OG.3.3.11

Cosmic Ray Acceleration in Young Supernova Remnants

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Abstract

We consider particle acceleration in the interaction region of a young supernova remnant. In the early phase of a supernova remnant, the ejecta drives a blast shock wave into the interstellar medium, and the high pressure behind the blast wave also drives a reverse shock wave back into the ejecta. We investigate particle acceleration in this converging flow region between two shocks.

1 Introduction:

Supernova remnants (SNRs) are believed to be the source of galactic cosmic rays (GCRs) from the arguments of energetics and the elemental abundance in the source of GCR. The recent detections of non-thermal X-ray emissions by ASCA (Koyama et al., 1995) and TeV gamma rays by CANGAROO from the shell of SN1006 (Tanimori et al., 1998) show the existence of $\sim 10^{14}$ eV electrons accelerated by the shock in SNR (Yoshida & Yanagita, 1997) and imply an existence of nuclear components with similar energies.

However, it is still an open question whether these energetic nuclei are accelerated from interstellar matter (ISM), or from supernova ejecta. Meyer, Drury, and Ellison (1997) and Ellison, Drury, and Meyer (1997) claims that GCRs observed in the present are injected into the shocks in SNRs from the ISM. On the other hand, the linear growth in Be abundance with Fe abundance observed in old, halo stars strongly suggests that GCRs come from supernova ejecta (Ramaty et al., 1997). Yanagita and Nomoto (1998) show that the bulk of GCRs is interpreted as a mixture of ejecta of Type Ia and Type II supernovae, by determining the best mixing ratio on the basis of the nucleosynthetic models of supernovae.

In this paper, we investigate particle acceleration in a SNR from the ejecta-dominated phase to the Sedov phase. In the ejecta-dominated phase of a SNR, the ejecta drives a blast shock wave into the interstellar medium, and the high pressure behind the blast wave also drives a reverse shock wave back into the ejecta (Chevalier 1982). Berezinsky and Ptuskin (1989) and Zhang (1993) investigated particle acceleration in this converging flow region between two shocks. Drury and Keane (1995) discussed the role of the reverse shock in GCRs acceleration. In this paper, by using McKee and Truelove's universal solution (1995), we examine the maximum achievable energy of particles accelerated by shock waves and the condition that particles can be accelerated within the shocked shell bounded by the two shock fronts.

2 Particle Accelerations by Two Shock Waves:

In order to consider particle accelerations at supernova shock waves, we use the analytic hydrodynamical model. McKee and Truelove (1995) show that there exists a universal solution for the evolution of a adiabatic SNR from the ejecta–dominated phase to the Sedov phase, in which they assume that the ejecta and the ambient medium have a uniform density. This solution is uniquely specified by three parameters: the total energy of the explosion E_e, the ejecta mass M_e, and the ambient hydrogen number density n_0. The units of length

$$R_{ST} = 2.23 (M_e/M_\odot)^{1/3} {n_0}^{-1/3}\ \mathrm{pc}$$

and time

$$t_{ST} = 209 (E_e/10^{51}\ \mathrm{erg})^{-1/2} (M_e/M_\odot)^{5/6} {n_0}^{-1/3}\ \mathrm{yr}$$

can be formed from the above parameters. The unit of time t_{ST} means the transition time between the ejecta-dominated phase and the Sedov phase. Approximate analytic time evolutions of radii and velocities are obtained for the blast shock in the ambient medium and the reverse shock back into the ejecta in terms of the units R_{ST} and t_{ST}. In the ejecta–dominated phase ($t < t_{ST}$),

$$R_b/R_{ST} = 1.37(t/t_{ST})[1+0.60(t/t_{ST})^{3/2}]^{-2/3}, \qquad v_b/v_{ST} = 1.37[1+0.60(t/t_{ST})^{3/2}]^{-5/3},$$
$$R_r/R_{ST} = 1.24(t/t_{ST})[1+1.13(t/t_{ST})^{3/2}]^{-2/3}, \qquad \tilde{v}_r/v_{ST} = 1.41(t/t_{ST})^{3/2}[1+1.13(t/t_{ST})^{3/2}]^{-5/3},$$

where the suffixes b and r denote the blast shock and the reverse shock respectively, and v_{ST} denotes the unit of velocity defined as $1.04 \times 10^4 (E_e/10^{51}\ \text{erg})^{1/2} (M_e/M_\odot)^{-1/2}\ \text{km}\,\text{s}^{-1}$. Here $\tilde{v}_r$ is the velocity of the upstream flow in the rest frame of the reverse shock: $\tilde{v}_r = R_r/t - v_r$, where v_r is the velocity of the reverse shock in the rest frame of the ambient medium. In the Sedov phase ($t \geq t_{ST}$),

$$R_b/R_{ST} = [1.56(t/t_{ST}) - 0.56]^{2/5}, \qquad v_b/v_{ST} = 0.63[1.56(t/t_{ST}) - 0.56]^{-3/5},$$
$$R_r/R_{ST} = (t/t_{ST})[0.78 - 0.03(t/t_{ST}) - 0.37\ln(t/t_{ST})], \qquad \tilde{v}_r/v_{ST} = 0.37 + 0.03(t/t_{ST}).$$

This approximate analytic solution reproduces well the result from a numerical simulation during the period before the reverse shock reaches the center at $t/t_{ST} \simeq 4.9$.

In this shock structure, when the mean free path of a particle is smaller than the distance between the blast shock and the reverse shock $\Delta R = R_b - R_r$, the particle is accelerated at the individual shock. If the mean free path of a particle becomes larger than the distance between the two shocks, the particle is accelerated in the region between the two shocks (Berezinsky and Ptuskin, 1989). The necessary condition under which the latter occurs is that the the time scale of diffusion t_{df} within the shocked shell bounded by the two shocks is shorter than the age of The SNR t_{age}. The diffusion time can be estimated as

$$t_{df} = \frac{(\Delta R)^2}{\kappa_2}, \tag{1}$$

where we assume that the diffusion coefficient κ_2 in the shocked shell is spatially constant. This assumption may be valid because the flow in the shocked shell is subject to convective or Rayleigh–Taylor instability and the mixing occurs around the contact discontinuity (Chevalier, Blondin, & Emmering, 1992). Here, the suffix 2 denotes the downstream and later the suffix 1 which denotes the upstream is introduced. The flow in the shocked shell is in the downstream at each rest frame of both shocks. We also assume that the diffusion coefficient is $\kappa_2 = f r_L c/3 = f_2 Ec/(3ZeB_2)$, where f is the ratio of the mean free path of the particle to the Larmor radius $r_L = E/(ZeB)$, E is the energy of the particle, c is the velocity of light, Ze is the electric charge of the particle, and B is the magnetic field strength in Gaussian unit.

The estimate of the maximum energy E_{max} of the particle accelerated by two shock waves is needed to calculate the minimum diffusion time t_{df}. For this estimate, it is needed to know the solution of the time-dependent cosmic-ray transport equation which describes the particle acceleration process by the two spherical shocks. Here, however, for simplicity, we use well known results for a single plane shock separately for the blast and reverse shocks. For nucleons the maximum achievable energy is limited by the age of the SNR t_{age}, because the energy loss time of high energy nucleons for the synchrotron radiation and the inverse Compton scattering is much longer than t_{age} (Zhang, 1993). In the first Fermi particle acceleration the acceleration time t_{acc} is represented by

$$t_{acc} = \frac{3}{V_1 - V_2}\left(\frac{\kappa_1}{V_1} + \frac{\kappa_2}{V_2}\right),$$

where V and κ are the flow velocity and the diffusion coefficient in the the upstream and downstream(Drury, 1983). We assume that the diffusion coefficients in the upstream and the downstream region are κ_1 =

$f_1 Ec/(3ZeB_1)$ and $\kappa_2 = f_2 Ec/(3ZeB_2)$. For a strong shock with $V_1 = V_s$ and $V_2 = V_s/r_c$, where V_s is the shock velocity and r_c is the compression ratio, the the acceleration time t_{acc} is

$$t_{acc} = \frac{r_c}{r_c - 1}\frac{Ec}{ZeV_s^2}(\frac{f_1}{B_1} + \frac{f_2}{B_2}r_c).$$

Therefore, for each shock, the maximum energy E_{max} is determined by equating $t_{acc} = t_{age}$ as

$$E_{max} = \frac{r_c - 1}{r_c}\frac{ZeV_s^2}{c}(\frac{f_1}{B_1} + \frac{f_2}{B_2}r_c)^{-1}t_{age}. \quad (2)$$

Figure 1 shows the maximum energies E_{max} for the blast shock and the reverse shock as a function of the the age of the SNR, where we assume that the shocks are strong: $r_c = 4$, wave excitations are rapid: $f_1 = f_2 = 1$, magnetic fields are parallel with respect to the shock normal: $B_1 = B_2 = 3\,\mu$G, and $Z = 1$ for both shocks. We also choose $E_e = 10^{51}$ erg, $M_e = 1.4\ M_\odot$, and $n_0 = 0.055$ cm^{-3} as the parameters which determine the time evolutions of radii and velocities of both shocks. After $t/t_{ST} = 1.6$, the maximum energy

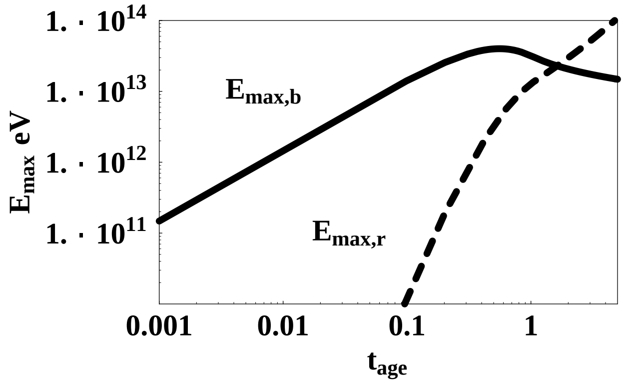

Figure 1: The maximum energies E_{max} estimated at the blast shock and the reverse shock as a function of the the age of the SNR t_{age} normalized by t_{ST}.

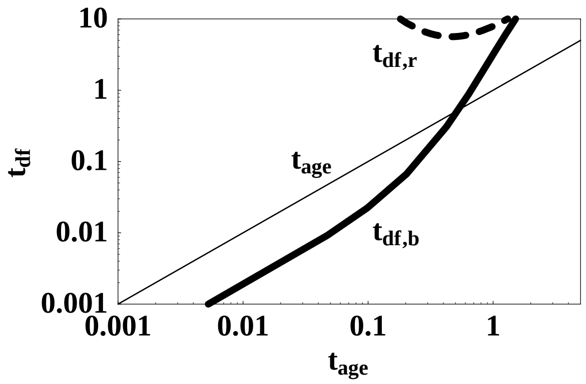

Figure 2: The minimum diffusion times t_{df}/t_{ST} within the shocked shell are compared with the age of the SNR t_{age}/t_{ST}.

$E_{max,r}$ estimated at the reverse shock is larger than $E_{max,b}$ estimated at the blast shock, because $\tilde{v}_r$ becomes larger than v_b.

The minimum diffusion time scales $t_{df,b}$ and $t_{df,r}$ can be calculated by using the maximum energy $E_{max,b}$ and $E_{max,r}$. In Figure 2 the diffusion times $t_{df,b}$ and $t_{df,r}$ are compared with the age of the SNR t_{age}. When $t_{age}/t_{ST} < 0.52$, the condition that particles can be accelerated in the region between two shocks $t_{df,b} < t_{age}$ is satisfied, although the minimum of of $t_{df,r}/t_{ST}$ is 5.6 at $t/t_{ST} = 0.46$ and $t_{df,r}$ does not satisfy the condition. This result implies that particles can be accelerated effectively in the region between two shocks.

3 Discussions:

We discuss the effect of magnetic field amplification in the shocked shell. As mentioned above, the flow is expected to be turbulent due to convective or Rayleigh-Taylor instability. And the turbulence may amplify the magnetic field (Zhang, 1993). If we assume that the magnetic filed B_2 in the shocked shell become larger than $r_c B_1$ and f_2 becomes smaller than f_1 due to strong scattering by the turblence in equation (2), the maximum energy E_{max} mainly depends on B_1 and f_1 and the diffusion coefficient κ_2 in the shocked shell becomes smaller. Then, since the diffusion time t_{df} becomes larger, particles may not be accelerated effectively in the region between two shocks.

It is pointed out by Chevalier and Blondin (1995) that the effect of radiative cooling in the shocked shell is important when the ejecta with a steep density profile interact with the surrounding medium with a density profile of $\rho \propto r^{-2}$ which is produced by the mass loss of the progenitor star. If the cooling occurs in the shocked shell, the shell thickness ΔR becomes thin. Then, we can expect that the diffusion time t_{df} becomes smaller than that for the adiabatic case. Accordingly, in order to investigate the condition of particle acceleration in the shocked shell, it is important to consider the effect of cooling on the hydrodynamics of shocked shell. For further investigation, it is needed to know the the process of the particle acceleration by the two spherical shocks, by solving cosmic-ray transport equation coupled with the hydrodynamic equations including radiative cooling.

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