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Gamma-ray emission from Cassiopeia A produced 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 relevant properties of the Cas A remnant. We use the model of a locally smooth circumstellar medium developed by Borkowski et al. (1996) which consists of a tenuous inner bubble, a dense shell of swept-up slow red supergiant wind material, and a subsequent red supergiant wind region, in order to reproduce the SNR's observed size, expansion rate and thermal X-ray emission. The values of other physical parameters which influence the CR acceleration are taken to fit the observed synchrotron emission of Cas A in the radio and X-ray range. The calculated integral γ-ray flux from Cas A is dominated by π^0-decay γ-rays produced by relativistic protons. It extends up to almost 100 TeV and at TeV-energies considerably exceeds the value 5.8×10^{-13} cm^{-2}s^{-1} detected by the HEGRA collaboration (Aharonian et al., 2001). Possible explanations of this discrepancy are proposed which correspond either to leakage of the highest energy CRs from the remnant already at the current stage, to a lower gas density, or to an unusually high electron to proton ratio for the accelerated CRs.

1 Introduction

Cassiopeia A is a shell type supernova remnant (SNR), and a bright source of synchrotron radiation observed from the radio (e.g. Baars et al., 1977) to the X-ray (Allen et al., 1997) band. The detection of a weak signal in TeV γ-rays has been recently reported by the HEGRA collaboration (Aharonian et al., 2001).

We apply here the nonlinear kinetic model for CR acceleration in SNRs (Berezhko et al., 1996; Berezhko and Völk, 2000) in order to discuss the observed features of Cas A , presumably produced by shock accelerated CRs, even though such a spherically symmetric model can not reproduce all the observed detail (e.g. Atoyan et al., 2000).

2 Model

To describe the circumstellar medium we use the model of Borkowski et al. (1996) which is consistent with the observed dynamics of Cas A and its thermal X-ray flux. According to this model, part of the slow red supergiant wind of the supernova (SN) progenitor was swept up into a dense shell by a fast stellar wind during the final blue supergiant (possibly Wolf-Rayet) phase of the progenitor star. Therefore the inner circumstellar medium consists of three zones: a tenuous wind-blown bubble, a dense shell, and a freely expanding red supergiant wind. The outer regions due to the main sequence evolution play no role here.

We describe the profile of gas number density $N_g = \rho/m$ in the analytic form

$$N_g = \frac{N_{bsh} + N_w}{2} + \frac{N_w - N_{bsh}}{2} \tanh\left(\frac{r - R_2}{l}\right),$$

where

$$N_{bsh} = \frac{N_b + N_{sh}}{2} + \frac{N_{sh} - N_b}{2} \tanh\left(\frac{r - R_1}{l}\right),$$

and

$$N_w = N_{w2}(R_2/r)^2$$

is the gas number density of the free red giant wind (region $r > R_2$), N_b and N_{sh} correspond to the bubble (region $r < R_1$) and shell (region $R_1 < r < R_2$) respectively, ρ is the gas density, m is the proton mass. This formula provides a smooth transition between above the three zones on the scale l which is taken so small, $l \ll R_1$, that its concrete value does not influence the final results.

We use the same type of formula for the magnetic field profile $B_0(r)$ with B_b, B_{sh} and

$$B_w = B_{w2}R_2/r$$

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for the bubble, shell and wind regions respectively.

A supernova (SN) explosion ejects an expanding shell of matter with energy E_{sn} and mass M_{ej}. During an initial period the ejecta have a wide distribution in radial velocity v. The fastest part of these ejecta is described by a power law $dM_{ej}/dv \propto v^{2-k}$ (Jones et al., 1981). The interaction of the expanding shell with the circumstellar/interstellar medium (ISM) creates a strong shock which will accelerate particles.

The acceleration model consists in a selfconsistent solution of the CR transport equation together with the gas dynamic equations in spherical symmetry (Berezhko et al., 1996; Berezhko and Völk, 1997), in an extension of this model to the case of a nonuniform circumstellar medium (Berezhko and Völk, 2000).

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 that is four times higher than the postshock sound speed, even though this is not a fully selfconsistent injection theory (Malkov and Drury, 2001).

The CR diffusion coefficient is taken at the Bohm limit

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

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

Accelerated electrons have a distribution function $f_e(p) = K_{ep} f(p)$ for sufficiently low momenta $p < p_l$ where synchrotron losses are not important. In fact

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

where B_d is the mean downstream magnetic field. In our case $B_d \approx \sigma B_s$, where $B_s = B_0(r = R_s)$ is the ambient field strength at the shock radius $R_s(t)$, t is the SNR age, and σ is the shock compression ratio. Thus $f_e(p)$ differs only by a numerical factor K_{ep} from the proton distribution function $f(p)$. At higher momenta $p > p_l$ the electron spectrum is softened to $f_e \propto p^{-5}$ due to synchrotron losses. These losses also determine the electron cutoff momentum

$$\frac{p^e_{max}}{mc} = 20\left(\frac{V_s}{\mathrm{km/s}}\right)\sqrt{\frac{10(\sigma-1)}{\sigma^2}\left(\frac{10\ \mu\mathrm{G}}{\sigma B_s}\right)},$$

if B_s is sufficiently high so that p^e_{max} is lower than the proton maximum momentum p_{max} which is assumed to be determined by geometrical factors (Berezhko, 1996); here V_s is the shock speed. We include the synchrotron loss term in the transport equation for the electron distribution function $f_e(r, p, t)$. The factor K_{ep} is determined by the ratio of the electron and proton injection rates. Normally one would expect that electrons are injected less effectively than protons due to their much smaller mean free path. In the case when electrons are injected at the same rate as protons, we have $K_{ep} \simeq 10^{-2}$ (Bell, 1978).

The choice of K_{ep} allows the determination of the electron distribution function and the calculation of the associated emission.

3 Results

We shall use the SN parameters, calculated by Borkowski et al. (1996): explosion energy $E_{sn} = 10^{51}$ erg, ejecta mass $M_{ej} = 3M_{\odot}$, and $k = 6$.

The results of our calculations together with the experimental data are shown in Fig.1. In Fig.1a we also show the profiles of the gas number density N_g and magnetic field B_0.

As it is seen from Fig.1a the shock speed drops during the initial 60 years by more than a factor of ten, and then remains almost constant up to the current epoch.

According to Fig.1b the shock is essentially modified by the CR backreaction: the total shock compression ratio $\sigma \approx 6$ exceeds the classical value 4, whereas the subshock compression ratio is considerably smaller, $\sigma_s \approx 2.7$.

The overall momentum spectrum of accelerated protons (Fig.1c) turns over at $p = 10^5 mc$ and extends almost up to $p_{max} = 10^6 mc$ due to the extremely high magnetic field strength. Synchrotron losses restrict the spectrum of electrons to maximum momenta p^e_{max} below $10^4 mc$. Subsequent synchrotron cooling of the accelerated electrons in the downstream region steepens the high energy part of their spectrum: at $p > p_l = 100 mc$ $N_e \propto p^{-3}$ instead of $N \propto p^{-2}$ for protons.

According to Fig.1d about 20% of the explosion energy has been transformed into CRs at the current stage.

The electron to proton ratio $K_{ep} = 0.01$ gives a perhaps acceptable agreement of the calculated synchrotron emission with the observations in the radio and X-ray regions (Fig.1e).

A magnetic field strength $B_{sh} = 200\mu$G is taken to reproduce the observed radio and X-ray synchrotron fluxes. Since we assume that the postshock field $B_2 = \sigma B_s$, the downstream magnetic field $B_d \approx B_2 \sim 1.2$ mG in the shell (Fig.1a) is roughly consistent with previous estimates (e.g. Atoyan et al., 2000).

Our results show that even at the current epoch (when the SN shock propagates through the free RSG wind) the observed synchrotron emission is still determined by the electrons accelerated during the shock propagation through the shell. Therefore the magnetic field $B_0(r)$ in the wind zone is not a very relevant parameter for the fit to the observations.

Fig.1f represents the expected integral γ-ray flux due to three different processes. The IC and Bremsstrahlung fluxes are comparable and at TeV energies have the value $F_\gamma \sim 10^{-13}$ cm^{-2}s^{-1} whereas the π^0-decay flux $F_\gamma \propto \epsilon_\gamma^{-1}$ extends up to 10 TeV and at $\epsilon_\gamma = 1$ TeV has a value 6×10^{-11}cm^{-2}s^{-1} which is two orders of magnitude higher than observed (Aharonian et al., 2001).

This is a straightforward realization of the expected dynamical situation, consistent with the thermal X-ray emission. We shall discuss possible modifications of the model parameters in the sequel.

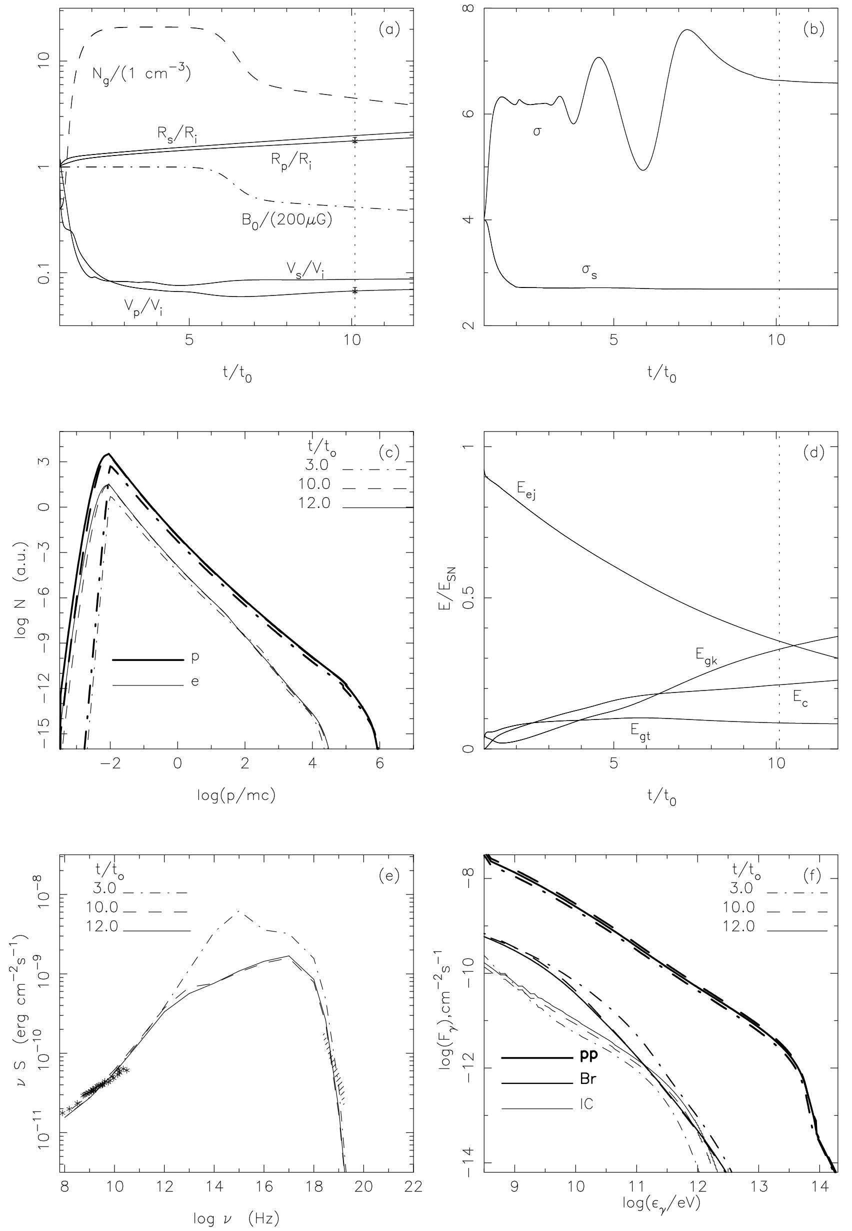

Fig. 1. Shock (R_s) and piston (R_p) radii, shock (V_s) and piston (V_p) velocities (a); total shock (σ) and subshock (σ_s) compression ratios (b); ejecta (E_{ej}), CR (E_c), gas thermal (E_{gt}) and gas kinetic (E_{gk}) energies (d) as a function of time. Overall momentum spectrum of accelerated protons and electrons (c); synchrotron emission flux as a function of frequency (e); integral flux of π^0-decay (p-p), Bremsstrahlung (Br) and inverse Compton (IC) γ-rays as a function of γ-ray energy (f) for three different evolutionary phases (dashed lines correspond to the current stage) of Cas A evolution. Vertical dotted lines correspond to the current evolutionary stage. The calculations were performed for explosion energy $E_{sn} = 10^{51}$ erg, ejecta mass $M_{ej} = 3M_\odot$, distance $d = 3.4$ kpc, proton injection rate $\eta = 10^{-4}$, electron to proton ratio $K_{ep} = 0.01$, and the circumstellar gas number density $N_g(R_s)$ and magnetic field $B_0(R_s)$ profiles are shown in Fig.1a. Scale values are $R_i = 1$ pc, $V_i = 30000$ km/s, $t_0 = 31.7$ years. The radio-emission above 100 MHz (Baars et al., 1977), and X-ray (Allen et al., 1997) spectra (e), size (Reed et al., 1995) and speed (Andersen and Rudnick, 1995) of the shock (a) are presented.

4 Discussion

The characteristics of Cas A as a SNR with a drastic modification of the circumstellar medium by the progenitor star are sufficiently complex that several rather strong modifications of the acceleration model can be considered. The discussion is at this stage more qualitative than quantitative and has therefore a preliminary character.

The simplest resolution of the discrepancy would be the suggestion that the actual CR production due to some reasons is much lower than reproduced by the theory. We note however that this can concern only protons because the total number of accelerated electrons fits the observations. Therefore, to decrease the π^0-decay γ-ray production by a factor of 100 one needs to specifically decrease the proton injection rate more than a 100 times. In this case the electron injection rate at the same injection energy would exceed the proton injection rate by more than order of magnitude.

This may be a solution, given the fact that the *average* magnetic field direction in the wind should be more or less azimuthal, whereas the SNR shock normal is essentially radial, resulting in a quasi-perpendicular shock into which electrons may be injected quite efficiently, whereas proton injection should be strongly depressed (see Malkov and Drury, 2001, for a recent review). On the other hand, the large field strength in the shell is likely due to turbulent amplification of the RSG wind field by the shell formation in the final W-R phase, and also to the subsequent Rayleigh-Taylor instability at the ejecta interface with swept-up material. Then there are many field lines that are locally radial, allowing efficient proton injection onto them. Still, acceleration of electrons and protons to high energies would likely be either suppressed beyond rather low, even nonrelativistic proton energies (Völk and Forman, 1983), or be reduced to a soft spectrum with very low fluxes in the TeV range (Kirk et al., 1996). The problem then is that this would equally lower the electron fluxes.

Another possibility to resolve the above discrepancy is the choice of a lower circumstellar gas density compared with the case considered. In order to study this possibility we have performed the calculation with a gas number density that is seven times lower. To reproduce the observed size and expansion rate of the remnant we have used a value of the explosion energy $E_{sn} = 3 \times 10^{50}$ erg.

The calculated γ-ray fluxes are considerably lower than in the previous case, and $K_{ep} = 0.07$. The expected TeV γ-ray flux $F_\gamma \approx 8 \times 10^{-13}$ cm^{-2}s^{-1} only slightly exceeds the observed value. However, it is not clear, whether such system parameters can be brought into agreement with the thermal X-ray emission, and this needs to be investigated further.

As a third possibility we consider the scenario of CR escape during the more recent phase of the SNR evolution.

Let us assume that the RSG wind speed $V_w \approx 10$ km/s does not exceed the Alfvén speed, and that the field strength in the free RSG wind B_{w2} is as low as 10 μG.

In this case the maximum momentum of accelerated protons

$$p_{max} \propto R_s V_s / \kappa(mc)$$

is at least 20 times smaller compared with its value in the shell since the minimum CR diffusion coefficient $\kappa \propto 1/B$ increases by a factor of 20, and the early ($V_s/V_i \approx 1$) accelerated particles will escape in addition. In such a situation one should expect that the diffusion coefficient of particles with $p > p^w_{max}$, where p^w_{max} is the maximum momentum of CRs accelerated in the RSG wind region $r > R_2$, exceeds the (Bohm limit) particle diffusion in the shell significantly. It is like if the shock had become ”old”, being unable to confine the highest energy particles it accelerated previously in the shell. Therefore these particles leave the SNR very soon after the SN shock reaches the RSG wind region, resulting in a much smaller production of π^0-decay γ-rays with the highest energies compared with the previous cases. For the electron X-ray emission this is a small effect since their main synchrotron radiation comes from the shell; their IC emission remains essentially the same with or without escape.

This reduction of the hadronic γ-ray cutoff may still not be enough to reduce their TeV emission to the observed value. In addition a depression of the proton injection/acceleration rate may be necessary. Again, a detailed calculation will have to be done to judge this possibility. In any case, a considerable increase of the γ-ray flux towards lower energies should be expected.

Forthcoming lower threshold instruments should be able to check this hypothesis.

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