Polarized synchrotron X-ray emission from supernova shells: XIPE/IXPE perspective

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Abstract. Young supernova remnants are the sources of a broadband nonthermal synchrotron continuum emission from radio to X-rays produced by accelerated electrons. Diffusive shock acceleration (DSA) of relativistic particles is accompanied by strong amplification of the turbulent magnetic field. This is an intrinsic feature of an efficient DSA. Synchrotron X-rays are produced by the multi-TeV electrons which are concentrated in a narrow region near the shock due to the strong energy losses. The confinement of the X-ray emitting electrons in this region filled with highly fluctuating magnetic field results in a complex time dependent clumpy structure of the observed X-ray images of supernova shells. The lack of Faraday depolarization in X-rays makes X-ray polarimetry a powerful tool to study synchrotron structures in the young galactic shell type SNRs Cas A, Tycho, SN 1006, RX J1713.7−3946. We present here simulated synchrotron images of SNR shells for different models of isotropic and anisotropic magnetic turbulence in a shell and argue that polarized X-ray imaging can be constructed for Tycho and Cas A SNRs with the expected sensitivity and the angular resolution of the upcoming missions XIPE (ESA) and IXPE (NASA).

1. Introduction
A young supernova remnant that supersonically expands in the interstellar medium generates a strong collisionless shock wave. This shock is an effective accelerator of charged particles due to the DSA mechanism. This mechanism produces a power law particle spectrum in a broad energy range. In the vicinity of the shock a strong super-adiabatic amplification of the fluctuating magnetic field likely takes place due to the cosmic-ray driven plasma instabilities. This turbulent magnetic field is an important part of the DSA itself and is responsible for particle diffusion \([1, 2, 3, 4]\). In this process electrons can be accelerated up to an energy of tens (or even hundreds) TeVs. These energetic particles are immersed in a magnetic field and efficiently emit nonthermal synchrotron radiation up to keV energies \([5]\). Modern observations confirm this model with detection of nonthermal radiation in a broad spectral range from radio to X-rays.

Recent high resolution synchrotron X-ray images of some SNRs (Cas A, Tycho, RX J1713.72−3946 etc) obtained with Chandra observatory revealed a complicated small-scale structure that includes thin filaments, clumps and dots. In the case of SNR RX J1713.72−3946 it was shown that small X-ray structures can be time-variable on a timescale of few years \([6]\). The nature of filaments can be explained as a combination of a geometry projection effect together with the limited width of the emission region. This limitation can be a result of a strong electron synchrotron losses \([7, 8]\) or a rapid magnetic field decay \([9]\) in the downstream region.
Time variability and clumpy structure can be naturally explained by the turbulent nature of magnetic field in the vicinity of a shock front. The influence of the stochastic turbulent magnetic field on spectra and images was studied in [10, 11] where some of the observed features of clumpy structures were indeed reproduced by simulated images. It occurs that intensity and polarization maps are sensitive to the turbulent magnetic field spectrum. The isotropic turbulent spectrum was assumed in that model. In this work we also consider an anisotropic turbulent field that can be formed naturally in the downstream medium after shock compression of the incoming isotropic magnetic turbulence. Polarization can be significantly higher in the case of the anisotropic turbulence and it can be observed with the future generation of X-ray polarimeters such as XIPE [12] or IXPE. The preferred direction of polarization in this case is radial.

2. The model

2.1. Stochastic magnetic field

The stochastic properties of a turbulent magnetic field with an axis of symmetry is $\langle B_\perp^2 \rangle = \xi \langle B_\parallel^2 \rangle = \xi \langle B^2 \rangle / (\xi + 1)$, where $\xi = 2$ in the isotropic case and $\xi > 2$ in the case of the compressed anisotropic turbulence. We introduce here the Cartesian coordinate system with axis $||$ directed along the symmetry axis. We simulate isotropic and anisotropic turbulence according to our previous works [10], [11] that use method based on [13]. We consider a summation of a big number of harmonics with random wave vectors and phases:

$$B(r, t) = \sum_{n=1}^{N_m} \sum_{\alpha=1}^{2} A^{(\alpha)}(k_n) \cos(k_n \cdot r - \omega_n(k_n) t + \phi_n^{(\alpha)})$$

Polarizations $A^{(\alpha)}(k_n) (\alpha = 1, 2)$ of magnetic field are orthogonal to each other and to the wave vector $A^{(\alpha)}(k_n) \perp k_n$ in order to satisfy $\nabla \cdot B = 0$ condition. For the 1st polarization we chose direction in a plane formed by the symmetry axis and the wave vector. The direction of the 2nd polarization is orthogonal both to the symmetry axis and to the wave vector. The 2nd polarization contributes only to the value of $B_\perp$ while the 1st polarization contributes both to $B_\perp$ and $B_\parallel$. If $A_1(k) = A_2(k)$ this method simulates an isotropic turbulence [13]. If $A_1^2(k) = (1 - a) A^2(k)$, $A_2^2(k) = (1 + a) A^2(k)$, where $1 > a > 0$, this method simulates anisotropic turbulence with stochastic properties $\langle B_\parallel^2 \rangle = \xi \langle B_\perp^2 \rangle$, where $\xi = (2 + a) / (1 - a)$. The amplitude is connected with turbulence spectrum energy density by the relation $W(k) \sim k^{-\delta} \sim k^{2} A^2(k)$, where $\delta$ is a spectral index.

2.2. Particle distribution function and SNR geometry

We use an electron distribution function obtained in the one-dimensional DSA model of particle acceleration including synchrotron losses [14], [15]. High energy electrons are concentrated in a thin layer near the shock (see Figure 1) due to the synchrotron losses.

We simulated SNR with radius $\sim 3$ pc at a distance of 2.5 kpc, so the SNR angular radius was 4 arcmin. These parameters are similar to those of the Tycho SNR. For the field simulations we used a rectangular region $(16 \times 8 \times 4) \cdot 10^{18}$ cm consisting of $(4 \times 2 \times 1)$ cubic boxes with size $D = 4 \cdot 10^{18}$ cm (Figure 1). The minimal and maximal characteristic scales of turbulence that we used were $L_{\text{min}} \sim 2.5 \cdot 10^{15}$ cm and $L_{\text{max}} \sim 1.2 \cdot 10^{18}$ cm ($\sim 0.07$ and $\sim 30$ arcsec in angular units). We calculated synchrotron emission for isotropic and anisotropic turbulence with spectral index $\delta = 1; 5/3$.

2.3. Synchrotron radiation properties

Emission and polarization properties of radiation can be fully described by the Stokes parameters. We consider magnetic field fluctuations of scales larger than the synchrotron
Figure 1. In the left panel the electron distribution function at different distances from the shock front is shown. Negative values correspond to the upstream region while positive to the downstream flow. In the middle panel the geometry of the model is shown: 4 cubic boxes with simulated magnetic field (one half of 8 boxes we used) and the spherical SNR shock. In the right panel the schematic 2D image is shown that is obtained by projection along the line of sight (z-axis).

radiation formation length $l_f \approx mc^2/eB \approx 1.7 \times 10^9 B_{\mu G}^{-1} \text{ cm}$, so we can use standard relations for the synchrotron radiation in a homogeneous magnetic field [16].

$$\tilde{I}(r, t, \nu) = \frac{3\nu^3}{mc^2 \nu_c^2} B_{\perp}(r) \int_{\nu/\nu_c}^{\infty} K_{5/3}(\eta) d\eta, \quad \tilde{Q}(r, t, \nu) = \frac{3\nu^3}{mc^2 \nu_c^2} B_{\perp}(r) K_{2/3} \left( \frac{\nu}{\nu_c} \right) \cos(2\chi),$$

$$\tilde{U}(r, t, \nu) = \frac{3\nu^3}{mc^2 \nu_c^2} B_{\perp}(r) K_{2/3} \left( \frac{\nu}{\nu_c} \right) \sin(2\chi),$$

$B_{\perp}$ is a magnetic field projection to a plane transverse to the line of sight, $\chi$ is an angle between the selected direction in this plane and the main axis of polarization ellipse. The projected maps can be obtained by integrating over the line of sight taking into account the isotropic distribution of emitting particles $f_e(E, r)$:

$$I(\nu) = \frac{3\nu^3}{mc^2} \int d\nu dE \frac{\nu}{\nu_c} B_{\perp}(r) f_e(E, r) \int_{\nu/\nu_c}^{\infty} K_{5/3}(\eta) d\eta,$$

$$Q(\nu) = \frac{3\nu^3}{mc^2} \int d\nu dE \nu_c \cos(2\chi) B_{\perp}(r) f_e(E, r) K_{2/3} \left( \frac{\nu}{\nu_c} \right),$$

$$U(\nu) = \frac{3\nu^3}{mc^2} \int d\nu dE \nu_c \sin(2\chi) B_{\perp}(r) f_e(E, r) K_{2/3} \left( \frac{\nu}{\nu_c} \right),$$

$\nu_c = \frac{3eB}{4mc^2} \gamma^2$, $f_e(E, r) dE = n(r)$. Here $I, Q, U$ are normalized so that the radiation flux near Earth can be obtained as $dF(\nu) = d\Omega I(\nu) = \frac{d\nu}{\nu^2} I(\nu)$ and so on, parameters $\nu_c, \chi$ depend on location. The degree of polarization can be obtained as: $P = \sqrt{U^2 + Q^2}/I$. The main axis of the polarization ellipse of the synchrotron radiation is perpendicular to the direction of the local magnetic field projection $B_{\perp}(r)$. If the rotation angle of the polarization ellipse $\chi$ is counted clockwise from the negative direction of the z-axis then $\cos(\chi) = B_{1z}/B_{\perp}$ and $\sin(\chi) = B_{1x}/B_{\perp}$, so

$$\tilde{Q}(r, t, \nu) = \frac{3\nu^3}{mc^2 \nu_c^2} B_{\perp}(r) K_{2/3} \left( \frac{\nu}{\nu_c} \right) \frac{B_{1x}^2 - B_{1z}^2}{B_{\perp}^2}, \quad \tilde{U}(r, t, \nu) = \frac{3\nu^3}{mc^2 \nu_c^2} B_{\perp}(r) K_{2/3} \left( \frac{\nu}{\nu_c} \right) \frac{2B_{1x}B_{1z}}{B_{\perp}^2}.$$

It is evident that in the case of the isotropic turbulence $\langle \tilde{Q}(r, t, \nu) \rangle = 0$, $\langle \tilde{U}(r, t, \nu) \rangle = 0$. In reality the stochastic ensemble is not full so the average is not zero but it is substantially suppressed. If in the case of the anisotropic turbulence the axis of symmetry coincides with axis Ox (or Oy) then $\langle B_{1y}^2 \rangle \neq \langle B_{1x}^2 \rangle$ and $\langle \tilde{Q}(r, t, \nu) \rangle \neq 0$ while $\langle \tilde{U}(r, t, \nu) \rangle = 0$. If $B_{1x}^2/B_{\perp}^2$ is high then $\langle \tilde{Q}(r, t, \nu) \rangle$ can be close to the value of the homogeneous magnetic field and polarization can be close to the maximum theoretical limit.
Figure 2. The model synchrotron images at 5keV. The total emission is in the left panel, the polarized emission is in the middle panel while the polarization degree is in the right panel. In the left column the images have the angular resolution of 1.2 arcsec while in the right column the images are shown after the convolution with XIPE PSF. The first and second rows show the maps for an isotropic turbulence case and anisotropic turbulence case with $\xi = 5$ and value of the spectral index of magnetic field fluctuations $\delta = 5/3$. The third and forth rows show maps for an isotropic turbulence case and anisotropic turbulence case with $\xi = 5$ and $\delta = 1$. 
3. Discussion

Based on the model described above we constructed X-ray intensity and polarization maps with angular resolution of 1.2 arcsec. We also constructed maps with the lower angular resolution expected for the next generation X-ray polarimeters such as XIPE or IXPE. To do so we used the PSF of polarimeter XIPE [17]. Simulations were made for both the isotropic and the anisotropic magnetic turbulence with $\xi = 5$ and the spectral indexes $\delta = 1$ (strong CR-driven turbulence) and $\delta = 5/3$ (Kolmogorov turbulence). The simulated synchrotron X-ray images at the photon energy 5 keV are shown in Figure 2 for different values of $\delta$. The spectral index determines the relative sizes of the magnetic structures at the high resolution intensity and polarization images.

The influence of anisotropy on the degree of polarization is also clearly seen in Figure 2. The XIPE PSF width exceeds the smallest sizes of the image structure, so after convolution the difference in the small scale structure becomes much less prominent, and the intensity images obtained for turbulent fields with different power spectrum look almost the same. On the other hand the difference in the polarization degree is still present after the convolution, so future X-ray polarimeters could constrain the level of anisotropy of the magnetic turbulence in SNRs.

We show that in the case of the high anisotropy of the magnetic field turbulence the polarization degree can be close to the maximum possible theoretical limit attainable in the case of the homogeneous magnetic field. The difference between the case of the highly anisotropic turbulence and the case of the homogeneous magnetic field is that in the latter case the total emission from SNR is highly polarized. While in the case of the turbulent field only some polarized patches of various scales can be seen in the spatially resolved X-ray images.

Acknowledgments

The authors acknowledge support from RSF grant 16-12-10225. Most calculations were done on computers of the RAS JSCC, St. Petersburg department of the RAS JSCC and on the Tornado cluster of SPbGTU.

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