Microquasar Perspectives with the Square Kilometre Array

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Abstract

The first half of the twenty-one century Astrophysics will be marked by different ground-based observatories that provide a major leap in photon collecting area across the whole electromagnetic spectrum, coupled with state-of-the-art instrumentation. Among them, the low-energy end of the spectrum in the domain of radio wavelengths will be covered by the Square Kilometer Array (SKA). Here we address the potential offered by this new observational tool when applied to the study of microquasars. The superb SKA capabilities will enable us to explore in depth many issues, such as revealing the Galactic and extragalactic census of these enigmatic systems, opening the window of high-time resolution radio photometry, how do they behave in quiescent states, polarization of the jets, and their weak signatures of interaction with the ambient medium.

1 Introduction

The concept of microquasars refers to a special kind of X-ray binary stars (XB) in our Galaxy, one with the ability to generate collimated beams, or jets, of relativistic plasma. The ejection takes place in a bipolar way perpendicular to the accretion disk associated with the compact star, a black hole or a neutron star. The word 'microquasar' was chosen due to the extraordinary analogy between these astronomical objects and quasars and other active galactic nuclei (AGN) at cosmological distances [16].

The relativistic jets of plasma are probably the most reliable fingerprints of microquasar sources and are responsible for the non-thermal emission, of synchrotron origin, that is often detected from them. The upcoming construction of the SKA will provide an unprecedented tool to study many aspects of this emission at radio wavelengths. This papers addresses different paths of progress that we naturally expect in the microquasar field thanks to SKA.

The predicted SKA-mid continuum sensitivity of 0.72 μJy $h^{-1/2}$, in the 0.35-14 GHz frequency range[1], will be used hereafter for the performance estimates discussed here. Nevertheless and as it often occurs in science, some of the most important advances will likely result from findings not being possible to anticipate now.

2 The microquasar population

Microquasars, as XB with relativistic radio jets, represent a subset (15 numbers) of the XB population in the Galaxy [19]. XB in general are binary systems containing a compact object (a neutron star (NS) or a stellar mass black hole (BH)) accreting matter from the companion star. Depending on the spectral type, the optical companions are classified into High Mass X-ray binaries (HMXB) or Low Mass X-ray Binaries (LMXB). The most recent catalogue of HMXB contains 114 sources [11], while the catalogue of LMXB amounts to 187 objects [12]. A significant part of them, about 22% of all XB, have been detected at radio wavelengths with flux densities $\geq$ 0.1–1 mJy, being 9 of them HMXB and 56 LMXB. The 9 radio emitting HMXB include 6 persistent and 3 transient sources, while among the 56 radio emitting LMXB we find 18 persistent and 38 transient sources. Some of these radio sources have been revealed to be microquasars after VLBI observations resolved the radio structure showing the presence of relativistic jets. So far, whenever radio emission has been resolved, it appears with a clear elongated shape, as would be expected from a collimated jet flow. In this sense, it is very likely that the simple detection of radio emission from an XB in a particular X-ray spectral state has to be considered as a tell-tale sign of jets[8].

It has been estimated that the total number of XB in the Galaxy brighter than 2×10^{34} erg s^{-1} is about 705, these being distributed as $\sim$ 325 LMXB and $\sim$ 380 HMXB [9]. This suggests an upper limit on the population of microquasars in the Galaxy of about one hundred and fifty systems. This number could increase if we consider that the fraction of radio emitting XB observed today (22%) is an underestimate.

The non-detection of radio emission from most XB could be due to a low level of emission undetectable for the current radio telescopes and/or variability. Confirming this suspicion will require a substantial improvement in interferometers, both in terms of their sensitivity and angular resolution. SKA is one of the projects currently underway with the potential to achieve this. SKA will contribute to increase significantly the population of microquasars, allowing a more general study of this class of sources that now is still very limited by the small number of them.

The discovery of new microquasars in nearby galaxies could become easily feasible with SKA. A typical microquasar, within 10 kpc from us with a flux density of $\sim$ 10 mJy at 6 cm wavelength, would emit at the $\sim$ 2 μJy level if placed in the Andromeda galaxy (0.8 Mpc away). This object could be detected using for instance SKA-mid with signal-to-noise ratio of $\sim$ 10 after about 12 hour of integration. Therefore, most microquasars known in our Galaxy would be detected by SKA in a reasonable observing time period if they were located

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[1] http://www.skatelescope.org/wp-content/uploads/2012/07/SKA-TEL-SKO-DD-001-1_BaselineDesign1.pdf

in Andromeda. The above estimates are based on the radio emission level of an average microquasar when in quiescence. During strong flaring events, where the radio luminosity may increase up to two or three orders of magnitude, microquasars belonging to different galaxies in the Local Group could also be within SKA reach.

3 High-time resolution radio photometry

The expected SKA sensitivity will allow the capability of routinely monitoring the radio variability of microquasars and gamma-ray binaries[2] with second, and possibly sub-second, detail too. This will open the high-time resolution window to radioastronomy in a way similar to X-ray astronomy today. In all these objects, the genesis of jets and outflows occur in a relatively small volume ($\ll 1$ AU) within the binary system. Consequently, the associated time scales can be very short. Previous radio photometric studies, such as those of the highly variably microquasars Cygnus X-1 and Cygnus X-3, have revealed a richness of radio flaring phenomena but they remain still limited by moderate time resolution of a few minutes at most [13, 18]. The predicted SKA-mid continuum sensitivity implies that an rms noise of a few mJy could be attained in just one second. For instance, this will improve our sampling capability of targets such as Cygnus X-1 and Cygnus X-3 by at least two orders of magnitude in time, and still achieve a signal-to-noise ratio well above 10.

Another variability issue that SKA will satisfactory address is related to the fast flux density and structural changes that both microquasars and gamma-ray binaries experience at radio wavelengths in time scales of hours and days. This morphological variability has created strong difficulties when mapping these systems with present day interferometers, that require an on-source time of a few hours to produce reliable images of the ejecta [21]. This is because most deconvolution algorithms implicitly assume a constant source in the sky, and this is clearly violated in this case throughout the duration of the observations. Indeed, these sources can be simultaneously variable both in brightness level and structure in contrast to other less changing targets. The SKA possibility of performing quick snapshots in a matter of minutes with sub-mJy sensitivity will overcome this problem. Our physical understanding of these systems will strongly benefit from deep radio maps free from variability artifacts.

4 Testing the X-ray vs radio correlation at very low luminosities

The black hole X-ray binaries go through transitions between different spectral states that are defined according to X-ray spectral and timing properties [14]. Continuous steady jets are observed in radio during the low-hard state whereas the ejection of blobs is produced during the transition between spectral states. In the high-soft state the radio emission is strongly suppressed, indicating the disapearance of the radio jet. There exists a correlation between the radio and X-ray fluxes in these systems in the hard and quiescent states, demonstrating

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[2] Similar Galactic systems also thought to host relativistic outflows.

a coupling between the jet and the accretion disk [4, 6]. However, the quiescent part of this correlation has been poorly explored because the limited sensitivity of the available instruments. With the good sensitivity that SKA will provide it will be possible to determine the coupling between ejection and accretion at low radio luminosities.

5 Polarization properties of radio emission from microquasars

The observational study of radio polarization is a mature tool in the domain of AGN physics as evidenced in recent reviews such as [23] and references therein. Being able to produce not only intensity maps, but also maps in all the four $IQUV$ Stokes parameters provides the strongest physical constrains. The three-dimensional components of the jet magnetic field (e.g. toroidal or helical), its degree of order, and the jet particle content and distribution of Faraday rotating material can be inferred or, at least, significantly restricted. In the domain of microquasars and gamma-ray binaries, the radio polarization studies are much less developed because we are usually dealing with very faint radio jets and compact cores sometimes with typical centimetric flux densities as low as 0.1 mJy or fainter. Therefore, progress has been achieved only in a reduced sample of bright cases. These include for instance systems such as LS I +61 303[20], GRS 1915+105[5], GRO J1655−40[15], SS 433[22] or XTE J1748−288[3]. Thanks to the exquisite SKA sensitivity, this situation will radically change and polarization studies of microquasars and gamma-ray binaries will become routine in the future on an equal basis with today's AGN situation.

6 Unveiling the weak signatures of interaction between microquasar jets and the Interstellar Medium

The microquasar jets are known to inject a substantial amount of energy into their nearby surrounding ISM whose effects have not been seriously considered until recent times [2, 1, 17]. The signatures of jet-ISM have the potential to be used as calorimeters to assess the true power of relativistic outflows in a stellar system. In a few cases, the observational effects of this interaction have been detected at a radio wavelengths in the form plumes or jet-driven bubbles [7, 21]. However, for the majority of systems the expected effects are too weak and elusive to be imaged by the previous generation of interferometers. This is mainly due to the fact that most microquasars are located in regions less dense than the canonical ISM density of ~ 1 cm^{-3} [10]. In this context, deep SKA imaging of a representative sample of microquasars is very likely to reveal a wide range of faint extended structures created as a result of the interaction between relativistic particles and the cold ISM, from which independent constrains on the time-averaged jet power could be inferred.

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