu K., 1999, MNRAS, 308, 415
Kuulkers, E., Fender, R. P., Spencer, R. E., Davis, R. J., Morison, I., 1999, MNRAS, 306, 919
Mirabel, I.F., Rodriguez, L.F., 1999, ARA&A, 37, in press (astro-ph/9902062)
Penninx W., Lewin W.H.G., Zijlstra A.A., Mitsuda K., van Paradijs J., van der Klis M., 1988, Nature, 336, 146
van der Klis M., 1995, ‘Rapid aperiodic variability in X-ray binaries’, In: Lewin W.H.G., van Paradijs J., van den Heuvel E.P.J., eds., X-ray binaries, CUP, p. 252
van der Laan H., 1966, Nature, 211, 1131