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Magnetic field in supernova remnant SN 1987A

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Abstract: A nonlinear kinetic theory of cosmic ray (CR) acceleration in supernova remnants is employed to investigate the properties of the remnant SN 1987A. It is shown that a large downstream magnetic field $B_d \approx 10$ mG is required to fit the existing observational data. Such a strong field together with the strong shock modification due to CR backreaction provides the steep and concave radioemission spectrum and considerable synchrotron cooling of high energy electrons which diminish their X-ray synchrotron flux below the observed Chandra flux which has to be considered as an upper limit for nonthermal X-ray emission. The expected γ-ray energy flux at TeV-energies at the current epoch is 2×10^{-13} erg/(cm^{2}s).

Introduction

Supernova (SN) 1987A occurred in the Large Magellanic Cloud. It has been extensively studied in all wavelengths from radio to γ-ray (for review see, e.g.[1]).

To describe the observed properties of nonthermal emission of SN 1987A we use here a nonlinear kinetic theory [2, 3]. The application of this theory to individual SNRs (see [4] for a review) has provided the explanation of the observed SNR properties under the assumption of strong interior magnetic field.

Model and Results

We use canonical values of stellar ejecta mass $M_{ej} = 10 M_{\odot}$, distance $d = 50$ kpc, hydrodynamic explosion energy $E_{sn} = 1.5 \times 10^{51}$ erg, e.g. [1]. During an initial period the shell material has a broad distribution in velocity v. The fastest part of this ejecta distribution can be described by a power law $dM_{ej}/dv \propto v^{2-k}$. We use a value $k = 8.6$ appropriate for SN 1987A [1].

Strongly nonuniform circumstellar medium (CSM) is a result of interaction of progenitors winds: dense slow RSG wind and subsequent fast and diluted BSG wind. During initial period after the explosion the SN shock propagated in the free BSG wind and reached after about a day ~ 1000 the termination shock in BSG wind, situated at the radial distance $R_T = 3.1 \times 10^{17}$ cm [5]. After that the SN shock propagates in the thermalized BSG wind of density ρ_B. Considerable rapid decrease of the SN shock speed occurred during the days $1500 - 2500$ [6] showed that SN shock entered the H II region of density $\rho_R \gg \rho_B$. Therefore we model the CSM density distribution at distances $r > R_T$ in the form

$$\rho_0 = \frac{\rho_B + \rho_R}{2} - \frac{\rho_B - \rho_R}{2} \tanh \frac{r - R_C}{l_C}, \quad (1)$$

where $R_C = 6.1 \times 10^{17}$ cm is the contact discontinuity between two winds, $l_C = 0.05 R_C$ is the scale of the smooth transition between them.

The analysis of the rapidly increasing X-ray emission provides the evidence that H II region in turn is not uniform: at day ~ 6200 the SN shock begins to interact with the dense inner ring. Its radial behavior can be represented in the form

$$\rho_R = \frac{\rho_{R1} + \rho_{R2}}{2} - \frac{\rho_{R1} - \rho_{R2}}{2} \tanh \frac{r - R_R}{l_R}, \quad (2)$$

where $R_R = 6.8 \times 10^{17}$ cm, $l_R = 0.08 R_R$, $\rho_{R2} \approx 20 \rho_{R1}$. Such a gas radial profile is close to what was extracted from the above analysis [7]. We adopt here for the gas number density $N_g = \rho/m_p$ the following values: $N_g^B = 0.29$ cm^{-3}, $N_g^{R1} = 280$ cm^{-3} and $N_g^{R2} = 4000$ cm^{-3}. Here m_p is the mass of proton. The value $N_g^{R1} = 280$ cm^{-3} which is by a factor of 1.5 lower than was used in our previous study [5], provides a good compromise between the SN shock dynamics seen in radio and in X-ray emissions (see below).

A rather high downstream magnetic field strength $B_d \sim 1$ mG is needed to reproduce the observed steep radio spectrum [5]. We believe that the required strength of the magnetic field have to be attributed to nonlinear field amplification at the SN shock by CR acceleration itself. According to plasma physical considerations [8, 9], the existing CSM magnetic field can indeed be significantly amplified at a strong shock by CR streaming instabilities. In fact, for all the thoroughly studied young SNRs, the ratio of magnetic field energy density $B_0^2/8\pi$ in the upstream region of the shock precursor to the CR pressure P_c is about the same [10]. Here $B_0 = B_\mathrm{d}/\sigma$ is the far upstream field presumably amplified by CRs of highest energy, σ is the total shock compression ratio. Within an error of about 50 percent we have $B_0^2/(8\pi P_c) \approx 5 \times 10^{-3}$. CR pressure in young SNRs has a typical value $P_c \approx 0.5\rho_0 V_s^2$, therefore we adopt here upstream magnetic field

$$B_0 = \sqrt{2\pi \times 10^{-3}\rho_0 V_s^2}. \qquad (3)$$

Since the process of magnetic field amplification is not included in our theory we simply postulate the existence of far upstream field B_0 given by Eq.(3). We start our consideration from the SNR evolutionary epoch $t = 1000$ d, when the outer SN shock has a radius $R_i = R_T$ and speed $V_i = 28000$ km/s. These values of R_s and V_s according to our calculations [5] correspond to the end of SN shock propagation in the free BSG wind region $r < R_T$. We neglect the contribution of CRs accelerated in the region $r < R_T$, because due to a high gas density the number of CRs produced in the region $r > R_T$ very soon becomes dominant.

Calculated shock radius R_s and speed V_s shown in Fig.1a as a function of time are in satisfactory agreement with the values obtained on the basis of radio and X-ray measurements.

To fit the spectral shape of the observed radio emission we assume a proton injection rate $\eta = 3 \times 10^{-3}$, which is a fraction of gas particles involved into the acceleration at the from of SN shock. This

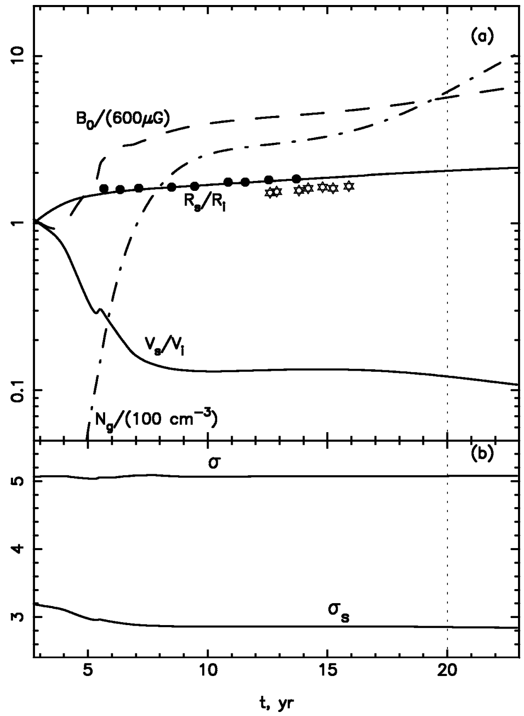

Figure 1: (a) Shock radius R_s, shock speed V_s, gas density N_g and upstream magnetic field B_0 at the current shock position; (b) total shock (σ) and subshock (σ_s) compression ratios as functions of time. The *dotted vertical line* marks the current epoch. The observed radius of the SN shock, as determined by radio [11] and X-ray measurements [7], are shown by circles and stars respectively. The scaling values are $R_i = R_T = 3.1 \times 10^{17}$ cm and $V_i = 28000$ km/s.

leads to a significant nonlinear modification of the shock: as it is seen in Fig.1b total shock compression ratio $\sigma \approx 5.1$ is essentially larger and a subshock compression ratio $\sigma_s \approx 2.8$ is lower than classical value 4.

Strongly modified SN shock generates CR spectrum $N \propto p^{-\gamma}$, which is very steep at momenta $p < m_p c$, with index $\gamma = (\sigma_s+2)/(\sigma_s-1) \approx 2.7$. CR electrons with such a spectrum produces synchrotron radioemission spectrum $S_\nu \propto \nu^{-\alpha}$ with spectral index $\alpha = (\gamma - 1)/2 \approx 0.9$, that very well corresponds to the experiment, as it is seen in Fig.2, where we present synchrotron energy spectra νS_ν, calculated for five subsequent epoch to-

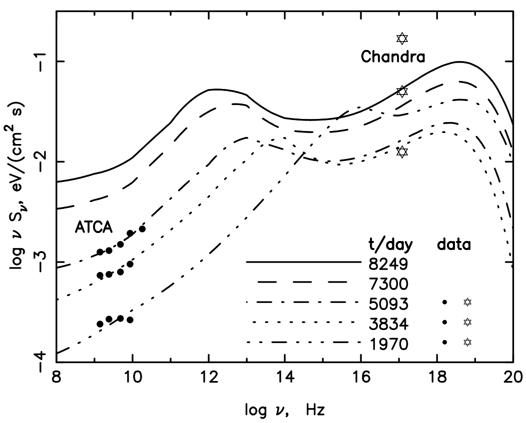

Figure 2: Synchrotron energy spectrum of SN 1987A, calculated for the five evolutionary epochs. The *ATCA* radio [11, 12] and Chandra X-ray [7] data for three epochs are shown as well. Higher measured fluxes correspond to later epoch.

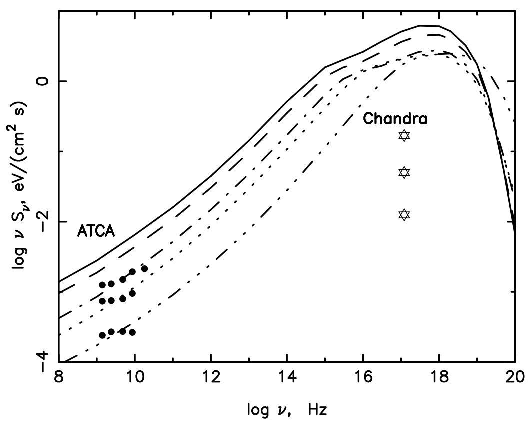

Figure 3: Same as in Fig.2, but the calculations are for the case of constant upstream magnetic field $B_0 = 200\ \mu$G.

gether with the experimental data. Note that CR spectrum has a concave shape: it becomes flatter at higher momenta p. As a consequence synchrotron spectrum $S_\nu(\nu)$ is also concave as it is clearly seen in Fig.2 at $\nu < 10^{12}$ Hz. Radio data reveal this property in good consistency with theoretical prediction.

Strong downstream magnetic field $B_d \approx 15$ mG, that corresponds to the upstream field $B_0 \approx 3$ mG (see Fig.1), provides synchrotron cooling of electrons with momenta $p > 10 m_p c$ that in turn makes synchrotron spectrum at high frequencies $\nu > 10^{12}$ Hz very steep (see Fig.2). Concave shape of electrons continuously produced at the shock front together with their synchrotron cooling lead to a formation of two peaks in synchrotron energy spectrum νS_ν. The first one at $\nu \approx 10^{12}$ Hz corresponds to CR electron momentum $p \approx 10 m_p c$ above which synchrotron energy looses are relevant, whereas the second peak at $\nu \approx 10^{18}$ Hz corresponds to the maximum momentum $p \approx 10^4 m_p c$ of accelerated electrons. Under this condition calculated synchrotron flux at frequency $\nu \approx 10^{17}$ Hz, which corresponds to the photon energy $\epsilon_\gamma = 0.5$ keV, is below the measured flux at the epochs $t > 3000$ d. Since the contribution of the nonthermal radiation in the observed X-ray emission of SN 1987A is not very well known, e.g. [13], the observed X-ray flux has to be considered as the upper limit for the expected nonthermal emission. At early epoch $t < 2500$ d however the calculated flux exceeds the measured one (see the curve, corresponding $t = 1970$ d in Fig.2). This can be considered as indication, that the actual magnetic field B_0 is few times larger then given by the Eq.(3).

To illustrate the situation expected at considerably lower magnetic field we present in Fig.3 synchrotron energy spectra calculated at the same set of parameters as before except magnetic field, which was taken $B_0 = 200\ \mu$G independent of time. Since the interior magnetic field $B_d \approx 2$ mG ($\sigma \approx 10$) is essentially lower in this case, synchrotron losses of high energy CR electrons are considerably smaller compared with the previous case. Due to this fact synchrotron spectra considerably exceeds at any given epoch the measured Chandra flux. Therefore we can conclude, that the actual interior magnetic field strength is not lower than 5 mG.

Completely different possibility to have the synchrotron flux, which fit the radio data and goes below Chandra data, is low field scenario, when the magnetic field is as low as $B_0 < 2\ \mu$G. In such a case the cutoff frequency of synchrotron spectrum ν_{max} is lower than 10^{17} Hz and calculated fluxes go down exponentially at $\nu > \nu_{max}$ below Chandra points. However the value $B_0 < 2\ \mu$G is un-

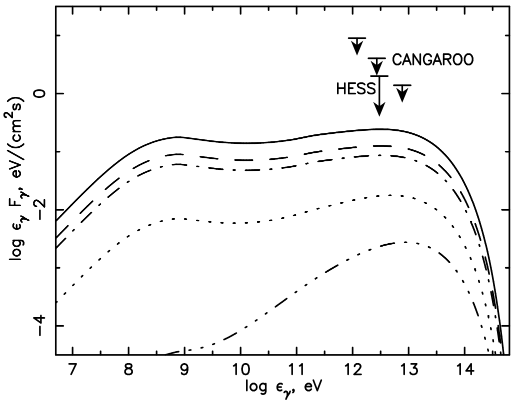

Figure 4: Integral γ-ray energy flux from SN 1987A, calculated for the same five epoch as in Fig.2. CANGAROO [14] and HESS [15] upper limits are shown as well.

realistically small for such a dense medium, which we have in SN 1987A. In addition the effective energy of electrons which radiate at $\nu \sim 1$ GHz in the interior field $B_d = 10\ \mu$G is about $\epsilon_e = 5$ GeV. The electron spectrum at GeV-energies is characterized by a power low index $\gamma \approx 2$ that is considerably smaller than what is required for the observed radio spectrum. Note that as it is seen in Fig.3 even the field $B_d \approx 2$ mG is too small to have a good fit of radio data as in Fig.2. Therefore low field scenario should be rejected.

Calculated γ-ray integral flux shown in Fig.4 at all energies is dominated by the π^0-decay component. Since the SN shock is strongly modified γ-ray spectrum at energies $\epsilon_\gamma > 0.1$ TeV is very hard: $F_\gamma \propto \epsilon_\gamma^{-0.9}$. At the current epoch the expected γ-ray energy flux at TeV-energies is about $\epsilon_\gamma F_\gamma \approx 2 \times 10^{-13}$ erg/(cm^{2}s) and during the next four years it expect to grow by a factor of two. The existence of strongly asymmetric CSM structure, which is dense inner ring, makes our prediction of γ-ray flux uncertain. According to the rough estimate this uncertainty is not very large, about a factor of two, due to the stronger SN shock deceleration in denser medium. At the moment there are only upper limits of TeV emission obtained by CANGAROO [14] and HESS [15] instruments (see Fig.4). The detection of γ-ray emission at these energies would imply clear evidence for a hadronic origin and for a strong magnetic field amplification inside SN 1987A.

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