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MODELING OF X-RAY STRIPES IN TYCHO'S SUPERNOVA REMNANT

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Abstract: Chandra observations of Tycho's supernova remnant (SNR 1572) allowed us to get high-resolution X-ray images of SNR. It was discovered that there are several series of coherent X-ray structures (bright, almost parallel stripes) in some regions of SNR. It is likely that the observed radiation of Tycho's SNR is synchrotron radiation of electrons with energies about 10^{14} eV. We develop a model, which represents synchrotron X-ray images of Tycho's SNR in order to reveal the physical mechanism of the observed structures formation. The model allows one to connect the bright stripes with a specific mechanism of the energetic particle transport in SNR. In particular, it is shown that the mirror instability, which evolves in plasma near SNR shock as a result of anisotropic distribution function of electrons, can be the reason of the observed stripes.

Keywords: supernova remnants, mirror instability, synchrotron radiation, superdiffusion

Introduction

Supernova remnants are very interesting and important objects for high energy astrophysics. Inside the remnant non-trivial configurations of magnetic field, density and pressure can occur. Observations and modeling of SNRs are necessary to shed light on physical properties and chemical composition of SNR.

Firstly the results of Chandra observations with series of X-ray stripes were published by Eriksen et al. in 2011[1]. In that paper there was also a first attempt to give explanation to the existence of such an ordered structure. In the same year, Bykov et.al. [2] performed modeling of synchrotron radiation of electrons in a magnetic field, amplified by Bell instability, which was supposed to be the main reason of the stripes. However, understanding the true origin of Tycho’s stripes remains a challenge for high energy astrophysics.

The aim of this work is not only to make a model to fit the observations, but also to reveal physical processes which are standing behind the observed structures. It is likely that the stripes occur as a result of synchrotron radiation of electrons in modulated magnetic field. The scientific novelty of our research is in taking into account mirror instability. We assume that mirror instability can be the reason of modulation and amplification of the magnetic field in the remnant. Mirror instability arises when there is quadrupole anisotropy of a particle distribution function, which, in turn, exists, when particle transport is superdiffusive. Unlike Bell instability, mirror instability affects both magnetic field and distribution function of electrons, and, which is the most important, mirror instability is long-wavelength.

Electron distribution function and mirror instability

We can model electron distribution function near the front of a collisionless shock wave using Monte Carlo (MC) simulations (the method is described by Bykov et.al. in [3]). As it was already said above, mirror instability occurs only with non-zero quadrupole anisotropy of a distribution function. Because of that we use a superdiffusive (i.e. $\langle \Delta x^2 \rangle \sim \Delta t^\delta$; $\delta > 1$) model of particle propagation in simulations. Although in [3] the shock wave front is plane, the results of this method can be used in our work, because at small distances from the front we can neglect its sphericity.

The electron distribution function with the second anisotropy has the form:

$$f_0(p,\mu) = \frac{n_{cr} N(p)}{4\pi}\left[1 + \frac{\chi}{2}(3\mu^2 - 1)\right] \tag{2.1}$$

Here, χ is the parameter of anisotropy, $\mu = \cos\theta$, where θ is an angle between velocity and background magnetic field $\mathbf{B}_0$. The dispersion relation for mirror instability can be derived from linearized fluid mechanics equations (for background plasma) and kinetic equation (for energetic electrons), where anisotropic electron distribution function (2.1) should be used. All the parameters of plasma are defined as $\xi = \xi_0 + \delta\xi, \delta\xi \propto e^{i\mathbf{kr} - i\omega t}$. The dispersion relation has the form [3]:

$$\omega_{mir}^2 = \left(v_a^2 + a_0^2 + 2\frac{\delta P}{\rho_0}\right)k^2 \tag{2.2}$$

Here, v_a is the Alfven velocity, $a_0 = \sqrt{\frac{\gamma_g p_0}{\rho_0}}$, $\delta P = P_\parallel - P_\perp = \frac{3\chi}{5}P_0$, $P_0 = \frac{n_{cr}}{3}\int_0^\infty v p^3 N(p) dp$. Equation (2.2) shows that magnetic field modes (we are mostly interested in a mode, parallel to the background field $\delta B_z \propto e^{i\mathbf{kr} - i\omega t}$) are growing, when $\delta P \propto \chi < 0$. Thus, the physical explanation of mirror instability is anisotropic pressure of electrons. The complete derivation of the formula (2.2) can be found in [3].

We also should take into account the modulation of the distribution function by mirror instability. It transforms into $f = f_0 + \delta f$, where

$$\delta f \approx \frac{\delta B_z}{B_0}\frac{n_{cr} N(p)}{4\pi}\frac{3\chi}{2}\sin^2\theta \tag{2.3}$$

Hence, distribution function oscillates due to the oscillations of *z*-component of the magnetic field.

Modeling of the magnetic field

As it follows from the MC simulation [3], the best amplified mode (as a result of mirror instability) is the mode with $k_0 r_{g0} = 2\cdot 10^{-7}$, where $r_{g0} = \frac{mcu_{sh}}{eB_0}$, $u_{sh} = 5\cdot 10^8 cm/s$ is a shock velocity, $B_0 = 3\ \mu G$ is the background (interstellar) magnetic field. Its growth rate gives $\frac{\delta B_z}{B_0} \approx 3$. We put in the code the magnetic field in the remnant as:

$$B^2 = B_0^2 + B_{rand}^2 + B_{mode}^2 \tag{3.1}$$

The total magnetic field in the remnant is the sum of background field, mode, amplified by mirror instability and random magnetic field, which necessarily occurs near the shock wave. The random part of the magnetic field in our code is just a sum of plane waves with random phases, wavevectors and polarizations. The rate of a total magnetic field is defined by MC simulations.

Synchrotron radiation modeling

To get the intensity of synchrotron radiation of electrons we use a formula from [4]:

$$J(\nu,k) = \frac{\sqrt{3}e^3}{mc^2}\int\left\{N(E,\mathbf{r},\mathbf{k})B\sin\theta\,\frac{\nu}{\nu_c}\int_{\frac{\nu}{\nu_c}}^{\infty}K_{\frac{5}{3}}(\eta)d\eta\right\}dEdr \tag{4.1}$$

where

$$\nu_c = \frac{2eB_\perp}{4\pi mc}\left(\frac{E}{mc^2}\right)^2 \tag{4.2}$$

We have no need to perform a modeling of the whole remnant, so we compute the intensity of synchrotron radiation only for a small part of a remnant, where the stripes were discovered. To imitate the observed picture we integrate the intensity along the line of sight.

Results

The result of modeling is shown in fig.1.

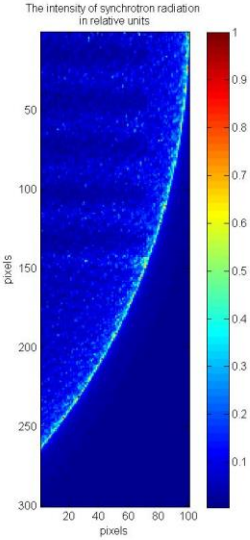

Fig. 1 The image of synchrotron radiation of Tycho's SNR with stripes. 1 pixel corresponds to 0.01 pc.

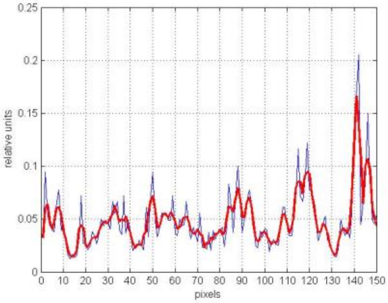

Fig. 2 The intensity of stripes in relative units.

One can see a series of parallel stripes appearing. The distance between stripes in our calculations is $\lambda = \frac{2\pi}{k_0} \approx 5.2 \cdot 10^{17} cm$, while the observed distance is $8'' \approx 4.56 \cdot 10^{17} cm$ [1]. So, we can say that the distances received by modeling correspond well with the observations.

The other parameter of stripes is their brightness. Fig. 2 shows that the ratio between intensities of stripe and non-stripe regions is from 2 to 8. From Chandra [5] image it is visible that for brightest stripes that ratio can reach 10, but the average value also corresponds with our model.

Conclusions

The model results presented in Fig.1 are in a reasonably good correspondence with the observations by Chandra. It gives a satisfactory explanation for appearing a highly-ordered structure in the radiation of Tycho’s supernova remnant. Moreover, if the stripes are indeed produced by the mirror instability then the superdiffusive particle transport should be considered as a plausible mechanism in the supernova remnants.

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ANALYTICAL TIME-DEPENDENT INSTANTANEOUS FREQUENCY THEORY OF CHARGED PARTICLE MOTION IN ELECTROMAGNETIC FIELDS IN SPACE

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Abstract: A theoretical analysis has been carried out by means of novel differential equation for charged particles motion in electromagnetic fields in space plasma.

Keywords: Space, plasma, charged particle, electromagnetic field.

Introduction

The Solar System and the Universe in whole are filled with space plasma. Plasmas occupy the magnetospheres of the Earth and