Magnetic turbulence in supernova remnants: perspective for IXPE polarimeter

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Abstract. Supernova remnants (SNRs) are well known sources of the non-thermal radiation, particle acceleration and magnetic field generation and amplification. Synchrotron radiation of the accelerated electrons in the magnetic field is an important emission mechanism in SNRs that can dominate in radio and X-ray energy bands. Turbulent magnetic field yields to formation of the special inhomogeneous (clumpy) structure in the SNR synchrotron X-ray images. This structure could differ significantly on the SNR polarization maps for different types of the magnetic turbulence. A new family of the gas pixel detector X-ray polarimeters that are supposed to have good sensitivity and angular resolution should be well suited for SNR polarimetry. IXPE (NASA) will be the first polarimeter of this kind. Lately a model IXPE synchrotron polarization images of Tycho SNR were simulated in the 3 – 8 keV energy band. It was shown that IXPE observation time of $\sim 1$ Ms should be enough to distinguish characteristic features that are specific for some types of the magnetic turbulence. We perform simulations of Tycho SNR polarization maps for a wider set of energy bands in order to determine the most suitable energy range for study of the SNR turbulent magnetic field using IXPE. The dependence of the polarization degree on the photon energy is accurately considered in the simulations. IXPE background influence on the observations of Tycho SNR is also discussed here together with possible ways of data processing and interpretation reducing this effect.

1. Introduction

Supernova remnants are bright sources of the non-thermal radiation in a wide energy band from radio to gamma rays. This radiation is generated by charged particles accelerated at the shock formed during the expansion of the remnant envelope into the interstellar medium. Particles are accelerated due to the diffusion acceleration mechanism (DSA) [1]. As a result a population of the accelerated non-thermal particles is formed in the vicinity of the shock, which energy distribution is well described by the power law spectrum. The synchrotron radiation of accelerated electrons in the magnetic field forms the radiation of SNR together with the thermal plasma emission of the shell and ejecta ([2]). Synchrotron radiation is an important radiation mechanism in SNRs. In many cases it generates a significant part of the observed emission in the frequency range from radio to X-rays and sometimes it dominates the radiation of the thermal plasma. A sufficiently strong turbulent magnetic field should be present in the vicinity of the shock in order to make DSA mechanism to work ([3, 4, 5]). The generation and evolution of such field can be a result of various processes: field amplification at the hydrodynamic density jump, nonlinear collective plasma instabilities induced by the influence of Cosmic Rays accelerated at the shock ([6, 7]) and cascade plasma processes ([8, 9, 10, 11]). All these processes of field generation and
evolution lead to specific configurations of the turbulent magnetic field, characterized by different preferred directions and degrees of spatial anisotropy of the random magnetic field. This clumpy turbulent structure is visible in the high angular resolution X-Ray images of various SNRs: RX J1713.72−3946, SN 1006, Cas A, Tycho and others. In [12, 13, 14] simulations of the young SNR synchrotron X-ray maps were done taking into account the effects of stochastic magnetic field. Obtained images reproduce the real observable clumpy structure rather good ([12, 13]). While it looks similar on synchrotron radiation intensity maps, the stochastic magnetic structure with different evolution history should reveal itself differently on the maps of polarized radiation. The X-ray energy band is best suited for polarimetric observations, because particles radiating in this band are concentrated in a narrow region near the shock, that allows to observe magnetic field directly near it. The depolarizing Faraday effect is also absent for X-rays. The new generation of X-ray polarimeters that will have good sensitivity and angular resolution can become an indispensable tool for study of the turbulent magnetic fields in SNRs. IXPE (NASA) is going to be the first detector of this kind [15].

In [16, 17] a model X-ray synchrotron polarization maps of Tycho SNR were simulated with XIMPOL\(^1\) python package in the 3−8 keV energy band. Simulations were done with various assumptions on the formation mechanisms of the turbulent magnetic field\(^2\). It was shown that IXPE observation time of $\sim$ 1 Ms should be enough to distinguish characteristic features that are specific for some mechanisms of field generation. In this work Tycho polarization maps are simulated for a wider set of energy bands. The dependence of the polarization of synchrotron radiation, produced in the turbulent magnetic field, on the photon energy is accurately considered in the simulations. This dependence is a consequence of the following: due to energy looses a spatial volume occupied by accelerated particles depends on their energy so magnetic field configuration in which they radiate also depends on the particle energy, and particle spectrum is much harder than the power law at the energies near or above the spectrum cut off energy so constant polarization degree approximation is no longer valid.

In [18] IXPE background was studied together with methods of its filtering that use a difference between photoelectron track and background tracks in the gas pixel detector. It was shown that IXPE results should be rather sensitive to background in the case of extended sources. An emission from the 100'' × 200'' box region in the Tycho ridge area observed with 1 Ms IXPE observation time should have the source to background ratios $\sim$ 16 and $\sim$ 1.8 in the cases of observation data processing with background filtering applied and without it. IXPE background influence on Tycho polarimetry observations is discussed in the following sections.

\(^1\) http://github.com/lucabaldini/ximpol

\(^2\) See section 2 and [17] for details.
Figure 2. XIMPOL simulated maps for the anisotropic turbulence produced by shock compression with \( q = 5 \) (left column, panels a,c,e) and \( q = 20 \) (right column, panels b,d,f), IXPE exposure time is 1 Ms. The upper row (panels a,b), middle row (panels c,d) and bottom row (panels e,f) show maps simulated for 2-8, 2.5-8 and 3-8 keV energy ranges respectively. Each panel shows mini panels of the polarization degree, angle, significance, and total counts. Polarization angle is measured from the Oy direction.

2. Simulation of synchrotron X-ray images

To simulate synchrotron radiation images a model turbulent magnetic field and an electron distribution function, which is a solution of the diffusion kinetic equation, are used. Methods that were used to model the turbulent magnetic field and to solve the kinetic equation are discussed in full detail in [12, 13, 14, 16, 17]. In this work only the case of the anisotropic turbulence emerging from the isotropic one after magnetic field amplification at the shock is considered. The initial Kolmogorov turbulence is assumed. The stochastic properties of the anisotropic axially symmetric magnetic turbulence are \( \langle B_{\perp}^2 \rangle = q \langle B_{\parallel}^2 \rangle = \langle B^2 \rangle q/ (q + 1) \). In the case of isotropic turbulence \( \langle B_{\perp}^2 \rangle = \langle B_{\parallel}^2 \rangle = \langle B^2 \rangle = \langle B^2 \rangle / 3 \) and \( q = 2 \), in the case of turbulence produced by shock compression \( q > 2 \) and parallel axis is directed along the shock plain normal.

In order to study IXPE perspective in the polarized emission study of Tycho, turbulent magnetic field and synchrotron emission simulations were done for a model remnant which physical properties are similar to Tycho’s SNR. Fig. 1 shows the 4-6 keV Chandra image of Tycho SNR with 120° x 240° box region used for simulations. The spectrum from the box area...
is well fitted by XSPEC\textsuperscript{3} pow law spectrum model with spectral index 2.2 and normalization $1.2 \times 10^{-2} ph/keV/cm^2/s$ at 1 keV. XIMPOL package was used in simulations. It was designed to simulate X-ray polarimetric observations and was firstly used for ESA mission XIPE [19, 20].

To take into account the dependence of the polarization degree of synchrotron radiation produced in the turbulent magnetic field on the photon energy we simulated initial $1''$ resolution synchrotron maps for photon energies 2, 3, 4, 5, 6, 7, 8 keV. Based on [17] we estimated the contribution of the unpolarized emission of thermal plasma in the whole emission to be 0.7, 0.4, 0.2, 0.3 in the $2 - 3$, $3 - 4$, $4 - 6$, $6 - 8$ keV energy bands. The final maps were obtained with XIMPOL after averaging with weights proportional to multiplication of the photon flux and the detector effective area for the chosen energy grid. Fig. 2 shows simulated maps for the anisotropic turbulence with $q = 5$, 20 and IXPE observation time 1 Ms. For comparison Fig. 3 shows similar maps for the anisotropic turbulence with $q = 5$ and IXPE observation time 2 Ms. Images were constructed for the dense grid with $\approx 17''$ pixel size that is smaller than the circular region with 30'' radius that was used to collect statistics. This sliding circle approach is described in [17]. Maps of the polarization degree, angle, and significance show only pixels that accumulated more than $10^4$ counts. According to [21] $\sim 10^4$ counts is enough to detect 10% polarization with 99% confidence if detector modulation factor is $\sim 0.5$ and there is no background.

Additional polarization maps were simulated in order to test possible influence of the IXPE background on the Tycho polarization observations. The background estimations from [18] for the case of 1' Ms Tycho observation were used. Box region $120'' \times 240''$ that is used in the analyses in this article has 1.4 times greater area than $200'' \times 200''$ box considered in [18]. For

\textsuperscript{3} http://heasarc.gsfc.nasa.gov/xanadu/xspec/
Figure 4. XIMPOL simulated maps in the $3-8$ keV energy band with IXPE background estimated in [18] taken into account. Simulations are done for the shock compressed anisotropic turbulence with $q=5$ and IXPE observation time 1 Ms. The left (a) and the right (b) panels show maps simulated for cases with and without background filtering applied. Mini panels layout is similar to Fig. 2.

the extended source the source to background ratio of the emission from the region located in the part of the source with roughly homogeneous emission is almost independent on the region area. Unpolarized background contribution increases the measured flux and decreases the measured polarization degree. Simulated maps are shown in Fig. 4 for the anisotropic turbulence with $q=5$ and IXPE observation time 1 Ms.

3. Discussion and Summary

A set of energy bands was used in the simulations in order to find more sensitive range for IXPE observations of SNR polarized emission. The $3-8$ keV energy band looks an optimal one because the contamination of the unpolarized thermal emission is too high at lower energies and high energy boundary of 8 keV allows to use full energy range of the detector at high energies. This energy band was used in simulations in [17]. Energy bands with higher low energy boundary (e.g. $3.5-8$ keV) are also promising ones but due to fast fall of the detector effective area with energy the 1 Ms observation time may be not enough to collect $10^4$ counts in pixels of constructed maps, as is for $3.5-8$ keV energy range. With longer observation time (or greater pixel size), e.g. 2 Ms, such bands can be used in the analyses. All this is illustrated in Figs. 2,3.

Energy bands $2-8$ and $2.5-8$ keV were expected to be not sensitive enough to polarized emission because of severe contamination with thermal radiation at low energies ($2-3$ keV). Nevertheless, simulations show that pixels with high polarization degree ($15-20\%$) detected with significance $\sim 5$ are also present in simulated images in this case. These pixels are located outside of the SNR ridge. Their appearance is a result of the broad detector PSF which radius is $\sim 30''$. Radiation of a set of small clumps of polarized emission located in the ridge after convolution with IXPE PSF has reduced polarization degree value due to averaging. But if such clumps are located at the outer edge of the ridge and their emission is high enough a detectable flux could be produced outside of the ridge in a ring which width is approximately equal to the PSF radius. Averaging with nearby clumps is partially suppressed in this case so the observable polarization could be higher. The flux from the outside area should be much lower than from the ridge itself. Such outside ring is not present on the polarization maps made in the $3-8$ keV energy band if IXPE observation time is 1 Ms because there is less than $10^4$ counts in pixels of the ring area. However this effect is seen in Figs. 2,3 if observation time is 2 Ms or energy band is $2-8$ keV. It doesn’t allow to discard low energies ($2-3$ keV) from the consideration. The optimal strategy should be to use both $3-8$ and $2-8$ keV energy bands for maps creation and to analyse these maps together.

Simulations show that IXPE background could significantly reduce the levels of detected
polarization degree and its significance in the case of Tycho SNR. This is demonstrated in the right panel of Fig. 4. However the discussed above effect of possible detection of highly polarized emission from the outer region, that encircles SNR, is also possible. For the case of anisotropic turbulence with $q = 5$ and IXPE observation time 1 Ms the clump with polarization degree $\sim 25\%$ and significance $\gtrsim 8$ is seen on the $3 - 8$ keV energy map simulated without background effects. On the map simulated with background taken into account, pixels in the ridge area have polarization degree $\sim 10\%$ and significance $\sim 4$ while there is a pixel in the outer area with polarization degree $\sim 17\%$ and significance $\sim 6$. Background filtering methods could significantly reduce the level of the detector background. This is illustrated in the left panel of Fig. 4 where the same emission clump has polarization degree $\sim 22\%$ and significance $\gtrsim 7$. The use of the detector background filtering methods is highly desirable in the X-ray polarimetry study of Tycho and other extended objects.

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