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Expected TeV gamma-ray emission from Tycho's supernova remnant

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Abstract. A nonlinear kinetic model of cosmic ray (CR) acceleration in supernova remnants (SNRs) is used to describe the properties of Tycho's SNR. Observations of the expansion law and of the radio and X-ray emission spectra, assumed to be synchrotron spectra, are used to constrain the astronomical and acceleration parameters of the system, in addition to independent estimates of the distance and thermal X-ray observations. The π^0-decay γ-ray flux turns out to be somewhat greater than the inverse Compton (IC) flux at 1 TeV, dominating it strongly at 10 TeV. The predicted TeV γ-ray flux is consistent with the very low upper limit recently obtained by HEGRA. A future detection at ~ 10 TeV would clearly indicate a hadronic emission.

1 Introduction

Tycho's supernova remnant (SNR) has recently been observed by the HEGRA stereoscopic system of imaging atmospheric Cherenkov telescopes (IACTs) on La Palma. This object has long been considered as a prototype candidate hadronic CR source in the Northern Hemisphere (e.g. Drury et al., 1994), although it was always clear that the sensitivity of the present generation of IACTs was marginal for a detection. In fact, after ~ 65 hours of observation time, HEGRA did not detect Tycho's SNR, but it could establish a very low 3σ upper flux limit of 5.78×10^{-13} photons cm^{-3} s^{-1}, or 33 milli-Crab, at energies > 1 TeV (Aharonian et al. 2001). This value is consistent with, but about a factor 4 lower than that previously published by the Whipple collaboration (Buckley et al. 1998), assuming a spectral index of -1.1 for the comparison. In the above HEGRA paper on Tycho the existing radio and X-ray synchrotron observations were used to infer a lower limit to the mean magnetic field strength in the remnant due to the nondetection of Inverse Compton (IC) emission. At the same time, published estimates of the hadronic π^0-decay gamma-ray emission (Berezhko and Völk, 1997; Völk, 1997) were employed and scaled to the parameters of Tycho's SNR, to compare with the upper flux limit. The predictions from the time-dependent kinetic model Berezhko et al., 1996) were also renormalized to take into account the expected deviations from spherical symmetry for a Type Ia SNR, and were found to be consistent with the present HEGRA nondetection in γ-rays, although the predicted flux values for the hadronic emission were only slightly smaller than the observational upper limit.

This tantalizing situation has prompted us to model the acceleration of both electrons and protons in some detail with the nonlinear kinetic theory, using the observed synchrotron emission as a constraint on the electron acceleration characteristics, and thereby to model hadronic and IC γ-ray emission simultaneously.

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 η 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 self-consistent injection theory (e.g. Malkov and Drury, 2001).

The CR diffusion coefficient is taken as the Bohm limit

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

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where $\kappa(Mc) = Mc^2/(3eB)$, e and M are the proton charge and mass, p denotes the particle momentum, B is magnetic field strength, 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 dynamic variables. This allows the calculation of the expected flux $F_\gamma^{pp}(\epsilon_\gamma)$ of γ-rays from π^0-decay due to $p-p$ collisions of CRs with the gas nuclei (e.g. Berezhko and Völk, 1997).

If electrons are also accelerated, 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 strength and t is the SNR age, the electron spectrum is softened to $f_e \propto p^{-5}$ and has a cutoff momentum

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

where V_s is the shock speed, B_2 is the postshock magnetic field strength, and σ 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 then to determine the electron distribution function and to calculate the associated emission. Details about this standard calculation are given in a companion paper on SN 1006 (Berezhko et al., these Proceedings).

3 Results and Discussion

Tycho was a SN of type Ia. Therefore we use typical SN Ia parameters in our calculations: ejected mass $M_{ej} = 1.4 M_\odot$, $k = 7$, and a uniform ambient ISM with hydrogen number density $N_H = 0.48$ cm^{-3} and temperature $T_0 = 10^4$ K. Following Aharonian et al. (2001) we adopt a distance $d =$ 2.3 kpc, and radius $\sim 4'$.

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 $\rho_0 = 1.4 M N_H$ 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 Tycho's SNR (Tan and Gull, 1985) is $R_s \propto t^\mu$ with $\mu = 0.46 \pm 0.02$. Tycho's SNR should be near the adiabatic phase.

The calculations together with the experimental data are shown in Fig.1. An explosion energy $E_{sn} = 0.27 \times 10^{51}$ erg is taken (in addition to the above ISM density, and the ejected mass) to fit the observed SNR size R_s and its expansion rate V_s.

According to Fig.1a Tycho is indeed nearing the adiabatic phase. The assumed injection rate $\eta = 10^{-4}$ leads to a significant nonlinear modification of the shock which at the current age of $t = 428$ yrs, has a total compression ratio $\sigma = 5$ and a subshock compression ratio $\sigma_s = 3.8$ (Fig.1b). This determines the radio spectral index (see below).

The acceleration process is characterized by a high efficiency in spherical symmetry: at the current time $t/t_0 = 0.7$ about 13% 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 31% 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 $E_c \approx 0.1 E_{sn}$. 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 quasi-perpendicular portions of the shock at least ion injection (and subsequent acceleration) is presumably depressed compared with the quasi-parallel portion. Therefore the number of CRs, calculated within the spherically-symmetrical approximation, should be renormalized by this depression factor. Assuming Tycho's SNR to be an average Galactic CR source, the renormalizing factor should be about 1/3. With this reduction, the hadronic gamma-ray flux should lie just below the HEGRA upper limit in Fig. 1f. Since the electron synchrotron, and thus also IC fluxes have to remain the same, fixed by the radio and X-ray observations, the *renormalized* K_{ep}-value is now $K^r_{ep} = 1.8 \times 10^{-2}$.

The volume-integrated CR spectrum

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

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 $p_{max} = \epsilon_{max}/c \approx 2 \times 10^{14}$ eV/c (Fig.1c). The overall electron spectrum deviates from the power-law dependence $N_e \propto p^{-2}$ at high momenta $p > p_l \gtrsim 10^3 Mc$, due to the synchrotron losses in the downstream region with magnetic field strength $B_d \lesssim 200\ \mu$G which is assumed uniform in this region ($B_d = B_2 \lesssim \sigma B_0$). The parameter $K_{ep} = 6 \times 10^{-3}$ (renormalized to $K^r_{ep} =$

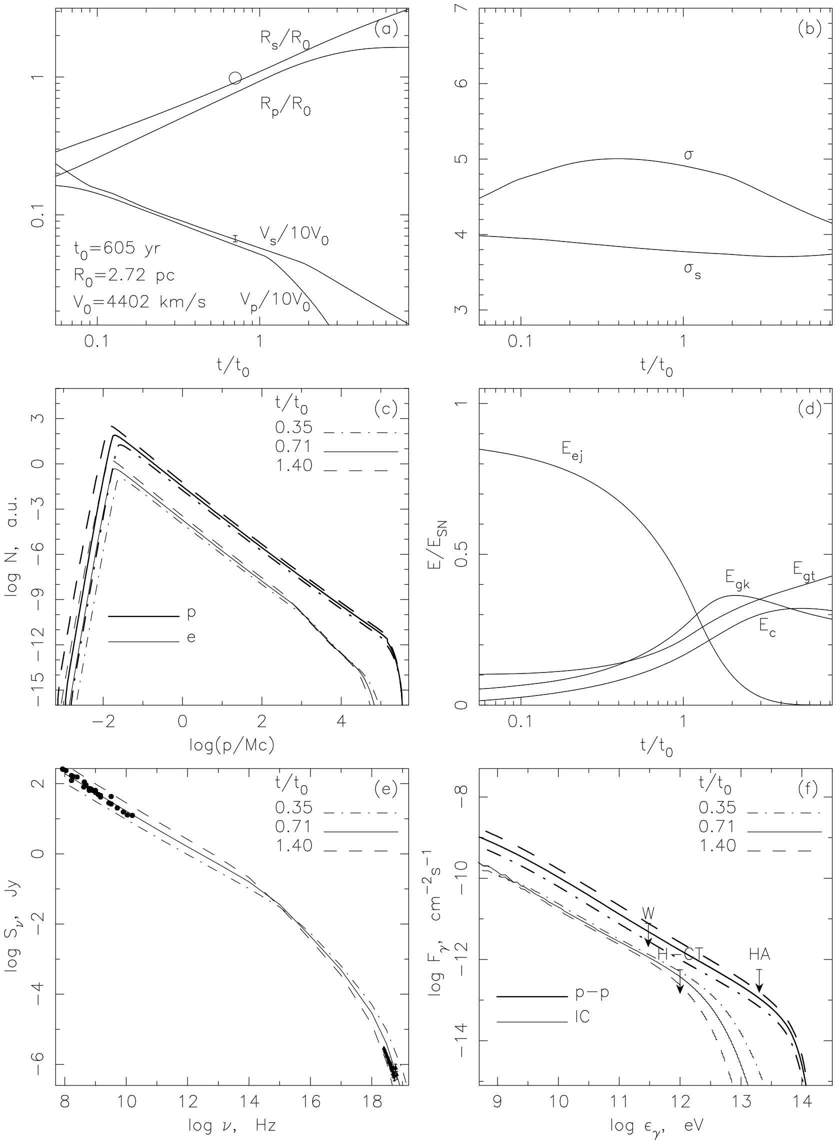

Fig. 1. Shock (R_s) and piston (R_p) radii, shock (V_s) and piston (V_p) velocities (a); total shock (σ) and subshock (σ_s) compression ratios (b); spatially integrated momentum spectra of accelerated protons and electrons (c); ejecta (E_{ej}), CR (E_c), gas thermal (E_{gt}) and gas kinetic (E_{gk}) energies, as a function of time (d); nonthermal radio-emission (Reynolds and Ellison, 1992), and nonthermal the X-ray emission (Allen et al., 1999) (e); integral (not renormalised, see text) π^0-decay γ-ray flux (thick lines) and IC γ-ray flux (thick lines) as a function of γ-ray energy ϵ_γ (f), for three different evolutionary phases (solid lines correspond to the current stage of Tycho's evolution) for $E_{sn} = 0.27 \times 10^{51}$ erg, $M_{ej} = 1.4 M_\odot$, $N_H = 0.48$ cm^{-3}, $d = 2.3$ kpc, $B_0 = 40\ \mu$G, $\eta = 10^{-4}$, $K_{ep} = 6 \times 10^{-3}$. Scale values are $R_0 = 2.72$ pc, $V_0 = 4402$ km/s, $t_0 = 605$ years. The observed γ-ray upper limits W – Whipple (Buckley et al., 1998), H-CT – HEGRA IACT-system (Aharonian et al., 2001), HA – HEGRA AIROBICC (Prahl et al., 1997), are shown as well.

1.8×10^{-2}) gives reasonable agreement between calculated and measured synchrotron emission in the radio- and X-ray ranges (Fig.1e). Due to the nonlinear effects, the electrons produce a radio spectrum $S \propto \nu^{-0.6}$ which fits the experimental data quite well (Fig.1e). A high magnetic field strength $B_0 = 40\ \mu$G, compared with typical ISM rms values $B_0 = 5\ \mu$G, is required to give a smooth turnover in the synchrotron spectrum $S(\nu)$ from frequencies $\nu \sim 10^{15}$ Hz to $\sim 10^{18}$ Hz. This might be partially explainable by larger fields in high density regions swept up by the SNR shock (Reynoso et al., 1999). In addition, according to the recent nonlinear wave model by Lucek and Bell (2000), the existing ISM field can be significantly amplified near the shock by the CR streaming instability.

According to the calculation, the renormalized hadronic γ-ray production exceeds the electron contribution by a factor of about 1.7 at energies $\epsilon_\gamma \lesssim 1$ TeV, and dominates at $\epsilon_\gamma > 10$ TeV by a factor ~ 35 (Fig.1f). The total (ie. hadronic + IC) renormalized γ-ray flux is by a factor of 1.6 larger than the HEGRA upper limit at 1 TeV. It could be lowered by reducing the values for E_{sn} and/or N_H, keeping E_{sn}^2/N_H fixed, but we shall of course not be concerned with any fine tuning of model parameters here. Basically, the model prediction corresponds to the observational upper limt, confirming the previous simple estimates (Aharonian et al., 2001).

The γ-ray spectra produced by the electronic and hadronic CR components have closely similar shapes at the energies 10 GeV$\lesssim \epsilon_\gamma \lesssim$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 γ-ray spectrum at energies significantly 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 $\Delta r \simeq R_s/(3\sigma) \simeq 0.05 R_s$ behind the shock front, whereas the highest energy electrons which generate the X-ray and TeV γ-ray emission, occupy the whole SNR volume almost uniformly. Therefore, the required magnetic field value is $B \sim 200$ μG in the downstream region.

This leads to a relative decrease of the IC TeV γ-ray production because a larger magnetic field at given radio-emission flux implies a lower total number of accelerated electrons.

4 Summary

The kinetic nonlinear model for CR acceleration in SNRs has been applied to Tycho's SNR in order to compare its results with the recently found very low observational upper limit for the TeV γ-ray flux. We have used stellar ejecta parameters $M_{ej} = 1.4 M_{\odot}$, $k = 7$, distance $d = 2.3$ kpc, and ISM number density $N_H = 0.48$ cm^{-3}. Two other physical parameters, the explosion energy $E_{sn} = 0.27 \times 10^{51}$ erg and a rather high upstream magnetic field strength $B_0 = 40$ μG, were taken to fit the observed size R_s and expansion speed V_s which are determined by the ratio E_{sn}^2/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 μG, might have to be attributed in part 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, quite a reasonable consistency with most of the observational data can be achieved. The total (hadronic + IC) γ-ray flux at 1 TeV (with the π^0-decay component exceeding the IC component) is slightly larger than the observational upper limit from the HEGRA experiment. This leads us to the prediction that detectors with several times higher sensitivity, like MAGIC or VERITAS in the Northern Hemisphere, should indeed detect this source at 1 TeV in , predominantly hadronic γ-rays.

The expected π^0-decay γ-ray flux $F_\gamma \propto \epsilon_\gamma^{-1}$ extends up to $\gtrsim 30$ TeV, whereas the IC γ-ray flux has a cutoff above a few TeV. Therefore the detection of γ-ray emission at ~ 10 TeV would imply clear evidence for a hadronic origin.

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