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Studying Microquasars with X-Ray Polarimetry

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Abstract: Microquasars are Galactic black hole systems in which matter is transferred from a donor star and accretes onto a black hole of, typically, 10–20 solar masses. The presence of an accretion disk and a relativistic jet made them a scaled down analogue of quasars—thence their name. Microquasars feature prominently in the scientific goals of X-ray polarimeters, because a number of open questions, which are discussed in this paper, can potentially be answered: the geometry of the hot corona believed to be responsible for the hard X-ray emission; the role of the jet; the spin of the black hole.

Keywords: X-ray polarimetry; microquasars; Comptonization

1. Introduction

Microquasars are Galactic binary systems in which matter is transferred from a donor companion star and accretes onto a stellar-mass black hole, typically of 10–20 solar masses. (Some microquasars may harbour a neutron star instead of a black hole; in this paper we will discuss only the latter case). Accretion usually occurs via an accretion disk. A corona of hot electrons (typical temperatures of tens of keV) may form close to the black hole, and jets may also be present. The phenomenology of microquasars is quite complex, with several flux/spectral states [1] which follow a particular temporal pattern [2]. For the sake of simplicity, here we limit ourselves to considering the two main states, the soft and the hard state.

In the soft state, the accretion disk is believed to extend down to the Innermost Stable Circular Orbit (ISCO), which is discussed later. The thermal emission of the accretion disk dominates the X-ray emission up to several keV. Above that energy, a steep power law is present, likely due to Comptonization of the disk photons in the hot corona. No jet is present in this state. In the hard state, the maximum disk temperature is much lower, likely because the disk is truncated at a radius much larger than the ISCO, and in the classical 2–10 keV energy band the—now much flatter—power law from the corona dominates. A jet is present in this state.

While the general processes at work in microquasars are basically understood, several aspects still remain unclear. Among them, the geometry of the corona (which may reveal its nature and origin), the role of the jets in the X-ray emission of hard state, and the spin of the black hole can be addressed and hopefully solved by X-ray polarimetry, as discussed in the next section.

2. X-Ray Polarization in Microquasars

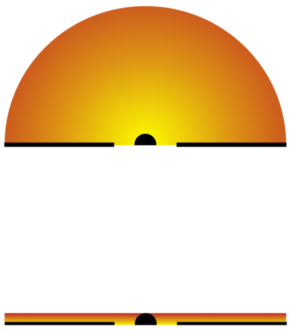
Because the most sensitive X-ray polarimeters are the photoelectric ones (see below), which work in the 2–10 keV energy range, the following discussion will focus on this band.

2.1. The Geometry of the Hot Corona

In the hard state, the 2–10 keV emission of microquasars is dominated by a power law component, which is believed to arise in a corona of hot electrons (temperatures of tens of keV, [3]), which Comptonizes the UV/soft X-ray photons emitted in the accretion disk. Spectral fitting can provide the physical parameters of the corona (temperature and optical depth), but spectral models are largely degenerate as far as the geometry is concerned. This is very unfortunate, because the geometry can tell us about the nature and origin of the corona. For instance, a small corona close to the black hole may indicate that it is the base of a jet, while a more extended, slab-like corona above the disk would point to disk instabilities as its origin. For Active Galactic Nuclei, we know from X-ray time lags (e.g., [4]) and from quasar microlensing (e.g., ([5]) that the coronae are quite compact, but such information is not available for microquasars, and in any case no information on the shape of the corona is available even for AGN.

Different geometries, however, imply different polarization degrees. Calculations of the expected polarization from a hot corona can be found e.g., in [6,7], even if the former paper specializes in Active Galactic Nuclei. Here we present results from the MonteCarlo code for Comptonization in Astrophyics (MOCA; [8]). The code calculates the spectral and polarization properties of a hot corona above an accretion disk, even if its modular structure allows it to be easily adapted to different astrophysical scenarios. The code is fully Special Relativistic and, by adopting the Klein-Nishina cross section and the Maxwell-Juttner electron distribution has limitations in neither the temperatures of the hot electrons nor in that of the seed photons. The photon-by-photon MonteCarlo approach means that it has no limitations in optical depths, either. In the present version, the code deals with either a spherical or a slab geometry of the corona, but it can be easily modified to allow for other geometrical shapes. The results presented here have been obtained without including GR effects, and without including disk and corona rotations. However, an improved version of the code with all these effects included has been recently completed and tested, and it will be described in Tamborra et al. (in preparation).

In the right panel of Figure 1, the 2–8 keV polarization degree as a function of μ, the cosine of the inclination angle, is shown for a slab and a spherical geometry (sketched in the left panel). The coronal temperature is 100 keV, while the optical depth (radial in the spherical case, vertical in the slab case) is 1. The inner and outer radii of the corona, as well as those of the disk, are set to 6 and 500 gravitational radii, respectively. More compact coronae would require the inclusion of GR and rotation effects, and they will be discussed in Tamborra et al. (in preparation). The present, simplified version of the code, however, provides a first idea of the polarization properties and dependencies. The seed radiation is then emitted by an accretion disk around a 10 solar masses black hole, accreting at one tenth of the Eddington ratio. The disk thermal radiation, assumed to be unpolarized (in the hard state, the ionization of the disk is low and absorption effects are important), is a multicolor blackbody with the radial dependence of the temperature as for a Shakura-Sunyaev disk. In both geometries, the polarization angle is parallel to the projection of the disk axis onto the plane of the sky. While in the spherical geometry the polarization degree is always lower than 2%, in the slab geometry it just exceeds 4% for favourable inclinations (note that the maximum polarization degree occurs at an inclination not very different from that estimated for the famous microquasar GRS 1915+105, [9]). The angular dependence of the polarization degree, with a maximum at intermediate inclination angles, is due to the fact that at high inclinations there is a significant contribution by single-scattered photons, which are polarized perpendicularly to the projection of the disk axis onto the plane of the sky ([8]).



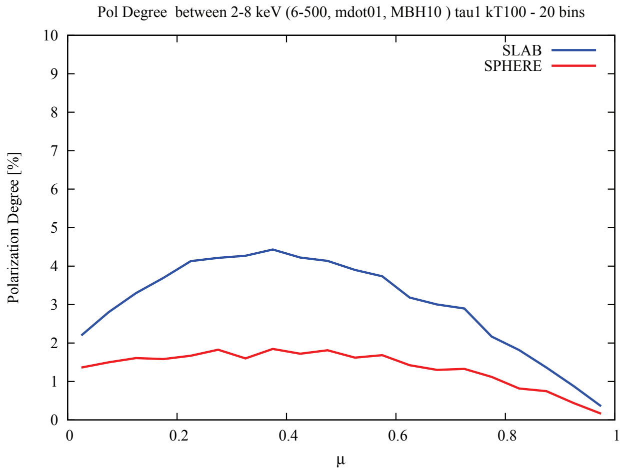


Figure 1. The 2–8 keV polarization degree (**right panel**) for a spherical and a slab geometry (**left panel**) of the Comptonizing corona. See text for details.

2.2. The Role of the Jet

The polarization degree due to coronal emission is significant but not very large. Much larger polarization degrees are instead expected if the X-ray emission originates in a jet. E.g., [10] calculate the Synchrotron Self-Compton (SSC) emission in a jet with different assumptions on the synchrotron emission site. The results are very different, but the polarization degree always exceeds 10%, reaching very high values (40%–60%) in the most favourable conditions. By comparing these results with those on the coronal emission, it is clear that if polarization degrees of 10% or more are detected, a significant, or even dominant contribution from jet emission is necessarily present.

2.3. The Spin of the Black Hole

Astrophysical black holes are characterized by only two parameters, the mass M and the angular momentum J. The latter parameter is limited in the range $0 \leq a \leq 1$, where a (the spin) is the adimensional angular momentum, $a = cJ/GM^2$, where c and G are the speed of light and the gravitational constant, respectively. The value of the ISCO depends on the spin, going from $6r_g$ (r_g, the gravitational radius, is equal to GM/c^2) for a static black hole down to 1 r_g for a maximally rotating black hole, if the accretion disk angular momentum is parallel to that of the black hole (up to $9r_g$ if it is antiparallel, see Figure 2). The relation between the ISCO and the spin is used in many techniques to measure the latter parameter, under the assumption that the ISCO coincides with the inner radius of the accretion disk.

Knowledge of the spin in Galactic black holes is important, because it provides information on the black hole birth. Three techniques so far have been employed to measure the black hole spin: relativistic reflection (e.g., [11] and references therein), thermal continuum emission ([12], and references therein), and the relativistic precession model for QPOs [13] [1] In some cases, however, the techniques provide inconsistent results. The most notable case is that of GRO J1655-40, the only source for which all three techniques have been applied. While the relativistic reflection technique indicates a spin larger than 0.9 ([15]), the continuum technique gives $a = 0.7 \pm 0.1$ ([16]) and the QPO technique an even lower value (0.290 ± 0.003, [17]). This is likely due to systematics in each technique: the relativistic reflection technique requires an accurate spectral decomposition, while the continuum technique requires the knowledge of the mass of the black hole and the distance to the system. Both methods are based on the

[1] It is worth mentioning that a modulation of the polarization signal is expected at the precession frequency itself, i.e., for LF QPOs: [14].

assumption that the inner disk radius is equal to the ISCO, which limits applicability to the soft state (but see e.g., [18]). Finally, the QPO technique (the only one which does not assume that the inner disk radius is equal to the ISCO) can be applied only if the relativistic model for the QPOs is the correct one, which is still a matter of debate.

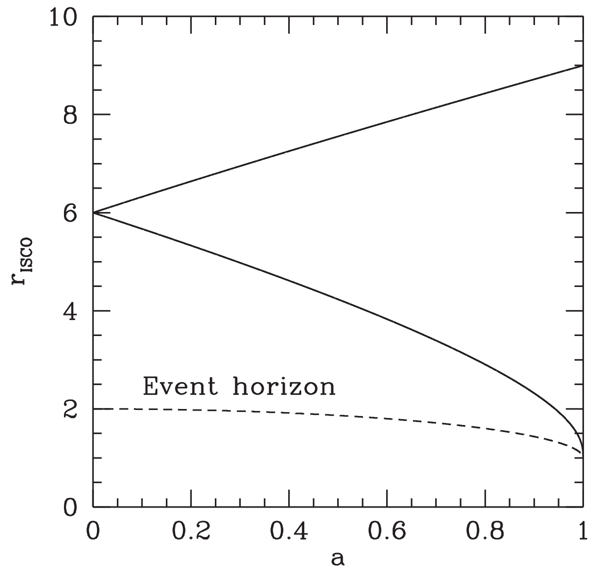


Figure 2. The radius of the Innermost Circular Orbit as a function of the adimensional angular momentum of the black hole, a (solid curves). The lower curve refer to matter corotating with the black hole, the upper curve to counter-rotating matter. The radius of the event horizon is also shown (dashed curve).

X-ray polarimetry offers a fourth, independent technique for the measurement of the black hole spin ([19–22]), which applies to the soft state, where the dominant spectral component, at least up to several keV, is thermal emission from the accretion disk. Such emission is expected to be intrinsically polarized up to about 12% for an edge-on view, if the dominant interaction between photons and matter is scattering, with the polarization vector parallel to the disk ([23]). Strong gravity effects rotate the polarization angle of the disk radiation traveling along a geodesic towards the observer. The amount of rotation depends on the location of the emitting point on the disk. After integrating the emission across the disk azimuth, a net rotation remains. The closer to the black hole the emitting point is, the larger this rotation. Since the emission is locally thermal and since the temperature decreases with the disk radius, a rotation of the polarization angle with energy is expected. Because the inner disk radius (assumed to coincide with the ISCO) is decreasing with increasing black hole spin (Figure 2), the rotation of the polarization angle is increasing with a, and can therefore be used to measure this parameter.

3. Observational Perspectives

Now forty years since the last satellite with an X-ray polarimeter on-board ceased operations, a fresh restart in this field will happen soon with the launch, in early 2021, of the Imaging X-ray Polarimetry Explorer (*IXPE*, see [24]), a NASA Small Explorer project with Italian Space Agency (ASI) contribution working in the 2–8 keV band. Its photoelectric polarimeter, coupled with a <30″ angular resolution X-ray mirror, will provide a great leap forward in sensitivity. The time and energy resolution are well matched with the sensitivity.

Microquasars will certainly feature prominently in the observing plan of *IXPE*. They are bright, when in active phase, and the scientific goals described in this paper are all well within *IXPE*'s capabilities. Uncertainties on the polarization degree below 1% are expected on bright microquasars with one hundred ks long observation with $IXPE$. When in hard state, $IXPE$ will easily assess the role of the jet and, if the coronal emission will turn out to be dominant, will put constraints on its geometry. If in soft state, when the 2–8 keV emission is dominated by disk thermal radiation, a few hundred ks long observation is expected to provide precise measurements of the spin. Given the importance and novelty of polarimetric measurement, it is reasonable to expect that $IXPE$ observations will significantly improve, if not revolutionize, our understanding of microquasars.

On a longer timeframe, other X-ray polarimetric missions are under study. In particular, $eXTP$ [25], a chinese-led mission studied for a launch in the second half of the 2020s, will provide X-ray polarimetric measurements (with an effective area about four times that of $IXPE$) in the 2–8 keV simultaneously with high sensitivity timing and spectroscopic detectors. So, while $IXPE$ will provide a quantum leap in X-ray polarimetric studies, $eXTP$ promises to put them on a routine base.

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