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Diffusive Shock Acceleration of Electrons and Radio Emission from Large Diameter Shell-Type Supernova Remnants

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Abstract

In present study I examine the capability of diffusive shock acceleration mechanism to explain existing data on radio emission from evolved large diameter shell-type adiabatic supernova remnants (SNRs). Time-dependent "onion-shell" model for the radio emission of SNRs is developed, which is based on the assumptions: a) acceleration takes place from thermal energies and test-particle approximation is valid; b) the problem of injection is avoided by introducing, like Bell (1978), two injection parameters; c) to take into consideration very late stages of SNR evolution the analytic approximation of Cox and Andersen (1982) for the shell structure is used; c) no radiative cooling. Constructed Surface Brightness - Diameter (Σ-D) tracks are compared with the empirical Σ-D diagram. The main conclusion of the study is that the DSA mechanism is capable of explaining all the statistics of radio SNRs including very large diameter remnants and giant galactic loops.

1 Introduction:

Diffusive shock acceleration (DSA) mechanism are believed to be the source of radio emitting relativistic electrons in young and middle age SNRs of diameter $D \leq 20$ pc. But for the radio emission of evolved large diameter SNRs the mechanism of van der Laan (1962) or some modification of this mechanism (e.g., Blandford and Cowie 1982) are widely believed to be responsible. According to these models preexisting in the ambient ISM electrons compressed to high level at the radiative shock are responsible for the radio emission of the remnant. Due to the unstability of radiative shock waves this mechanism may however encounter a number of difficulties in reproducing the radio emission from very large diameter SNRs evolving in warm phase of the ISM. Moreover, if the density of the ambient medium is very low, the SNR will finish its life by merging with the ISM before cooling becomes important. For such remnants DSA becomes a main candidate for generation of relativistic electrons radio emitting in the magnetic fields of 10^{-5} –10^{-6} G. But electron acceleration in SNRs is more difficult to estimate quantitatively since the injection efficiency and even the very process of acceleration for electrons are still unclear.

The goal of present study is to apply DSA mechanism, under very simple and common assumptions about the injection, to follow the evolution of shell-type SNRs up to the very large radii and, at the same time, to obtain some new constraints on the theory of acceleration mechanism if we will be able to achieve agreement between the model predictions and observations.

2 The Model

We used the onion-shell model of Moraal and Axford (1983) as it was done in Asvarov (1992, 1994) where the Sedov solution for the remnant structure had been adopted. In present study SNR is modeled by using an analytical approximation of Cox and Anderson (1982) which follows the development of an adiabatic spherical blast wave in homogeneous ambient medium of finite pressure. At early times this approximation resembles the zero pressure Sedov similarity solution but extends the range of investigation well into the regime in which the external pressure is significant.

To avoid the problem of injection we introduced, like Bell (1978), two injection parameters – we inject electrons as ``test particles" at momentum $p_{\rm inj}=\psi\ p_{\rm th}$, where $p_{\rm th} = (2 m_e T_s)^{1/2}$ is the downstream electron thermal momentum, the concentration of which assumed to be proportional to the density of the ambient thermal electrons: $N_{inj} = \varphi\ n_{oe}$. At the shock front equipartition between electron and proton temperatures is assumed which means that p_{inj} is proportional to the velocity of shock wave.

For the accelerated electrons from the energy loss processes only adiabatic cooling was taken into consideration.

Assuming the magnetic field to be frozen in to the plasma, we model the density dependence of H as $H=H_0(\rho/\rho_0)^k$, where H_0 is the ambient value of the magnetic field strength.

Although in our analysis we consider only extended SNRs we calculate several models in high density environments for which the radiative phase begins relatively soon after the explosion of SN. In this case total flux is obtained by integration over the layers of the shell where radiative cooling does not occur. This implies that we completely ignore the action of DSA at radiative shocks.

3 Results and Discussion:

Empirical Σ-D – relations are very useful tools for testing the theoretical models of SNR evolution. Before comparing our model with the observations, we formulate the common properties of the model predictions. Here we concentrate on two main observable radio characteristics of SNRs: the spectral index and surface brightness. DSA at strong shock waves in test particle approximation predicts for spectral index the value of 0.5, which will increase as the shock intensity (Mach number) decreases. Calculations show that at Mach numbers $M \leq 4$ the value of the mean radio spectral index gets greater then 0.6 but it remains bounded by maximal value of 0.75 during the following evolution. This is the result of distribution of magnetic field strength at the shock but the real average spectrum of electrons inside the remnant will be somewhat softer than $2\alpha+1=2.5$.

What concerns another important radio characteristic of the SNR, the surface brightness, the remnant evolves at nearly constant radio surface brightness followed by very steep drop. It is important to note that the dependence of these and other radio characteristics of the remnant on shock Mach number has almost universal nature, very weakly depending on the input parameters.

To compare the model predictions with the observations we have collected a set of shell-type and a few composite SNRs in our Galaxy with known distances and remnants in LMC. Corresponding Σ-D diagram is shown in Fig.1. Error bars are due to uncertainties in the distances for some SNRs; for several objects only lower and for one SNR upper limits are known.

As a standard set of input parameters we used: the energy of SN explosion E_{SN} which is varied in the range $(1 \div 5)\ 10^{51}$ erg; the ambient thermal electrons density n_{0e} in the range $(5 \div 5\ 10^{-3})$ cm^{-3}; the strength of the ambient magnetic field H_0 in the range $(3 \div 10)\ 10^{-5}$ G. In all models the mass of SN ejecta is taken to be one solar mass. In Fig.1 several $\Sigma_{1GHz}(D)$ - tracks are shown for different values of n_{oe}, E_{SN} and H_0. In all calculations we used $\psi=3$ and $\varphi=4\ 10^{-4}$ justifying the use of test particle approximation. It is important to note that the shapes of the evolutionary tracks depend very weakly on these parameters although the magnitude of Σ depends on ψ linearly.

As can be seen in Fig.1 varying mainly the values of n_{oe} and E_{SN} the model is able to cover all the remnants in the Σ-D diagram including two large diameter relatively bright SNRs (HB 9, OA 184) and giant radio loops. As the latter is attained with the price of somewhat large value for E_{SN} of $5\ 10^{51}$ erg we calculated several models in which the contribution of the ambient relativistic electrons was included via the injection of them into the DSA. As an example we have taken the spectrum $j = 1.4 \times 10^2\ E^{-2.2}$ electrons m^{-2} s^{-1} sr^{-1} GeV^{-1} (E in GeV) from Fichtel et al. (1991). In Fig.1 two tracks are drawn by dashed lines.

It is interesting to not that the shapes of predicted by our model evolutionary tracks are in excellent accordance with the prediction made by Berkhuijsen (1986) that “radio remnants may evolve adiabatically at nearly *constant* Σ_R, followed by a steep decrease…”

As can be seen in Fig.1 radio evolution of SNRs depends on two parameters, E_{SN} and n_{0e}, equally.

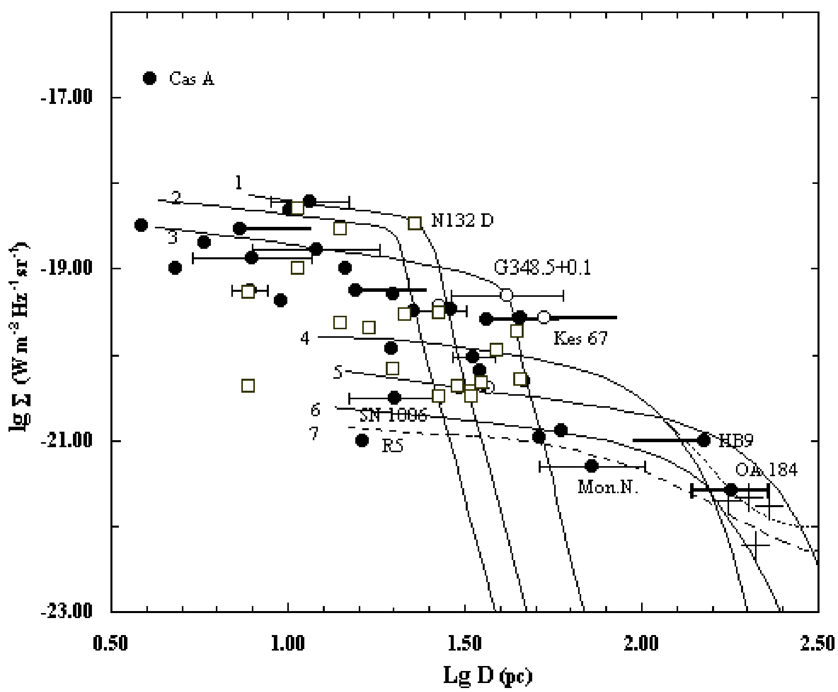

Figure 1.

Surface brightness – diameter diagram at 1 GHz for SNRs in Galaxy (circles) and LMC (squares) and giant galactic loops (crosses). All the data for galactic SNRs are taken from the catalogue of Green (1998), the data for Loops are taken from Berkhuijsen (1986), and the data for SNRs in LMC are from (Mills et al. 1984). Galactic SNRs with $\alpha \leq 0.4$ or/and composite SNRs indicated by open circles. Curves are the modeled evolutionary tracks: *1* – n_{oe}=5, H_0=1, E_{SN}=2; *2* – the same as 1 but E_{SN}=1; *3* – n_{oe}=1, H_0=1, E_{SN}=1; *4* – n_{oe}=0.05, H_0 =0.5, E_{SN}=2; *5* – n_{oe}=0.01, H_0 =0.3, E_{SN}=5; *6* – n_{oe}=5 10^{-3}, H_0 =0.3, E_{SN}=2; *7* – n_{oe}=5 10^{-3}, H_0 =0.3, E_{SN}= 1. Here E_{SN} is in 10^{51} erg, H_0 is in10^{-5} G, n_{oe} is in cm^{-3}. Dashed curves correspond to models in which the contribution of background cosmic ray electrons was considered.

In the framework of present model a number of features of the empirical Σ-*D* relation obtains a simple explanation. For instance, the small number of remnants with small diameters and low Σ (lower left corner in the diagram) is the result of very fast evolution of SN blast wave in the low density ISM where SNRs have low Σ. According to our model it is easy to account for high concentration of SNRs at diameters 30-50 pc in the Σ-*D* diagram: different kind of evolutionary tracks intersect at these diameters and the sample of remnants here consists of objects evolving at different initial conditions. Of course, in the origin of the empirical Σ-*D* relations we can not exclude at all the contribution of various selection effects. Moreover, not all the remnants can be described by our model. Indeed, in the Σ-*D* diagram (Fig.1) the composite SNRs and SNRs with $\alpha \leq 0.4$ (indicated by open circles) have systematically large values of Σ, which can be understood that in these remnants an additional more effective mechanism acts.

It is important to note that adopted values for Bells' parameters do not contradict the observations at standard values for the input parameters, characterizing the ISM and the SNR itself. This fact implies that the test particle approximation has factual realization in evolved shell-type SNRs. One more argument which favors the DSA mechanism is the statistics of spectral indices. The catalogue of SNRs of Green (1998) contains 80 SNRs with well determined values of the spectral indices, α, from which 57 remnants (71%) have $\alpha \geq 0.45$ and only two SNRs (one of them is young peculiar SNRs Cas A) $\alpha \geq 0.75$. Practically there are no objects contradicting the prediction of our model that $\alpha_{max} \leq 0.75$. It is well known that young

SNRs have systematically large values of α, which can be explained by back reaction effects or by the action of other then DSA mechanisms. According to the model the SNRs with Mach numbers $M \geq 4$ has the mean value of $\alpha \geq 0.6$. Assuming for simplicity that SNR evolves according to the Sedov law, $M \propto t^{-3/5}$, for the number of SNRs with Mach numbers greater then M we have $N(\geq M) \propto M^{-5/3}$ from which it follows that the number of SNRs with $\alpha \geq 0.6$, $N(\alpha \geq 0.6) = N(M \geq 4)$, must be about 55% of total number of SNRs. Here we have adopted for the final Mach number $M_f = 2.5$ at which Σ drops more then two order of its initial value and the SNR becomes invisible. In the catalogue Green (1998) 22 out of 80 SNRs have $0.60 \leq \alpha \leq 0.75$ which makes 27.5%. This discrepancy easily can be explained by the selection effects that SNRs with large diameters and small Mach numbers have low Σ, consequently, difficult to be detected, though their number is more than the number of bright remnants by a factor of 8-10.

The mean size and age of SNR with $E_{SN} = 10^{51}$ ergs, evolving in the ISM with $n_{0e} \approx 0.01$ cm^{-3}, when Σ drops to $\sim 5 \times 10^{-22}$ (W m^{-2} sr^{-1} Hz^{-1}) are 150 pc and 2×10^5 years, respectively. If SN occur with a rate of 30 year^{-1} then such SNRs occupy 3.5×10^{65} cm^3 of the galactic volume of $\pi \times (25\ \mathrm{kpc})^2 \times (1\ \mathrm{kpc})/6 = 9.65 \times 10^{66}$ cm^3, or 1 part in 28 (3.6%). This estimate depends on the value of E_{SN} as $E_{SN}^{4/3}$. The probability that random line of site will hit such SNR is 0.21 or 10 in 47 and the dependence on E_{SN} the same. The last estimate shows that SNRs can play important role in the origin of background radio and gamma emissions of our Galaxy. Predicted by our model spectral indices are in accordance with the radio background observations. What concerns the gamma-background our model in accordance with the model of "bubbling swiss cheese" of Pohl \& Esposito (1998) thought the value of electron spectral index of 2.0 demanded in their model is in contradiction with our predictions.

4. Conclusions:

The model based on the assumption that the radio emitting electrons are accelerated by DSA mechanism very well explains the statistics of shell-type radio SNRs. From this we can conclude that the test particle approximation and the supposition that acceleration of electrons takes place from the thermal energies has realization in evolved SNRs in spite of all theoretical difficulties concerning the physics of collisionless shock waves. We obtain that $\psi = p_{inj}/p_{th} \cong 3$.

The idea that there is no acceleration at the radiative stage of SNR evolution does not contradict observation.

Presented model also in accordance with radio and gamma background observations.

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