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ACTIVE GALACTIC NUCLEI IN THE ERA OF THE IMAGING X-RAY POLARIMETRY EXPLORER

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Abstract. In about four years, the National Aeronautics and Space Administration (NASA) will launch a small explorer mission named the Imaging X-ray Polarimetry Explorer (IXPE). IXPE is a satellite dedicated to the observation of X-ray polarization from bright astronomical sources in the 2 – 8 keV energy range. Using Gas Pixel Detectors (GPD), the mission will allow for the first time to acquire X-ray polarimetric imaging and spectroscopy of about a hundred sources during its first two years of operation. Among them are the most powerful sources of light in the Universe: active galactic nuclei (AGN). In these proceedings, we summarize the scientific exploration we plan in the field of AGN using IXPE, describing the main discoveries that this new generation of X-ray polarimeters is expected to make. Among these discoveries, we should see the indisputable detection of signatures of strong gravity, which will help us quantify the effects of scattering by distant cold material on the iron Kα line observed at 6.4 keV. IXPE will also be able to probe the morphology of parsec-scale AGN regions, to evaluate the magnetic field strength in quasar jets and their direction, and, among the most important results, to deliver an independent measurement of the spin of black holes.

Keywords: black hole physics, galaxies: active, magnetic fields, polarization, relativistic processes, scattering

1 Introduction

The study of cosmic polarization led to numerous discoveries in almost all astronomical fields. The first measurement of starlight polarization goes back to Hiltner (1949), who found that the light of distant stars is polarized as high as 12% due to interstellar clouds. More importantly, the position angle of the polarization was found to be close to the galactic plane, opening the way for a deeper comprehension of the nature of the interstellar medium (Davis & Greenstein 1951). The polarization of the Sun itself was measured by many astrophysicists, one of the most spectacular and earliest discoveries being the observation of the Zeeman effect in sunspots by Hale (1908), followed by the first evaluation of the solar magnetic field strength (Salet 1910). Broadband polarization was recorded for all possible astronomical objects, since it is present in radiation from coherent sources such as astrophysical masers to incoherent sources such as the large radio lobes of active galaxies. However, not all energy windows are available nowadays for a systematic exploration of astronomical polarization.

The X-ray band is a step behind in comparison to all other wavebands in this regard. The first X-ray polarization measurements go back to Tindo et al. (1970) in the case of solar flares. Extra-solar X-ray polarization observations were achieved by Novick et al. (1972), targeting the Crab nebula and several other bright X-ray sources. A unique precision measurement of the X-ray polarization of the Crab Nebula (without pulsar contamination) was achieved by Weisskopf et al. (1978) thanks to the Eighth Orbiting Solar Observator (OSO-8) graphite crystal polarimeters. Since then, only a couple of attempts were made in the hard X-ray band (Suarez-Garcia et al. 2006; Dean et al. 2008; Chauvin et al. 2017).

In these proceedings, we present the Imaging X-ray Polarimetry Explorer (IXPE), a NASA-led spatial mission that will fly in 2021 and carry, for the first time, a set of imaging X-ray polarimeters. Dedicated to the study of high energy sources, IXPE will re-open the window of X-ray polarimetric observations. Focusing on the field of active galactic nuclei (AGN), we summarize here what IXPE will be able to achieve in the first years of operation.

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2 The IXPE mission

IXPE is part of the NASA's Explorer Mission project and is led by the Principal Investigator, Dr. Martin C. Weisskopf. Within a cost cap of $ 188 M, IXPE will be comprised of three identical, grazing-incidence, X-ray mirror module assemblies that will collimate radiation to three accompanying polarization sensitive Gas Pixel Detectors (GPD). The NASA/MSFC is producing the X-ray mirror modules while the Italian Space Agency is providing the GPD, making IXPE an international mission. Ball Aerospace is taking care of the spacecraft and the services of mission integration that are also included in the cost of IXPE. The satellite will be launched from Kwajelein Atoll into a 540 km circular orbit at almost 0° inclination. The envisioned launcher is a Pegasus XL vehicle that can carry a mass of 450 kg.

The nominal lifetime of IXPE is two years and about one hundred targets will be observed, including AGN, microquasars, pulsars (plus wind nebulae), magnetars, X-ray binaries, supernova remnants, and the Galactic center. Thanks to its GPDs (Costa et al. 2001; Bellazzini et al. 2006, 2007), IXPE will be able to measure the spatial, spectral, timing, and polarization state of X-rays in the 2 – 8 keV band. NASA officially selected IXPE on January the 3rd, 2017, among fourteen proposals. As the first dedicated X-ray polarimetry observatory, IXPE will significantly enlarge the observational phase space, probing fundamental questions concerning high densities, high temperatures, non thermal particle acceleration, strong magnetic and electric fields, and strong gravity. Additional details about the mission can be found on-line at https://wwwastro.msfc.nasa.gov/ixpe/ and in Weisskopf et al. (2016).

3 Scientific goals in the field of AGN

As stated above, IXPE will observe a large variety of X-ray sources. Among them are the bright cores of active galaxies. The presence of accreting supermassive black holes can be inferred from the near-infrared to the X-ray domains but only X-ray polarization measurements can probe the geometry, composition, temperature and physics of matter at the smallest gravitational radii. In the following, we give three examples of the importance of IXPE in solving several key questions about AGN.

3.1 Spin determination

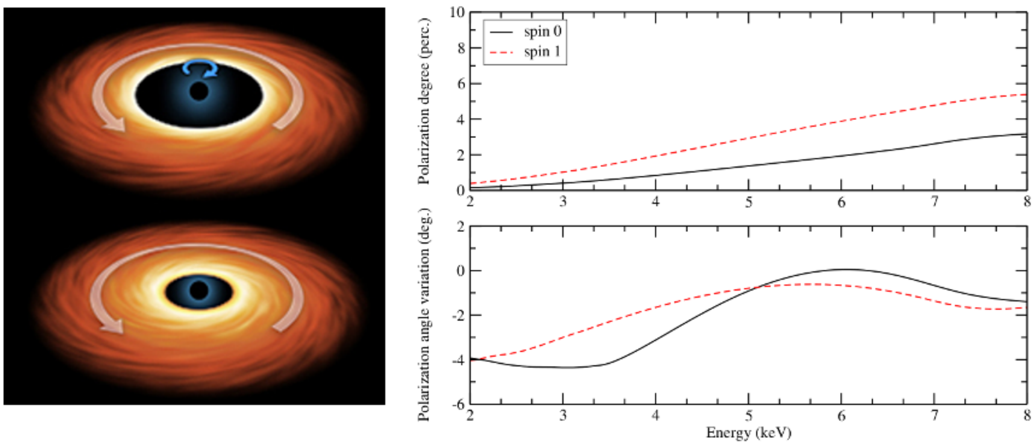

Fig. 1: Spin determination through X-ray polarization continuum measurements. The left-hand panel represents two flavors of supermassive black hole spins: a non-rotating, a=0, (or a<<1) Schwarzschild black hole at the top and a maximally rotating, a=1, Kerr black hole below. The blue arrow shows the direction of rotation, if any, for both these figures. Credits: NASA/JPL-Caltech. The right-hand panel is the polarization degree and polarization angle variation associated with the two black hole spins in the IXPE energy band. Simulations from Dovčiak et al. (2011) and Marin et al. (2017, submitted).

Measuring the spin of black holes is a long-standing problem as the spin only affects the local spacetime around the potential well. It is thus necessary to observe the central parts of the accretion disk in the X-ray band in order to determine the dimensionless angular momentum parameter, a, one of the two key parameters of black holes (with their mass). Several methods exist: one can fit the profile of the relativistically-broadened iron Kα line (e.g., Reynolds 2014) or fit the thermal X-ray continuum (e.g., McClintock et al. 2014). However the two methods do not always agree and there are many sources of possible systematic errors (e.g., intrinsic absorption, presence of a radio jet, modelling of the soft excess, role of emission from within the innermost stable circular orbit).

Measuring the X-ray polarization from AGN adds two independent quantities to the spectroscopic channel: the polarization degree and the polarization position angle. These new observational constraints remove many degrees of freedom from our current models that must fit both the spectroscopic and polarimetric data. In particular, it was shown by Schnittman & Krolik (2009) and Dovčiak et al. (2011) that the X-ray polarization from X-ray binaries and AGN is particularly sensitive to the spin, luminosity and inclination of the source. Fig. 1 illustrates the difference between a non-spinning and a maximally spinning supermassive black hole in terms of polarization degree and angle*.

3.2 *Strong gravity and distant scattering*

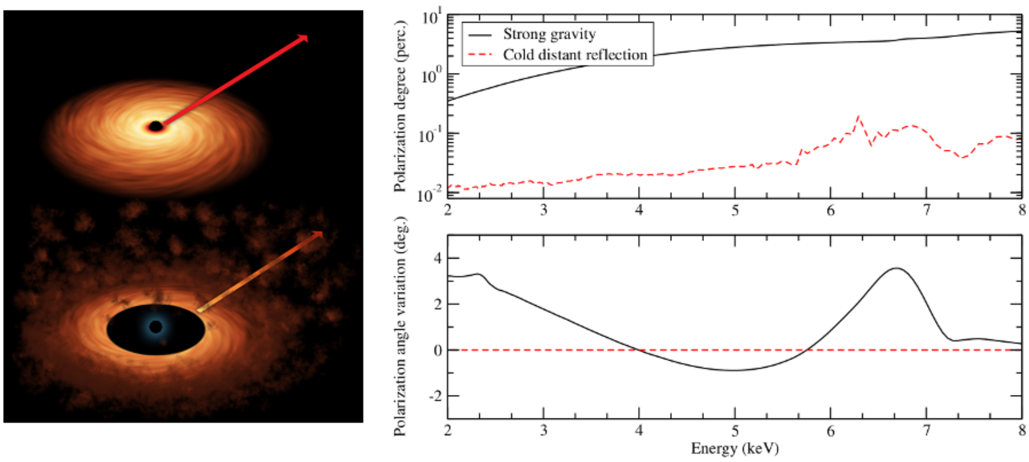

Fig. 2: Two alternative models to explain the observed asymmetrical broadening of the iron Kα line in Seyfert-1 galaxies. The left-hand panel shows that the feature can be produced by special and general relativistic effects close to the potential well (top) or by pure absorption and Compton scattering in a distant cloudy medium (bottom). Credits: NASA/JPL-Caltech. The right-hand panel is the polarization degree and polarization angle variation associated with the two models in the IXPE energy band. Simulations from Marin et al. (2012).

Another application of X-ray polarization measurements from AGN is the determination of the importance of Compton scattering by a distant cloudy medium, using the shape of the relativistically-broadened iron Kα line (Marin et al. 2012). If the broadening of the red wing of the emission line at 6.4 keV is not solely due to strong gravity effects near the black hole horizon, then the spin determined by the reflection method is probably over-estimated (Miller et al. 2008). Down-scattering of photons onto gaseous clumps along the observer's line-of-sight can significantly shift the line centroid, resulting in stronger asymmetries.

We show in Fig. 2 that the two scenarios give very different polarization signatures in the IXPE band. In particular, the polarization degree of the gravity-dominated model is more than ten times stronger than the absorption scenario and, due to the energy-dependent albedo and scattering phase function of the disk material, the relativistic model shows a non-constant polarization position angle with energy. It is quite probable that both mechanisms are happening at the same time and X-ray polarization can definitively determine the dominant process.

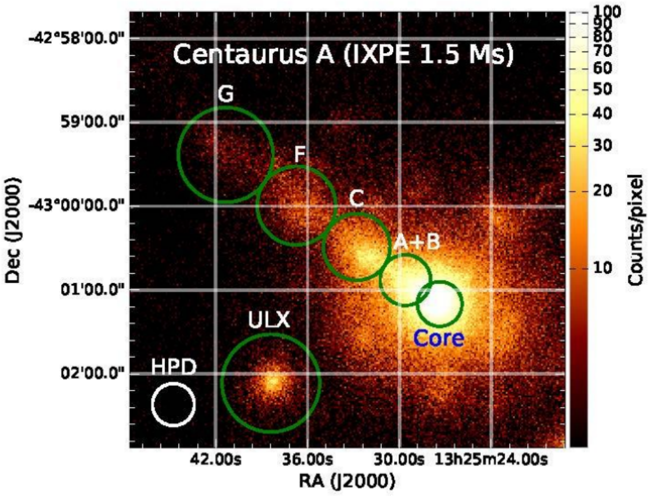

Fig. 3: IXPE-convolved Chandra image of the X-ray brightest extragalactic source Centaurus A (Cen A). The white circle indicates the half-power diameter of IXPE and the green circles (angular resolution) demonstrate the ability of the instrument to perform space-resolved X-ray polarization measurements, testing the structure of the magnetic field along the jet. An ULX, in the field of view of Cen A, can be simultaneously picked up. Credits: IXPE team.

3.3 Magnetic fields strength in jets

Radio-loud AGN, whose spectral energy distribution is dominated by jet-induced synchrotron emission in the radio-band, are also excellent targets for IXPE. For a nearby radio galaxy such as Cen A (4.6 Mpc and the X-ray brightest extragalactic source), the imaging capability of the satellite offers the possibility to perform space-resolved polarization studies, testing the structure of the magnetic field along the jet (Weisskopf et al. 2016).

Fig. 3 shows that it is possible with IXPE to map the magnetic field of resolved X-ray emitting jets close to the injection point of the electrons. Fig. 3 is a convolved Chandra image of Cen A with the IXPE response, together with a plausible model for the magnetic fields. The model consists of a transverse field in hot spots (shocks) along the jet, a longitudinal field between hot spots and, in the core, a polarization of 30% was assumed in order to estimate position-angle errors (McNamara et al. 2009). Interestingly, the imaging capabilities of the instrument allow us to simultaneously pick up ultra-luminous X-ray sources in the field, and one is shown in Fig. 3.

4 Conclusions

IXPE will revolutionize our comprehension of the energetic Universe by opening a new observational window. The measurement of X-ray polarization and/or significantly small upper limits from a large variety of sources will enable us to constrain our numerical models by reducing their degrees of freedom. It is quite probable that many of our current theories will be revised in the light of IXPE observations. In this article, we have shown three different results we expect from observations of AGN. Among others constraints, we expect to obtain precise measurements of the spin of black holes, together with a proper estimate of the impact of Compton down-scattering on the iron Kα line profile. We will also target radio-loud, jet-dominated AGN in order to probe the structure and strength of their kilo-parsec scale magnetic fields.

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*We show the rotation of the polarization position angle with respect to a convenient average of the polarization position angles over the depicted energy band. The actual normalization of the polarization angle with respect to the disk axis is not of primary interest as we cannot determine it from these observations (Marin et al. 2012).

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