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Accretion Onto Weakly Magnetized Neutron Stars: Polarization Theory and Its Application to X-Ray Burster GX 13+1

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ABSTRACT

Observations show that the x-ray emission of the accreting weakly magnetized neutron stars (WMNSs) is polarized. In this article, we summarize the analytical models for the polarized emission of various components of the WMNSs. We introduce a missing theoretical model, where we assume the emission comes from the spreading layer, the extension of the boundary layer between the accretion disk and the neutron star. We show how these models and the results of the simulations provide new insights into the x-ray polarization from weakly magnetized neutron stars observed with the imaging x-ray polarimetry explorer (IXPE). We specifically focus on the most peculiar case of the X-ray burster GX 13+1.

1 | Introduction

Accreting neutron stars in low-mass x-ray binaries are important systems that we observe in order to study the properties of NSs and the physics of x-ray emission. As the name suggests, these systems comprise a NS and a normal star of a mass lower than the mass of the Sun. Accretion of matter in these systems happens as follows: the matter from the stellar companion overflows the Roche lobe and falls onto the compact object, forming an accretion disk around it. If the compact object is a weakly magnetized neutron star (WMNS), the matter from the inner part of the accretion disk interacts directly with the surface of the neutron star near the equator. There, the in falling matter forms a boundary layer (BL, see e.g., Shakura and Sunyaev 1988) that can, depending on the accretion rate, spread from the disk plane toward the poles of the neutron star and form so-called spreading layer (SL, see e.g., Inogamov and Sunyaev 1999; Lapidus and Sunyaev 1985). Phenomenologically, x-ray binaries with a WMNS as a compact object (WMNS-XRBs) are classified into Z sources and Atoll sources (Van der Klis 1989a). Atolls are traditionally less bright (0.01–0.1 L_{Edd}, Eddington luminosity) and paint a round-shape structure (comprised of the so-called "island" and a "banana" parts) on the color–color diagram (CCD). On the other hand, Z sources write a letter "Z" on the CCD and can reach Eddington luminosity.

In the spectrum of WMNS-XRBs, we see two main components, a soft thermal black-body-like emission coming from the accretion disk or the neutron star surface and a hard Comptonized emission coming from the BL or SL. Spectroscopy allows us to decompose the spectrum and assess the contribution of each component. However, spectroscopy is insensitive to the geometry of the BL/SL region. Timing analysis provided further information on the geometry and emission mechanisms of WMNS-XRBs with the quasi-periodic oscillations (QPOs, Van der Klis 1989a, 2000) observed in Hz and kHz ranges. Studying the origin of

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the QPOs led to new theories regarding the media near the NS surface (Gilfanov, Revnivtsev, and Molkov 2003; Revnivtsev and Gilfanov 2006; Revnivtsev, Suleimanov, and Poutanen 2013).

Polarimetry, almost nonexistent in the x-ray band before the launch of Imaging x-ray polarimetry explorer (IXPE, see Weisskopf et al. 2022) in December 2021, adds information about the geometry of the emitting regions as well as the mechanisms of emission. In the last two years, IXPE has observed a dozen WMNS in x-ray binaries, obtaining peculiar and insightful results. These results are discussed in detail in Section 3.

While analyzing the IXPE observations of WMNSs, several techniques were developed. First, the dependency of polarimetric properties on energy proved to be informative and useful for deriving both geometrical constraints on the emitting regions. Second, disentangling the polarization coming from the two main components of the spectrum was used to assign the spectral components to specific emitting regions. For each of the components, theoretical predictions for polarimetric properties are derived. These are introduced and discussed in Section 2 together with the model we developed for the SL emission. Combining these models with peculiar results of GX 13+1 observations, we make conclusions regarding the geometry of the source and evaluate the need for further observations and model developments in Section 4.

2 | Theoretical Predictions

In the binary systems with a WMNS as a compact object, the emission is dominated by the close surroundings of the NS, mostly from the inner part of the accretion disk and from the inflow of the accreted matter onto the surface of the NS. Depending on the parameters of the binary system such as mass accretion rate and rotation frequency of the NS, matter either forms a torus of equal radial length and height around the equator of the star (BL, see e.g., Popham and Sunyaev 2001) or spreads in a (relatively) thin layer over the surface of the star (SL, see e.g., Inogamov and Sunyaev 1999). A combination of these two geometries is also possible. The geometry of the system with a BL and SL is presented schematically in Figure 1.

Apart from the direct emission of the disk and a comptonized emission of the BL/SL region that, combined, form the continuum of the WMNS emission, minor features appear in the spectrum. For instance, an emission line around 6.4 keV is traditionally associated with the reflection of the emission from the surface of the accretion disk. On the other hand, absorption lines in the spectrum are usually associated with the scattering of the emission in the wind above the disk surface.

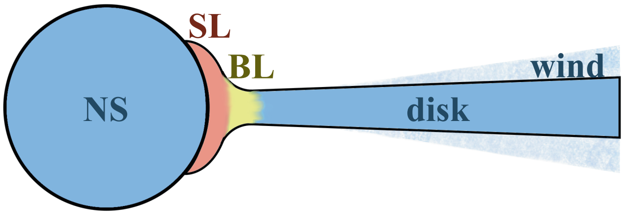

FIGURE 1 | Schematic representation of the WMNS geometry. Not to scale.

2.1 | Disk and Its Surroundings

An accretion disk is formed when the matter from the companion star is pulled by the gravity of a compact object and falls onto it, losing angular momentum and gravitational energy in the process. Gravitational energy is radiated via emission. Because of the scattering in the highly ionized surface of the disk, this emission is expected to be polarized (see e.g., Rees 1975). Disk emission is supposed to be polarized in the plane of the disk, but if one takes into account the special and general relativity effects, the picture becomes more complicated (see e.g., Dovciak et al. 2008; Loktev, Veledina, and Poutanen 2022). The accretion disk emission in the IXPE energy range can be polarized up to 4% for the high inclination of 80°, but the polarization degree (PD) decreases rapidly with inclination—so, for 60° inclination, the maximum PD is just about 1%, and for 30° inclination, a PD of 0.2% is expected. The emission is polarized in the plane of the disk, although some rotation of polarization angle (PA) with energy is expected in the low-inclination case.

In the sources with high inclination, the reflection from the disk is often present in the spectrum. Although the most prominent feature of the reflection component is the iron fluorescent line, the component is present at all energies within the *IXPE* range and beyond. The iron line itself is not polarized, but the reflection continuum is expected to be strongly polarized (see e.g., Matt 1993; Poutanen, Nagendra, and Svensson 1996). As the spectrum is traditionally dominated by the disk and the SL/BL emission, we do not expect to see the overall PD of the binary emission reach values as high as predicted for the reflected component.

Last but not least, scattering in the wind above the disk is also a potential source of the highly polarized emission. According to Sunyaev and Titarchuk (1985), we can expect up to 33% polarization of the light scattered in a flattened medium and observed at a high inclination. Recent research (Tomaru, Done, and Odaka 2024, and Nitindala, Veledina, and Poutanen 2024) predicts a modest PD of up to 10% in the total light. According to Tomaru, Done, and Odaka (2024), this scattered emission is polarized either in the disk plane or perpendicular to it.

2.2 | SL/BL

At the inner edge of the accretion disk, the accretion flow is modified due to the near presence of the NS surface. To estimate the polarization of the emission coming from this region, we make several assumptions. When we are talking about the BL, we consider it to be a hotter region that is geometrically similar to the accretion disk. So, we take figure 10 from Loktev, Veledina, and Poutanen (2022) as a guideline for estimating the polarization of the disk and the BL. For the same inclination, we expect BL and the disk to have the same PA, while the PD is slightly higher for the hotter BL compared to the one of the colder disk in the *IXPE* energy range.

When calculating the expected polarization of the SL emission, we assume the SL to be an electron-scattering-dominated thin layer that is spread over the NS surface. We also look at the aligned system in which the NS rotation axis is perpendicular to the plane of the binary orbital motion and the accretion disk. Spectroscopic observations estimate the temperature of the Comptonizing media to be around 1–3 keV, so we assume the scattering to be Thomson, without any change of the seed photons' energy during the scattering. We account for the rapid movement of the matter in the SL, and we take into account the relativistic effects such as gravitational light-bending by calculating the Stokes parameters of the SL emission in the Schwarzschild metric. The model is introduced in detail in (Bobrikova, Poutanen, and Loktev 2024c), here we focus on the energy-dependent results. Figure 2 illustrates the dependence of the SL emission polarization on the inclination of the system. Here, we fixed the co-latitude of the SL edge at 60°, the effective temperature of the seed photons $T_{\rm eff}$ at 2 keV, and the flow of matter in the SL to be Keplerian at the equator and slowing down to $0.1c$ at the edge of the SL. We note that the light is weakly polarized, with PD slightly exceeding 0.6% for high inclinations, and it is polarized perpendicular to the disk plane with a slight rotation of PA with energy.

2.3 | Overall Picture

In the IXPE energy range, the lower energies (2–3 keV) are traditionally dominated by the disk emission, while in the higher energies, the BL/SL emission is strong. As these emission components are thought to have different polarimetric properties, the expected polarimetric picture depends on the spectral decomposition, but most importantly, on the geometry of the BL/SL region. If we assume that the accreted matter does not spread over the surface of the NS but rather decelerates quickly in the BL, then we expect PA to be more or less stable throughout the whole IXPE energy range, and PD slightly increasing with energy, from the disk PD at lower energies (Loktev, Veledina, and Poutanen 2022) to a disk-like, but slightly hotter BL at higher energies. However, if the matter forms a SL above the NS surface, the picture becomes more complex. At lower energies, especially below the *IXPE* energy range, we expect to see the light polarized in the plane of the disk. Depending on the temperatures of the disk and the SL, somewhere around 3 keV, we expect a strong depolarization, as SL and accretion disk emission contribute equally, but are polarized perpendicularly one to another. At the higher energies, we expect to see the light polarized perpendicular to the plane of the disk, as explained in Section 2.2.

Regarding the PD, it strongly depends on the temperatures of the disk and SL. If SL is relatively hot (2–3 keV), we will be able to see the PD of the disk emission at the lower energies, then a depolarization due to the combination of the orthogonally polarized emission in the middle, and then the PD of the SL emission similar to the one shown in Figure 2 at higher energies. If SL emission is present also at lower energies, we might see the same depolarization due to two orthogonally polarized components of the emission at lower energies and then the PD of the SL emission at higher energies.

Suppose the reflection is strong in the system. In that case, we expect to see a depolarization around the iron line (however, it is tricky to resolve it with IXPE) and a higher PD at lower energies. The presence of the scattering in the wind can also significantly alter the polarimetric picture. Depending on the thickness of the wind, the emission scattered in the wind can be polarized either in the plane of the disk or orthogonal to it. Combined with the unscattered emission, it can both enhance and reduce polarization at higher energies, depending on the PA alignment between these two components.

Misalignment in the system adds complications to the predicted polarimetric picture. In the aligned system, emission components are polarized in the plane of the disk or perpendicular to it. In this case, a combination of two or more components at the same energy range either enhances or reduces the polarization without changing the PA. However, if BL is not in the plane of the disk and SL is not perpendicular to it; their combination can have very different PA. For instance, misalignment is suggested as one of the explanations of the peculiar polarimetric picture observed in Cir X-1 Rankin et al. (2024).

3 | Observational Results

3.1 | Atolls

Atoll sources are relatively hard and dim with a luminosity of 0.01–0.1 of Eddington luminosity. They smoothly evolve between

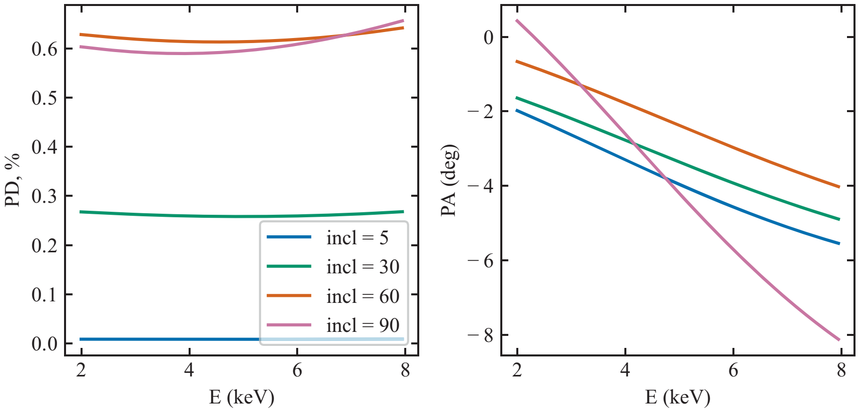

FIGURE 2 | Polarimetric properties of the SL emission as functions of energy. Co-latitude of the SL is fixed at 60°. Blue, green, red, and pink lines correspond to the inclinations of 5°, 30°, 60°, and 90°.

their harder and softer states, named respectively “island state” and “banana state.” In the last two years, IXPE observed five atolls. For two of them, IXPE only provided an upper limit on the PD, see Capitanio et al. (2023) for GS 1826−238 and Ursini et al. (2024) for Ser X-1. The other three, however, appeared to be polarized with a highly significant detection. In GX 9 + 9 (Ursini et al. 2023), the polarization of the overall emission in the IXPE energy band of 2–8 keV was not detected, but they reported a trend of increasing PD with energy. In 4 U 1820−303 (Di Marco et al. 2023) and 4 U 1624−49 (Saade et al. 2024), PD was also strongly dependent on energy. If we take into account the estimations from Section 2, this picture hints toward a relatively cool SL that depolarizes the emission when mixed with disk emission at lower energies and is dominating at higher energies. At least for the 4 U 1820−303, we see a confirmation of this theory in the PA, as there is a clear change by 90°. However, PD at higher energies is higher than the one we expect from the SL. This hints toward a need for further theoretical efforts regarding the SL polarization or searching for alternative component.

3.2 | Z Sources

Z sources are bright, reaching the Eddington limit in luminosity. They are softer and are evolving between the three distinct states (so-called normal branch, horizontal branch, and flaring branch), over which they can evolve within days (Van der Klis 1989b). IXPE observed Z sources in all three states. For two sources, GX 5−1 (Fabiani et al. 2024) and XTE J1701−462 (Cocchi et al. 2023), IXPE made two observations in different states. It appeared that Z sources are barely polarized in a soft state, but have higher PD in a hard state. Sco X-1, observed with IXPE only once and in a soft state with a PD of 1% (La Monaca et al. 2024), fits into this picture nicely. All three of these Z sources showed no dependency of PD and PA on energy. In the terms described in Section 2, this corresponds to a BL near the NS surface, not a SL. Cyg X-2, on the other hand, showed a pattern similar to the atoll sources (Farinelli et al. 2023). In this source, the polarization at higher energies is aligned with the jet direction, which suggests a SL geometry near the NS surface. However, the high values of the PD at higher energies are something we struggle to reproduce by any SL model, see also Farinelli et al. (2024).

Cir X-1, a peculiar source that does not fit the traditional classification, showed a strong variation of PA with time and hardness (Rankin et al. 2024). One of the possible explanations for Cir X-1 behavior is a misaligned NS that, depending on the state, has either a SL or a BL geometry of the NS surroundings. Another peculiar and unclassified source, GX 13+1, provided us with a puzzle that is described in the next subsection.

3.3 | GX 13+1

GX 13+1 is a bright, persistent neutron star low-mass x-ray binary located in the Galactic bulge, the distance is estimated at 7 ± 1 kpc (Bandyopadhyay et al. 1999). The binary consists of an evolved late-type K5 III star and a weakly magnetized neutron star that accretes matter from the companion via the Roche lobe. GX 13+1 is most commonly classified as an atoll due to the path it draws on the CCD (see e.g., Schnerr et al. 2003), although it is bright as a Z source (up to $0.5L_{\mathrm{Edd}}$, D’Aí et al. 2014), and lately was described as a Z source (see e.g., Saavedra et al. 2023). The source shows dips in the x-ray light that are usually interpreted as a hint toward the high inclination of the system, $i = 60^\circ - 75^\circ$ (D’Aí et al. 2014; White and Holt 1982). Both in the x-ray and infrared light there is an almost periodic variability with a period of around 24.5 days (Corbet et al. 2010).

GX 13+1 is known to have a powerful wind that remains active in all the states of the variability of the source, even in the hardest state (Tomaru et al. 2020). The highly ionized absorption features of the GX 13+1 spectrum are associated with the scattering in the wind, and it was shown that the disk wind must comprise multiple absorption zones to explain all the absorption features (Allen et al. 2018). The spectrum is most commonly interpreted as a combination of a disk emission (black body component), an NS atmosphere emission (comptonized component), and a Gaussian component modified for the absorption features (Díaz Trigo et al. 2012).

IXPE observed GX 13+1 three times in the last year. Here, we focus on the first two observations reported in Bobrikova et al. (2024b) and Bobrikova et al. (2024a). During these observations, GX 13+1 showed peculiar behavior, with both overall polarimetric properties and energy dependency of PD changing with time, see Figure 3. In the first part of the first observation, the source showed a strong dependency of PD on energy. As was discussed above, traditionally we see such a behavior in the atoll sources. However, within less than 24 h the source changed the polarimetric behavior, as in the middle panel of Figure 3 PD no longer depended on energy (except for the last bin), and the PA was almost constant within error bars. This is a behavior we usually observe from the Z sources. Note also the significant difference between the overall PA values in these two parts of the same observation. It was shown in Bobrikova et al. (2024b) and confirmed in Ravi et al., in prep that during the first observation, a rotation of polarization plane by 70° appeared, and even more peculiarly, this rotation was not present during the second and third observations.

Polarimetric pictures presented in Figure 3 are challenging to interpret with the current models we have. Figure 4 shows the possible SL polarization for GX 13+1 calculated with our model. We fixed the inclination at 70° and tried different co-latitudes of the SL edge based on the estimations from Inogamov and Sunyaev (1999) for the luminosity ranges of GX 13+1. At the spectrum of GX 13+1 is dominated by the harder component in the IXPE energy range (see e.g., Díaz Trigo et al. 2012), we expect the polarimetric picture to be affected by the disk only at lower energies, 2–3 keV. The results are not in agreement with any of the observations presented in Figure 3. The first part of the first observation can be interpreted as a result of a switch between two components, with the weakly polarized disk at lower energies, and a strongly polarized BL component at higher energies, as PA is almost constant within the error bars. However, on the next day, the PD exceeded 5% on average and through all the IXPE energy range. The source did not change state between these two parts of the observation, but there was a dip in the light curve in between. Our hypothesis is that the clump of the wind responsible for the dip can also be responsible for the change in the polarimetric picture. This idea is supported by the confirmed rotation

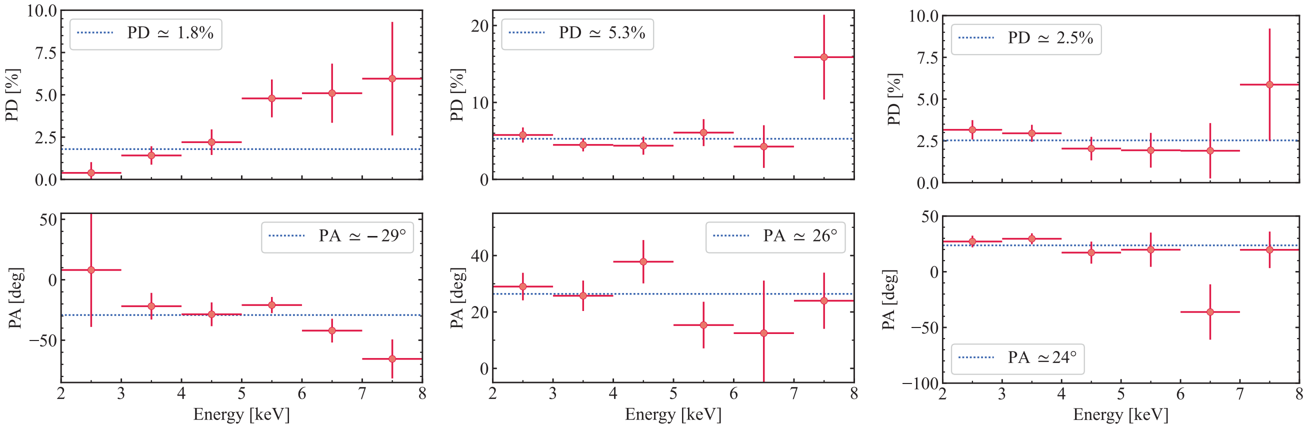

FIGURE 3 | Polarimetric properties of GX 13+1 as functions of energy measured by *IXPE*. Left: the first part of the first observation, 17–18 October 2024. Middle: the second part of the first observation, 19 October 2024. Right: the second observation, 25–27 February 2024. Uncertainties are reported at 68% confidence level.

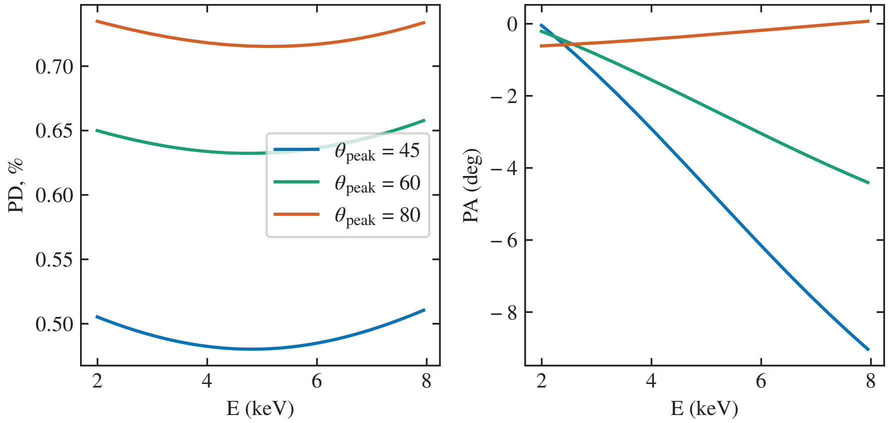

FIGURE 4 | Polarimetric properties of the SL emission as functions of energy, the case of GX 13+1. Inclination of the system is fixed at 70∘. Blue, green, and red lines correspond to the co-latitude of the SL edge of 45∘, 60∘, and 80∘.

of the PA with time. To produce a rotation of PA, something must be constantly changing in the system, and a slow movement of the clump of matter in the wind is one way to explain this. The second observation performed a couple of months later with the source in the same state, showed PA similar to the one in the second part of the first observation, with a constant but weaker polarization. This is the picture we saw in Z sources in the hard state.

As PA of GX 13+1 does not depend on energy, we tend to believe it to have a BL geometry of the NS surrounding. However, the strong variability of the wind of the source make it extremely hard to test our theories and derive conclusions about the geometry of the source.

4 | Conclusions

Over the last couple of years, massive development happened in the field of WMNS studies. IXPE observed more than ten WMNS in binary systems, obtaining a significant detection of polarization for the majority of sources. Theoretical predictions for the polarimetric properties of this class were updated and developed, and we contributed to this by adding an analytical model for the SL polarized emission.

Comparing the observational results to the theoretical predictions allowed us to reach some conclusions about the geometry of some sources. On the other hand, as models cannot always explain the observed polarization, we now have some more space for new models and updates of the current ones. There is hope now to provide a new, polarimetry-based approach to distinguish atoll and Z sources and investigate the physical processes that stand behind the state evolution of these objects.

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Conflicts of Interest

The authors declare no conflicts of interest.

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