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# Emission of SN 1006 produced by accelerated cosmic rays

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**Abstract.** The nonlinear kinetic model of cosmic ray (CR) acceleration in supernova remnants (SNRs) is used to describe the properties of the remnant of SN 1006. The calculated expansion law and the radio-, X-ray and $\gamma$-ray emission produced in SN 1006 by accelerated CRs agree quite well with the observations. The $\pi^0$-decay $\gamma$-rays, generated by the nuclear CR component, dominate over the IC $\gamma$-ray component, generated by CR electrons in the inverse Compton (IC) process on the cosmic microwave background, in the observed TeV $\gamma$-ray flux from SN 1006. The predicted integral $\gamma$-ray flux $F_\gamma \propto \epsilon_\gamma^{-1}$ extends up to energies $\sim 100$ TeV if CR diffusion is as strong as the Bohm limit.

## 1 Introduction

Recently significant efforts were undertaken to obtain direct observational evidence whether CRs are indeed generated in SNRs. The expected $\pi^0$-decay $\gamma$-ray emission, produced in nearby SNRs by the accelerated protons in their collisions with gas nuclei, is high enough to be detectable by imaging atmospheric Cherenkov telescopes (e.g. Drury et al., 1994; Berezhko and Völk, 1997). Positive results of such observations would constitute a necessary condition for a dominant role of SNRs in the production of the Galactic CRs and their spectrum.

In this paper the selfconsistent kinetic model of diffusive acceleration of CRs in SNRs (Berezhko et al., 1996; Berezhko and Völk, 1997) is used to explain the $\gamma$-ray emission from SN 1006. The detailed comparison of theory with observations permits the derivation of a most probable set of physical parameters for this object. In contrast to a previous study (Berezhko et al., 1999) we restrict ourselves to the so-called Bohm limit for CR diffusion near the shock, presumably due to efficient Alfvén wave excitation by the accelerating particles themselves.

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## 2 Model

A supernova (SN) explosion ejects a shell of matter with total energy $E_{sn}$ and mass $M_{ej}$. During an initial period the shell material has a broad distribution in velocity $v$. The fastest part of these ejecta is described by a power law $dM_{ej}/dv \propto v^{2-k}$ (e.g. Jones et al., 1981; Chevalier, 1982). The interaction of the ejecta with the interstellar medium (ISM) creates a strong shock there which accelerates particles.

Our nonlinear model is based on a fully time-dependent solution of the CR transport equation together with the gas dynamic equations in spherical symmetry.

The number of suprathermal protons injected into the acceleration process is described by a dimensionless injection parameter $\eta$ which is a fixed fraction of the ISM particles entering the shock front. For simplicity it is assumed that the injected particles have a velocity four times higher than the postshock sound speed, although this is not a fully selfconsistent injection theory (e.g. Malkov and Drury, 2001).

The CR diffusion coefficient is taken as the Bohm limit

$$\kappa(p) = \kappa(Mc)(p/Mc),$$

where $\kappa(Mc) = Mc^2/(3eB)$, $e$ and $M$ are the proton charge and mass, $p$ denotes the particle momentum, $B$ is magnetic field, and $c$ is the speed of light.

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

If electrons are also involved in the acceleration process, their distribution function $f_e(p) = K_{ep}f(p)$ (at sufficiently low relativistic momenta $p < p_l$ where synchrotron losses are not important) differs only by a numerical factor $K_{ep}$ from the proton distribution function $f(p)$. Due to synchrotron losses, at higher momenta $p > p_l$, given by

$$\frac{p_l}{Mc} \approx \left(\frac{10^8 \text{ yr}}{t}\right)\left(\frac{10\ \mu\text{G}}{B_d}\right)^2,$$

where $B_d$ is the mean downstream magnetic field, and $t$ is the SNR age, the electron spectrum is softened to $f_e \propto p^{-5}$ and has a cutoff momentum

$$p^e_{max} \approx 20Mc\left(\frac{V_s}{\text{km/s}}\right)\sqrt{\frac{10(\sigma-1)}{\sigma}\left(\frac{10\ \mu\text{G}}{B_2}\right)},$$

where $V_s$ is the shock speed, $B_2$ is the postshock magnetic field strength, and $\sigma$ is the shock compression ratio; the synchrotron loss term is included in the transport equation for the electron distribution function $f_e(r,p,t)$. We assume that the maximum proton momentum $p_{max}$ which, in the case considered, is higher than $p^e_{max}$, is determined by geometric factors (Berezhko, 1996). The parameter $K_{ep}$ is determined by the ratio between the electron and the proton injection rates. One may expect that electrons are on average injected less effectively than protons due to their much smaller scattering mean free path. In the limiting case, when electrons are injected with the same rate as protons, at given energy, we have $K_{ep} \simeq 10^{-2}$ (Bell, 1978).

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

$$S_\nu = \frac{3\times 10^{-21}}{d^2}\int_{R_p}^{\infty} drr^2 B_\perp \int_0^\infty dpp^2 f_e(r,p) F\left(\frac{\nu}{\nu_c}\right)$$

in erg/(cm$^2$s), where $F(x) = x\int_x^\infty K_{5/3}(x')dx'$; $K_\mu(x)$ is the modified Bessel function; $\nu_c = 3eB_\perp p^2/[4\pi(mc)^3]$; $m$ is the electron mass; $R_p$ is the radius of the piston which separates the ejecta and the swept-up ISM. We assume the simple relation $B_\perp = 0.3B$ between the regular (mean) magnetic field strength $B(r)$ and its component $B_\perp$ perpendicular to the line of sight. In a young SNR like SN 1006 the ambient ISM magnetic field is swept into a quasi-spherical shell where its strength is about uniform.

The relativistic electrons produce $\gamma$-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 case considered. The expected integral flux of IC $\gamma$-rays with energy greater than $\epsilon_\gamma$ can be represented in the form (e.g. Berezinskii et al. 1990):

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

in photons/(cm$^2$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 microwave photons, $\epsilon_{ph} = 6.7\times 10^{-4}$ eV is their mean energy, and $p(\epsilon_\gamma) = mc\sqrt{3\epsilon_\gamma/4\epsilon_{ph}}$.

## 3 Results and Discussion

SN 1006 is a type Ia SN. Therefore we use typical SN Ia parameters in our calculations: ejected mass $M_{ej} = 1.4M_\odot$, $k = 7$, and a uniform ambient ISM with hydrogen number density $N_H = 0.3$ cm$^{-3}$ and temperature $T_0 = 10^4$ K. We adopt a distance $d = 1.8$ kpc, consistent with X-ray and optical imagery of the SN 1006 (Winkler and Long, 1997).

The gas dynamic problem is characterized by the following length, time and velocity scales:

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

where $\rho_0 = 1.4MN_H$ is the ISM mass density. The shock expansion law during the free expansion phase ($t < t_0$) is then $R_s \propto E_{sn}^{(k-3)/2k}\rho_0^{-1/k}t^{(k-3)/(k-2)}$ (Chevalier 1982) which for $k = 7$ gives $R_s \propto (E_{sn}^2/\rho_0)^{1/7}t^{4/5}$. In 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 $\mu = 0.48 \pm 0.13$. Within the observational errors SN 1006 should be in the adiabatic phase.

The calculations together with the experimental data are shown in Fig.1. An explosion energy $E_{sn} = 3\times 10^{51}$ erg is taken to fit the observed SNR size $R_s$ and its expansion rate $V_s$.

According to Fig.1a SN 1006 is indeed already in the adiabatic phase. The assumed injection rate $\eta = 10^{-4}$ leads to a significant modification of the shock which at the current time, $t = 995$ yr, has a total compression ratio $\sigma = 5.6$ and a subshock compression ratio $\sigma_s = 3.8$ (Fig.1b).

The acceleration process is characterized by a high efficiency in spherical symmetry: at the current time $t/t_0 = 4.68$ about 40% of the explosion energy has been already transferred to CRs and the CR energy content $E_c$ continues to increase to a maximum of about 50% in the later Sedov phase (Fig.1d), when particles start to leave the source. As usually predicted by the model, the CR acceleration efficiency is significantly higher than required for the average replenishment of the Galactic CRs by SNRs, corresponding to $E_c \approx 0.1E_{sn}$. This discrepancy can be attributed to the physical conditions at the shock surface which influence the injection efficiency. The magnetic field geometry is the most important factor: at the quasiperpendicular portion of the shock at least ion injection (and subsequent acceleration) is presumably depressed compared with the quasiparallel portion. Therefore the number of CRs, calculated within the spherically-symmetrical approximation, should be renormalized by this depression factor. Assuming SN 1006 to be an average Galactic CR source, the renormalizing factor should be 1/5. Based on these arguments, the fluxes presented in Fig.1e and 1f were calculated with 5 times less CRs than formally predicted by our model.

The volume-integrated CR spectrum

$$N(p,t) = 16\pi^2 p^2 \int_0^\infty drr^2 f(r,p,t)$$

has, for the case of protons, almost a pure power law form $N \propto p^{-2}$ over a wide momentum range from $10^{-2}Mc$ up to the cutoff momentum $p_{max} = \epsilon_{max}/c$, where $\epsilon_{max} \approx 2\times 10^{14}$ eV is the maximum CR energy (Fig.1c). The overall electron spectrum deviates from the power-law dependence $N_e \propto p^{-2}$ at high momenta $p > p_l \approx 10Mc$, due to the

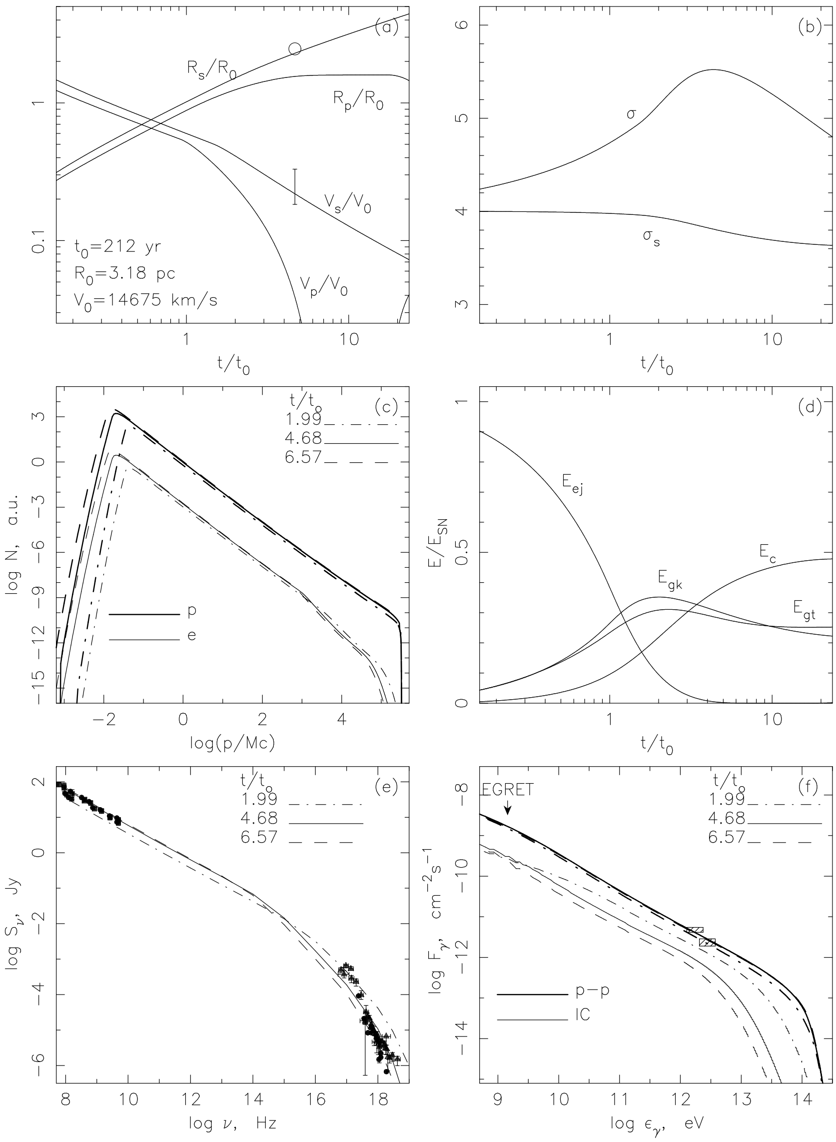


**Fig. 1.** Shock ($R_s$) and piston ($R_p$) radii, shock ($V_s$) and piston ($V_p$) velocities (a); total shock ($\sigma$) and subshock ($\sigma_s$) compression ratios (b); ejecta ($E_{ej}$), CR ($E_c$), gas thermal ($E_{gt}$) and gas kinetic ($E_{gk}$) energies (c) as a function of time; overall momentum spectrum of accelerated protons and electrons(d); synchrotron emission flux as a function of frequency (e); total $\gamma$-ray flux (thick lines) and $\pi^0$-decay $\gamma$-ray flux $F_\gamma^{pp}$ (thin lines) as a function of $\gamma$-ray energy (f) for three different evolutionary phases (solid lines correspond to the current stage of SN 1006 evolution) for $E_{sn} = 3 \times 10^{51}$ erg, $M_{ej} = 1.4 M_\odot$, $N_H = 0.3$ cm$^{-3}$, $d = 1.8$ kpc, $B_0 = 20\ \mu$G, $\eta = 10^{-4}$, $K_{ep} = 3 \times 10^{-3}$. Scale values are $R_0 = 3.2$ pc, $V_0 = 14675$ km/s, $t_0 = 212$ years. The observed radio-emission (Reynolds, 1996), the X-ray (Hamilton et al., 1986) and $\gamma$-ray (Tanimori et al., 1998) spectra, and the size and speed of the shock (Moffett et al., 1993), are shown as well.

synchrotron losses in the downstream region with magnetic field $B_d \sim 100\ \mu$G which is assumed uniform in this region ($B_d = B_2 = \sigma B_0$). The main part of the electrons with the highest energies $\epsilon \gtrsim 10$ TeV is produced at the end of the free expansion phase. At this stage $V_s \sim V_0$ which leads to a maximum electron momentum $p^e_{max} \leq 10^5 Mc$ in agreement with the numerical results (Fig.1c).

The parameter $K_{ep} = 3 \times 10^{-3}$ gives good agreement between calculated and measured synchrotron emission in the radio- and X-ray ranges (Fig.1e). Note, that due to 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, have a spectrum $N_e \propto p^{-2.1}$ that leads to the expected radio spectrum $S \propto \nu^{-0.55}$ which fits the experimental data very well (Fig.1e). A relatively high magnetic field strength $B_0 = 20\ \mu$G, compared with typical ISM values $B_0 = 5\ \mu$G, is required to give a smooth cutoff in the synchrotron spectrum $S(\nu)$ at frequencies $\nu = 10^{15} \div 10^{18}$ Hz. According to Lucek and Bell (2000), the existing ISM field can be significantly amplified near the shock by CR streaming.

According to the calculation, the hadronic $\gamma$-ray production exceeds the electron contribution by a factor of about 5 at energies $\epsilon_\gamma \lesssim 1$ TeV, and dominates at $\epsilon_\gamma > 10$ TeV (Fig.1f). The calculation is in reasonable agreement with the TeV-measurements reported by the CANGAROO collaboration (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 (cf. Mastichiadis and De Jager, 1996).

The $\gamma$-ray spectra produced by the electronic and hadronic CR components have closely similar shapes at the energies 10 GeV$< \epsilon_\gamma <$1 TeV due to the synchrotron losses of the electrons. Therefore, the only observational possibility to discriminate between leptonic and hadronic contributions is to measure the $\gamma$-ray spectrum at energies essentially higher than 1 TeV, where these two spectra are expected to be essentially different. The detection of a substantial flux at energies $\epsilon_\gamma \gtrsim 10$ TeV would provide direct evidence for its hadronic origin.

Note that the radio-emitting electrons with $\epsilon \lesssim 10$ GeV occupy a very thin region of thickness $\Delta r \simeq R_s/(3\sigma) \simeq 0.05R_s$ behind the shock front, whereas the highest energy electrons which generate the X-ray and TeV $\gamma$-ray emission, occupy the whole SNR volume almost uniformly. Therefore, the required magnetic field value $B \sim 100\ \mu$G in the downstream region is significantly larger compared with simple estimates (Mastichiadis and de Jager, 1996; Tanimori et al., 1998) which use the unrealistic assumption that particles fill the same volume independently of their energy. This leads to a relative decrease of IC TeV $\gamma$-ray production because a larger magnetic field at given radio-emission flux implies a lower total number of accelerated electrons.

There is also an observational argument favoring an essential role of the CR nuclear component. The reported $\gamma$-ray flux was detected from the same outer part of SN 1006 which shows the radio-emission. Such a situation is expected for $\pi^0$-decay $\gamma$-rays because the shocked gas density distribution which determines the $\gamma$-ray production rate, has a peak value just at the shock front. In contrast, the IC $\gamma$-ray emission is expected from the entire remnant if the TeV electrons are distributed uniformly there (Aharonian and Atoyan, 1999), or from a shell, if the electrons are confined to such a shell (see above).

## 4 Summary

The kinetic nonlinear model for CR acceleration in SNRs has been applied to SN 1006 in order to explain its observed properties. We have used stellar ejecta parameters $M_{ej} = 1.4M_\odot$, $k = 7$, distance $d = 1.8$ kpc, and ISM number density $N_H = 0.3$ cm$^{-3}$ from X-ray and optical imaginary of SN 1006. Two other physical parameters, explosion energy $E_{sn} = 3 \times 10^{51}$ erg and ISM magnetic field $B_0 = 20\ \mu$G, with rather high values, were taken to fit the observed size $R_s$ and expansion speed $V_s$ which are determined by the ratio $E_{sn}/N_H$, and the spectrum of the synchrotron radiation which is sensitive to the value of $B_0$, especially in the X-ray region. We cannot exclude that the required magnetic field strength, that is significantly higher than the rms ISM value $5\ \mu$G, might have to be attributed to its non-linear amplification near the SN shock by CR acceleration itself.

We find that after adjustment of the predictions of the nonlinear spherically-symmetric model by a renormalisation of the number of accelerated CRs to take account of the quasiperpendicular shock directions in a SNR, good consistency with all observational data can be achieved, including the reported TeV $\gamma$-ray flux.

The $\pi^0$-decay $\gamma$-ray flux produced by the nuclear CR component exceeds the flux of IC $\gamma$-rays generated by the electronic CR component at 1 TeV. Therefore the reported TeV flux from SN 1006 supports the idea that the nuclear CR component is indeed produced in SNRs.

The expected $\pi^0$-decay $\gamma$-ray flux $F_\gamma \propto \epsilon_\gamma^{-1}$ extends up to 100 TeV, whereas the IC $\gamma$-ray flux has a cutoff above a few TeV. Therefore the detection of $\gamma$-ray emission above $10$ TeV would imply evidence for a hadronic origin.

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