

Study of quasi-periodic oscillations from black hole X-ray binaries with IXPE

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Summary. — The Imaging X-ray Polarimetry Explorer (IXPE) can measure linear polarization over the photon energy range 2–8 keV. X-ray polarimetry provides a new observable that can help to answer some still open questions about different astrophysical sources. Among these, IXPE can study X-ray Binaries (XRB) and their polarization measurements allow us to better understand the geometry of the XRB emission region and the physics of mass accretion.

1. – Introduction

The characteristics of an astrophysical source can be investigated through the spatial, spectral, timing and polarization properties of the emitted electromagnetic radiation. In particular, the polarization allows us to obtain information about the geometry of both the emitting matter and the magnetic and gravitational fields.

The state-of-art telescope for X-ray polarimetry is the Imaging X-ray Polarimetry Explorer, IXPE [1], a space mission (NASA and ASI Collaborations) launched on December 9th 2021 in an equatorial orbit at 600 km, that measures the linear polarization of different astrophysical sources in the energy range 2–8 keV. It is equipped with three detector units (DUs), each with a Gas Pixel Detector [2].

2. – X-ray binaries and polarization

X-ray Binaries (XRBs) are one of the different astrophysical source classes observed by IXPE. In particular, they represent perfect targets to study the physics of mass accretion, that powers some of the brightest X-ray sources. This mechanism operates very efficiently for compact objects, *i.e.*, neutron stars and black holes (BHs), which accrete matter from a nearby companion star.

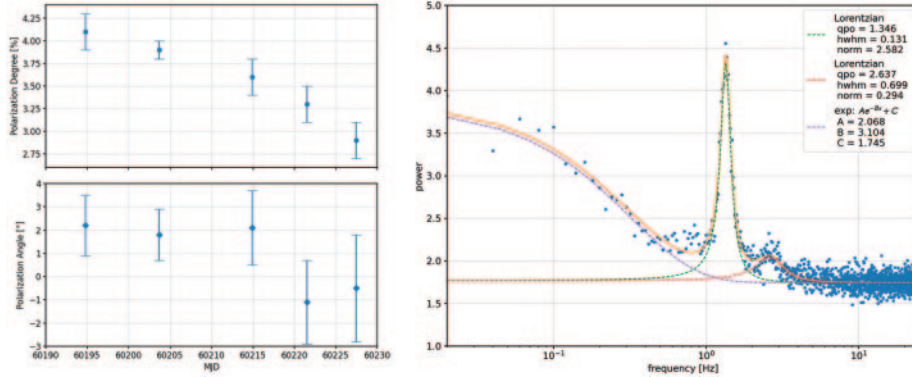


Fig. 1. – Left: swift J1727.8-1613 polarization degree and angle of the five observations [4]. Right: power spectrum of the whole observation of Swift J1727.8-1613 by IXPE: the two QPO peaks are visible.

BH XRBs display two major spectral states [3], soft and hard, which are believed to be related to different accretion regimes. The first is characterized by blackbody thermal emission produced by photons from an optically thick but geometrically thin accretion disk. In the hard state, on the contrary, the spectrum is described by a continuum powerlaw due to the Inverse Compton of the seed photons produced by the disk, that interact with the hot electrons cloud, the *X-ray Corona*, located close to the central BH.

X-ray polarization can provide a new observable to understand the geometry of the XRB emission region, that conventional spectroscopy and timing observables have not fully explained yet. Results can help to solve some still unanswered questions regarding for example: the accretion geometry and physical mechanisms producing broadband emission in the spectral states, the geometry and location of the hot medium in the hard spectral state, the structure of the accretion.

2.1. IXPE observation of SWIFT J1727.8-1613. – An interesting XRB studied by IXPE is Swift J1727.8-1613. This source underwent a bright outburst on August 24th 2023 [3] and, since then, it has been observed by IXPE four other times. All indirect signatures suggest that it is a BH XRB [3], making it an ideal scientific target to probe the accretion geometry. The five IXPE observations allow us to study and monitor its polarization properties across the transition from hard to soft state [4]. As shown in the left panel of fig. 1, the polarization degree slowly decreases over time from $\sim 4\%$ to $\sim 3\%$, while the polarization angle remains constant and aligned with the radio jet. These results suggest that the *X-ray Corona* is not extended along the jet axis, but orthogonally to it, in the disk plane, for the entire hard intermediate state ([3, 4]).

3. – Quasi-periodic oscillations

XRBs light curves are often characterized by low-frequency quasi-periodic oscillations (QPOs), that can be identified as features in the power spectral density, and described with a Lorentzian ([5-7]). QPOs are correlated to a misalignment between the BH spin and the XRB orbital axis, that leads to a warping of the accretion disk and/or to the Lense-Thirring precession. If QPOs have a geometric origin, the physical mechanisms behind BH QPOs could be investigated thanks to the knowledge of the XRB geometry, that can be inferred from X-ray polarization measurements performed by IXPE.

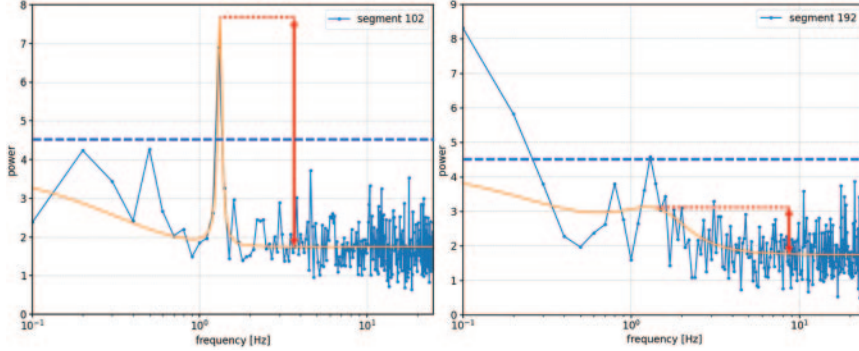


Fig. 2. – Power spectra for two different time segments with the fit function (orange line) and the comparison between the amplitude of the QPO peak (vertical red arrow) and the threshold of fast Fourier transform power (horizontal dashed blue line): in this case, being the threshold the same for the two plots, the selected segment is the left one.

In addition, the frequency of the QPO is correlated with the spectral state and their origin can be due to the already mentioned relativistic precession effects.

3.1. SWIFT J1727.8-1613: Polarization and QPOs. – Swift J1727.8-1613 showed QPOs in all the five observations ([3, 4]). As the XRB passes from the hard to the soft state in the time range of the five observations, the QPO amplitude decreases, making the first observation the most suitable to study links between the polarization and the QPOs being the one with highest peak amplitude.

In this work we explain the method we are testing to analyze these correlations, trying to evaluate the polarization degree and angle for the events where the QPO is high or low and looking for statistically significant differences. The following analysis has been performed using the software STINGRAY [8, 9] for the power spectra studies and IXPEOBSSIM [10] for the polarization. While IXPE data are in the time domain, QPOs are in the frequency domain, so we had to set up a strategy to study correlations between polarization and QPOs. This analysis technique has been tested only for the three IXPE DUs separately and from now on everything will be referred to one single DU.

First of all, the power spectrum from the events time series (from DU1 for example) is evaluated and modeled using the following fit function (right panel of fig. 1):

$$(1) \quad f(\nu) = \frac{1}{\pi} \frac{H_1 \gamma_1^2}{(\nu - \nu_{01})^2 + \gamma_1^2} + \frac{1}{\pi} \frac{H_2 \gamma_2^2}{(\nu - \nu_{02})^2 + \gamma_2^2} + A e^{-B} + C,$$

where ν is the frequency and the first two terms are the Lorentzian functions that describe the two QPOs of Swift J1727.8-1613. The last exponential term describes the noise component of the power spectrum.

Then the observation is divided into time segments, taking into account the Good Time Intervals (GTIs), using STINGRAY. The length of these time segments is chosen so that the statistics in each of them is high enough to allow us to perform the fit of the power spectrum. In each time segment, the power spectrum is evaluated and fitted: the fit function is again eq. (1) (without the second Lorentzian term since its signal-to-noise ratio is too low), with the parameters of the Lorentzian initialized to the values found from the fit of the whole observation. On the other hand, the parameters of the exponential are frozen to the values previously retrieved.

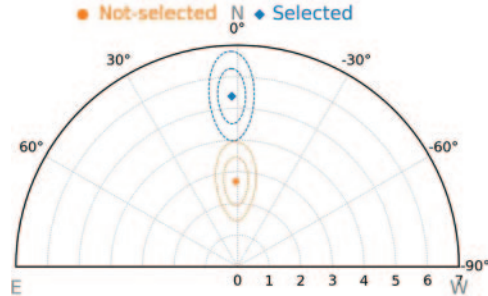


Fig. 3. – Polarization contour plots at 68% and 95% confidence level for a threshold equal to 3.3. Dashed blue lines (diamond marker) and dotted orange lines (circle marker) represent the polarization contours for the selected and not-selected events respectively.

Using STINGRAY, the amplitude of the QPO peak is evaluated and corrected for the baseline of the power spectrum (C parameter of the exponential). It is then compared to a varying threshold of Fast Fourier Transform powers (fig. 2): if the QPO peak amplitude exceeds the threshold, the events that lie within that time segment are selected. The not-selected events form a separate population.

The polarization is calculated using IXPEOBSSIM separately for the selected events and for the not-selected ones. Figure 3 shows the polarization contour plots at 68% and 95% confidence level for an example threshold (3.3). It can be seen that there is a hint of separation between the two populations, selected and not-selected events, at 95% confidence level. This is true for all the thresholds below ~ 4.5 in power, whereas for a higher threshold, the number of selected events is too low to allow any statistical test.

4. – Conclusions

X-ray polarization results from IXPE help to answer some open questions about XRBs, investigating for example the geometry and structure of the accretion in such sources. More insights can be provided by the study of the polarization of the QPO for a BH XRB. Preliminary results are very promising, showing a hint of statistically significant differences in the polarization between the time segments where the QPO peak amplitude is high and those where it is low. This supports the feasibility of using polarization measurements to further explore connections between QPOs and the geometry of the emitting region. In the future, this analysis will be extended to the three DUs together, it will be optimized and the choice of the threshold will be fine tuned.

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