Using SKA to observe relativistic jets from X-ray binary systems

R. Fender[a]

[a] Astronomical Institute 'Anton Pannekoek', University of Amsterdam

I briefly outline our current observational understanding of the relativistic jets observed from X-ray binary systems, and how their study may shed light on analogous phenomena in Active Galactic Nuclei and Gamma Ray Bursts. How SKA may impact on this field is sketched, including the routine tracking of relativistic ejections to large distances from the binaries, detecting and monitoring the radio counterparts to 'quiescent' black holes, and detecting the radio counterparts of the brightest X-ray binaries throughout the Local Group of galaxies.

1. Introduction

1.1. Jets from X-ray binaries

X-ray binary systems (Lewin & van der Klis 2004; Lewin, van Paradijs & van den Heuvel 1995) are the sites of the most dramatic, ongoing, high-energy astrophysical phenomena on non-cosmlogical scales. Compact, relativistic stars – neutron stars or 'stellar mass' black holes – accrete material from a binary companion in a relatively short (hours to weeks) period double system. An earlier brief discussion on the potential of SKA for the study of these objects was presented in Fender (1999).

The key signature of the relativistic accretion process in the radio band are the *jets*. As in Active Galactic Nuclei (AGN), and probably Gamma-Ray Bursts (GRBs) these jets seem to correspond to highly relativistic outflows of matter, probably at least in part baryonic, from very close to the accreting central object (in some cases the launch point may be as close as a handful of gravitational radii, GM/c^2). As with AGN and GRBs the emission mechanism is almost certainly synchrotron from relativistic electrons spiralling in magnetic fields. These synchrotron-emitting clouds of electrons have themselves relativistic bulk motions, along a (more or less) fixed axis, and this is the jet. Fig 1 provides a sketch of the probable geometry of a jet-producing X-ray binary.

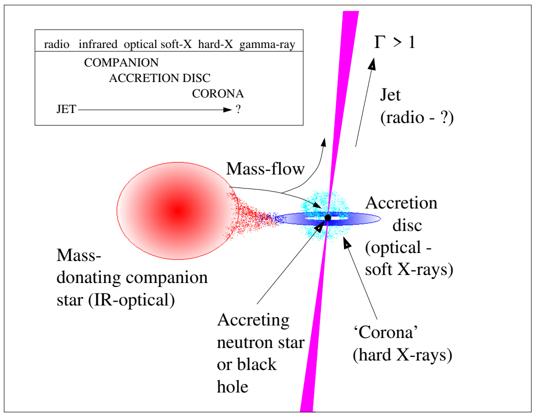

Figure 1. A schematic diagram of a (low-mass) X-ray binary system, sketching the various physical components and regions of the electromagnetic spectrum in which they emit. The jet is unique in having an extremely broad spectral component, from being the only major contributor to the radio emission to one of probably several emitting components in the X-ray band. When we detect an X-ray binary in the radio band we are almost certainly detecting the jet (see further arguments in Fender 2004).

We know of currently 200-300 X-ray binaries (Liu, van Paradijs & van den Heuvel 2000,2001), probably corresponding to an underlying population of some tens of thousands of compact objects in binary systems in our galaxy. The distribution of these X-ray binaries within our galaxy has been addressed most recently by Grimm, Gilfanov & Sunyaev (2001) and Jonker & Nelemans (2004). We see the brightest X-ray binaries essentially to the other side of the galaxy. The distribution of systems from Grimm et al. is presented in Fig 2. High-mass and low-mass X-ray binaries (where the prefix applies to the mass of the companion star, not the accreting object) are distributed differently, with the generally younger high-mass systems concentrated near regions of star formation, i.e. the spiral arms. Note however, that there does not appear to be a strong effect on the disc-jet coupling whatever the mass of the companion star. This is natural since the inner regions of a bright accretion disc do not feel the influence of the companion star in any strong way. Nevertheless, in some cases the photon field of a bright companion star *might* act as a source of photons for external comptonisation of the extended jet structure (e.g. Georganopoulos, Aharonian & Kirk 2002).

Over the past decade, key observations with ATCA, MERLIN, The Ryle Telescope, VL(B)A, EVN and WSRT have provided remarkable insights into the variable process of jet formation in these systems. When coupled with simultaneous X-ray measurements these observations have probed the dynamical coupling between accretion and outflow around accreting relativistic objects in a way which is not possible for AGN (which vary too slowly, in general) or GRBs (in which, in a sense, its all over in an instant).

Based upon studies such as these, clear patterns have emerged in the coupling between accretion and outflow in these sources, which we shall outline below.

1.1.1. Black hole X-ray binaries

Fig 3 presents the radio vs. X-ray plane for nearly all the radio-loud black hole X-ray binaries (a notable exception is SS 433, which evades easy classification, but is essentially as radio-loud as Cyg X-3 at a significantly lower apparent X-ray luminosity), scaled to a distance of 1 kpc in order to compare luminosities (from Gallo, Fender & Pooley 2003). Examples are also shown of resolved jets from different regions of the plane. Note that scaling by the estimated two orders of magnitude sensitivity improvement expected from SKA, much more of the plane will be accessible to direct imaging of the jets.

The 'hard' (or 'low/hard') X-ray spectral state is ubiquitous at X-ray luminosites below about 1% of the Eddington luminosity (typically considering a $\sim 10 M_{\odot}$ black hole), and in some sources may persist to as bright as 10% of this in the rising phase of an outburst. The state gets its name from its hard X-ray spectra which shows only a weak blackbody component which may be ascribed to an accretion disc, but is instead dominated by a component which peaks in most sources around 100 keV and is generally interpreted as arising in thermal Comptonisation (see e.g. McClintock & Remillard 2004 and references therein for this interpretation, and Markoff, Falcke & Fender 2001 for a 'synchrotron-based alternative'). In this state there is a 'compact' self-absorbed jet which manifests itself as a 'flat' (spectral index $\alpha \sim 0$ where $\alpha = \Delta \log S_{\nu} / \Delta \log \nu$) or 'inverted' ($\alpha \geq 0$) spectral component in the radio, millimetre and (probably) infrared bands (e.g. Fender 2001, Corbel & Fender 2002). The radio luminosity of these jets shows a strong, non-linear correlation with X-ray luminosity (Corbel et al. 2003; Gallo, Fender & Pooley 2003) – see Fig 3 up to a scaled X-ray flux of about 1 Crab. The correlation takes the form

$$L_{\mathrm{radio}} \propto L_{\mathrm{X}}^{b}$$

where $b \sim 0.7$. This is consistent with the 'Fundamental Plane' (see below, and Fig 6) for sources of all approximately the same mass. The steady jets which we infer to exist have only been directly spatially resolved in the case of Cyg X-1 (Stirling et al. 2001), although the 'plateau' jet of GRS 1915+105 is phenomenologically similar and has also been resolved (Dhawan et al. 2000; Fuchs et al. 2003). The suggestion that such steady, compact jets are produced even at very low accretion rates (Gallo, Fender & Pooley 2003; Fender, Gallo & Jonker 2003) has recently received support in the flat radio spectrum observed from the 'quiescent' transient V404 Cyg at an average X-ray luminosity $L_{\rm X} \sim 10^{-6} L_{\rm Edd}$ (Gallo, Fender & Hynes 2004).

Brighter sources may enter the 'soft' (or 'high/soft' or 'thermal dominated') X-ray state at higher luminosities (typically around 10–50% Eddington). In this state the X-ray spectrum is dominated by a ∼blackbody component probably corresponding to an optically thick and geometrically thin accretion disc extending to the innermost stable circular orbit (McClintock & Remillard 2004 review the properties in more detail). In this state the radio emission, and probably therefore jet production, is strongly suppressed (Tanabaum et al. 1972; Fender et al. 1999b; Gallo, Fender & Pooley 2003). This effect in which softer X-ray states reduce the radio emission can be seen clearly in the interval 1–10 Crab in Fig 3.

Fig 4 (from Tigelaar 2004) presents the broadband spectrum of the black hole X-ray binary Cygnus X-1 in hard (labelled 'Low/Hard') and soft(-er) (labelled 'High/soft or Intermediate') states. The change in the X-ray spectrum from hard to soft states, resulting in a reduction in emission around 100 keV ($\sim 10^{19}$ Hz) and an increase in the temperature and luminosity of the accretion disc (around 1 keV $\equiv$ 10^{17} Hz), are clearly associated with a dramatic 'quenching' of the radio component.

Additionally there are bright events associated with transient outbursts and state transitions (of which more later), which are often directly resolved into components displaying relativistic motions away from the binary core (e.g. Mirabel & Rodriguez 1994; Hjellming & Rupen 1995; Fender et al. 1999,2002b) not only in the radio but also – at least once – in the X-ray band (Corbel et al. 2002). These events typically display optically thin (synchrotron) radio spectra ($\alpha \leq -0.5$). Both kinds of jets are clearly very powerful and coupled to the accretion process. See Mirabel & Rodriguez (1999) and Fender (2004) for a more thorough review of the observational properties of X-ray binary jets.

Fig 5 summarises our current best model for the phenomenology of the disc–jet coupling in black hole X-ray binaries (from Fender, Belloni

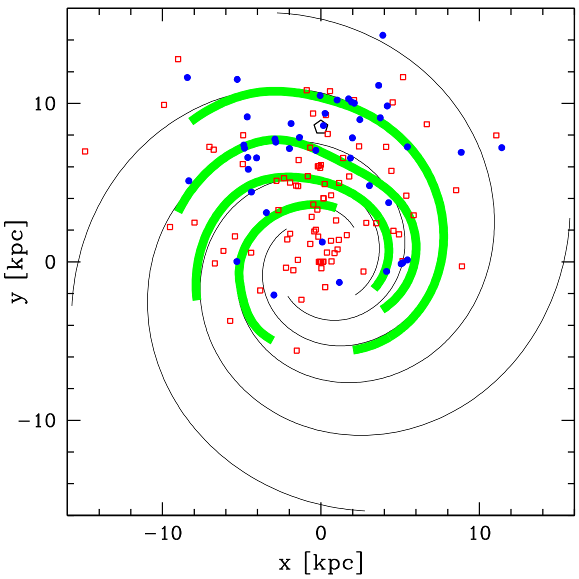

Figure 2. The distribution of known X-ray binary systems within the Milky Way. From Grimm, Gilfanov & Sunyaev (2002). Some of the distances may be significantly underestimated (e.g. Jonker & Nelemans 2004), in which case we have probably observed sources up to 20+ kpc distant. The Sun is at (0,8.5) kpc. Sold circles indicate high-mass X-ray binaries (those with massive companions) while open symbols indicate low-mass X-ray binaries (typically with companions of a solar mass or less).

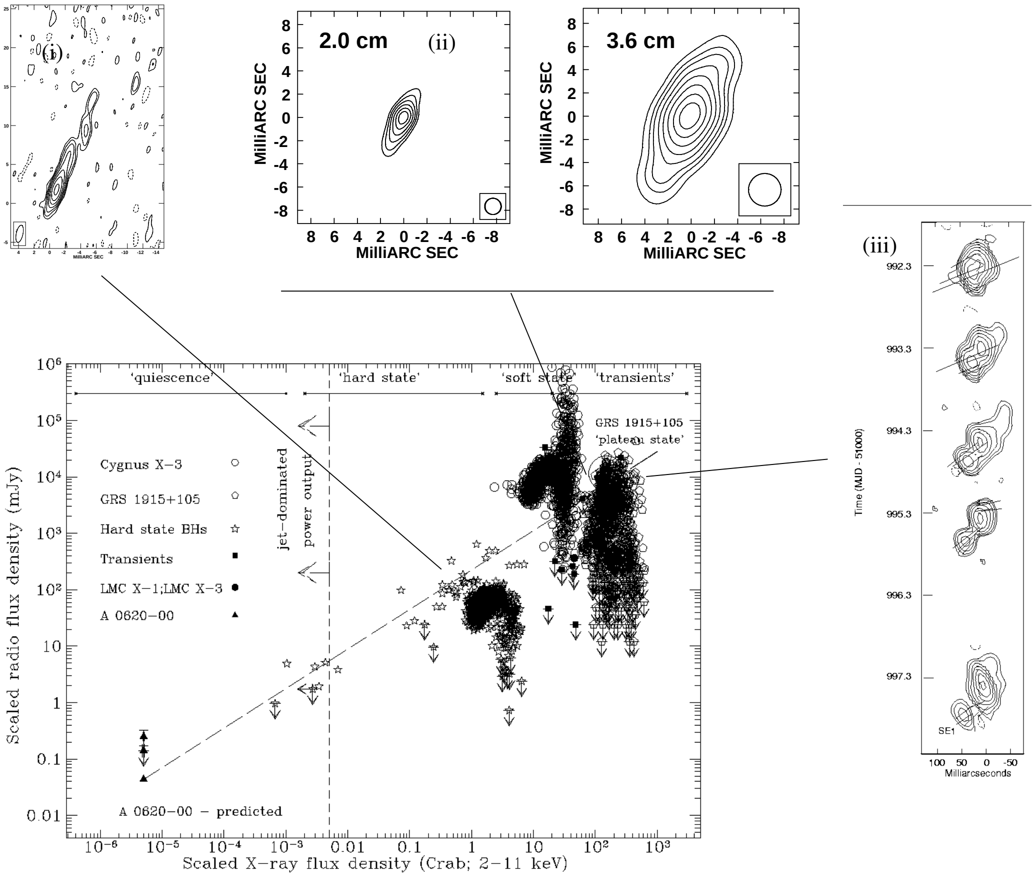

Figure 3. The radio : X-ray plane for galactic black hole X-ray binary systems, with all sources scaled to a distance of 1 kpc. The brightest transient sources have peak radio flux densities in excess of 1 Jy at GHz frequencies. The faintest sources currently detected at about the ~ 0.1 mJy level. SKA will allow us to detect sources confidently down to the μJy level. From Gallo, Fender & Pooley (2003). The insets, clockwise from top left correspond to (i) the steady jet in the 'low/hard' state from Cyg X-1 (Stirling et al. 2001) (ii) the very powerful steady jet from GRS 1915+105 in the 'plateau' hard X-ray state (Fuchs et al. 2003) and (iii) relativistic ejections from GRS 1915+105 with spatially resolved linear polarisation (Fender et al. 2002b).

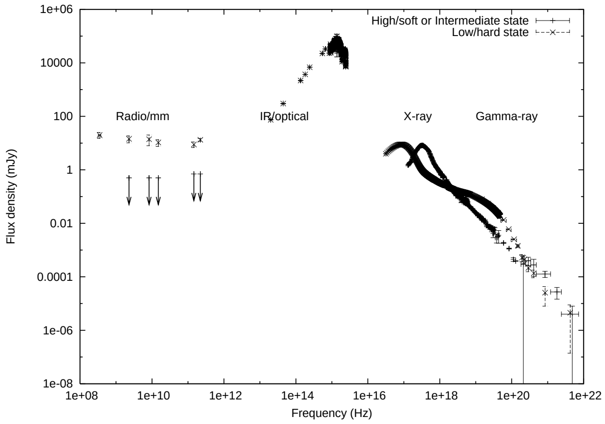

Figure 4. The change in the broadband spectrum of the black hole X-ray binary Cygnus X-1 between two X-ray 'states'. In the 'low/hard' state the accretion disc has a lower temperature, with a strong 'excess' around 100 keV, and the radio emission is 'on', with a relatively flat spectrum. This probably corresponds to the generation of a self-absorbed ∼conical jet during phases when we do not see a bright accretion disc extending to the innermost stable circular orbit. In the softer state the X-ray spectrum is dominated by a hotter accretion disc, probably closer to the black hole, and the radio emission (→ jet) is 'quenched'.

& Gallo 2004). In essence, we suggest that until the disc comes very close to the black hole (around the time we observe it dominating the X-ray spectrum) a ∼steady jet is formed. During transitions to soft states as the disc is making its final 'collapse' inwards, the jet velocity increases sharply. This results in a relativisitically moving, optically thin, internal shock, followed by a suppression of the 'core' radio emission while the source is in a soft X-ray state. The seemingly ubiquitous presence of jets in hard X-ray states has been taken as strong evidence for the magnetohydrodynamic (MHD) production of jets (see e.g. Meier 2001).

1.1.2. Neutron star X-ray binaries

The study of the disc-jet coupling in neutron star (NS) X-ray binaries has lagged behind that of the black holes in recent years. The reason for this is that the NS X-ray binaries are considerably less 'radio loud' than the black holes (Fender & Kuulkers 2001; Migliari et al. 2003 and in prep). Even when considering the mass term in the 'Fundamental plane' (see below), they appear to be less efficient at producing radio emission for a given X-ray flux.

Despite complex patterns of behaviour in X-rays on relatively short (hours) timescales, the radio:X-ray plane for NS X-ray binaries appears similar to Fig 3, but with the neutron stars occupying a region a factor of ~ 30 below the black holes (Migliari et al. in prep). This strongly implies that the study of these NS jet sources can tell us something about the black holes, since

- The apparent similarity in the patterns tells us that the global properties of the disc-jet coupling in black holes are as a result of the accretion flow and not something unique to black holes themselves

- The clear difference in radio power indicates that some difference between NS and black hole X-ray binaries (surface, radiation, magnetic field) is enough to affect the observed jet power

Furthermore, we already have evidence that the most relativistic flows from binaries are in fact from the neutron star systems (see below). The detailed study of jets from accreting neutron stars is likely, for the reasons given above, to be crucial in our understanding of the jet formation process in black holes.

1.2. X-ray binaries as tools to understand AGN

Much has been made in the past decade of the apparent analogy between the relativistic jets produced by supermassive ($10^6 M_\odot \leq M_{\rm BH} \leq 10^{10} M_\odot$) black holes (AGN) and those produced in BH XRBs ($3 M_\odot \leq M_{\rm BH} \leq 20 M_\odot$) – hence the popular name 'microquasars' for this latter class of object. However, for most of this period the

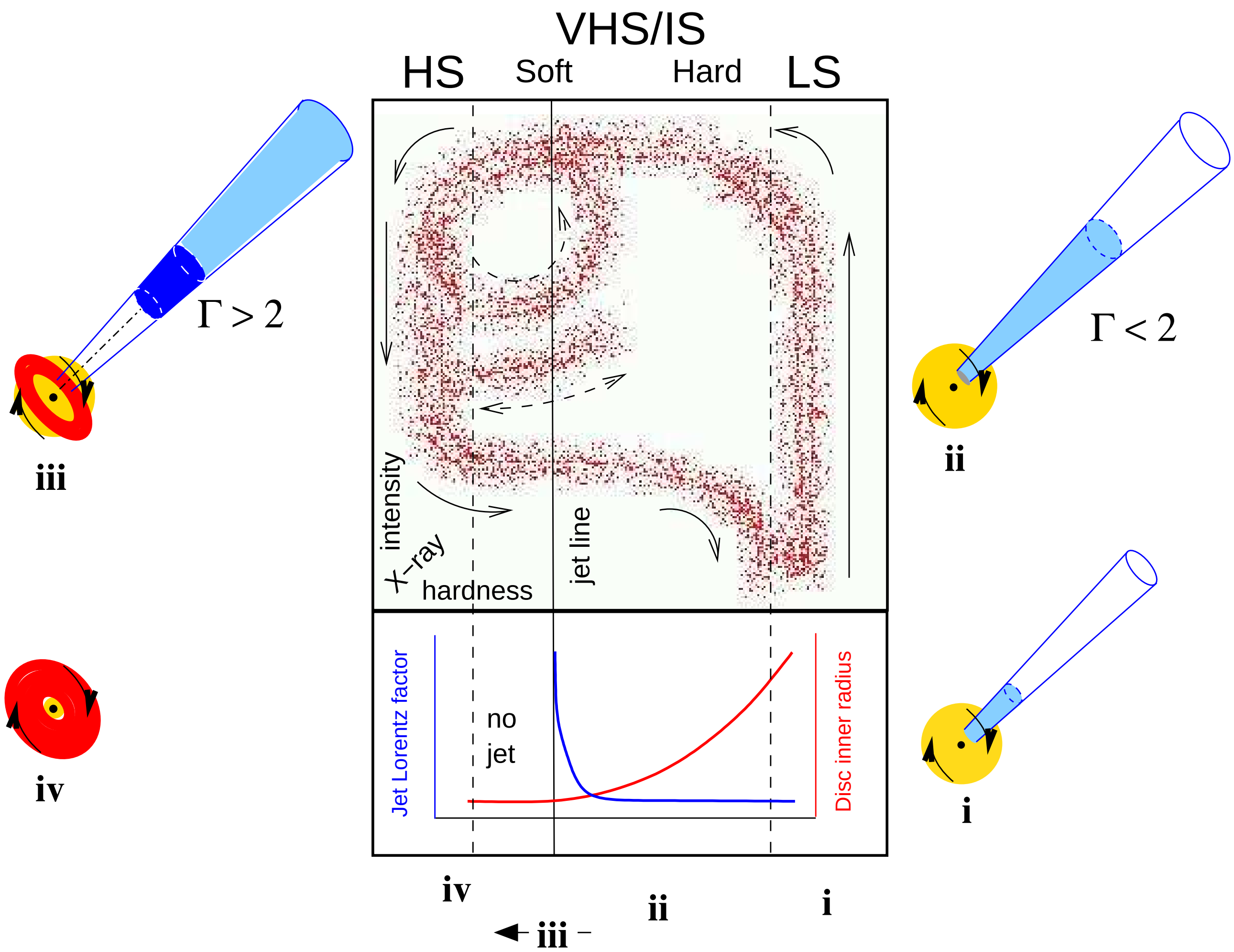

Figure 5. A schematic of our simplified model for the jet-disc coupling in black hole binaries. The central box panel represents an X-ray hardness-intensity diagram (HID); 'HS' indicates the 'high/soft state', 'VHS/IS' indicates the 'very high/intermediate state' and 'LS' the 'low/hard state'. In this diagram, X-ray hardness increases to the right and intensity upwards. The lower panel indicates the variation of the bulk Lorentz factor of the outflow with hardness – in the LS and hard-VHS/IS the jet is steady with an almost constant bulk Lorentz factor $\Gamma < 2$, progressing from state **i** to state **ii** as the luminosity increases. At some point – usually corresponding to the peak of the VHS/IS – Γ increases rapidly producing an internal shock in the outflow (**iii**) followed in general by cessation of jet production in a disc-dominated HS (**iv**). At this stage fading optically thin radio emission is only associated with a jet/shock which is now physically decoupled from the central engine. As a result the solid arrows indicate the track of a simple X-ray transient outburst with a single optically thin jet production episode. The dashed loop and dotted track indicate the paths that GRS 1915+105 and some other transients take in repeatedly hardening and then crossing zone **iii** – the 'jet line' – from left to right, producing further optically thin radio outbursts. Sketches around the outside illustrate our concept of the relative contributions of jet (blue), 'corona' (yellow) and accretion disc (red) at these different stages.

comparisons remained largely phenomenological. However, in the past year all this has changed as *quantitative* scalings between jets, and between X-ray and radio power in black holes of *all masses* and *all accretion rates* have emerged (Heinz & Sunyaev 2003; Merloni, Heinz & di Matteo 2003; Falcke, Körding and Markoff 2004). Specifically, Merloni, Heinz & di Matteo (2003) and Falcke. Körding & Markoff (2004) have demonstrated the existence of a 'fundamental plane' of black hole activity in the 3D parameter space of black hole mass ($M_{\rm BH}$), X-ray luminosity ($L_{\rm X}$) and radio ($L_{\rm radio}$) luminosity (Fig 6). This fundamental plane spans a range in $> 10^8$ in M, albeit currently with a lot of scatter. Maccarone, Gallo & Fender (2003) have recently rebinned the data set of Merloni, Heinz & di Matteo to demonstrate the 'quenching' of jets in the same fractional Eddington range as known to occur in XRBs, suggesting the disc-jet phenomenology may also be the same.

Detailed quantitative comparisons are only just beginning to be made; and will no doubt be the subject of many future research papers. At the very roughest level, it is tempting to associate the (disputed) 'radio loud' and 'radio quiet' dichotomy observed in AGN with jet-producing (hard and transient) and non-jet-producing (soft) states in X-ray binaries (see e.g. Maccarone, Gallo & Fender 2003), including of course the effect of the mass term. Furthermore perhaps FRI jet sources can be associated with the low/hard state and FRIIs with transients. Meier (1999; 2001) has considered jet production mechanisms in both classes of object, and drawn interesting parallels. Gallo, Fender & Pooley (2003; amongst others!) have made a qualitative comparison between FRIs and low/hard state black hole X-ray binaries and FRIIs and transients.

It is interesting to note that the short timescale disc-jet coupling observed in GRS 1915+105 (Pooley & Fender 1997; Eikenberry et al. 1998; Mirabel et al. 1998; Klein-Wolt et al. 2001), in its most basic sense – that radio events are preceded by a 'dip' and associated spectral hardening in the X-ray light curve – may also have an analog in AGN: Marscher et al. (2002) have reported qualitatively similar behaviour in 3C 120.

2. Studying X-ray binaries with SKA

The potential offered by the SKA to study the formation of jets in X-ray binaries, and their relation to the accretion process (by means of simultaneous X-ray observations) is immense. With a two orders of magnitude sensitivity leap and VLBI-scale angular resolution, we expect to regularly resolve relativistic events from a large number of X-ray binary systems, as well as detecting unresolved radio emission from radio cores at very low luminosities.

2.1. Monitoring bright sources

A handful of X-ray binaries remain semi-continuously in very bright and variable X-ray and/or radio states ('outburst'). These systems include SS 433, Cygnus X-3, GRS 1915+105 (see Fig three inset (iii))and Circinus X-1 (see Fig 8). For such sources, with typical flux densities 1—1000 mJy at GHz wavelengths, and previously resolved jet-like structures, we may expect low-duty-cycle radio monitoring to result in movies capturing the jet formation and propagation in exquisite detail.

Furthermore, bright (close to Eddington at peak) new X-ray transients are expected to produce (sequences of) strong radio outbursts (probably corresponding to internal shocks; see Fig 5) with a frequency typically around ~ 1/year. Such sources when resolved typically reveal ejections with projected velocities in the range 1–15c, decelerating at larger distances from the core (see e.g. Fender 2004 and references therein; Fender, Belloni & Gallo 2004; Kaaret et al. 2003). These jets typically fade rather rapidly (with e-folding times of hours to weeks) and become unobservable due to the sensitivity of the radio array before we have observed them doing anything 'interesting' such as interacting with the ISM. SKA has the potential to track these sources much further from the core, observing such interactions and decelerations. Furthermore, the short integration time required to make 'snapshot' monitoring observations of recent transients will undoubtedly facilitate the discovery of more 'rebrightening' events such as those observed in the case of XTE J1550-564 years after the initial outburst

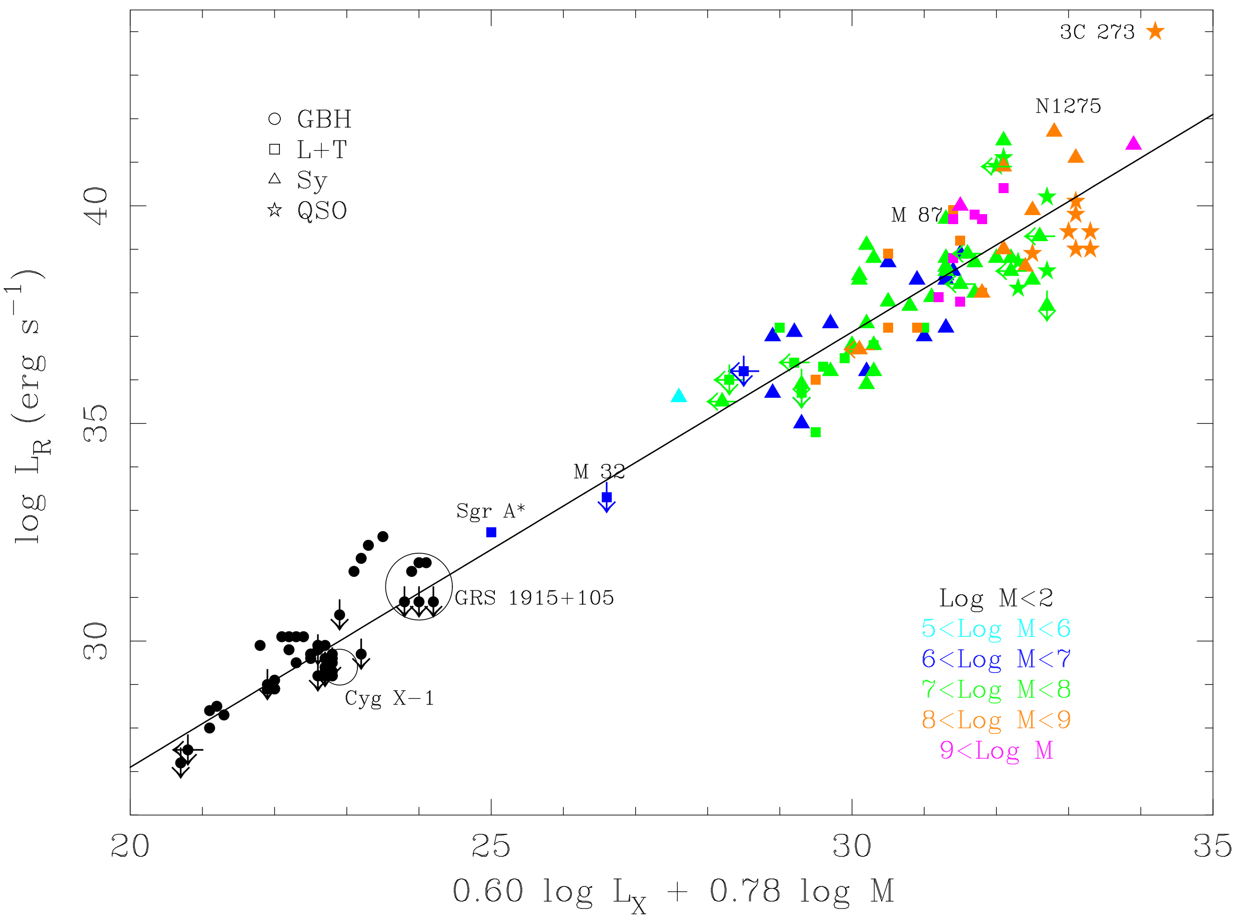

Figure 6. The fundamental plane of black hole activity (Merloni, Heinz & di Matteo 2003; see also Falcke, Körding & Markoff 2004). Combined data from both X-ray binaries and AGN indicates the existence of an approximate plane in the $L_{\rm radio}$:$L_{\rm X}$:$M_{\rm BH}$ parameter space. This underlines the scale-invariance of the accretion:outflow coupling (Heinz & Sunyaev 2003) and demonstrates that results from X-ray binaries and AGN may be compared *quantitatively*.

(Corbel et al. 2002).

The jets from these sources are also known to display both linear and circular polarisation (e.g. Fender et al. 1999,2000a,b; Macquart & Fender 2004). Linear polarisation observations provide unique information on the degree or ordering and orientation of the magnetic field within the ejecta. The situation is clearly not straightforward – spatially resolved linear polarisation images of GRS 1915+105 made with MERLIN (Fender et al. 1999) revealed a field which was different each day. Other, unresolved, events from the same source observed with ATCA have revealed both constant polarisation angles and 'rotator' events (Fender et al. 2002a,b – see inset (iii) in Fig 3). Circular polarisation (Macquart & Fender 2004) offers a complex but potentially very powerful insight into the composition of relativistic jets. For example, the detection of a circular polarisation spectrum of the form $V/I \propto \nu^{-0.5}$ from a homogenous, optically thin, synchrotron source would be strong evidence for a baryonic component in the jet plasma, something which (with the exception of SS 433) has eluded observations so far.

2.2. Resolving 'steady' jets in hard X-ray states

As outlined above (see e.g. Fender 2004 for a more detailed discussion), black holes in 'hard' X-ray states seem to be ubiquitously associated with steady jet production (see insets (i) and (ii) in Fig 3). The power and physical conditions in these jets are central to our understanding of how accretion proceeds near a black hole. The overwhelming majority of black holes of all masses are likely to exist in this state.

Observations of synchrotron time lags (e.g. Mirabel et al. 1998; Fender et al. 2002a) as well as direct imaging (Fuchs et al. 2003) indicate that the compact jet in GRS 1915+105 has a physical size of around 10^{14-15} cm at GHz wavelengths for a flux density in the range 40–120 mJy. If we assume that this physical size corresponds to the distance from the black hole to the $\tau \sim 1$ surface (where τ is the optical depth) in a self-absorbed jet (e.g. Blandford & Konigl 1979; see also chapter by Falcke, Körding & Nagar), and that all compact jets have approximately the same brightness temperature (as seems to be the case for AGN – e.g. Ghisellini et al. 1993), then we can estimate the physical size of such a jet as

$$r_{\rm GHz} \sim 5 \times 10^{14} \left(\frac{S_{\nu}}{40 \ \rm mJy}\right) \left(\frac{d}{11 \ \rm kpc}\right)^2 \quad \rm cm$$

This corresponds to an angular size of

$$\alpha \sim 35 \left(\frac{S_{\nu}}{40 \ \rm mJy}\right) \left(\frac{d}{11 \ \rm kpc}\right) \quad \rm mas$$

which means that for a given radio flux density, a distant source will be more easy to resolve than a nearby one, because it is more powerful. This function is plotted in Fig 7. A typical hard state X-ray transient will have a flux density of $\geq$ a few mJy and lie at a distance of 2–20 kpc. Such sources are potentially resolveable with high sensitivity VLBI. Note that Gallo, Fender & Hynes (2004) have recently measured the radio spectrum of the black hole X-ray binary V404 Cyg in 'quiescence' and have found it to be similar to that of Cyg X-1, supporting the interpretation of low-level radio emission originating in a compact jet.

The handful of measurements of linear polarisation from hard state sources indicate a typical level of $\sim$ 2% (Fender 2001). Furthermore, the polarisation angle seems to be aligned with the jet axis, for at least one source (Gallo et al. 2004). Careful monitoring of variations with time of the linear polarisation vector could, potentially, reveal the precession of steady jets whose angular extent will never allow them to be directly resolved (the effect can be quite large: in SS 433 the jets precess with a half-angle of $\sim 20°$).

2.3. Black holes in 'quiescence' – probing advection

The power-law correlation found for low/hard state black hole binaries (Corbel et al. 2003; Gallo et al. 2003), combined with X-ray measurements, allows us to predict the radio luminosities of 'quiescent' black hole systems (Gallo et al. 2003). These systems are believed to be strongest examples of 'advection dominated accretion flows' (ADAFs) and typically have soft X-ray luminosities around $L_{\rm X} \sim 10^{-8}$ Eddington. The predicted quiescent radio flux densities are in the range 1–30 μJy (Gallo et al. 2003).

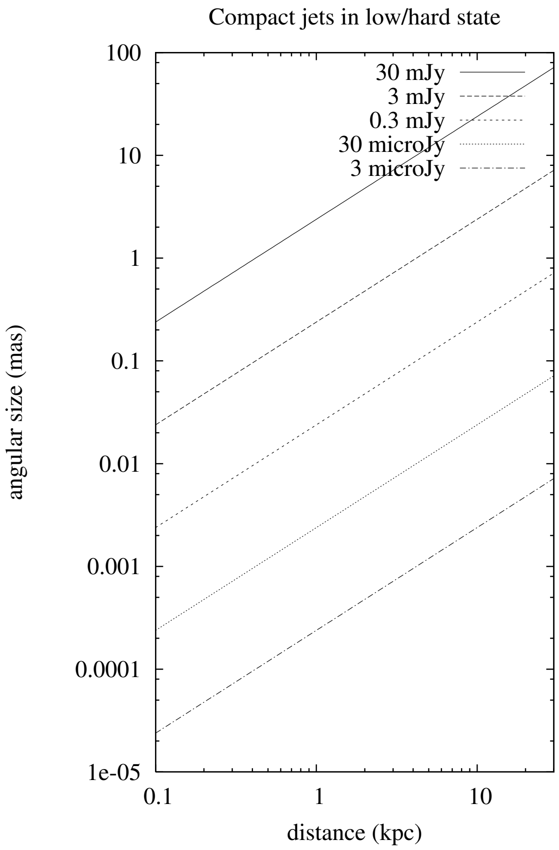

Figure 7. Estimates (GHz) size of compact 'core' jets from black holes for GHz radio flux densities of 30, 3 and 0.3 mJy. A typical hard state has a flux density of $\geq$ few mJy at a distance of 2–20 kpc and so is potentially resolveable with high sensitivity VLBI.

Fender, Gallo & Jonker (2003) demonstrated that the same power-law relation, if maintained to such low luminosities, would be very strong evidence for the existence of 'jet dominated states' in which the dominant power output channel for the liberated accretion energy is a radiatively-inefficient jet, and not X-ray emission. Measurements of the broadband spectra of these 'quiescent' black holes in the way done for Cygnus X-1 at higher luminosity (Fig 4) is strongly limited by our radio sensitivity (and also γ-ray, but this component is rather unexplained anyhow!). We have recently obtained a four-frequency radio spectrum of a black hole X-ray binary, V404 Cyg, with a mean X-ray luminosity of $\sim 10^{-6}$ Eddington (Gallo, Fender & Hynes 2004). The radio spectrum is flat, supporting a jet interpretation, and the mean radio flux density is ~ 0.3 mJy.

The SKA will allow us to measure the broadband radio spectra of the truly 'quiescent' sources, which are expected to be one to two orders of magnitude fainter than V404 Cyg (Gallo, Fender & Pooley 2003). which may be combined with IR/optical/X-ray measurements to allow us to estimate the jet power at such low accretion rates. Furthermore, a galactic plane survey with SKA may well discover a population of unknown quiescent accreting objects which stand out due to their compact size and flat spectra, but would not stand out in X-ray surveys. Inspection of Fig 7 shows that its rather unlikely we will be able to directly resolve the jets from such weak sources, with anticipated micro-arcsecond angular sizes.

2.4. Intermediate mass black holes in globular clusters?

It has been argued that globular clusters are likely to contain in their centres 'intermediate mass' black holes, formed via stellar mergers. The masses of these central black holes may be as high as 10^{-3} of the cluster mass.

Maccarone (2004) has recently demonstrated that the fundamental plane of black hole activity implies that radio emission is a much more stringent test for the existence of these intermediate mass black holes in the centres of globular clusters than X-ray observations. For accretion from the ambient medium in these clusters, radio flux densities in the range 1–100 μJy are expected. The SKA will be able to achieve such sensitivities with relative ease, and strong tests for the existence of the postulated central black holes in globular clusters may be undertaken.

2.5. Extremes and unexpected phenomena

Just as we are preparing to settle into a pattern of observation designed to confirm and consolidate our ideas, along come, thankfully, some unexpected phenomena, There is no doubt that SKA will discover more such phenomena, but the examples outlined below both illustrate the surprises and present areas in which SKA will be able to make significant progress.

2.5.1. Ultrarelativistic flows from neutron stars

Fomalont et al. (2001a,b) and Fender et al. (2004; see Fig 8) have reported evidence for the existence of highly relativistic, but essentially 'unseen' outflows from neutron stars accreting at high rates. In the case of Sco X-1 (Fomalont et al. 2001a,b) the outflow is observed to move with a bulk Lorentz factor $\Gamma \geq 3$; in the case of Cir X-1 (Fender et al. 2004) the lower limit is much greater $\Gamma \geq 15$. This is probably due to the small angle of the Cir X-1 jet to the line of sight and suggests that at least all six neutron star 'Z' sources (of which Sco X-1 is the archetype) are producing such 'ultrarelativistic' flows. SS 433 may also be producing such a flow, resulting in transient energisation of the well-known knots which move at $\sim 0.26c$ (Migliari et al. 2004).

These flows are rather unexpected in the simple, widely-accepted framework in which jets reflect the escape velocity in the region in which they are formed, since this should not be more than $\sim 0.4c$ for a neutron star (e.g. Livio 1999). The nature of these flows also remains a mystery; for example they may be bright but so fast they they're always beamed out of our line of sight, or they may be 'cold' or highly radiatively inefficient and only ever observed via their interactions with other components. Their importance lies in the fact that they clearly demonstrate that whatever it is that is necessary for the formation of highly relativistic flows, it is not something which is unique to black holes. The very rapid variability of the jet in Cir X-1, with a projected velocity $\geq 15c$ and hints in the radio maps of a very transient structure (Fender et al. 2004) highlight the need for high sensitivity snapshots such as will be provided by SKA.

2.5.2. Jets from obscured X-ray binaries as γ-ray sources

Paredes et al. (2000) reported the discovery of a powerful, seemingly persistent, radio jet from the massive X-ray binary LS 5039. This system had however a strange broadband spectrum, being weak in X-rays but potentially associated with an unidentified EGRET gamma-ray source.

Furthermore, INTEGRAL observations have revealed what might be a population of X-ray binaries undergoing such intense local absorption (by gas, and maybe also dust, local to the binary system), that they have remained undetected by previous soft X-ray surveys. In such sources, whatever the source of the X-ray absorption, the jet is likely to extend beyond this region, and they will remain detectable as radio sources. A deep, multi-frequency radio survey of the galactic plane with SKA may well discover many such sources.

2.6. Beyond the Milky Way

No X-ray binary system has been unambiguously detected in the radio band beyond the Milky Way, despite the observations of hundreds of such sources in external galaxies (e.g. Fabbiano & White 2004).

The radio:X-ray plane for galactic black hole binaries presented in Fig 3 may be simply scaled to the distances of local galaxies to see how SKA may help our cause in this area. The top panel of Fig 9 shows the plane scaled to the distance of the LMC (and, effectively, the SMC). Bright transients in these two satellite galaxies are already potentially visible with e.g. ATCA, and would be easily accessible to SKA. Perhaps more importantly, so would the steady 'low/hard' state sources, and the brightest neutron stars. Since we know of at least one of each class of object in the LMC (LMC X-3 and X-2 respectively), we could test the possible dependence of the disc-jet in both black holes and neutron stars as a func-

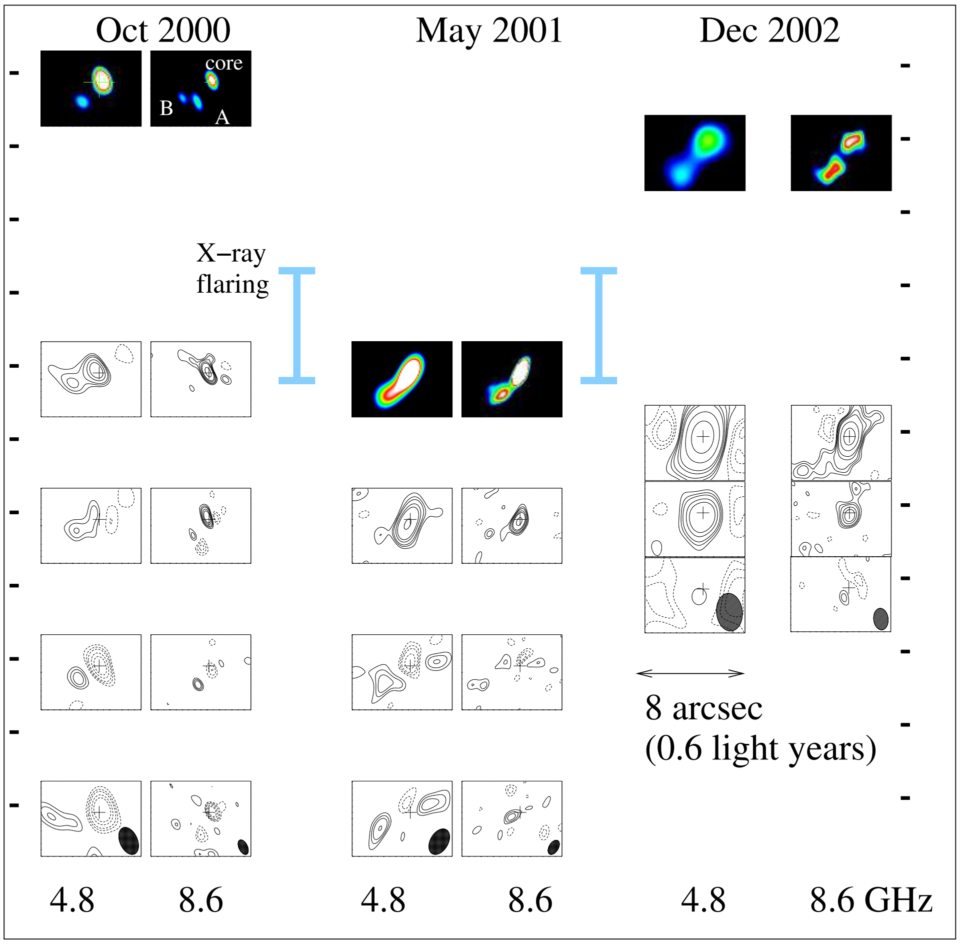

Figure 8. An ultrarelativistic outflow: sequences of radio observations of Circinus X-1 in October 2000, May 2001 and December 2002. At each epoch, observations were made simultaneously at 4.8 and 8.6 GHz. White tickmarks indicate time steps of one day; the blue bar indicates the time of the X-ray flaring as observed by the *Rossi* X-ray Timing Explorer All-Sky Monitor. In October 2000 and May 2001 the observations were spaced every two days; in December 2002 they are daily. At each epoch the u-v coverage of the radio observations is identical for each image; maps in October 2000 and May 2001 are 'uniformly weighted', those in December 2002 are 'naturally weighted'. The crosses indicate the location of the binary 'core' from Fender (1999), and their size is proportional to the 'core' radio flux density. The observations reveal that following the X-ray flaring the extended radio structure brightens on timescales of days. The apparent velocities associated with this expansion are $\geq 15c$, indicating an underlying ultrarelativistic flow.

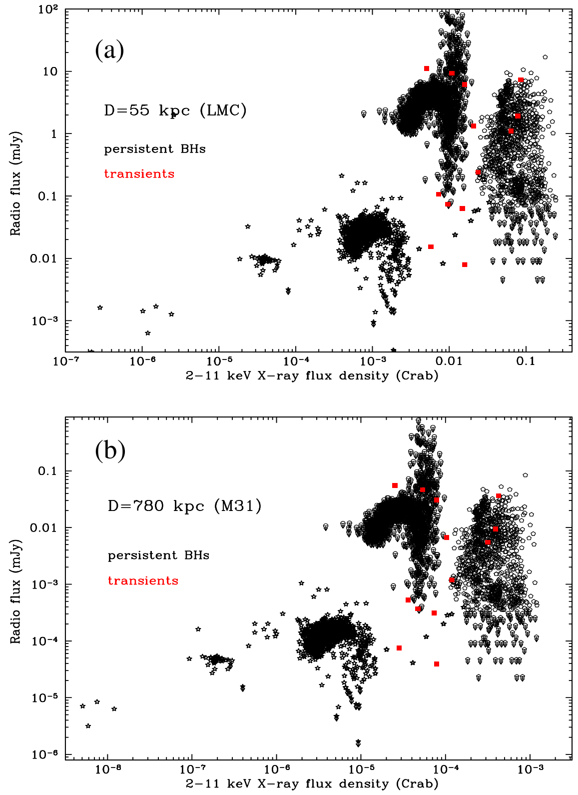

Figure 9. Top panel (a): As Fig 3, but scaled for a distance of 55 kpc, corresponding to the LMC, and also approximately appropriate for the SMC and Sagittarius, Sculptor, Sextans, Draco and Ursa Minor dwarf spheroidals. Clearly transient radio sources in these nearby galxies will be easily detectable with SKA, as will the brightest of the 'steady' (hard X-ray state) sources. Lower panel (b): as (a) but scaled to M31 / M33. Even at this distance, corresponding effectively to the radius of the Local Group of (~ 40) galaxies, bright radio transients should be readily detectable with SKA. The field of M31 / M33 in particular, as it will no doubt be regularly monitored in X-rays, will provide fertile ground for comparing the disc-jet coupling with that in our own galaxy.

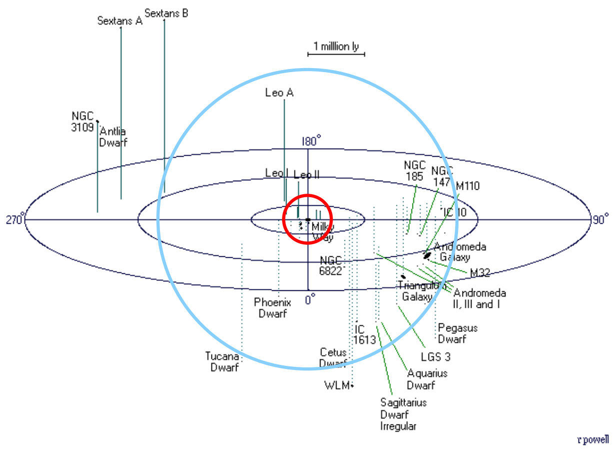

Figure 10. The local group of galaxies. The SKA will detect persistent (hard X-ray state) binaries in the nearest galaxies (LMC, SMC and other nearby dwarf galaxies). Transient sources will be detectable throughout the local group, covering approximately 40 galaxies and $\sim 10^{11}$ stars.

tion of metallicity.

Extending our view across the Local Group of galaxies to M31 (Fig 9, lower panel), we can see that relatively little effort still is required to detect bright transients at this distance. Even the brightest steady sources would be detectable with sufficiently long ($\sim$ 1 day) integrations. This is a very exciting prospect, allowing us to calibrate the radio and X-ray correlation without the strong distance uncertainties which plague us within the Milky Way.

Fig 10 illustrates in summary the 'reach' of SKA for the study of X-ray binary systems. The inner dark circle indicates those regions for which the detection of radio emission from both transients and steady sources would be more or less trivial. For sources at the distance of the lighter, larger, ring (encompassing nearly all the mass of the Local Group), transients would still be relatively easy to detect, and steady sources would be accessible via long integrations.

3. Requirements for the SKA

The exact specifications for the SKA are slowly being assembled. Such a large step in sensitivity will have enormous benefits for this field of research, whatever the precise design. Nevertheless, it is useful to lay out what we have anticipated for the design, and what will be important for the study of jets from X-ray binaries.

- The discussions in this document have been based upon a SKA which has, a sensitivity at GHz frequencies which is about two orders of magnitude better than the current VLA / ATCA / WSRT. This corresponds to, for example, a 10-min rms sensitivity at 5 GHz of $\sim 0.1\mu$Jy.

- The angular resolution of the SKA required for the various studies outlined in this paper should be comparable to that obtained currently at a few GHz with VLBI. This is not only necessary for the direct imaging of jets for sources within our own galaxy but also for clearly resolving individual sources from the background at larger distances.

- The frequency range of the proposed SKA is also important for the context of X-ray binary studies. A broad frequency range will allow the spectrum of the radio emission, which we have found to be dependent on the X-ray state and – possibly – to the X-ray luminosity within that state, to be well determined.

- Simultaneous multi-frequency capability will be important. The observations of time delays in the synchrotron emission from the powerful jet source GRS 1915+105 (e.g. Mirabel et al. 1998; Fender et al. 2002a) give us a direct insight into the scale of the jet unobtainable by other means.

- Good polaristion sensitivity ('purity'). Both linear and circular polarisation provide important clues about the structure and composition of the synchrotron emitting components which cannot be obtained in any other way.

Acknowledgements

The author would like to thank Elena Gallo for producing Fig 9. Robert Braun, Heino Falcke, Ben Stappers and many others have contributed indirectly to this work via many useful discussions about the detection of transient radio sources with the next generation of radio telescopes.

REFERENCES

1. Corbel S., Fender R.P., 2002, ApJ, 573, L35
2. Corbel S., Fender R.P., Tzioumis A.K., Tomsick J.A., Orosz J.A., Miller J.M., Wijnands R., Kaaret P., 2002, Science, 298, 196
3. Corbel S., Nowak M.A., Fender R.P., Tzioumis A.K., Markoff S., 2003, A&A, 400, 1007
4. Dhawan V., Mirabel I.F., Rodríguez L.F., 2000, ApJ, 543, 373
5. Fabbiano G., White N.E., 2004, 2004, in 'Compact Stellar X-ray Sources', eds. W.H.G. Lewin and M. van der Klis, in press, (**astro-ph/0307077**)
6. Falcke H., Körding E., Markoff S., 2004, A&A, 414, 895
7. Fender R.P., 1999, In 'Perspectives on Radio Astronomy: Science with Large Antenna Arrays', M.P. van Haarlem (Ed), ASTRON, Dwingeloo, The Netherlands
8. Fender R.P., 2001, MNRAS, 322, 31
9. Fender R.P., 2004, in 'Compact Stellar X-ray Sources', eds. W.H.G. Lewin and M. van der Klis, in press, (**astro-ph/0303339**)
10. Fender R.P., Gallo E., Jonker P., 2003, MNRAS, 343, L99
11. Fender R.P., Belloni T., Gallo E., 2004, MNRAS, submitted
12. 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., 1999a, MNRAS, 304, 865
13. Fender R. et al., 1999b, ApJ, 519, L165
14. Fender R.P., Rayner D., Trushkin S.A., O'Brien K., Sault R.J., Pooley G.G., Norris R.P., 2002a, MNRAS, 330, 212
15. Fender RP, Rayner D, McCormick DG,

Muxlow TMB, Pooley GG, et al. 2002b. MNRAS. 336:39–46
16. Fender R., Wu K., Johnston H., Tzioumis T., Jonker P., Spencer R., van der Klis M., 2004, Nature, 427, 222
17. Fomalont E.B., Geldzahler B.J., Bradshaw C.F., 2001a, ApJ, 553, L27
18. Fomalont E.B., Geldzahler B.J., Bradshaw C.F., 2001b, ApJ, 558, 283
19. Fuchs Y. et al., 2003, A&A, 409, L35
20. Gallo E., Fender R.P., Pooley G.G., 2003, MNRAS, 344, 60
21. Gallo E., Fender R.P., Hynes R.I., 2004, MNRAS, submitted
[] Gallo E., Corbel S., Fender R.P., Maccarone T.J., Tzioumis A.K., 2004, MNRAS, 347, L52
22. Georganopoulos M., Aharonian F.A., Kirk J.G., 2002, A&A, 388, L25
23. Ghisellini G., Padovani P., Celotti A., Maraschi L., 1993, ApJ, 407, 65
24. Grimm H.J., Gilfanov M., Sunyaev R., 2002, MNRAS, 391, 923
25. Heinz S., Sunyaev R.A., 2003, MNRAS, 343, L59
26. Hjellming R.M., Rupen M.P., 1995, Nature, 375, 464
27. Jonker P.G., Nelemans G., 2004, MNRAS, submitted
28. Kaaret P., Corbel S., Tomsick J.A., Fender R., Miller J.M., Orosz J.A., Tzioumis T., Wijnands R., 2003, ApJ, 582, 945
29. Lewin W.H.G., van der Klis M. (Eds), 2004, 'Compact Stellar X-ray Sources', Cambridge University Press, in press
30. Lewin W.H.G., van Paradijs J., van den Heuvel E.P.J., 1995, 'X-ray binaries', Cambridge University Press, Cambridge Astrophysics Series 26.
31. Liu Q.Z., van Paradijs J., van den Heuvel E.P.J., 2000, A&AS, 147, 25
32. Liu Q.Z., van Paradijs J., van den Heuvel E.P.J., 2001, A&A, 368, 1021
33. Livio M., 1999, Physics Reports, 311, 225
34. McClintock J.E., Remillard R.A., 2004, in 'Compact Stellar X-ray Sources', eds. W.H.G. Lewin and M. van der Klis, in press, (**astro-ph/0306213**)
35. Maccarone T., 2003, A&A, 409, 697
36. Maccarone T., Gallo E., Fender R.P., 2003, 345, L19
37. Macquart J.-P., Fender R.P. (Eds), 2004, Circular Polarisation from Relativistic Jet Sources', Kluwer Academic Publishers, Dordrecht, NL
38. Markoff S., Falcke H., Fender R.P., 2001, A&A, 372, L25
39. Meier D.L., 1999, ApJ, 522, 753
40. Meier D.L., 2001, ApJ, 548, L9
41. Merloni A., Heinz S., di Matteo T., 2003, MNRAS, 345, 1057 (MHdM03)
42. Migliari S., Fender R.P., Rupen M., Jonker P.G., Klein-Wolt M., Hjellming R.M., van der Klis M., 2003, MNRAS, 342, L67
43. Migliari S., Fender R.P., Blundell K., Mendez M., van der Klis M., 2004, MNRAS, submitted
44. Mirabel, I.F., Rodríguez, L.F, 1994, Nature, 371, 46
45. Mirabel I.F., Dhawan V., Chaty S., Rodríguez L.F., Martí J., Robinson C.R., Swank J., Geballe T., 1998, A&A, 330, L9
46. Paredes J.M., Marti J., Ribo M., Massi M., 2000, Science, 288, 2340
47. Stirling A.M., Spencer R.E., de la Force C.J., Garrett M.A., Fender R.P., Ogley R.N., 2001, MNRAS, 327, 1273
48. Tanabaum H., Gursky H., Kellogg E., Giacconi R., Jones C., 1972, ApJ, 177, L5
49. Tigelaar S., 2004, MSc thesis, University of Amsterdam