New Frontiers in Black Hole Astrophysics
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X-ray polarimetry – A new Window on Black Hole Systems

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Abstract. Three dedicated X-ray polarimetry mission projects are currently under phase A study at NASA and ESA. The need for this new observational window is more apparent than ever. On behalf of the consortium behind the X-ray Imaging Polarimetry Explorer (XIPE) we present here some prospects of X-ray polarimetry for our understanding of supermassive and stellar mass black hole systems. X-ray polarimetry is going to discriminate between leptonic and hadronic jet models in radio-loud active galactic nuclei. For leptonic jets it also puts important constraints on the origin of the seed photons that constitute the high energy emission via Comptonization. Another important application of X-ray polarimetry allows us to clarify the accretion history of the supermassive black hole at the Galactic Center. In a few Black Hole X-ray binary systems, X-ray polarimetry allows us to estimate in a new, independent way the angular momentum of the black hole.

Keywords. polarization, relativity, space vehicles, techniques: polarimetric, galaxies: active, X-rays: binaries

1. Introduction

Electromagnetic radiation remains our most important messenger from the Universe. From the radio band to very high photon energies light contains multiple layers of information that can be analyzed by the means of imaging, spectroscopy or timing. Since the early 1970s X-ray data is being collected from space-borne observatories and has greatly improved our knowledge about the extreme Universe. The physics of black hole and neutron star systems, of extra-galactic jets, or of violent explosions in space would still be in the dark without X-ray astronomy.

Nonetheless, X-ray observatories do not yet explore the complete set of information that is comprised in X-rays from space. In addition to the intensity flux, I, the two Stokes parameters Q and U can now be measured systematically. This became possible by the development of a new generation of X-ray polarimeters that are based on Gas Pixel Detectors (GPDs, Bellazzini *et al.* 2003). Such detectors are much more efficient than the Bragg reflection polarimeter that was mounted on the only preceding X-ray polarimeter aboard the OSO-8 satellite more than four decades ago (Weisskopf *et al.* 1976). This pioneering experiment gave us a solid measurement of the soft X-ray polarization emitted by the Crab Nebula and upper limits for less than a handful X-ray binary systems.

Currently, a total of three dedicated X-ray polarimetry missions are considered for a phase A study by NASA and ESA. Based on the GPD or related technologies we are now at the threshold to enter a new era of X-ray astronomy that includes polarization resolved in energy, time and position in the sky. This note describes some key prospects of X-ray polarimetry for black hole systems. The examples and simulations presented here are based on the study of the X-ray Imaging Polarimetry Explorer (XIPE) being a mission candidate in ESA's M4 competition.

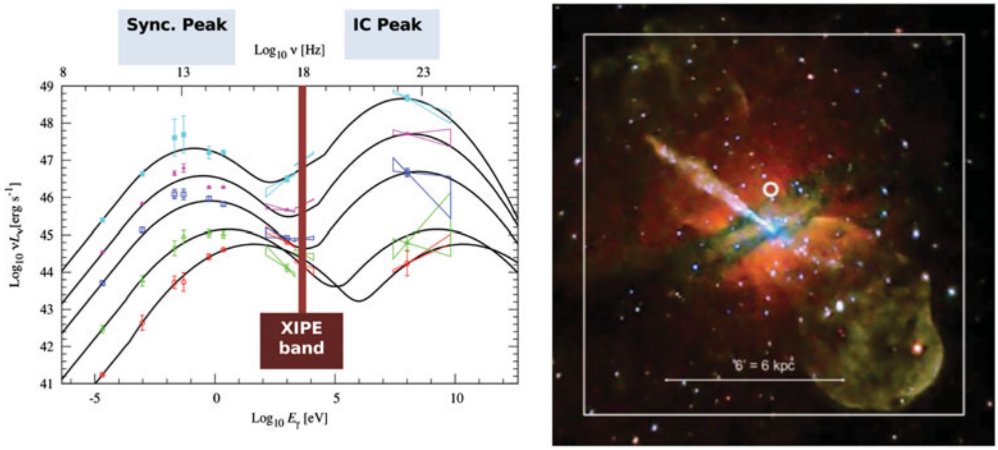

Figure 1. Left: the blazar sequence with respect to the spectral band of XIPE. From top to bottom, the broad band blazar spectra evolve from low synchrotron peak to high synchrotron peak sources. The data points are collected from various radio, optical, X-ray and gamma ray telescopes. Depending on where a given blazar is located in the sequence, XIPE is going to measure the polarization of the low energy or the high energy peak. In the former case it can constrain the level of turbulence of the magnetic field. In the latter case XIPE is going to discriminate between hadronic and leptonic jets. Right: multicolor image of the radio-loud AGN Centaurus A. The collimated jet component is colored in white and the XIPE resolution limit is denoted by the white circle. Multiple imaging with XIPE will allow us to probe the magnetic field of the jet at various distances from the nucleus.

2. Astrophysical jets launched in Active Galactic Nuclei

Radio-loud Active Galactic Nuclei (AGN) show kpc-scale jets often reaching out far beyond the host galaxy. Depending on the observer's viewing angle with respect to the jet, radio-loud AGN are divided into blazars, with a line of sight close to the jet axis, and radio-loud quasars / radio galaxies seen at larger viewing angle. The broad band spectrum of the jet emission shows two bumps. Strong polarization tells us that the low-energy bump centered on the radio-to-sub-mm range is due to synchrotron emission. The origin of the high-energy bump covering the X-ray and γ-ray bands depends on the underlying jet scenario. If the jet is leptonic, the high energy bump is interpreted as Comptonized radiation. In hadronic jets, the high energy bump is due to efficient particle acceleration and subsequent synchrotron radiation by protons or secondary pions.

There are several open questions for AGN jets and also for astrophysical jets in related objects: are jets hadronic or leptonic? What can we say about the level of turbulence in the magnetic field along the jet? What is the dominating emission mechanism in leptonic jets, synchrotron self-Compton (SSC) or inverse Compton radiation with external seed photons (e.g. coming from the accretion disk)?

X-ray polarimetry can give unbiased answers to these questions, in particular when combined with polarimetry at optical and radio wavelengths. In high synchrotron peaked blazars, XIPE can probe the synchrotron polarization and thereby the level of turbulence of the magnetic field at the location of the hottest electrons, i.e. close to the injection sites. Comparison with optical polarization then allows us to draw conclusions on the size of the emission sites at different wavelengths. The X-ray-to-optical polarization degree of low synchrotron peaked blazars can discriminate hadronic from leptonic scenarios. In the latter case, the X-ray polarization can also disentangle an SSC origin of the seed photons from external Comptonization scenarios.

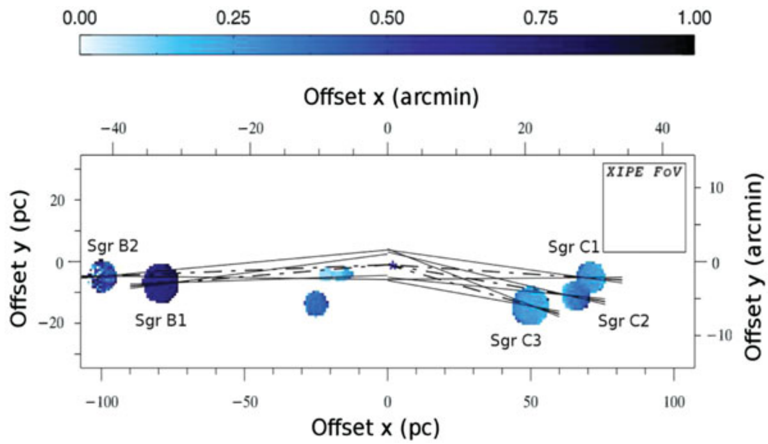

Figure 2. Simulated XIPE observation of the X-ray reflection nebulae around the supermassive black hole at the Galactic Center (Marin *et al.* 2015). The color scale represents polarization fraction. The imaging capability is going to allow us to pin down the position angle of the scattering plane for each cloud. If the primary emission comes indeed from Sgr A*, these planes must coincide at the location of the black hole (coordinates 0, 0). The field of view (FoV) of XIPE would enable us to observe the cloud complexes Sgr B, Sgr C and the Bridge region (located to the lower left of Sgr A*) by only three separate observations.

3. Past activity of the supermassive black hole at the Galactic Center

The supermassive black hole at the Galactic Center, known as Sgr A*, is surrounded by a number of X-ray reflection nebulae (XRN) sitting inside a radius of about 100 pc. X-rays of unknown origin emerge from these prominent molecular clouds. No corresponding source or emission mechanism is known inside or nearby the clouds and therefore the hypothesis was made that the XRN are irradiated by the remnant X-ray emission associated to an active phase of Sgr A* that took place hundreds of years ago (Sunyaev *et al.* 1993, Koyama *et al.* 1996).

Nonetheless, some alternative mechanisms were suggested such as a population of X-ray transients situated in the vicinity of the clouds (Sunyaev *et al.* 1993) or interaction of low energy cosmic ray electrons with the molecular gas (Valinia *et al.* 2000). Both alternative scenarios seem somewhat fine-tuned but still may contribute to some extent to the X-ray emission emerging from the XRN.

The imaging capabilities of XIPE would allow us to measure the polarization position angle of individual cloud complexes in the vicinity of Sgr A*, i.e. Sgr B, Sgr C and the so-called Bridge region. The scattering scenario with a past active state of Sgr A* then implies that the observed flux from a molecular cloud is polarized perpendicularly to the direction towards the supermassive black hole (Churazov *et al.* 2002). XIPE has sufficient sensitivity to test this scenario and to eventually identify Sgr A* as the unambiguous primary X-ray source (Marin *et al.* 2015).

4. Measuring black hole spin in X-ray binaries

A census of the supposedly primordial angular momentum (spin) of stellar mass black holes in X-ray binary systems has strong implications for our understanding of black hole formation. For X-ray binary systems, such measurements have been carried out in the past and meanwhile three different methods to measure black hole spin are well established. The classical spectroscopic method using skewed iron fluorescence lines (Fabian

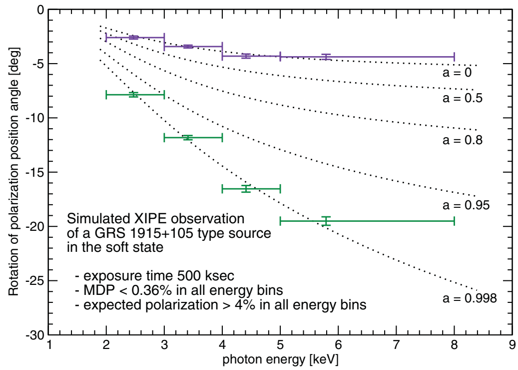

Figure 3. Simulated XIPE observations based on a relativistic ray tracing model (dashed lines). The two sets of simulated data points trace the rotation of the X-ray polarization angle with photon energy for the case of a Schwarzschlid ($a = 0$, upper set) and a maximally rotating Kerr black hole ($a = 0.998$, lower set).

et al. 1989), spectral fits to the continuum emission of the accretion disk (Li *et al.* 2005), and estimates based on quasi-periodic oscillations (Abramowicz & Kluźniak 2001). Unfortunately, the three methods tend do disagree in many cases. With X-ray polarimetry it is possible to put independent constraints on the black hole spin that are based on a rotation of the polarization position angle with energy.

In this independent approach we exploit the effect that the polarization direction rotates while it is parallel-transported along a null geodesics connecting the vicinity of a black hole with the distant observer (Connors *et al.* 1980). The rotation angle depends on the starting location of the geodesics and since the temperature of the accretion disk also varies with the distance from the black hole, the net polarization angle integrated across the inner accretion disk rotates with energy.

The radius of the so-called innermost stable circular orbit, which is assumed to coincide with the inner edge of the accretion disk in a thermal state, depends on the angular momentum of the black hole. For higher black hole spin, the accretion disk extends down to smaller distances from the black hole and therefore produces higher temperatures. As a consequence, the rotation of the polarization position angle with photon energy depends on black hole spin (see Fig. 3). Therefore, X-ray polarimetry gives us a handle on constraining the angular momentum (Dovčiak *et al.* 2008, Schnittman & Krolik 2009).

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