PROBING THE GALACTIC CENTER WITH X-RAY POLARIMETRY

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Abstract. The Galactic center (GC) holds the closest-to-Earth supermassive black hole (SMBH), which makes it the best laboratory to study the close environment of extremely massive compact objects. Polarimetry is sensitive to geometry of the source, which makes it a particularly suitable technique to probe the medium surrounding the GC SMBH. The detection of hard X-ray spectra and prominent iron Kα fluorescence features coincident with localized gas clouds (e.g. Sgr B2, Sgr C) is known for nearly twenty years now and is commonly associated with a past outburst of the SMBH whose radiation is reprocessing onto the so-called "reflection nebulae". Since scattering leads to polarization, the re-emitted signal from the giant molecular clouds in the first 100 pc of the GC is expected to be polarized. X-ray polarization measurement is thus particularly adapted to probe the origin of the diffuse X-ray emission from the GC reflection nebulae and reveal the past activity of the central SMBH. In this research note, we summarize the results from past and current polarimetric simulations in order to show how a future X-ray polarimeter equipped with imaging detectors could improve our understanding of high-energy astrophysics.

Keywords: Galaxy: center, Galaxy: nucleus, Polarization, Radiative transfer, Scattering

1 Introduction

Using the ART-P telescope on-board of *Granat*, Sunyaev et al. (1993) were the first to image the Galactic center (GC) from the soft (2.5 keV) to the hard (22 keV) X-ray band. The discovery of a source characterized by a spherical morphology in the soft band, and by an extended (i.e. elongated along the Galactic plane) shape in the hard X-ray range, lead Sunyaev et al. (1993) to suggest that part of the hard X-ray emission could be due to Compton-scattered photons originating from a nearby compact source and reprocessed by dense molecular clouds. Later, X-ray images and spectra of the GC obtained by Koyama et al. (1996), using the Advanced Satellite for Cosmology and Astrophysics (*ASCA*), revealed fluorescent Kα emission lines from cold iron atoms in Sgr B2. Associated with a hard X-ray spectral slope, Koyama et al. (1996) estimated that the diffuse thermal emission could be due to a past intense irradiation from Sgr A*, the central supermassive black hole (SMBH) that lies in the GC. Such an argument is in agreement with the predictions of Sunyaev et al. (1993) and further detections from other extended gas cloudlets tend to corroborate this idea. In particular, Murakami et al. (2001) presented the first *ASCA* evidence of diffuse hard X-ray emission associated with strong 6.4 keV fluorescence line and large absorption from the Sgr C complex. Hard X-ray continuum and Fe Kα emission have also been found in several other GC molecular clouds: Sgr B1 (Koyama et al. 2007), M0.74-0.09 (Koyama et al. 2007), G0.11-0.11 (Ponti et al. 2010), M0.74-0.09 (Nobukawa et al. 2011), M1 and M2 (Ponti et al. 2010), the Arches cluster (Yusef-Zadeh et al. 2002) and the molecular complex called the Bridge (Bamba et al. 2002).

To uncover the nature of the hot diffuse X-ray emission and test the hypothesis of the flaring theory, Churazov et al. (2002) postulated that an X-ray mission equipped with a state-of-the-art polarimeter would be necessary. Indeed, if past radiation from Sgr A* is reprocessed by extended, distant reflection nebulae, the resulting X-ray emission should be polarized. In order to lay the groundwork for a future polarimetric explorer, several studies have been done (Churazov et al. 2002; Matt 2010; Marin et al. 2014), estimating the polarization degree and the orientation of the polarization position angle that a potential mission could detect. Hence, in this research note, we summarize the work accomplished so far to evaluate the net X-ray polarization emerging from the largest and brightest (i.e. easier to detect) GC molecular clouds.

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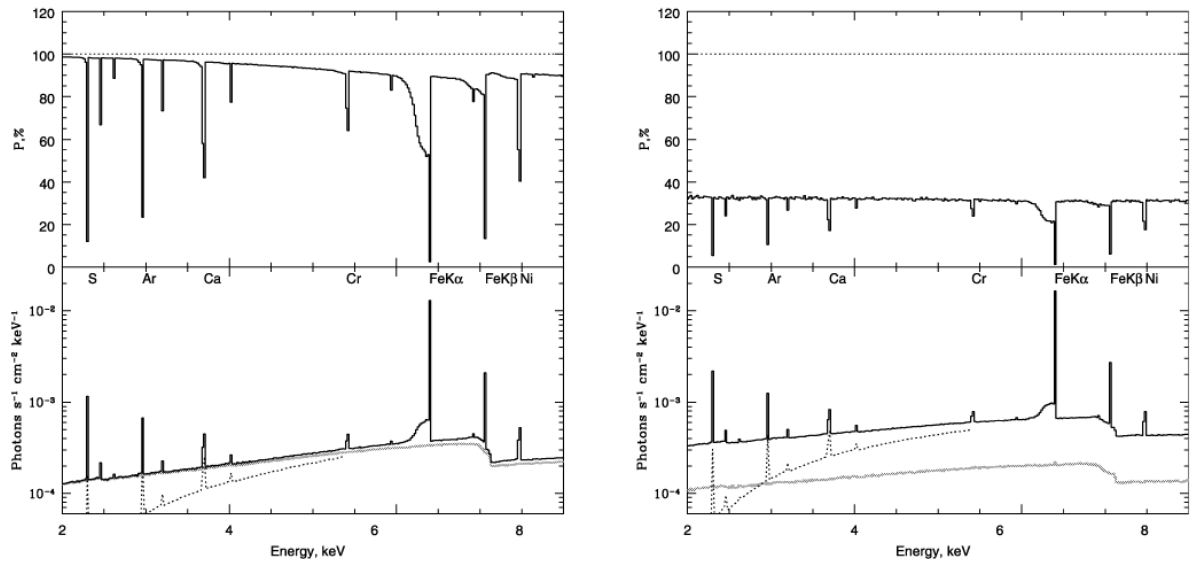[2] INAF/IAPS, Via del Fosso del Cavaliere 100, I-00133 Roma, Italy

Fig. 1. Reflected energy spectrum and polarization degree of a spherical gas cloud illuminated by a distant continuum source. *Top*: Polarization degree P, *bottom*: intensity spectra. The left column is representative of a gas clump situated at the same distance from the observer as the source, while the right column presents results for a cloud situated 100 pc away. Spectra are taken from Churazov et al. (2002).

2   Evaluating the polarization emerging from the GC

So far, there have been two main publications exploring the resulting X-ray polarization emerging from the GC. The first one, from Churazov et al. (2002), focused on the reprocessing molecular cloud Sgr B2 and estimated the net soft X-ray polarization signature of this cloud. The second paper, by Marin et al. (2014), modeled the $2° \times 2°$ ($\sim 288 \times 288$ pc; at 8.5 kpc $1'' \approx 0.04$ pc) central region of the Milky Way at energies higher than 8 keV and included polarization maps. We now review the main results from the two complementary publications.

2.1   Sgr B2 in the soft X-ray band

Churazov et al. (2002) investigated the polarization emerging from a single cloud of radius 10 pc representative of the reflection nebulae Sgr B2. In their simulation, the spherical gaseous medium was filled with neutral, solar abundance matter and had a Thomson optical depth of 0.5. It was irradiated by a steady beam of unpolarized photons with energy ranging from 2 to 8 keV. Photoelectric absorption, fluorescent emission and Compton scattering by bound electrons were included and the molecular cloud was located at 100 pc from the continuum source, which is representative of the known projected distance from Sgr A* (Murakami et al. 2001). However, since the three-dimensional parametrization of the GC is unknown, the reflecting nebula can be shifted from the Galactic plane but still conserve the same radial projections. To investigate this effect, Churazov et al. (2002) located their cloud model at two different positions: at the same distance and 100 pc away from the observer than the emitting region.

   Their work is summarized in Fig. 1 and the general result is that the reflected radiation should be highly polarized ($> 30\%$) with a direction of polarization normal to the scattering plane. The amount of P is a function of the three-dimensional position of the cloud, decreasing when Sgr B2 departs from the Galactic plane. Local dilution of the polarization degree by fluorescent photons (being unpolarized) is symptomatic of the composition of the cloud, and the slow but steady decrease of P with energy is due to multiple scatterings.

   Thus, using a simple model, Churazov et al. (2002) proved that any detection of polarized X-ray emission from the reflection nebulae around Sgr A* would give constraints on the morphology, composition and position of the scattering clouds.
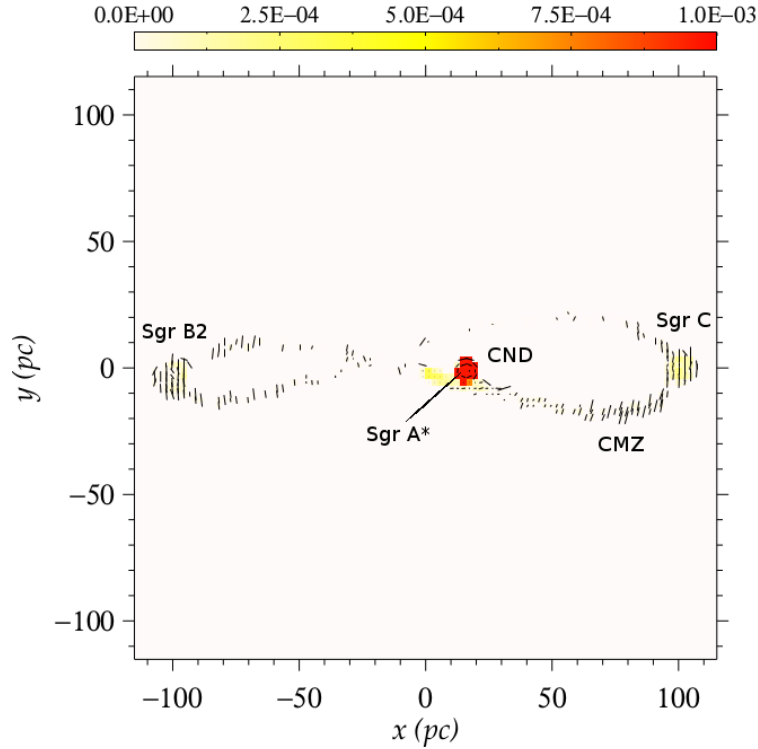
Fig. 2. Integrated 8 – 35 keV model image of the polarized flux, PF/F_*, for the $2° \times 2°$ region around the GC. PF/F_* is color-coded, with the color scale shown on top of the image (in arbitrary units). P and ψ are represented by black bars drawn in the center of each spatial bin. A vertical bar indicates a polarization angle of $\psi = 90°$ and a horizontal bar stands for an angle of $\psi = 0°$. The length of the bar is proportional to P. The polarization map is taken from Marin et al. (2014).

2.2 Broadband GC polarization imaging

The results obtained by Churazov et al. (2002) are valid in the 2 – 8 keV band for small hydrogen column densities ($n_H < 10^{22}$ cm^{-2}). At larger n_H, the emission below 5 keV is expected to be highly suppressed. In addition to that, past X-ray observations (Koyama et al. 1986, 1989) revealed the presence of a diffuse plasma emission toward the GC that may additionally dilute the polarization signal below 7 keV. Hence, to avoid most of the dilution by the GC plasma emission and extend the soft X-ray simulations achieved by Churazov et al. (2002), 8 – 35 keV modeling has been undertaken by Marin et al. (2014).

In our recent work, Marin et al. (2014) took into account the dense and warm environment around the central few parsecs around Sgr A* (known as the circumnuclear disc, CND); a cold dusty structure in the shape of a continuous chain of irregular clumps representative of the central molecular zone (CMZ, Molinari et al. 2011); the two bright, complex reflection nebulae Sgr B2 and Sgr C (located at the two extrema of the CMZ); and a continuum source displaced by ~ 22 pc in projection from the center of the model toward the Western galactic longitude (to be consistent with the shifted gas distribution within the CMZ (Molinari et al. 2011).

The polarization map presented in Fig. 2 is extracted from Marin et al. (2014). It is found that the polarized flux, PF/F_*, traces the overall shape of the GC, emphasizing the ∞-shaped CMZ. PF/F_* reaches a maximum at the location of the non-axisymmetric CND surrounding Sgr A*, but the local, integrated P is low ($\sim 1.0\%$). Sgr B2 and Sgr C show the secondary, brightest polarized flux knots of the map, associated with $P = 66.5\%$ for Sgr B2 and $P = 47.8\%$ for Sgr C. The difference in P is due to the asymmetrical spatial location of the cloud with respect to Sgr A*. Both the clouds present a polarization position angle ψ perpendicular to the vertical axis of the model (normal to the scattering plane). P is found to vary for each CMZ cloud and reaches a maximum for the Eastern and Western sections of the elliptical twisted ring but it is most likely that a large fraction of the ∞-shaped ring will be diluted by background, unpolarized emission from both plasma emission and Sgr A*. Finally, when integrating the whole $2° \times 2°$ GC polarized emission, the model produces a net polarization degree of 0.9% associated with $\psi = -22.8°$. The combined emission from Sgr A* and the CND thus

dominates the whole polarization picture.

Marin et al. (2014) extended the modeling of Churazov et al. (2002) by radiatively coupling the primary source to a large panel of reprocessing targets. They also extend their cloud parametrization to explore the influence of the location of the scattering nebulae on polarization (not shown in this research note), finding that the two reflection nebulae always produce high polarization degrees ($\gg 10\%$).

3 The need for a dedicated X-ray polarimetry mission

It has been shown by Churazov et al. (2002) and Marin et al. (2014) that the GC is expected to provide a variety of polarization signals where maximum P is expected to arise from reflection nebulae. Marin et al. (2014) also computed the minimum detectable polarization (MDP) that the *NHXM* (New Hard X-ray Mission, Tagliaferri & NHXM Consortium 2012; Tagliaferri et al. 2012) could have reached and found that such polarization levels are detectable using a 500 ks observation. Errors on ψ being marginal, the detection of ψ normal to the scattering plane would be unambiguous.

Was the GC active a few hundreds years ago? X-ray polarimetry can definitively prove or reject this hypothesis since the main molecular clouds should be highly polarized ($\gg 10\%$) with the electric vector perpendicular to the line connecting Sgr A* to the reprocessing nebula. To spatially constrain the three-dimensional location of each GC component with respect to the central SMBH, it will be necessary to observe at least two molecular clouds. An X-ray mission equipped with a polarization imaging detector, such as the Gas Pixel Detector (GPD) based on the photoelectric effect (Costa et al. 2001), is ideally suited since polarization mapping would reveal the complex morphology of the GC, spatially resolving the largest reflection nebulae, differentiating them from neighborhood sources and potentially enabling the investigation of stratified light echoes from the past activity of Sgr A*.

A dedicated space mission for imaging X-ray polarimetry such as the non-selected projects *NHXM* or *IXPE* (the Imaging X-ray Polarimeter Explorer, Weisskopf et al. 2008) would have been sufficiently sensitive to measure the polarization emerging from the 2° × 2° GC, even below 8 keV where plasma emission is acting like an unpolarized background and can be further substracted from past spectral data. Finally, X-ray polarization measurement would ultimately test the alternative scenario for the origin of X-ray emission from Sgr B2 and Sgr C in which X-ray features are produced by low-energy cosmic-ray electrons rather than by Compton scattering.

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