MAXI, LOFAR and Microquasars

– All-sky monitoring of X-ray binaries in X-rays and radio –

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Abstract

In this paper I will discuss future synergies between the Japanese MAXI X-ray all-sky monitor, to be placed on the International Space Station in 2009, and the next-generation radio astronomy array LOFAR, currenlty under construction in The Netherlands. The wide fields of view and multiple beams of LOFAR will allow, in combination with MAXI, simultaneous all-sky monitoring of the sky in both the X-ray and radio bands. Focussing on microquasars, X-ray binary jet systems, I discuss how the combination of MAXI and LOFAR will help us to further understand the accretion–outflow coupling in such systems.

Key words: MAXI – LOFAR – Microquasars

1. Introduction

Wide-field and/or all-sky monitoring in X-ray/γ-rayss, in particular (but not exclusively) with CGRO BATSE and RXTE ASM, has produced a vast array of new, valuable, and in many cases unexpected, results. MAXI will carry forward this approach in X-ray astronomy, with all-sky monitoring in the soft X-ray band for at least three years from 2009.

Beyond the X-ray/γ-ray regime, all-sky monitoring has proved much harder to achieve, primarily due to the small fields of view achievable with focussing instruments at optical, infared and radio wavelengths. However, the new generation of radio telescopes will in large part be optimized for such wide-field surveying and monitoring, and will provide for the first time something close to all-sky monitoring at radio wavelengths (unfortunately the planet always blocks some of the sky to these earthbound facilities). In particular, the LOFAR *Radio Sky Monitor* is proposed to provide $\sim$daily monitoring of over 60% of the sky at the $\sim$mJy level.

Why do we care about complementary X-ray and radio observations ? Nearly all phenomena associated with flaring and transient X-ray behaviour are in fact associated with radio emission, and each wavelength regime offers a different but complementary diagnostic of the processes behind the transient outburst. In many cases, such as accreting systems, the transient X-ray behaviour is associated with an increase in the instantaneous accretion rate onto the central compact object, and the radio emission is synchrotron emission resulting from particle acceleration and outflow in a jet. Comparing the two allows us to make quantitative estimates of the accretion power being liberated in radiation, kinetic outflows or, in the case of black holes, possibly being advected across an event horizon (e.g. Körding, Fender & Migliari 2006). In addition to this incoherent synchrotron emission, coherent emission with shorter durations and much higher brightness temperatures is associated with e.g. pulsars and may have transient counterparts in other high-energy sources which have not yet been detected (for example the nature of the coherent extragalactic radio burst reported by Lorimer et al. [2007] remains unclear).

1.1. Microquasars

The term 'microquasar' has been profitably adopted for X-ray binary systems with jets since Mirabel et al. (1992). Since all classes of X-ray binary, with the exception of high-field X-ray pulsars, appear to show jets (e.g. Fender 2006) the terms 'microquasar' and 'X-ray binary' are almost synonymous. These systems are extreme examples of the accretion:outflow scenario discussed above, and often undergo outbursts in which a $\sim 10 M_{\odot}$ black hole brightens to close to its Eddington limit ($\sim 10^{39}$ erg s^{-1} whilst producing, during certain phases of the outburst, a sporadic but very powerful jet. As the name suggests, they may be compared quantitatively with supermassive black holes in active galactic nuclei (AGN), allowing us to understand the (rather straightforward) mass scaling relations in black hole accretion (Merloni, Heinz & di Matteo 2003; Körding, Falcke & Corbel 2006;

McHardy et al. 2007). In addition, understanding such scaling may allow us to use insights learned from the binaries to understand the cosmological evolution of black hole accretion and feedback.

In the past decade a rough phenomenological understanding of the relation between X-rays and radio emission in such systems has developed, summarized most recently in Fender, Belloni & Gallo (2004). Below about $\sim 1\%$ of the Eddington luminosity, systems exist in a 'hard' X-ray state in which relatively steady radio emission indicates the presence of a long-lived, powerful outflow. Above this luminosity, systems often enter a hysteretic track involving a soft state with little core radio emission, and a powerful relativistic ejection event during the transition from hard to soft states (see e.g. Fig 1). Subsequently systems return to the 'hard' state track (in reality the picture is more complex and detailed than sketched out here, of course; see e.g. Homan & Belloni 2007 for more examples of such tracks).

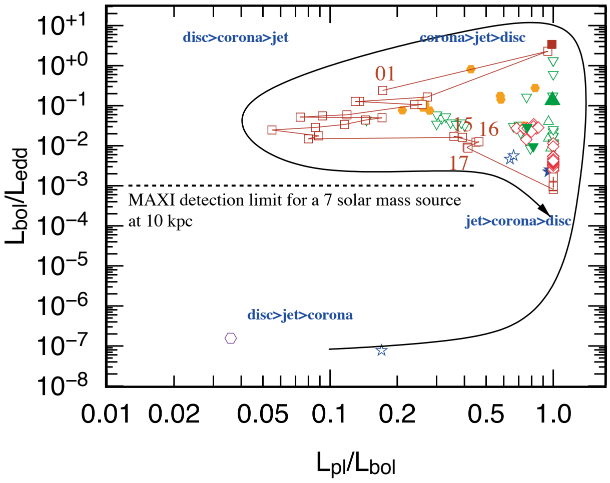

Fig. 1. A 'disc-fraction luminosity diagram' (DFLD; Körding Jester & Fender 2006) for a selection of X-ray binary systems (from Cabanac et al. 2008). A naive description of the division of accretion power between jet (kinetic), corona and accretion disc is indicated. Much of the most interesting behaviour occurs above $\sim 10^{-3}$ Eddington luminosity where the sources exhibit hysteresis and raapid switching of spectral and jet modes. MAXI will be able to detect a typical X-ray binary micoquasar source throughout the whole of this zone, with broad (0.5–30 keV) spectral coverage. Combination of this monitoring with radio observations will vastly improve our understanding of the disc-jet connection in microquasars. In addition, for more nearby sources MAXI will track the rise and decay to $\sim 10^{-4}$ Eddington, which is a very poorly sampled region of paramter space.

2. MAXI

As part of the proceedings of the MAXI workshop, the *Monitor of All-Sky X-ray Image* (e.g. Kawai et al. 1999; Matsuoka et al. 2007) requires little introduction. MAXI will attach to the *Kibo* exposed facility onboard the International Space Station (ISS) in 2009, scanning the entire sky once per ISS orbit and achieving milliCrab sensitivities on a timescale of a week. The monitoring will be made with both position sensitive gas-proportional counters for 2-30 keV X-rays and CCD cameras for 0.5-10 keV X-rays. Obvious targets include X-ray binaries, AGN and other outbursting high-energy objects such as soft gamma-ray repeaters, supernovae etc.

Much of the most interesting behaviour of X-ray binaries, and in particular the disc-jet coupling, occurs in the zone of hysteresis about $\sim 10^{-3}$ Eddington. MAXI will be able to track essentially all galactic transients throughout this zone and onto the hard state branch, providing a fantastic resource for our understanding of black hole accretion (see Fig 1). Combination of the MAXI results with those from radio monitoring programs, whether LOFAR or some other facility, should provide new insights into, and refinements of, our models for the accretion-outflow connection in relativistic objects.

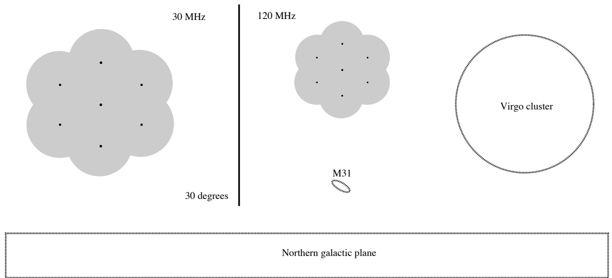

Fig. 2. The vast fields of view achievable with LOFAR due to its low frequency and multi-beam capability, compared to other astronomical facilities and astrophysical objects of interest in the local universe.

3. LOFAR

LOFAR is a next-generation radio telescope under construction in The Netherlands with long-baseline stations under development in other European countries (currently Germany, The UK, France, Sweden). The array will operate in the 30–80 and 120–240 MHz bands (80–120 MHz being dominated by FM radio transmissions in northern Europe). The telescope is the flagship project

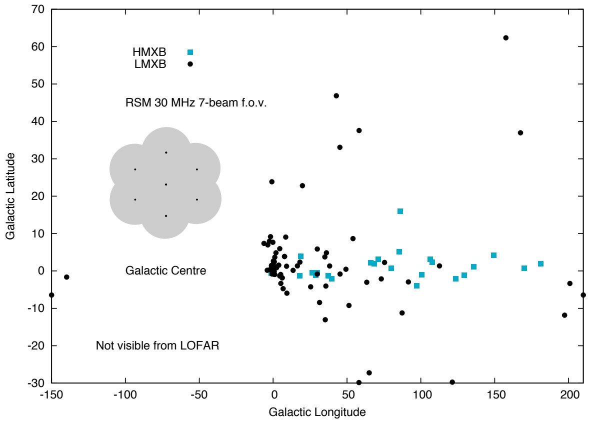

Fig. 3. A comparison of the galactic plane visible from LOFAR, the locations of known high-mass and low-mass X-ray binaries in the visible region, and the seven-beam 30 MHZ field of view. LOFAR pointings in the galactic plane will simultaneously measure many systems.

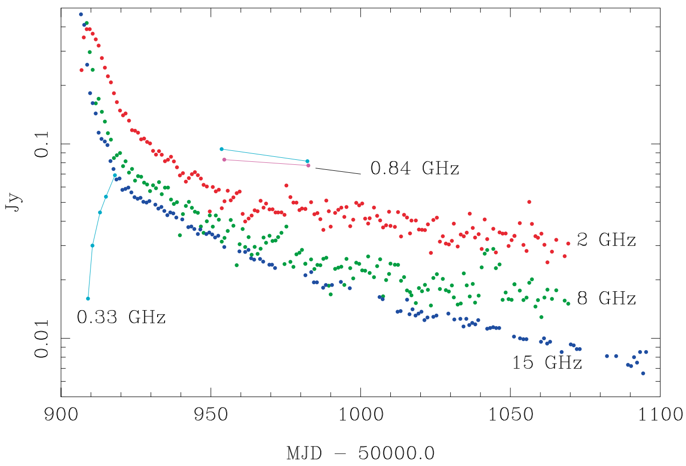

Fig. 4. Radio observations of the ouburst of the X-ray transient CI Cam, between 0.33 and 15 GHz. The lower frequencies, approaching the LOFAR frequency range, peak much later than the higher frequencies due to initial synchrotron self-absorption within the ejecta. This will result in a delay between the major outburst/ejection events and their detectability with LOFAR.

for ASTRON, and is the largest of the pathfinders for the lowest-frequency component of the Square Kilometere Array (SKA). Core Station One (CS1; see Gunst et al. 2006) is currently operating, and the next stage of deployment is about to begin, with 36 stations to be in the field by the end of 2009.

LOFAR has an enormous field of view compared to previous radio astronomy facilities (see Fig 2), allowing for the first time wide-field repetitive monitoring of the radio sky, in the *Radio Sky Monitor* mode (Fender et al. 2008).

For more information on the project, see:

http://www.lofar.org

4. Microquasars with MAXI and LOFAR

The sensitiviy of MAXI will be about one order of magnitude better than that of the RXTE ASM, and over a broader energy range, representing a significant improvement. Many X-ray transients will be detected and monitored by MAXI and, crucially, for nearby ($d \leq$ few kpc) sources MAXI will detect them while still below the $\sim 1\%$ luminosity limit above which the complex hysteretical behaviour occurs, thereby providing both early warning of outbursts and tracking of the decay phase of systems.

The population of X-ray binaries accessible to LOFAR is limited by its physical location in northern Europe, precluding observations of the galactic centre region which contains many bright X-ray binaries. Nevertheless, more than half of the galactic plane is visible from LOFAR, containing many known X-ray binary systems (see Fig 3).

While the low observing frequencies of LOFAR facilitate the extremely wide fields of view, they are not however optimum for observing X-ray binaries or other sources of synchrotron-emitting ejecta. The reason for this is that such ejecta are usually initially self-absorbed at such low frequencies, and may take some significant time to peak in the LOFAR band. In Fig 4 we present the light curve of an outburst from the binary system CI Cam (note: while the system itself is unusual, the outburst is fairly typical for a synchrotron 'bubble' event). The flux density at 330 MHz, just above the LOFAR high band, did not peak (corresponding to a transition from opticall thick to optically thin) until several tens of days after the initial outburst. Nevertheless, even the first observation at this frequency was above the detection limit of the LOFAR RSM.

If we use MAXI to trigger LOFAR on the rise of a new, nearby, transient, we should be able to track the flat-spectrum radio emission from the system over two to three orders of magnitude at the highest LOFAR frequencies (240 MHz; observations indicate the flat-spectrum emission from Cyg X-1 extends between 0.33–220 GHz so this is not too much of an extrapolation...). This will allow us to probe the luminosity range around which several anomalously radio-faint systems have been found (Gallo 2007) and so to further test and refine the 'universal' correlation in this state (Gallo, Fender & Pooley 2003). Note that post-outburst, this correlation may well be impossible to test as the emission in the LOFAR band may be dominated by emission from ejecta launched earlier during state transitions (see Fender, Belloni & Gallo 2004). Therefore, good coordination between MAXI and LOFAR is highly desirable in order to optimize their combined science in this area.

How many sources might we expect ? Grimm, Gil-

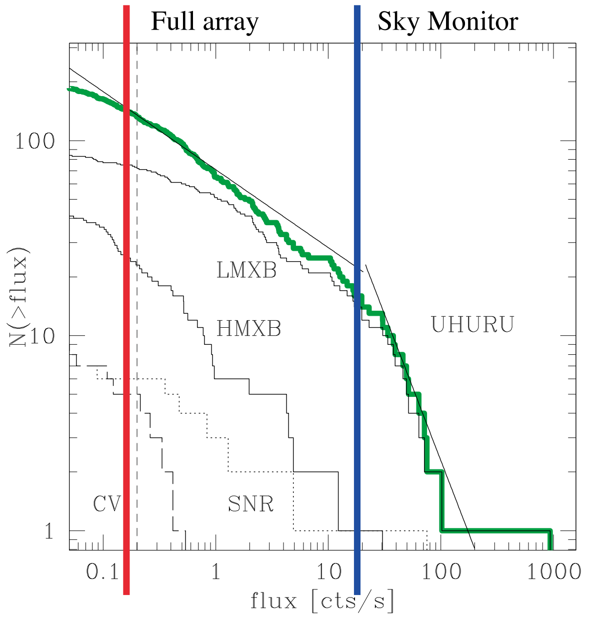

Fig. 5. The cumulative distribution function of X-ray sources detected by the RXTE ASM (Grimm, Gilfanov & Sunyaev 2002), dominated by LMXBs which are also likely to be jet (and therefore radio) sources in outburst. MAXI will be about ten times more sensitive than RXTE ASM, as a result of which more than 100 X-ray binaries should be detectable per orbit of the ISS. The vertical dashed line, originally placed to indicate the approximate completeness sample of the RXTE ASM data, also corresponds approximately to the one-second sensivity limit for MAXI. The red and blue vertical lines indicate an estimate of how far into the population LOFAR can observe, based upon empirical scalings between radio and X-ray luminosities in X-ray binaries. The RSM mode should be able to detect the brightest ~ 20 sources in each scan – this will include semi-persistent systems such as Cyg X-3, SS 433, as well the brightest binaries in outburst at that epoch. Deeper observations with the full array will allow detailed study of the entire binary population visible to MAXI, allowing tracking of radio behaviour over at least three orders of magnitude in luminosity for many sources.

fanov & Sunyaev (2002) derived the luminosity function for galactic X-ray binaries based upon RXTE ASM data. This is replotted in Fig 5 with approximate sensitivity limits for different LOFAR modes. Based on this it would be possible to monitor daily several hundred sources with a combination of MAXI and both *Radio Sky Monitor* mode and targetted observations of LOFAR. Even monitoring a few 10s of sources (*Radio Sky Monitor* mode alone) would be a very significant resource indeed.

Following the major jet ejection, associated with the hard to soft state transition (Fender, Belloni & Gallo 2004), has occurred, LOFAR is likely to be insensitive to the core once the ejecta have become optically thin and completely dominate at low frequencies. This will curtail attempts to track the core behaviour (for example, how much is the core emission really suppressed in the soft state, and when does it reactive in the soft to hard transition), which will be better done with higher-frequency facilities (e.g. EVLA, e-MERLIN, ATA over the MAXI lifetime). However, the emission at these frequencies is also very long-lived, and may be the best way to look at the large-scale jets which can develop over timescales of years and angular scales of arcminutes (e.g. Corbel et al. 2002). With international baselines of $\geq$ 1000km, at 240 MHz LOFAR will have an angular resolution of better than one arsec, plus very good sensitivity to low surface brightness emission, and so will be an excellent instrument to observe these jets as they decelerate and energise the ISM.

5. Summary

As a general tool for high-energy astrophysics, combined MAXI and LOFAR monitoring of the (northern) sky in the X-ray and radio bands will be etxremely valuable. Significant insights will be gained into the physics behind numerous phenomena not touched on here, such as soft gamma-ray repeaters, supernova, blazars etc.

In the field of microquasars, the combination of MAXI and LOFAR will probably be most apparent in two key areas:

1. **The radio:X-ray correlation in the hard state:** MAXI will detect a black hole X-ray transient at a distance of $\sim$ 10 kpc to an Eddington ratio X-ray luminosity of about 10^{-3}. During the rising phase of the outburst, assuming that the flat spectrum radio emission associated with the hard state extends to the LOFAR band ($\leq$ 240 MHz) then we will gain a valuable new sample of data for the radio:X-ray correlation in hard states. Once the radio spectrum becomes dominated by ejecta (as occurs following the brightest canonical hard state), LOFAR observations are likely to be less useful for this correlation as synchrotron-emitting ejecta will evolve slowly at

these frequencies, masking the level of core radio emission.

2. **Spatially resolving extended jets:** Once the major ejection during the hard → soft transition occurs, ejecta from black hole binaries typically separate from the core with proper motions of 10–30 mas d^{-1}. With international baselines, at the highest frequency (240 MHz), LOFAR has an angular resolution of ≤ 1 arsec, and so such eject should be resolvable after a couple of months. From this point onwards, with its sensitivity to optically thin radio emission and low surface brightness features, LOFAR may be the premium facility for emission the large-scale evolution of such ejecta as it interacts with the ISM (note that expanding radio emission on much large scales is still visible ten years after the 1998 outburst of XTE J1550-564: S. Corbel, private communication).

LOFAR is however much better suited to finding prompt *coherent* radio emission, such as that associated with pulsars, flare stars etc. and speculated to be associated with gamma-ray bursts, relativistic object mergers etc. Very naively, were such bursts to be associated with X-ray binary outbursts, we might expect them to occur around the most violently variable phase, i.e. the hard → soft state transition. Therefore we add another, much more speculative, point:

3. **Coherent bursts during state transitions:** there is a small chance that the violent processes associated with the state transitions, ejections, and reformation of the accretion flow, may be associated with coherent radio bursts.

These goals and speculations are summarized in Fig 6.

To end, within the LOFAR project, and the Transients Key Science Project (Fender et al. 2008) in particular, we look forward to a collaboration with MAXI which will be very profitable for the whole high-energy astrophysics community.

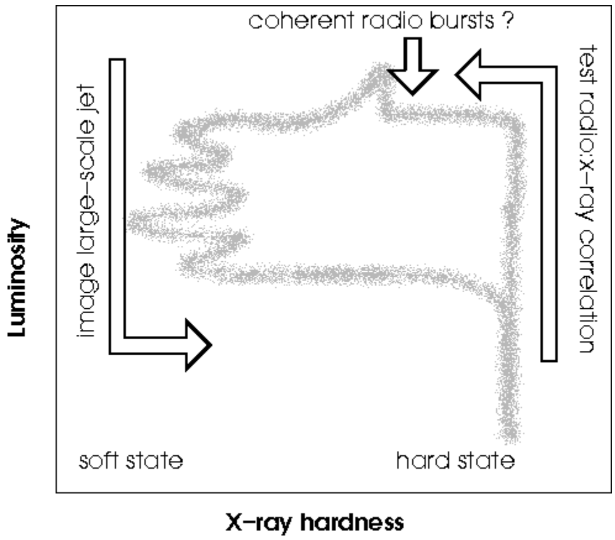

Fig. 6. Schematic illustrating two areas where MAXI and LOFAR will impact upon studies of microquasar systems. MAXI should detect many black hole transients in the rising phase of the outburst, above about $\sim 0.1\%$ Eddington. During this phase, until the transition to the soft state begins (left to right transition in the figure, typically between 1–30% Eddington; see also Fig 1), combined MAXI and LOFAR observations will be able to test the hard state radio:X-ray correlation. Once radio flaring occurs, during the hard to soft transition, the low-frequency LOFAR radio bands will be dominated for a long period of time by slowly evolving synchrotron emission and will not be useful for studying the correlation. However, after a couple of months any large-scale ejecta will be resolvable using the international LOFAR baselines, allowing us to trace the evolution of deceleration and in-situ particle acceleration as the jets interact with the ISM. Much more speculatively, during the explosive jet production phase there may be steep-spectrum coherent radio bursts which LOFAR would be well placed to observe.

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