Radio-, X-ray and Gamma-ray Emission Produced in SN 1006 by Accelerated Cosmic Rays

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Abstract

The kinetic nonlinear model of cosmic ray (CR) acceleration in supernova remnants (SNRs) is used to describe the properties of SN 1006 remnant. Calculated expansion law and radio-, X-ray and γ-ray emission produced in SN 1006 by accelerated CRs very well agree with the experiment. The π^0-decay γ-rays, generated by the nuclear CR component, and IC γ-rays, generated by CR electrons in the inverse Compton (IC) process on cosmic microwave background, give roughly equal contribution in the observed TeV γ-ray flux of SN 1006.

1 Introduction:

Lately a significant efforts were undertaken to get a direct experimental evidence that the nuclear component of CRs is generated in SNRs. The expected π^0-decay γ-ray emission generated in nearby SNRs by the accelerated protons in their collisions with medium nuclei is high enough to be detected by an imaging air Čerenkov telescopes (e.g. Drury et al., 1994; Berezhko & Völk, 1997). Positive results of such experiments would provide the direct evidence that SNRs are the main source of CRs in the Galaxy and what is the maximum energy of CRs generated in SNRs.

In this paper the kinetic selfconsistent theory of diffusive acceleration of CRs in SNRs (Berezhko et al., 1996; Berezhko & Völk, 1997) is used to explain properties of emission generated in SN 1006 by CR particles. The detailed comparison of theory with experiment permits to derive the most probable set of physical parameters for this object.

2 Model:

A supernova (SN) explosion produces an expanding shell of matter with some energy E_{sn} and mass M_{ej}. In the initial period the substance of the shell has a wide distribution by velocity v. The fastest part of this ejecta is described by the power law $dM_{ej}/dv \propto v^{2-k}$ (e.g. Chevalier, 1981; 1982). Interaction of the expanding shell with an interstellar medium (ISM) creates a strong shock which accelerates CR particles.

The kinetic nonlinear model for diffusive CR acceleration by SN expanded shock is based on the selfconsistent solution of the CR transport equation together with the gas dynamic equations in a spherical approach (Berezhko et al., 1996; Berezhko & Völk, 1997).

The number of suprathermal protons involved into the acceleration process is described by the dimensionless injection parameter η which is a fraction of ISM particles intersecting the shock front. For simplicity it is assumed that the injected particles have a velocity two times higher than the postshock sound speed.

The CR diffusion coefficient is taken in the form

$$\kappa(p) = \kappa(Mc)(p/Mc)^{\alpha}, \quad \alpha > 0.$$

Here M is the proton mass, p is the particle momentum, c is the speed of light.

The solution of dynamic equations at each time reproduces the CR spectrum and the spatial distributions of CRs and gas. This allows to calculate the expected flux $F_{\gamma}^{pp}(\epsilon_{\gamma})$ of γ-rays from π^0-decay originated in $p-p$ collisions of CRs with the medium nuclei (e.g. Berezhko & Völk, 1997).

If some amount of electrons are involved into the acceleration process, their distribution function $f_e(p) = K_{ep}f(p)$ differs only by some numerical factor K_{ep} from the proton distribution function $f(p)$. The factor K_{ep} is determined by the relation between electron and proton injection rates. One can expect that electrons are injected less effectively than protons due to much smaller mean free path. In the limiting case, when electrons are injected with the same rate as protons, we have $K_{ep} \simeq 10^{-2}$ (Bell, 1978).

The choice of value K_{ep} allows to determine the electron distribution function and to calculate the associate emission. The expected flux of synchrotron emission at the distance d from the SNR is determined by the expression (e.g. Berezinskii et al., 1990)

$$S_\nu = \frac{3\times 10^{-21}}{d^2}\int_{R_p}^{\infty} drr^2 B_\perp \int dpp^2 f_e(r,p) F\left(\frac{\nu}{\nu_c}\right) \qquad \frac{\text{erg}}{\text{cm}^2\ \text{s}},$$

where $F(x) = x\int_x^\infty K_{5/3}(x')dx'$; $K_\mu(x)$ is the modified Bessel function; $\nu_c = \frac{3}{4\pi}\frac{eB_\perp p^2}{(mc)^3}$; $-e$ and m is the charge and the mass of the electron; R_p is the piston radius, which separate the ejecta and the swept-up medium. We assume the simple relation $B_\perp = 0.5B$ between the regular magnetic field $B(r)$ and its perpendicular to a line of sight component $B_\perp$ and the expression for the magnetic field value in the disturbed region $B = B_0\rho/\rho_0$, where ρ is the gas density and subscript 0 corresponds to the undisturbed ISM.

The relativistic electrons produce the γ-ray emission due to inverse Compton (IC) scattering of background photons. It is not difficult to show that due to the relatively hard spectrum of accelerated electrons only the 2.7 K cosmic microwave background is important in the considered case. The expected integral flux of IC γ-rays with the energy greater than ϵ_γ can be represented in the form (e.g. Berezinskii et al. 1990):

$$F_\gamma^{IC}(\epsilon_\gamma) = \frac{4\pi\sigma_T N_{ph} c}{d^2}\int_0^\infty drr^2 \int_{p(\epsilon_\gamma)}^\infty dpp^2 f_e(r,p) \qquad \frac{\text{photon}}{\text{cm}^2\ \text{s}},$$

where $\sigma_T = 6.65\times 10^{-25}$ cm^2 is the Thomson cross-section, $N_{ph} = 373$ cm^{-3} is the number density of the microwave photons, $\epsilon_{ph} = 6.7\times 10^{-4}$ eV is their mean energy, $p(\epsilon_\gamma) = mc\sqrt{3\epsilon_\gamma/4\epsilon_{ph}}$.

3 Results and Discussion:

SN 1006 is the type Ia supernovae. Therefore we use in calculations the typical for SN Ia parameters: the ejected mass $M_{ej} = 1.4M_\odot$ and parameter $k = 7$ (Chevalier 1981, 1982), and consider the homogeneous ISM with the pressure $P_{g0} = 5.8\times 10^{-13}$dyne/cm^2 and the hydrogen number density N_H.

The problem is characterized by the scales of length, time and velocity:

$$R_0 = (3M_{ej}/4\pi\rho_0)^{1/3}, \quad t_0 = R_0/V_0, \quad V_0 = \sqrt{2E_{sn}/M_{ej}},$$

where $\rho_0 = 1.4MN_H$. The shock expansion law at the free expansion phase ($t < t_0$) is $R_s \propto E_{sn}^{(k-3)/2k}\rho_0^{-1/k}\times$ $\times t^{(k-3)/(k-2)}$ (Chevalier 1982), which for the value $k = 7$ gives $R_s \propto (E_{sn}^2/\rho_0)^{1/7}t^{4/5}$. At the adiabatic phase ($t \gtrsim t_0$) we have $R_s \propto (E_{sn}/\rho_0)^{1/5}t^{2/5}$.

The observed expansion law of SN 1006 (Moffett et al., 1993) is $R_s \propto t^\mu$ with $\mu = 0.48\pm 0.13$. One can conclude with some uncertainty that the SN 1006 current phase is the adiabatic one.

The parameter α determines the shape of the CR spectrum at high energies, where it has exponential form (e.g. Berezhko et al., 1996)

$$f(p) \propto p^{-q}\exp\left[-\frac{1}{\alpha}\left(\frac{p}{p_{max}}\right)^\alpha\right].$$

Here $3.5 \le q \le 4$ is the power law index at $p \sim p_{max}$. As in the previous paper by Ammosov et al. (1994), the value $\alpha = 0.5$ is taken to fit the observed X-ray spectrum of SN 1006. The maximum (or cutoff) momentum of accelerated CRs p_{max} is defined as a point where $d\ln f/d\ln p = -5$.

The calculations performed at $E_{sn} = 10^{51}$ erg, $N_H = 0.1$ cm^{-3}, $d = 1.7$ kpc, $B_0 = 9$ μG, κ(1 TeV)= $10\kappa_B$(1 TeV) together with the experimental data are shown in Fig.1, where κ_B is the Bohm diffusion coefficient.

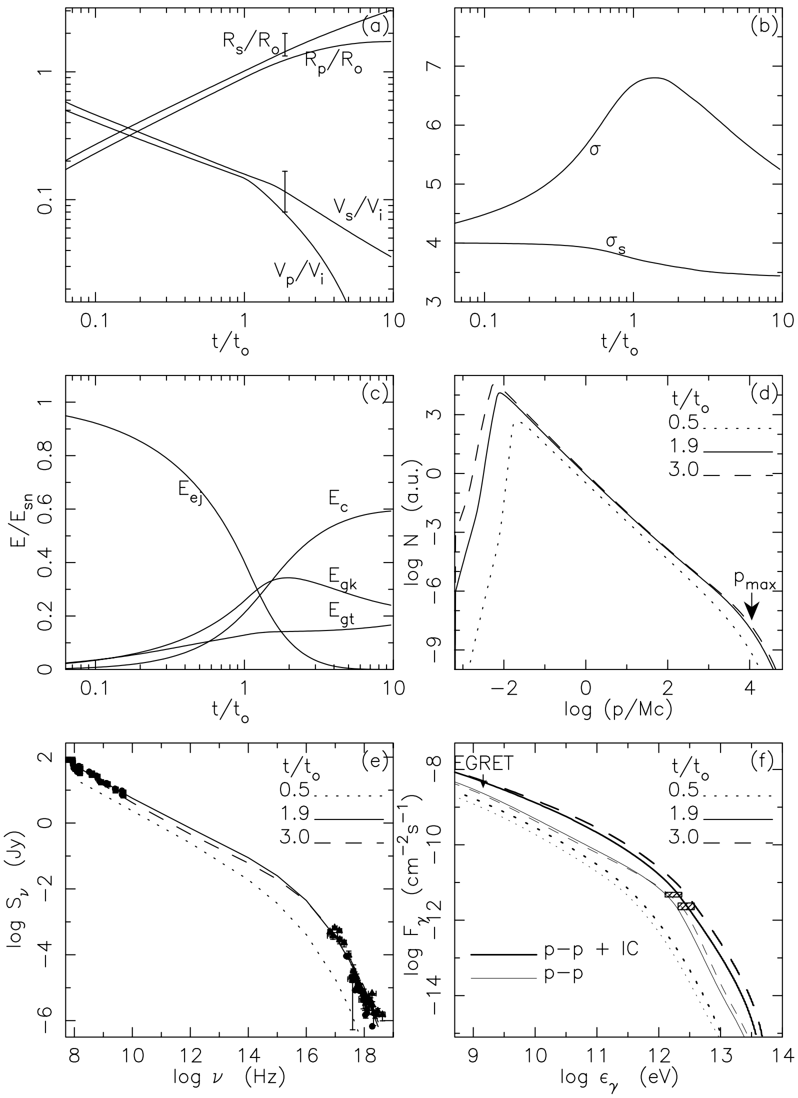

Figure 1: Shock (R_s) and piston (R_p) radii, shock (V_s) and piston (V_p) velocities (a); total shock (σ) and subshock (σ_s) compression ratios (b); ejecta (E_{ej}), CR (E_c), gas thermal (E_{gt}) and gas kinetic (E_{gk}) energies (c) as a function of time; overall momentum spectrum of accelerated protons (d); synchrotron emission flux as a function of frequency (e); total γ-ray flux (thick lines) and π^0-decay γ-ray flux F_γ^{pp} (thin lines) as a function of γ-ray energy (f) for three different evolutionary phases (solid lines correspond to the current stage of SN 1006 evolution) for $E_{sn} = 10^{51}$ erg, $M_{ej} = 1.4 M_\odot$, $V_i = 30000$ km/s (the initial piston speed), $N_H = 0.1$ cm^{-3} $B_0 = 9$ μG, $\eta = 5 \times 10^{-4}$, $K_{ep} = 2 \times 10^{-3}$. Scale values are $R_0 = 4.6$ pc, $t_0 = 530$ years. Experimental radio-emission (Reynolds, 1996) X-ray (Hamilton et al., 1986) and γ-ray (Tanimori et al., 1998) spectra, size and speed of the shock (Moffett et al., 1993) are presented.

According to Fig.1a the SN 1006 is at the beginning of the adiabatic phase. The taken injection rate $\eta = 5 \times 10^{-4}$ provides a significant modification of the shock which at the current phase $t = 992$ yr has the total compression ratio $\sigma = 6.7$ and the subshock compression ratio $\sigma_s = 3.6$ (Fig.1b).

The acceleration process is characterized by the high efficiency: at the current phase $t/t_0 = 1.9$ about 40% of the explosion energy has been already transferred to CRs and the CR energy content E_c continues to increase (Fig.1c).

The overall (i.e. integrated over the whole space) CR spectrum $N(p,t) = 16\pi^2 p^2 \int_0^\infty dr r^2 f(r,p,t)$ has almost pure power law form $N \propto p^{-2}$ in a wide momentum range from $10^{-2} Mc$ up to the cutoff momentum $p_{max} = \epsilon_{max}/c$, where $\epsilon_{max} \approx 10^{13}$ eV is the maximum CR energy (Fig.1d).

The parameter $K_{ep} = 2 \times 10^{-3}$ provides a good agreement of calculated and measured synchrotron emission in radio- and in X-ray ranges (Fig.1e). Note, that due to the nonlinear effects (e.g. Berezhko et al., 1996) the electrons with momenta $p/Mc \lesssim 10$ ($\epsilon_e \lesssim 10$ GeV), which produce synchrotron emission at $\nu \lesssim 10$ GHz, has the spectrum $N_e \propto p^{-2.1}$ that leads to the expected radioemission spectrum $S \propto \nu^{-0.55}$ which perfectly fit the experimental data (Fig.1e).

According to the calculation (Fig.1f) two different channels (p-p and IC) of γ-ray production gives almost equal contribution to the total flux $F_\gamma = F_\gamma^{pp} + F_\gamma^{IC}$ of SN 1006. The calculation is in a good agreement with measurements made at TeV-energies on CANGAROO telescope (Tanimori et al., 1998) and it does not contradict the EGRET upper limit $F_\gamma^E = 8 \times 10^{-9}$ cm^{-2}s^{-1} at $\epsilon_\gamma = 1.4$ GeV (Mastichiadis & De Jager, 1996).

The agreement between the theory and the experiment can be achieved also at the essentially different sets of parameters. Nevertheless, the above set of parameters has to be considered as the most preferable one due to the following reasons. The decrease of the injection rate η at the same ISM number density $N_H = 0.1$ cm^{-3} leads to the increase of the required parameter value K_{ep} so that at $\eta < 5 \times 10^{-5}$ it becomes greater than 0.01. In this case the electron injection rate is unacceptably high because it exceeds the proton injection rate. The same takes place at $N_H < 0.05$ cm^{-3}.

At high ISM density $N_H \gg 0.1$ cm^{-3} γ-rays generated by CR nuclear component becomes dominant in the TeV-energy range. Since the π^0-decay γ-ray spectrum is steeper than the IC one, the predicted γ-ray flux $F_\gamma(\epsilon_\gamma = 1.4$ GeV) at the most appropriate injection $\eta \gtrsim 10^{-4}$ exceeds the EGRET upper limit F_γ^E.

Note, that electrons with relatively low energy $\epsilon \lesssim 10$ GeV, the synchrotron emission of which lies in a radio-band, occupy a very thin region of thickness $\Delta r \simeq R_s/(3\sigma) \simeq 0.05 R_s$ behind the shock front, whereas highest energy electrons which generates X-ray and TeV γ-ray emission, occupy almost uniformly the whole SNR volume. Therefore, the required magnetic field value in the downstream region $B \simeq 30\ \mu$G is significantly larger as compared with simple estimations (Mastichiadis & De Jager, 1996; Tanimori et al., 1998) which uses unrealistic assumption that particles fill the same volume independently of their energy. It leads to a relative decrease of IC TeV γ-ray production because the larger magnetic field at given radio-emission flux means the lower total number of accelerated electrons.

One has to mention also an observational argument which indicates in favor of an essential role of CR nuclear component in the production of the observed TeV γ-rays. The measured γ-ray flux was detected from the same outer part of SN 1006 which produces the radio-emission. Such a situation is expected to be for π^0-decay γ-rays because the swept-up gas density distribution which determines the γ-ray production rate, has a peak value just at the shock front. In contrast, the maximum of IC γ-ray emission is expected from the central part of the remnant.

Therefore, one can conclude that the π^0-decay γ-rays generated by the nuclear CR component and IC γ-rays generated by the electronic CR component provide roughly the equal contribution in the observed TeV γ-ray flux of SN 1006 and that SN 1006 gives some evidence that the nuclear CR component is indeed produced in SNRs.

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