Cosmic Ray Acceleration and γ Ray induced by the Interaction of the Ejecta of SN1987A with the Magnetized Cloud

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We have studied the high energy physical process related to the cosmic ray acceleration for SN1987A. The X-ray flare observed by Ginga satellite (Makino 1988) and TeV γ-rays reported by the JANZOS collaboration (Bond et al. 1988) occurred in January, 1988. These events may be explained by the interaction of the supernova ejecta with the surrounding cloud, which induces the thermalization of shocked material and the acceleration of cosmic ray on the reverse shock at the front of cloud. Especially, the soft X-ray emission from SN1987A is well described by the interaction model of the ejecta with the circumstellar medium (Masai et al. 1988, and Yoshida and Hanami 1988). It seems to be natural to consider that the origin of the γ-ray is connected with that of the X-ray flare, since they had occurred at same time. Then, we consider about the relation of this acceleration mechanism and the evolution scenario of the progenitor.
As pointed out by Honda et al.(1989), the shortest time scale for particle acceleration to the energy E is represented as following,

$$t_{\rm acc} \approx 7.6 \times 10^5 \left(\frac{B}{30mG}\right)^{-1} \left(\frac{E_{\rm p}}{30Tev}\right). \tag{1}$$

where $E_{\rm p}$ is the energy of accelerated high energy particle. As observed by JANZOS, in the interaction between the ejecta and the cloud, the acceleration time is limited to $\leq 10^6$sec, which is the time scale of the γ-ray flare raising. Then, for accelerating to 30TeV for protons, we need 20mG as the magnetic field strength at the shock wave. However, the strength of magnetic field in interstellar medium ordinally is about 1μG (cf. Spitzer 1978). Even if we consider the magnetic field at the surface of the progenitor as this origin, since $B = r_0/r \times B_0$ considering the expansion of frozen-in field, where $B_0 \sim 1G$, B is 0.1mG at the radius of the cloud position 3×10^{16} cm. These values are smaller than the strength of magnetic field which we need for the particle acceleration. For retaining this cosmic ray accelerating model, we must introduce the process of magnetic field amplification. It seems to be that there are two way from a view point of magneohydrodynamics.

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One way is the turbulence dynamo amplification process, which is popular as the dynamo theory in stars. However, this process have not been well known in the highly supersonic expanding fluid like the case of supernova explosion. Another possibility is the magnetic field compression effects by the interaction between the wind of blue giant progenitor and the cloud. If there is the magnetic field in the wind material of blue giant, it can be pailed and swept up until the magnetic pressure become comparable to the ram pressure in the up-flow region of the shock. Thus, we get a following relation for the maximum amplified magnetic field and the momentum flux of the wind of the blue giant,

$$\frac{1}{2}\rho V_{\rm w}^2 \sim \frac{B_{\rm max}^2}{8\pi}. \tag{2}$$

Furthermore, we can rewrite this relation to

$$B \leq B_{\rm max} = \sqrt{4\pi\rho V_{\rm w}^2} = 23.8 \left(\frac{\dot{M}}{3x10^{-6} M_{\odot} yr^{-1}} \frac{V_{\rm w}}{3000 km/s}\right)^{\frac{1}{2}} \left(\frac{r}{10^{16} cm}\right) mG. \tag{3}$$

where, assuming the progenitor had supplied the wind with constant mass loss rate and terminal velocity, we had used $\rho = \dot{M}/4\pi V_{\rm w} r^2$ as the density of the wind at the certain radius r. As shown in equation (3), the strength of the magnetic field required for the particle acceleration is nearly equal to that compressed by the blue giant wind. Furthermore, when the supernova remnant interacts with the cloud, the magnetic field can be compressed and more enhanced by the reverse shock. If the supernova exploded in the blue giant phase as suggested by the IUE observation, the strong magnetic field around the cloud can be produced and induce the acceleration of cosmic ray producing γ-ray flare.

References

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