On the correlation between radio and X-ray flux in Low/Hard state Black Holes

E. Gallo\textsuperscript{1}, R. P. Fender\textsuperscript{1}, G. G. Pooley\textsuperscript{2}
\textsuperscript{1} Astronomical Institute “Anton Pannekoek” and Center for High Energy Astrophysics, Kruislaan 403, 1098 SJ Amsterdam, the Netherlands.
\textsuperscript{2} Mullard Radio Astronomy Observatory, Cavendish Laboratory, Madingley Road, Cambridge CB3 0HE, UK.

Abstract. Radio emission from X-ray binary systems (XRBs) has developed in recent years from being peculiar phenomenon to being recognised as an ubiquitous property of several classes of XRBs. In this scenario the synchrotron emission is interpreted as the radiative signature of jet-like outflows, some or all of which may possess relativistic bulk motion. We have analysed a collection of quasi-simultaneous radio/X-ray observations of Black Holes in the Low/Hard X-ray state, finding evidence of a clear correlation between their fluxes over many orders of magnitude in luminosity. Given that the correlation extends down to GX 339-4 and V404 Cyg in quiescence, we can confidently assert that even at accretion rates as low as $\dot{m}_{\text{Edd}} \sim 10^{-5}$ a powerful jet is being formed. The normalisation of the correlation is very similar across a sample of nine sources, implying that it is nearly independent of jet inclination angle. Remarkably, V 404 Cyg is the second source (after GX 339-4) to show the correlation $S_{\text{radio}} \propto S_{X}^{+0.7}$ from quiescent level up to close to the High/Soft state transition. Moreover, assuming the same physics and accretion:outflow coupling for all of these systems, the simplest interpretation for the observed scenario is that outflows in Low/Hard state do not have large bulk Lorentz factors.

1. Introduction: radio emission from Low/Hard state Black Holes

Radio emission is often observed from X-ray binaries, particularly transient systems and especially Black Hole (BH) candidates (for detailed reviews see e.g. \cite{1, 2, 3, 4}). The Low/Hard state is one of the five ‘canonical’ X-ray states observed from BH X-ray binaries in our Galaxy. It is characterized by a hard (spectral index $\sim 1.5$) X-ray spectrum, associated with a steady, self-absorbed jet which emits synchrotron radiation; the Off state may simply be the Low state ‘turned down’ to lower accretion rates. X-ray spectra of High/Soft state BHs are dominated by thermal radiation, while the radio emission drops below detectable levels, probably corresponding to the physical disappearance of the jet. For the so called Intermediate and Very High states the connection between X-ray and radio properties is not yet completely established. Transitions between states are often associated with multiple ejections of synchrotron emitting material, possibly with high Lorentz factors.

There is an extremely strong correlation between radio and X-ray emission: the former has been directly observed to arise in outflows and to produce synchrotron emission from a population of high energy electrons. The latter has been inferred
to arise via Comptonisation by a thermal electron distribution. All the evidence points to the corona in these systems being physically related to the presence of a jet: by far the simplest interpretation therefore is that the Comptonising region is just the base of the relativistic outflow.

2. Jet/corona coupling: $S_{\text{radio}}$ versus $S_X$

By means of simultaneous radio/X-ray observations performed on the Galactic BH GX 339-4, Corbel et al. (in preparation) have found an interesting correlation between fluxes, namely the radio density flux at 8.6 GHz scales as the 3-9 keV X-ray flux raised to 0.7.

Assuming the same physics and jet/corona coupling for all sources, based on simple arguments one would predict the following scenario in the $S_{\text{radio}}$ vs. $S_X$ parameter space (see sketch in fig. 1 for clarity):

1. All sources lying on a line with the same slope if neither X-ray or radio emission were strongly beamed (i.e. low $\beta$).
2. Different sources lying on lines with the same slope but different normalisations if X-rays were isotropic but radio was beamed, with radio-brighter sources corresponding to higher Doppler factors.
3. As point 2, but with higher Doppler factors sources being brighter in both radio and X-ray if either were beamed.

With the purpose of verifying if and possibly which kind of relation could be shared among a wide sample of sources in the same spectral state, we collected a variety of quasi-simultaneous radio/X-ray observations of Low state BHs and plotted the radio vs. the X-ray fluxes (below 12 keV) scaled to a distance of 1 kpc (units are mJy vs. Crab). As shown in fig. 1, there is actually clear evidence for a strong correlation, which - again - extends over more than three orders of magnitude in accretion rate, from around $10^{-5}M_{\text{Edd}}$ (calculated supposing $M_{BH}=10 M_{\odot}$) up to close to the High/Soft state transition. It is important to stress that, in principle, the range of normalisation values can be extremely large. Assuming again the same physics for all sources, and that X-rays are isotropic while radio is beamed, the ratio $S_{\text{radio}}/S_X$ for two sources would equal the ratio between their Doppler factors (calculated as sum of approaching and receding jet) to the second power. For instance, with $\beta=0.998$ (i.e. $\Gamma=16$) and angles ranging between 1° - 90°, that ratio covers 12 orders of magnitude!
On the correlation between radio and X-ray flux in Low/Hard state Black Holes

Figure 2. Radio density flux (mJy) at 15 GHz is plotted against X-ray flux (Crab) below 12 keV for a sample of nine Low/Hard state BHs, scaled to a distance of 1 kpc. An evident correlation between these two bands appears, and holds over more than three orders of magnitude in accretion rate.

3. Special cases: V 404 Cyg and GX 339-4

Remarkably, we found that the data of V 404 Cyg and GX 339-4, i.e. the sources for which we have the largest range in luminosity at our disposal, are well fitted by a power law with the same slope, as shown in fig. 3: we obtained $S_{\text{radio}} = k \times S_X^{0.7 \pm 0.1}$, with $k_{V404} = 254 \pm 18$ and $k_{GX339} = 124 \pm 2$. For the same simple arguments we mentioned in the previous section, assuming isotropic X-rays and beamed radio emission, the ratio $k_{V404}/k_{GX339}$ should be equal to $(\delta V_{404}/\delta GX_{339})^2$. GX 339-4 seems to be at quite low inclination (15° - 30° according with [5], [6]) while $i_{V404}=56°$ ([7], [8]); adopting these values the ratio $(\delta V_{404}/\delta GX_{339})^2 < 1$ for any value of $\beta = v/c$. Thus, V 404 being radio-brighter than GX 339-4 despite the higher inclination excludes both the second and the third scenario described in the previous section. The simplest possible explanation requires very low beaming for both sources, attributing the little scatter in normalisation to intrinsic errors. Obviously a great uncertainty in this argument is introduced by distance determinations, which strongly affect all the calculations. In addition we can not rule out the possibility of a much more complex physical model behind this relation.

4. Summary and conclusions

The results of our analysis can be summarized as follows:

- In Low/Hard state BHs the observed radio and X-ray fluxes are correlated over more than three orders of magnitude in accretion rate, implying a strong
Figure 3. For both V 404 Cyg and GX 339-4 (Corbel et al., in preparation), from quiescence up to High state transition, we found $S_{\text{radio}} = k \times S_{\text{X}}^{0.7}$, with $k_{\text{V 404}} = 254 \pm 18$ and $k_{\text{GX 339}} = 124 \pm 2$.

jet/corona coupling; no lower limit to the relation has been found.

- We can confidently assert that, even at accretion rates as low as $\sim 10^{-5} \dot{m}_{\text{Edd}}$ a powerful jet is being formed.
- V 404 Cyg is the second source to display $S_{\text{radio}} \propto S_{\text{X}}^{0.7}$, from quiescence up to Soft state transition. A physical explanation for this relation is proposed by Markoff et al. (9).
- Above $\sim 10^{-2} \dot{m}_{\text{Edd}}$ the jet disappears within a factor of a few, probably in all sources (observed in three sources and no exceptions).
- Comparison of different sources may indicate that jets in Low/Hard have a low velocity compared to those in transient outbursts. Of course better distance and inclination determinations are strongly required to probe this conjecture.

Finally, we would like to mention that the possible detection of the Soft X-ray Transient A0620-00 at the predicted – extrapolating the relation we found – radio level would demonstrate that jet production is an ubiquitous mechanism between $10^{-7}$ and $10^{-2} \dot{m}_{\text{Edd}}$.

References
1. 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, 308.
2. Mirabel, I. F., Rodriguez, L. F., 1999, ARA&A, 37, 443.
3. Fender, R., 2001, Astrophysics and Space Science, 276 (suppl), 69.
4. Fender, R., 2001, MNRAS, 322, 31.
5. Wu, K., Soria R., Hunstead R. W., Johnston H. M., 2001, MNRAS, 320, 177.
6. Soria R., Wu K., Johnston H. M., 1999, MNRAS, 310, 71.
7. Shahbaz, T., Ringwald, F. A., Bunn, J. C., Naylor, T., Charles, P. A., Casares, J., 1994, MNRAS, 271, L10.
8. Wagner, R. M., Kreidl, T. J., Howell, S. B., Starrfield, S. G., 1992, ApJ, 401, L97.
9. Markoff, S., Nowak, M., Corbel, S., Fender, R., Fälcke, H., 2002, A&A submitted.