Magnetic Field Configurations in SN 1006 NE Rim

Ryo Yamazaki,[1] Tatsuo Yoshida,[2] Toshio Terasawa,[3] Aya Bamba,[1] Masaru Ueno,[1] and Katsuji Koyama[1]
(1) Department of Physics, Kyoto University, Kyoto 606-8502, Japan
(2) Faculty of Science, Ibaraki University, Mito 310-8512, Japan
(3) Earth & Planetary Science, Graduate School of Science, University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, 113 Tokyo, Japan

Abstract

Characteristic scale lengths of nonthermal X-rays from the SN 1006 NE rim, which are observed by *Chandra*, are interpreted in the context of the diffusive shock acceleration on the assumption that the observed spatial profile of nonthermal X-rays corresponds to that of accelerated electrons with energy a few tens of TeV. To explain observed scale lengths, we construct two simple models with a test particle approximation, *the age-limited* and *the energy loss-limited model*, and discuss the condition that the magnetic field configuration or the diffusion coefficients of accelerated electrons should satisfy.

1. Introduction

SN 1006 is one of SNRs which are thought to be accelerators of galactic cosmic rays with energies less than the "knee" energy [1,2]. The mechanism of the cosmic ray acceleration has also been studied for a long time and the most plausible process is a diffusive shock acceleration (DSA). Many authors have explained the observed properties of SN 1006 in the context of the DSA but arrived at some different conclusions since one can arbitrarily assume the unknown physical parameters. This comes from a fact that theoretical understanding has been insufficient; apart from a globally successful picture of the DSA, detailed but important processes, such as the injection or the reflection of accelerated particles, which determine the above unknown quantities have not yet been well understood. Worse yet, previous observations in a hard X-ray band had insufficient spatial resolutions to resolve small-scale structures near the shock front, and therefore they cannot produce strong constraints on the theoretical parameters.

Recently, spectral and spatial studies on thermal and non-thermal shock structures in the NE rim of SN 1006 have been performed with the excellent spatial resolution of *Chandra* [3–5]. In [3] we made profiles of 6 filaments and found that the upstream scale length w_u ranges between 0.01 and 0.1 pc, while

pp. 2417–2420

w_d varies from 0.06 to 0.4 pc using the exponential function with adopted distance of 2.18 kpc [6]. The mean values of scale length of nonthermal X-ray filaments in upstream and downstream are 0.05 pc and 0.2 pc, respectively. The wide band spectrum from radio to X-rays from six filaments with *srcut* [7] are also discussed in [3] and we derive the best-fit roll-off frequency $\nu_{roll} = 2.6$ (1.9–3.3)$\times 10^{17}$ Hz, where ν_{roll} is written in terms of a downstream magnetic field and the maximum energy of accelerated electrons as $\nu_{roll} = 5 \times 10^{15}$ Hz $(B_d/10\mu\text{G})\,(E_{max}/10\text{TeV})^2$. We argue whether models in a context of a DSA can be constrained by these observed quantities.

2. Interpretations of the Observed Nonthermal X-ray Filaments

We construct two simple models in a context of the DSA with a test-particle approximation. We assume that the spatial distribution of nonthermal X-rays coincides with that of accelerated electrons with maximum energy, while thermal X-rays trace the spatial profile of a background plasma and hence a magnetic field. Note that for a steady state, there is no spatial structure of accelerated particles in the downstream, however, the finite-time or energy-loss effects make the spatial profile. For simplicity, we assume magnetic fields are spatially uniform both in the upstream and downstream at least in the nonthermal X-ray emitting region. One can see that since the wide-band spectrum shows a break at a hard X-ray band, accelerated electrons with energy near the maximum value E_{max} contribute the nonthermal X-ray emission.

We consider two important timescales. At first, the acceleration time is given as $t_{acc} = 3(K_u/u_u + K_d/u_d)/(u_u - u_d)$, where u and K are the velocity of bulk flow in the shock frame and the diffusion coefficients for accelerated electrons with the maximum energy, respectively. Subscripts "*u*" and "*d*" represent upstream and downstream, respectively. The diffusion coefficients are given by

$$K_u = \frac{cE_{max}}{3eB_u}\,\eta_u \left(\cos^2\theta + \frac{\sin^2\theta}{1+\eta_u^2}\right)\ , \tag{1}$$

$$K_d = \frac{cE_{max}}{3eB_d}\,\eta_d(\cos^2\theta + r^2\sin^2\theta)^{-1} \left(\cos^2\theta + \frac{r^2\sin^2\theta}{1+\eta_d^2}\right)\ , \tag{2}$$

where η, r, and θ are the gyro factor, the compression ratio, and the angle between upstream magnetic field and the shock normal, respectively [14]. Since we assume that the shock is sufficiently strong and that shock structure is not affected by the cosmic-ray pressure, r should be 4 and the upstream and downstream magnetic field be related as $B_d/B_u = R(\theta) := (\cos^2\theta + r^2\sin^2\theta)^{1/2}$.

Secondly, we consider the energy loss timescale given by $t_{loss} = 1.25 \times 10^3\,\text{yrs}\,(E_{max}/10\text{TeV})^{-1}(B/10\mu\text{G})^{-2}$, where we consider electron cooling via synchrotron radiation. Inverse Compton effect can be neglected since we will conclude the downstream magnetic field to be efficiently high. When one compares t_{loss} with t_{acc}, the mean value of the magnetic field that accelerated electrons suffer should be adopted. We can estimate the mean magnetic field as $\langle B^2 \rangle = \alpha B_u^2 + (1-\alpha) B_d^2 = \chi B_d^2$, where $\alpha = \Delta t_u / (\Delta t_u + \Delta t_d)$ is the fraction of time in which accelerating electrons stay in the upstream. For the particles in the acceleration process, we can estimate $\Delta t_u / \Delta t_d \sim (K_u/u_u)/(K_d/u_d)$. Then, we obtain $\chi = (R^{-2} K_u + r K_d)/(K_u + r K_d)$, which ranges between 0 and 1, and affects our results slightly.

2.1. Age-Limited Case

First, we investigate the case in which the acceleration time is nearly equal to the age of SN 1006 $t_{acc} \sim t_{age} < t_{loss}$. This condition implies that the observed nonthermal X-rays are emitted by electrons that have been accelerated up to now. In this case, in both upstream and downstream, accelerated particles can reach up to the place at which the advection is balanced with the diffusion. Therefore, the observed widths of nonthermal X-rays can be written as $w_u = K_u/u_u$ and $w_d = K_d/u_d$. Then, we derive $t_{acc} \sim 3.4 \times 10^2\,\mathrm{yrs}\,((w_u + w_d)/0.25\,\mathrm{pc})$, which is comparable to the age of the SN 1006, and our assumption $t_{acc} \sim t_{age}$ is justified. Here, we use $u_u = r u_d = u_s$, and we adopt $u_s = 2.89 \times 10^3$ km s^{-1} [9].

We have six unknown parameters E_{max}, B_u, B_d, η_u, η_d, and θ, while four equations that relate these quantities. For fixed θ and B_d, we solve η_u and η_d. When we take $\theta = 0°$, the case of $\eta_u = \eta_d = 1$ (the Bohm limit in both upstream and downstream) is marginally acceptable, since η should satisfy $1 \le \eta \le c/u_s \sim 10^2$ [8]. Then the magnetic field has values of $B_u = B_d =$ 20–78 μG. The maximum value of magnetic fields is achieved when observed quantities ν_{roll}, w_u, and w_d have the minimum values, respectively. On the other hand, when $\theta \ge 85°$, cases of small magnetic fields can be exist. We can see if we choose $w_u = 0.1$ pc, $w_d = 0.3$ pc, and $\nu_{roll} = 2 \times 10^{17}$ Hz, then $\eta_u \sim 10$ and $\eta_d \sim 1$, and the magnetic field has a value of $B_d \sim 4B_u \sim$ 14–20 μG.

2.2. Energy Loss-Limited Case

Here, we consider the case in which the maximum energy of accelerated electrons E_{max} is determined by $t_{acc} = t_{loss} < t_{age}$. In this case, the motion of accelerated particles might be obstructed by the energy loss effect. Therefore, we write $w_u = \min\{K_u/u_u, (K_u t_{cool})^{1/2}\}$ and $w_d = \max\{u_d t_{cool}, (K_d t_{cool})^{1/2}\}$. (Indeed, practical calculations show that in almost all cases, scale lengths are given by $w_u = K_u/u_u$ and $w_d = u_d t_{cool}$.)

We can now use five equations for six unknown parameters E_{max}, B_u, B_d, η_u, η_d, and θ, and solve these equations with fixed θ. When $\theta = 0°$, the case of $\eta_u = \eta_d = 1$ is again acceptable. Then, the magnetic field is in the range of $B_u = B_d =$ 23–85 μG. One can see that if $\theta \le 30°$, cases in which the downstream

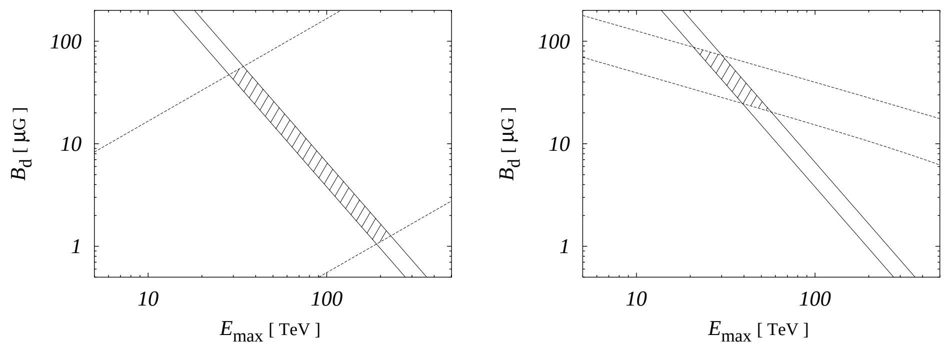

Fig. 1. The shaded areas indicate the most likely values of magnetic fields just behind the shock front B_d and the maximum energy of shock-accelerated electrons E_{max}. The left panel is for the age-limited case, while the right the energy loss-limited model. These areas are formed by the two solid lines, between which a roll-off energy is $\nu_{roll} = (1.9–3.3)\times10^{17}$ Hz, and the dashed lines, which are limitations from the observed width of nonthermal X-rays; in the age-limited case, a gyro-radius of accelerated electrons in the downstream should be $r_g = E_{max}/(eB_d) = (0.065–20) \times 10^{-2}$ pc, while in the energy loss-limited case, cooling time of accelerated electrons should be $t_{cool} = w_d/u_d = (0.81–5.4) \times 10^2$ yrs.

magnetic field is in the Bohm limit $\eta_d = 1$ could exist and then $\eta_u \sim 1–8$ and $B_d \sim 23–85\ \mu$G. However, if θ is larger than $\sim 30°$, one can see $\eta_d \geq 10$ and then $\eta_u \leq 10$, which implies that the upstream magnetic field is more turbulent than the downstream and seems to be unnatural.

3. References

1. Koyama, K. et al. 1995, Nature, 378, 255
2. Tanimori, T. et al. 1998, ApJ, 497, L25
3. Bamba, A., et al. 2003, ApJ, 589, in press
4. Bamba, A., et al. 2003, Adv. Space Res., in press
5. Long, K.S. et al. 2003, ApJ, 586, 1162
6. Winkler, P.F., Gupta, G., & Long, K.S. 2003, ApJ, 585, 324
7. Reynolds, S.P., & Keohane, J.W. 1999, ApJ, 525, 368
8. Jokipii, J.R, 1987, ApJ, 313, 842
9. Ghavamian, P. et al. 2002, ApJ, 572, 888