Kinetic Theory of CR and Gamma-ray Production in Supernova Remnants: Massive Progenitor Stars

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Abstract

The kinetic nonlinear model of particle acceleration in Supernova Remnants (SNRs) is extended to study the Cosmic Ray (CR) and associated high-energy γ-ray production during SNR shock propagation through the inhomogeneous circumstellar medium (CSM) of a progenitor star that emits a wind and forms a low-density bubble surrounded by a swept-up shell of interstellar matter. Examples typical for SN types Ib and II are considered. It is shown that CRs are accelerated as efficiently as in the case of a SN Ia in a uniform Interstellar Medium (ISM). During almost the whole evolution the expected high-energy γ-ray fluxes are much lower than in the case of an equivalent SN Ia and are below the detectable level due to the low density of the bubble.

1 Introduction:

CR acceleration in SNRs expanding in a uniform ISM, and the properties of the associated π^0-decay γ-ray emission were investigated in a number of studies. However SNe of type Ib and II, which are more numerous in our Galaxy, explode into a strongly inhomogeneous CSM, formed by the intensive wind of their massive progenitor stars. In this paper we present an extension of the kinetic model for CR acceleration in SNRs (Berezhko et al., 1996; Berezhko & Völk 1997) to the case of a nonuniform CSM.

2 Model:

The nonlinear kinetic description of CR acceleration by a spherical SNR shock wave is based on the diffusive transport equation which must be solved selfconsistently, together with the gas dynamic equations.

We assume that the injection of a (small) fraction $\eta \ll 1$ of gas particles into the acceleration process takes place at the subshock. For the sake of simplicity we restrict our consideration to protons, which are the dominant ions in the cosmic plasma. We also use the Bohm limit for the CR diffusion properties. It implies that the particle mean free path equals their gyroradius. The model includes the Alfvén wave dissipation effect which strongly influences the shock structure.

The strong wind from the massive progenitor star interacts with an ambient ISM of uniform density $\rho_0 = 1.4mN_H$, resulting to first approximation in an expanding spherical configuration, which is called a bubble. Here m is the proton mass and N_H is the hydrogen number density in the background ISM. Throughout its evolution, the system consists of four distinct zones. Starting from the center they are: (a) the hypersonic stellar wind (b) a region of shocked stellar wind (c) a shell of shocked interstellar gas , and (d) the ambient ISM. To describe the bubble parameters we use the theory developed by Weaver et al. (1977).

We consider here the stage of a so-called modified bubble whose structure is significantly influenced by mass transport from the dense and relatively cold shell (c) into the hot region (b). During this stage the shocked shell (c) has collapsed into a thin isobaric shell due to radiative cooling. The mass and heat transport between regions (b) and (c) are presumably due to turbulent motions in the bubble. We assume that they generate a magnetic field which grows up to the equipartition value.

3 Results and Conclusions:

In the case of a uniform ISM the CR acceleration efficiency is very high and not strongly dependent on the injection rate η. We shall use here $\eta = 10^{-3}$ which corresponds to a rather moderate injection rate for a parallel shock (e.g. Trattner et al., 1994). Yet even this value may be too high for the largely perpendicular

SNR shocks in wind bubbles. As a typical set of values of core collapse SN parameters we consider: hydrodynamic explosion energy $E_{sn} = 10^{51}$ erg, ejecta mass $M_{ej} = 10 M_\odot$, and the parameter $k = 10$ which describes the ejecta velocity distribution (Chevalier & Liang, 1989). As a typical example for a type Ib SN we use theoretical results of stellar evolution with initial mass $35 M_\odot$ cf. Garcia-Segura et al. (1996). According to these calculations the evolution consists of three stages: a main-sequence (MS) phase with mass-loss rate $\dot{M} = 5.6 \times 10^{-7} M_\odot$ yr^{-1}, wind speed $V_w = 2000$ km/s, and duration $\Delta t_w = 4.5 \times 10^6$ yr; a red supergiant (RSG) phase with $\dot{M} = 10^{-6} M_\odot$ yr^{-1} $V_w = 15$ km/s, $\Delta t_w = 2 \times 10^5$ yr, and a Wolf-Rayet (WR) phase with $\dot{M} = 2.25 \times 10^{-5} M_\odot$ yr^{-1}, $V_w = 2000$ km/s, and $\Delta t_w = 2 \times 10^5$ yr. During the MS phase the wind creates a bubble of size $R_2 = 76.8$ pc, gas number density $N_b = 5 \times 10^{-3}$ cm^{-3} and pressure $P_b = 5.47 \times 10^{-13}$ dyne/cm^2 in a ISM with $N_H = 0.3$ cm^{-3}. The wind emitted during the RSG phase occupies a region of size $R_f = \Delta t_w V_w = 0.3$ pc. The fast wind from the subsequent WR star interacts with this dense RSG wind. After a relatively short period of time the WR wind breaks through the RSG wind material leaving it in the form of clouds. Since the interaction time is short and the mass of the RSG wind is small compared with the bubble mass, we neglect the dynamical influence of the RSG phase on the final structure of the bubble.

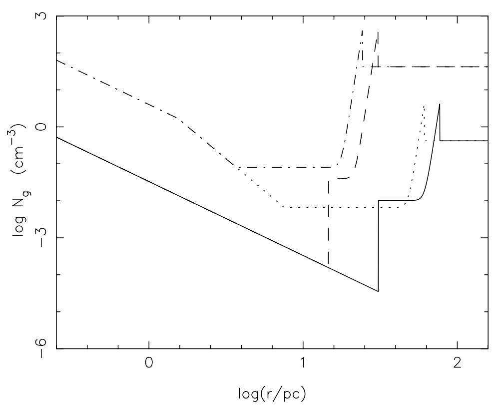

Figure 1: Circumstellar gas density distribution N_g as a function of radial distance r for the case of a SNR Ib in an ISM with hydrogen number densities $N_H = 0.3$ cm^{-3} (full line) and $N_H = 30$ cm^{-3} (dashed line), and for the case of a SNR II (dotted and dash-dotted lines, respectively).

The WR wind inside the MS-bubble creates now a WR bubble with number density $N_b = 10^{-2}$ cm^{-3} and a shell of size $R_2 = 56$ pc. Formally this value N_b is twice larger than the number density of the MS bubble. If we neglect the stellar mass lost in the WR phase compared to the mass of the partially swept-up MS bubble, the density of the new WR bubble can not exceed that of the MS bubble shell, simply for mass conservation. It can at best be equal if we assume that the WR shell is completely dissipated, i.e. smeared out over the WR bubble. Therefore we use a simplified structure of the bubble, whose parameters $R_2 = 77$ pc, $N_b = 5 \times 10^{-3}$ cm^{-3}, $P_b = 5 \times 10^{-13}$ dyne/cm^2, $B = 8$ μG correspond to the MS-bubble, together with a hypersonic WR wind region of size $R_1 = 31$ pc, corresponding to the pressure equilibrium condition $\rho V_w^2 = P_b$ (Fig. 1).

For the WR-star we use a radius $R_* = 3 \times 10^{12}$ cm, rotation rate $\Omega = 10^{-6}$, and surface magnetic field $B_* = 50$ G which determine the value of the magnetic field in the wind region (a). Fig.2 illustrates the SNR shock propagation through the modified CSM.

We model the type II SN case by a progenitor star with initial mass $15 M_\odot$ that spends a time period $\Delta t_w = 4 \times 10^6$ yr on the main-sequence with mass-loss rate $\dot{M} = 2.5 \times 10^{-7} M_\odot$ yr^{-1} and wind velocity $V_w = 2000$ km/s, and then a time $\Delta t_w = 10^5$ yr in the RSG phase with $\dot{M} = 2 \times 10^{-5} M_\odot$ yr^{-1} and $V_w = 15$ km/s. The MS wind creates a bubble of size $R_2 = 61$ pc in an ISM with $N_H = 0.3$ cm^{-3}. The bubble is characterized

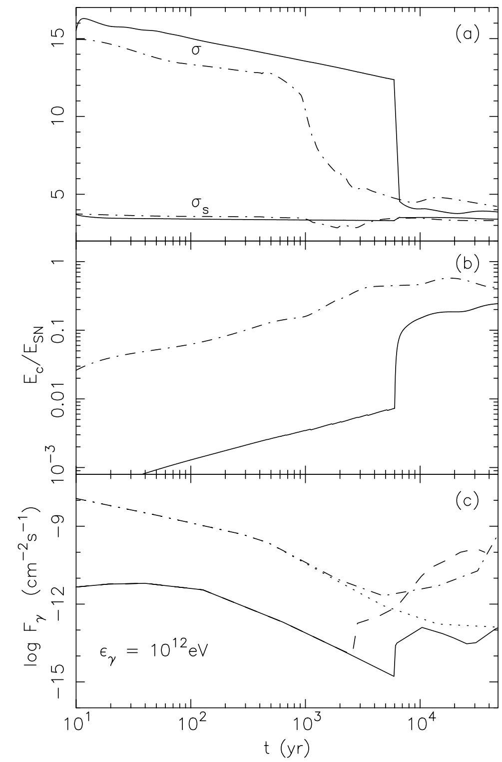

Figure 2: Shock (σ) and subshock (σ_s) compression ratios (a), CR energy content E_c (b) and TeV γ-ray flux F_γ normalized to 1 kpc distance (c) as a function of time.

by $N_b = 6.6 \times 10^{-3}$ cm^{-3} and $P_b = 4.4 \times 10^{-13}$ dyne/cm^2. The RSG wind occupies a region of size $R_f = V_w \Delta t_w = 1.5$ pc. At this point the ram pressure ρV_w^2 of the RSG wind exceeds the thermal pressure P_b in the bubble. Therefore we neglect the shell which can be formed by the RSG wind due to its interaction with the ambient bubble material. We model the transition zone between the RSG wind and the bubble by the set of parameters $\rho = \rho(R_f)(R_f/r)^{3.5}$, $V_w = V_w(R_f)(R_f/r)^2$. We introduce this zone to match smoothly the gas densities N_g between regions (a) and (b), see Fig.1. It contains a small amount of gas and plays no significant role in the overall SNR evolution. We also use a magnetic field strength $B = 2 \times 10^{-4}$ G in the RSG wind at the distance $r = 10^{17}$ cm. Formally it correspond to $B_* = 1$ G, $R_* = 3 \times 10^{13}$ cm and $\Omega = 3 \times 10^{-8}$.

Our numerical results show that when a SN explodes into a CSM strongly modified by a wind from a massive progenitor star, then, for $\eta = 10^{-3}$, CRs are accelerated in the SNR almost as effectively as in the case of a uniform ISM: about $20 \div 40$% of the SN explosion energy is transformed into CRs during the active SNR evolution (see Fig.2b).

During SNR shock propagation in the supersonic wind region ($t \lesssim 10^3$ yr) very soon the acceleration process reaches a quasistationary level which is characterized by a high efficiency and a correspondingly large shock modification (Fig.2a). Due to the relatively small mass contained in the supersonic wind region CRs absorb there only a small fraction of the explosion energy (about 1% in the case of a SN type Ib, and 10% in the case of a SN type II) and the SNR is still very far from a Sedov-type phase after having swept up this region (Fig.2b). Therefore we conclude, that the CRs produced in this region should not play a very significant role for the formation of the observed Galactic CR energy spectrum.

The peak value of the CR energy content in the SNR is reached when the SNR shock sweeps up an amount of mass roughly equal to several times the ejected mass. This takes place during shock propagation in the modified bubble. Compared with the uniform ISM case the subsequent adiabatic CR deceleration is less important now. The main amount of CRs in this case is produced when the SNR shock propagates through the bubble. In this stage the dynamical scale length is much smaller than the shock size. Therefore the relative increase of the shock radius during the late evolution stage and the corresponding adiabatic effects are small.

The CR and γ-ray spectra are more variable during the SN shock evolution than in the case of a uniform ISM. At the same time the form of the resulting overall CR spectrum is rather insensitive to the parameters of the ISM like in the case of uniform ISM.

The maximum energy of accelerated CRs, reached during the SNR evolution, is about 10^{14} eV for protons in all the cases considered, if the CR diffusion coefficient is as small as the Bohm limit.

As one can see from Fig. 2c, in the case of a SN Ib the expected TeV-energy γ-ray flux, normalized to a distance of 1 kpc, remains lower than 10^{-12} cm^{-2}s^{-1} during the entire SNR evolution if the ISM number density is less than 1 cm^{-3} except for an initial short period $t < 100$ yr when it is about 10^{-11} cm^{-2}s^{-1}. Only for a relatively dense ISM with $N_H = 30$ cm^{-3} the expected γ-ray flux is about 10^{-10} cm^{-2}s^{-1} at late phases $t > 10^4$ yr. A similar situation exists at late phases of SNR evolution in the case of a type II SN. The expected γ-ray flux is considerably lower, at least by a factor of hundred, compared with the case of a uniform ISM of the same density N_H.

In the case of a SN II, during the first several hundred years t_m after the explosion the expected TeV γ-ray flux at a distance $d = 1$ kpc exceeds the value 10^{-9} cm^{-2}s^{-1} and can be detected up to a distance $d_m = 30$ kpc with present instruments like HEGRA, Whipple or CAT. This distance is of the order of the diameter of the Galactic disk. Therefore all Galactic SNRs of this type whose number is $N_{sn} = \nu_{sn} t_m$ should be visible. But even in this case we can expect at best $N_{sn} \sim 10$ such γ-ray sources at any given time.

The typical value of the cutoff energy of the expected γ-ray flux is about 10^{13} eV, if the CR diffusion coefficient is as small as the Bohm limit. There is no unique explanation for some of the negative results of imaging atmospheric Cherenkov telescopes with thresholds less than about 1 TeV (Völk, 1997). For core collapse SN of types II or Ib with quite massive progenitors one can in part explain this fact by the extremely low γ-ray intensity expected from such SNRs during the period of SN shock propagation through the low-density hot bubble. Alternative possibilities relate to the assumption of the Bohm limit for the CR diffusion coefficient and the assumed injection rate which can very well be too optimistic.

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