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RADIO EMISSION FROM LATE STAGE SUPERNOVA REMNANTS

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In this paper, we consider radio emission from supernova remnants in the late stages of evolution. It is expected that a significant part of the observed SNRs are in the late stages of evolution. It is shown that the model of radio emission based on the mechanism of diffusive shock acceleration (DSA) is able to explain the statistics of observed SNRs. The possibility of DSA operation and the occurrence of radio emission in SNRs at the radiative stage of evolution is discussed. It is shown that empirical $\Sigma - D$ dependencies are not suitable for determining distances to SNRs.

Keywords: Supernova Remnants -— Radiative SNRs — Radio emission

1. INTRODUCTION

Radio emission is an important property of supernova remnants (SNRs). Although SNRs are now observed at almost all wavelengths of the electromagnetic spectrum, for galactic supernova remnants the most complete information is available in the radio range. The latest catalog of galactic supernova remnants contains 310 objects [4], the vast majority of which are nonthermal radio sources. It is generally accepted that the action of the mechanism of diffusive shock acceleration (DSA) at the front of the main shock wave is responsible for the generation of the relativistic electrons emitting synchrotron radio emission from supernova remnants. However, the injection problem – from what energies and what percentage of background particles are subject to acceleration – remains unresolved despite the mechanism's universality and physical clarity. It is possible to answer this problem and other questions concerning the physics of shock waves and space

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plasma by using data on the radio emission of SNRs. At the same time, a realistic model of the evolution of radio emission can help clarify issues like how the ISM affects SNR life, how SNRs contribute to the formation of the ISM's structure, and what part of the galaxy SNRs occupy. The fact is that simple estimates show that the number of SNRs in the galaxy is no less than 2000. A natural question arises about where to look for these not yet discovered SNRs, what properties, including in the radio range, they have. To answer these questions, it is preferable to study supernova remnants at the middle and late stages of evolution. The majority of in-depth research on SNR radio emission focuses on young SNRs, where, depending on the kind of supernova, circumstellar matter plays a significant role. Currently, the richest observational material is available for young supernova remnants, and the most detailed physical models are built for them. However, the role of young remnants in the overall statistics of SNRs is insignificant because the expansion of the supernova remnant occurs with deceleration, resulting in a far larger number of old and extended remnants than young ones [5]. It is expected that among the observed SNRs, the majority are in late stages of evolution. Several factors make it easier to study evolved supernova remnants: the explosion energy is the determining characteristic of the supernova, regardless of the type of supernova or the mass of the ejected shell; the state of the plasma behind the shock wave front becomes more equilibrium; and the use of the diffusion acceleration mechanism in the approximation of test particles becomes justified. Factors that complicate the study of the SNR in the middle and late stages of evolution are taking into account of the pressure in the ISM and the consideration of the onset of the radiative phase and fundamental changes in the structure of the remnant.

2. EVOLUTION OF SUPERNOVA REMNANTS.

During its evolution, a supernova remnant goes through several stages or phases: the free expansion phase; the Sedov adiabatic phase and the post-adiabatic phases. In the first two stages, the total energy of the remnant is conserved. In the first stage, all the energy is in the form of the kinetic energy of the shell ejected during the explosion of the star, in the second stage $\simeq 70\%$ of the total energy is converted into thermal energy, the remaining 30% is in the form of the kinetic energy of the shock wave, more precisely, this division depends on the adiabatic index γ. For statistical calculations, the law of expansion of the outer shock wave in the first two stages can be described by a single equation describing the conservation of the kinetic energy of the remnant shell:

$$\left(M_{ej} + \frac{4}{3}\pi\rho_0 R_s^3\right) \cdot \left(\frac{dR_s}{dt}\right)^2 = 2E_{0k}, \tag{1}$$

which gives for the shock wave velocity $\mathrm{v}_s = \frac{\mathrm{v}_{0s}}{\sqrt{1+(R_s/R_0)^3}}$, where R_s is the outer radius of the shock wave, in other words the SNR radius, $R_0 = (3M_{ej}/4\pi\rho_0)^{1/3}$, and $\mathrm{v}_0 = \sqrt{2E_{0k}/M_{ej}}$. From Eq.(1) it follows that when $R_s \ll R_0$ the velocity is constant $v_s = v_0 = \mathrm{const}$ (free expansion) and $v_s = v_{os} \cdot (R_s/R_0)^{-3/2}$ at $R_s >> R_0$ in accordance with the Sedov expansion law [3]:

$$R_s = \left(\frac{\xi E_0}{\rho_0}\right)^{1/5} t^{2/5} \tag{2}$$

where E_0 is total (thermal plus kinetic) energy of the blast wave, ξ is the dimensionless numerical constant, which depends on the adiabatic index of the plasma γ: $\xi = 2.026$ for $\gamma = 5/3$. Since an exact self-similar solution to the shock wave structure [9] is available, it is simple to perform an analytical examination of the physical processes in the SNR shells, making the phase of adiabatic expansion the most studied. At this phase, the SNR actively emits at almost all wavelengths of the electromagnetic spectrum. It should be noted that this phase does not account for ambient pressure. The end of the Sedov adiabatic phase occurs when this condition begins to be violated. The evolution of the SNR in this case will occur without large energy losses, but the structure of the shock wave ceases to be self-similar. In the work [4] presents an analytical model describing the SNR structure, considering the ambient pressure in the interstellar medium. The distinctive feature of the SNR development in this approximation is that the law of change of the forward shock wave's radius will differ from Sedov's law (2) only slightly, while the relative thickness of the shell will increase significantly compared to Sedov's solution (Fig 1).

The radiative cooling phase begins when the shock wave speed drops to ~ 200 km/s. During this phase, a thin cold shell, formed as a result of the rapid loss of thermal energy in the area behind the front of the forward shock wave, will expand in snowplow mode. The expansion law of this shell is determined by the pressure difference inside the shell and in the surrounding interstellar medium. Note that the forward shock wave continues to exist ahead of the dense shell, although its expansion rate decreases sharply due to the pressure drop behind the front. The simplest model describing the structure of the SNR in the radiative phase was proposed in the work [3], in particular, it was shown that the cooling region behind the front of the external shock wave has a locally self-similar structure. In the next section we will consider whether the conditions for DSA

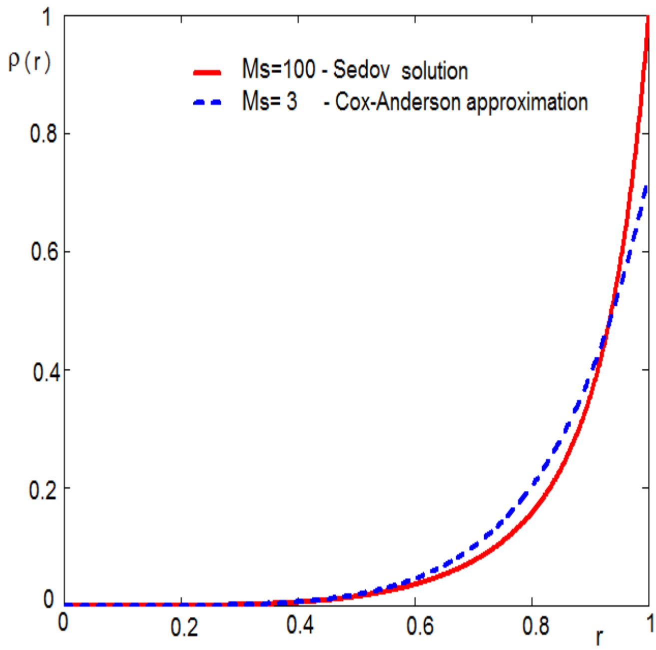

Fig. 1. Radial dependence of the normalized density of matter for Mach numbers Ms 100 and 3.

operation in this phase exist, since we are interested in the radio emission of the SNR.

3. RADIO EMISSION OF SNR

It is well known that radio emission of shell-type SNR has a synchrotron nature, i.e. relativistic electrons moving in magnetic fields are responsible for the radio emission.

The power-law dependence of the flux of observed radio emission on frequency in the form $S_\nu \propto \nu^{-\alpha}$ indicates that the radio-emitting electrons are distributed in energy according to the power law

$$N_e dE = K_e E^{-q} dE, \tag{3}$$

and the spectral index of radio emission α is directly related to the spectrum index q by the relation

$$\alpha = \frac{q-1}{2} \tag{4}$$

Isotropically distributed electrons with the distribution function (3) in the magnetic field B radiate synchrotron radio emission with the coefficient

$$\varepsilon_\nu = a(\alpha) \cdot K_e \cdot B^{\alpha+1} \cdot \nu^{-\alpha} \quad (\text{erg sec}^{-1}\ \text{cm}^{-3}\text{Hz}^{-1}) \tag{5}$$

$a(\alpha)$ is a coefficient that depends in a complex way on q. All quantities will be expressed in the CGS system below. In our model, K_e will be determined through DSA theory in the test particle approximation. The most valuable property of this mechanism is the universality of the accelerated particle spectrum, namely, in the test particle approximation it is determined only by the compression ratio across the shock front x_s as $q = \frac{x_s+2}{x_s-1}$, from which the spectral index (4) will also be determined only by x_s:

$$\alpha = \frac{3}{2(x_s-1)}$$

The compression ratio across the shock is determined by the adiabatic index γ of the local gas and the shock Mach number $M_s = v_s/c_s$:

$$x_s = \frac{\gamma+1}{\gamma-1+2/M_s^2}$$

In our model, the dependence of the spectrum of radio-emitting electrons on the evolution of the shock wave via the Mach number becomes important. Note that the speed of magnetosonic waves is used as c_s. It is also assumed that at each moment the fraction of accelerated electrons is a fixed fraction of particles from the tail of the Maxwell distribution function behind the shock front.

Integrating over the volume of the source (often over the volume of a sphere), we obtain the luminosity of the SNR

$$L_\nu = \int_V \varepsilon_\nu dV = \int_0^{R_{SNR}} \varepsilon_\nu(r) \cdot 4\pi r^2 dr \qquad (\text{erg sec}^{-1}\text{Hz}^{-1}) \tag{6}$$

Using this value, it is possible to calculate the observed characteristics of the radio emission of the SNR, such as the radio flux S_ν and the surface brightness Σ_ν

$$S_\nu = \frac{L_\nu}{4\pi d^2}$$

and

$$\Sigma_\nu = \frac{S_\nu}{\Omega} = \frac{L_\nu}{4\pi^2 R_{SNR}^2}$$

where Ω is the solid angle at which the SNR is observed. It is important to note that the surface brightness does not depend on the distance to the remnant; this parameter is often used when comparing theoretical models with observations. In the 60s of the last century, Shklovsky proposed to use the empirical $\Sigma - D$ relationship to measure distances to SSNs. At that time, the rather scanty statistics of available SNRs showed that developed remnants have a lower surface brightness than young ones; in addition, the young SNR Cas A showed an annual decrease in the radio flux, so the form $\Sigma \propto D^{-\beta}$ was proposed for the $\Sigma - D$ dependence. Many works are devoted to this dependence; on the one hand, it is often used to compare theoretical models of SNR evolution with observations; on the other hand, great hopes were associated with it as a tool for determining distances to supernova remnants. However, many experts are skeptical about $\Sigma - D$ as a tool for determining distances; even the 50% accuracy proposed by the authors of the work [8] can be considered as an overly optimistic estimate.

For young SNRs, it is justified to consider the emissivity as depending only on the radius of the forward shock wave R_s and, when calculating the total luminosity, multiply it by the volume of the layer: $L_\nu = \varepsilon_\nu (R_S) \cdot \triangle V \quad \propto K_e (R_S) \cdot B(R_S)^{\alpha+1} \cdot \triangle V$. Considering $K_e (R_S)$ and $B(R_S)$ to be power-law dependent on the SNR radius, we obtain power-law dependencies $\Sigma \propto D^{-\beta}$ with β values from 3 to 6 and more, sometimes a break is introduced in the $\Sigma - D$ dependence. Unlike young SNRs, for developed supernova remnants it is important to take into account the structure of the remnant, i.e. the total flux of the remnant consists of all the internal layers of the volume that passed the shock wave front at previous moments in time. Figure 2 shows how significant this effect is for developed and old supernova remnants. In this paper, we use the radio emission model proposed by us in paper [1]. This model is based on the assumption that electrons are accelerated from the thermal distribution behind the shock wave front by the DSA mechanism; there is no additional amplification of the interstellar magnetic field; the internal structure is specified in the Cox-Anderson approximation to be able to describe the SNR with a forward shock Mach number of up to two; with the onset of the radiative phase, the generation of new electrons ceases.

Figure 3 shows evolutionary tracks on the $\Sigma - D$ diagram taken from [1] with minor modifications. As can be seen, no power-law dependence of Σ on D is observed while the Mach number of the main shock wave is greater than 10, the dependence of the surface brightness on the diameter is very weak, but with a subsequent sharp drop. Even if all SNRs evolve under the same conditions, this type of evolutionary track does not allow using the $\Sigma - D$ dependence to find the distance by the surface brightness and angular size. In addition to this if we take into account the role of the parameters of both the supernova and the interstellar

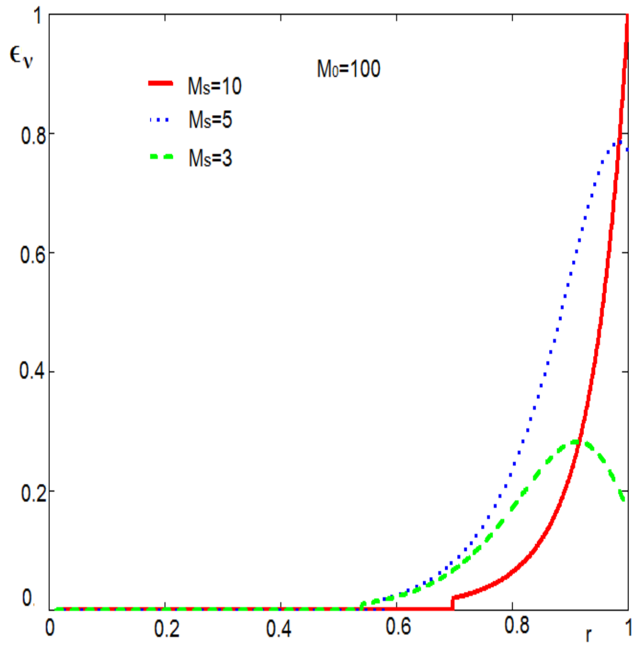

Fig. 2. The evolution of the radial profiles of an undimensional coefficient of emission with M_s.

medium, then the possible spread of these parameters makes it absolutely meaningless to use empirical $\Sigma - D$ dependencies to determine the distances to SNRs. The observational $\Sigma - D$ relations, are mainly due to: 1) presence of SNRs with diameters from wide range of sizes - small diameter bright young SNRs and large size faint old SNRs; 2) D^{-2} effect; 3) selection effects. Unfortunately, it is difficult to check the influence of various selection effects in this problem.

In our model [1], it was assumed that with the onset of the radiative cooling phase, the acceleration of new particles ceases. After this the radio emission of the SNR is provided by electrons accelerated by this moment, the contribution of which, due to adiabatic losses, rapidly decreases without an influx of new particles. In principle, our model with this assumption does not contradict observations, which may mean that the SNR radio emission in the radiative phase is indeed weak. However, it should be noted that the DSA mechanism, as a self-sustaining process, can operate under conditions of the radiative stage of evolution, provided that some not very strict requirements are fulfilled. The first requirement is the presence of a magnetic field and a sufficient degree of ionization in the ISM. The

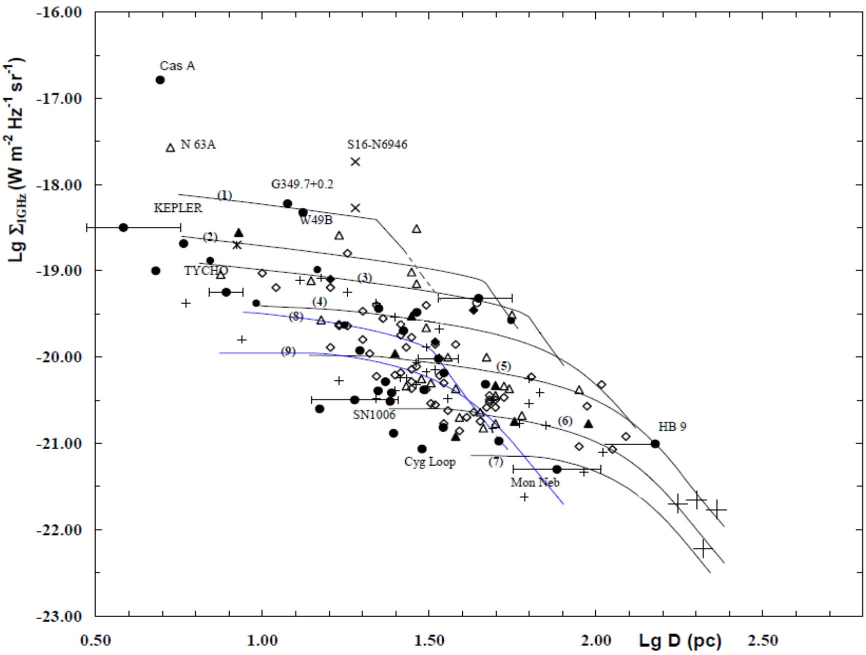

Fig. 3. $\Sigma - D$ tracks from [8] with minor changes.

second requirement is that the characteristic scale of radiative cooling l_{cool} should significantly exceed the characteristic diffusion length l_{diff} of electrons with energies of about GeV: $l_{\text{cool}} \gg l_{\text{diff}}$. If these conditions are satisfied, then we can apply a simple acceleration model in the test particle approximation. According to [6]

$$l_{\text{cool}} \cong 1.0 \cdot 10^{17} \left(\frac{n_0}{1\text{cm}^{-3}}\right)^{-1} \left(\frac{v_s}{200 \text{ km} \cdot \text{s}^{-1}}\right)^{-4} \text{cm},$$

for shock wave velocities $200 \text{ km s}^{-1} \leq \text{v}_\text{s} \leq 600 \text{ km s}^{-1}$,

$$l_{\text{cool}} \cong 10^{19} - 10^{20} \ (\text{cm}),$$

at $10 \text{ km s}^{-1} < v_s < 200 \text{ km s}^{-1}$

To calculate the diffusion length scale, we will adopt Bohm diffusion ($D_B = vpc/3qB$), and for electrons with energies of 10 GeV we obtain

$$l_{\text{diff}} \equiv \frac{D_B}{v_s} \cong 3.3 \cdot 10^{14} \, \eta \left(\frac{B_0}{5\mu G}\right)^{-1} \left(\frac{v_s}{200 \text{ km} \cdot \text{s}^{-1}}\right)^{-1} (\text{cm}),$$

where η is a parameter of the order of unity [10].

As we can see, the condition necessary for the operation of the acceleration mechanism is reliably satisfied for reasonable values of the parameters of the SNR and ISM. At velocities $v_s \geq 200$ km s^{-1} the shock wave itself is able to ionize the plasma around the shell. Thus, the forward shock wave of the SNR at the radiative stage is able to accelerate electrons to energies sufficient to generate synchrotron radio emission.

4. DISCUSSION AND CONCLUSIONS

As can be seen from the distribution of SNRs on the $\Sigma - D$ diagram, there is no dependence of the surface brightness on the diameter, and moreover, it is impossible to explain the observed distribution of supernova remnants by a single power-law dependence of the form $\Sigma = A \cdot D^{-\beta}$. Detailed theoretical models based on complex numerical calculations often predict a power-law form of this dependence (e.g., [2, 7]). This fact does not contradict our statement, since these models are applicable to young SNRs with high shock wave velocities, however, among the observational data on our diagram, the number of young shell-type SNRs is insignificant. Note that a large number of input parameters in such models allows one to obtain the desired or expected result. It should be taken into account that the diffusion acceleration mechanism is a highly nonlinear process, which can have ambiguous results. Therefore, the results of such models should be treated critically and applied to evolved and old SNRs with great caution.

From the analysis of the behavior of evolutionary tracks on the observational $\Sigma - D$ diagram, one can understand the role of various factors in the formation of such a distribution. As we have already stated, this diagram is practically unsuitable for determining distances to remnants. The main observational properties of observed SNRs in the radio range can be easily explained within the framework of the DSA mechanism. In this case, the evolutionary tracks have a universal character if the Mach number is taken as the value describing the evolution of SNRs. Then, regardless of whether the radiative phase begins or the evolution occurs adiabatically until the end of life, the DSA mechanism operates on the main shock wave, accordingly, the radio life is determined by the Mach number. Of course, old SNRs cannot be considered important accelerators of high-energy cosmic rays, but the process of particle acceleration in them continues. This issue was studied in detail in the work [11]. The best proof of the correctness of our idea that at the radiative stage the process of radio emission continues due to the work of DSA on the outer shock wave would be the detection of radio emission from the very edge of the SNR with $\alpha \geq 0.6$. However, such observational detection will be associated with great difficulties due to the weakness of the emission from the thin region, in the presence of inhomogeneities and irregularities characteristic of old objects.

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