SPECTRAL EVOLUTION OF γ-RAYS FROM ADIABATICALLY EXPANDING SOURCES IN DENSE CLOUDS

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ABSTRACT

The excess of antiprotons ($\bar{P}$) observed in cosmic rays has been attributed to their production in supernova (SN) envelopes expanding in dense clouds. While creating $\bar{P}$, γ-rays are also produced and these clouds would shine as γ-ray sources. The evolution of the γ-ray spectrum has been calculated for clouds of $n_H = 10^4$ and $10^5/cm^3$.

1. Introduction. The observed flux of $\bar{P}$ in cosmic radiation [1-3] has invoked many new ideas in recent years to explain these observations [4]. The observed excess of $\bar{P}$ implies large amount of matter to be traversed by cosmic rays and recently, Mauger and Stephens [5] have suggested the possibility of producing $\bar{P}$ in the envelopes of SN exploding in dense clouds. Cosmic rays while traversing matter produce pions and kaons, in addition to $\bar{P}$. These unstable particles decay to γ-rays and electrons; γ-rays are also produced by the interaction of electrons with matter and radiation fields. Such sources should shine in γ-rays and it is neces-sary to look for them [6]. In this paper, we derive the evolution of γ-ray spectrum in SN envelopes, which expand in dense clouds, and examine the consequences.

2. Theoretical Approach. The evolution of nucleon and electron compo-nents in supernova envelopes can be examined by solving the following coupled equations

$$\frac{dJ_p}{dt} = \frac{\partial}{\partial E}(J_p \frac{dE_p}{dt}) + \int_{E'} \frac{\rho v}{\lambda} J_p \frac{dE'}{E'} - \frac{\rho v}{\lambda} J_p \qquad \cdots \qquad (1)$$

$$\frac{dJ_e}{dt} = \frac{\partial}{\partial E}(J_e \frac{dE_e}{dt}) + Q_e \qquad \cdots \qquad (2)$$

In the above equations, the 1st term on the R.H.S. describes the conti-nuous energy loss of particles. In the case of protons, this energy loss corresponds to ionization and adiabatic cooling, the latter being $(dE/dt)_A = \{(E+2m)E/r(E+m)\}(dr/dt)$. The radius r and its derivatives are obtained from the dynamics of SN. The 2nd term describes the energy shift due to the finite elasticity of the interacting particle and the 3rd term corresponds to the loss of particles due to interaction. In these terms, λ is the interaction mean free path and v the velocity of the interacting particle. In the case of electrons (Eqn.2), the continuous loss term contains also loss due to bremsstrahlung, inverse

Compton and synchrotron processes. For the inverse Compton process, we have used a radiation density corresponding to an optical outburst of 10^{43} ergs/s soon after the SN explosion, which then decay with an e-folding time of 0.2 yr. The magnetic field inside the remnants is assumed to scale as $B^2 \alpha\, n_H$, with B = 4μG at n_H = 1 atom. cm^{-3}.

Equation 2 is coupled to the 1st equation through the term Q_e which is given by

$$Q_e = \int_{E_\mu} \int_{E_\pi} \int_{E_p} \int_\theta \frac{dE_\mu}{\Psi_e} \cdot \frac{dE_\pi}{\Psi_\mu} \cdot \{J_p\, \rho v\}\, dE_p \cdot \{2\pi (E \frac{d^3\sigma}{dp^3})\}\, p_\perp\, d\theta$$

$$\ldots \qquad (3)$$

Here, the integral over θ describes the production of pions, in which $p_\perp$ is the transverse momentum of pions, θ the angle of emission and $(E\, d^3\sigma/dp^3)$ the invariant cross section, which depends upon E_p. The integrals over E_π and E_μ take care of the energy distribution of muons and electrons during decay; Ψ's are normalized functions. We have also included the knockon electrons, which are important below a few tens of MeV. All these parameters are taken from the work of Badhwar and Stephens [7]. The set of coupled equations (1) and (2) has been solved by Runge Kutta method. It is assumed that the acceleration is complete at onset of adiabatic phase and the initial energy spectrum is assumed to be a power law in rigidity of the type A R$^{-2.75}$, where A = 2.5x10^4/(m^2. sr.s.GV/c) for nucleons and = 150/(m^2.sr.s.GV/c) for electrons. The parameters relating to the evolution of SN in dense clouds have been described earlier [8]. For the sake of simplicity, it is assumed that the size of cloudlets is such that the total amount of matter traversed by cosmic rays, when the envelope leaves the cloudlet, is about 50 g.cm^{-2}.

During the expansion of the remnant, cosmic rays interact with matter to produce neutral pions which decay into γ-rays. Electrons interact to produce bremsstrahlung γ-rays; the contribution from inverse Compton is very small during the adiabatic phase. γ-rays thus produced are calculated using the following integrals.

$$\dot{P}_\gamma(t)_{\pi^\circ} = 4\pi \int_{E_{\pi^\circ}} \int_{E_p} \int_\theta \frac{2dE_{\pi^\circ}}{\Psi_\gamma} \cdot \{J_p\, \rho v\}\, dE_p \cdot \{2\pi\, (E \frac{d^3\sigma}{dp^3})\, p_\perp\, d\theta\} \ldots (4)$$

$$\dot{P}_\gamma(t)_B = 4\pi \int_{E_c} \Phi\, (E_e, E)\, \rho v\, J_e dE_c \qquad \ldots \qquad (5)$$

Eqn. 4 is similar to Eqn. 3, except that π° decays to γ-rays and the energy distribution of γ-rays is taken care through the integral over E_{π°. The cross-section for π° production is taken from Stephens and Badhwar [9]; the bremsstrahlung cross-section $\phi(E_e, E)$ is with and without screening [10].

3. γ-ray Spectral Evolution. We have used for the calculation the interstellar cosmic ray spectrum to be the source spectrum in the SN, and to determine the total cosmic ray energy density in the source, the following procedure has been adopted. It is found that one needs 30% of
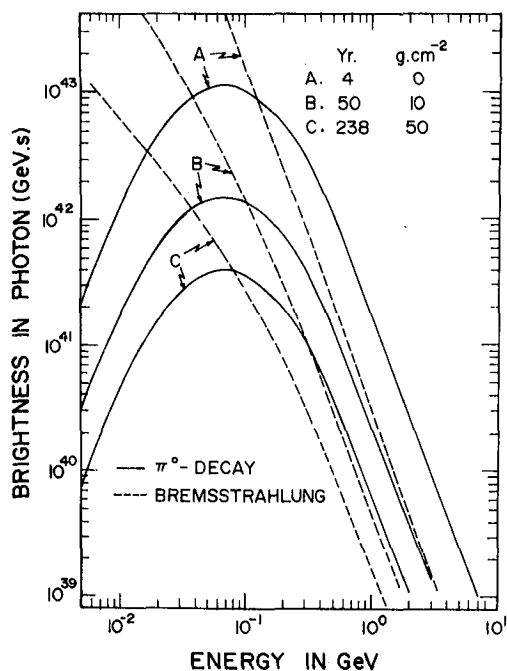
Fig.1. γ-ray spectra through π°
decay and bremsstrahlung are
shown for SN exploding in a
cloud with 10^5 atom.cm^{-3}.

Fig.2 γ-ray brightness is plotted
as a function of time for two n_H
values.

the cosmic ray nucleons to originate from SN in dense clouds in order to explain the $\bar{P}$ observations [8]. The remaining 70% is assumed to come from SN exploded in ordinary clouds with n_H = 10 atom.cm^{-3}; the observed birth rate of these SN is one in ~30 yrs. Considering a galactic space with radius 15 kpc and thickness 0.5 kpc, one requires an energy release ~ 7×10^{60} eV in cosmic rays by a SN to account for the present energy density over a period of 3×10^7 yrs. It is assumed that the acceleration is complete in these sources around 200 yrs. The adiabatic cooling is expected to cease at the end of adiabatic phase, when the envelope fragments. Taking into account the energy loss processes during expansion, the calculated energy output just after the acceleration is ~10^{62} eV. Therefore, we use this factor to obtain γ-ray brightness in our calculations.

The evolution of γ-ray spectrum is shown in Fig. 1 for various stages of SN evolution in clouds of density n_H = 10^5 atom.cm^{-3}. The ordinate brightness scale is given as photon per (GeV.s). It can be seen that during the early phase, the spectrum below a few hundred MeV is dominated by bremsstrahlung radiation and as a result, the total spectrum can be represented by a simple power law. However, at the later stages, π° decay γ-rays become dominant. In order to examine the variation of the total intensity with time, we have plotted in Fig. 2, the integral brightness above 100 MeV as well as above 30 MeV as a function of time, for n_H = 10^5 and 10^4 atom cm^{-3}; the upper scale is for n_H = 10^5 atom. cm^{-3}.
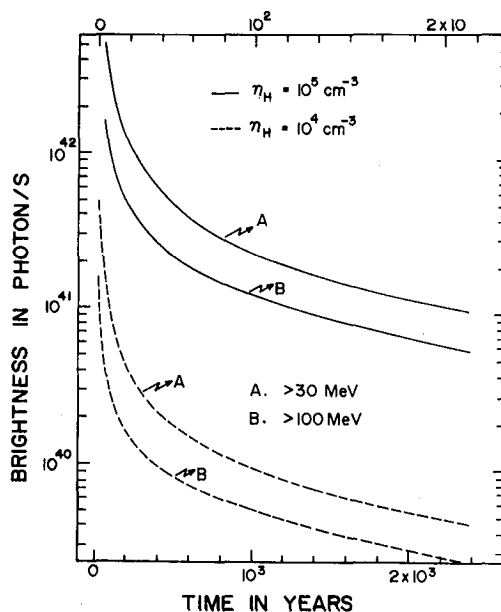
It can be noticed from Fig. 2 that, these sources are visible even upto far end of the Galaxy, if the threshold for detection is good to 10^{-6} photon/cm^2 for $n_H = 10^5$ atom.cm^{-3}. The life time of this source is only a few hundred yrs. and hence the number of such sources would be small in a given time. In the case of $n_H = 10^4$ atom.cm^{-3}, the threshold needed to detect them over the entire galaxy is $<10^{-7}$ photon.cm^{-2}. The energy dilution of cosmic rays in these sources from the onset of the adiabatic phase till they travel 50 g.cm^{-2} of matter is estimated to be by a factor 24.5 and 55 for $n_H = 10^5$ and 10^4 atom.cm^{-3} respectively, which can be compared to 17.5 for $n_H = 10$ atom.cm^{-3}. Therefore, the number of such sources in the galaxy in comparison with the number of SN exploding in normal cloud is 0.6:1.0 and 1.34:1.0 for $n_H = 10^5$ and 10^4 atom.cm^{-3} respectively. This would mean that equal number of SN are exploded in dense clouds with diameter $\lesssim 1$ pc, but only a few of them would be visible for observation.

References.

[1] R.L. Golden et al., Phys. Rev. Letters, 43, 1196 (1969)
[2] E.A. Bogomolov et al., Proc. 17th ICRC (Paris), 9, 146 (1981)
[3] A. Buffington et al., Ap.J., 248, 1179 (1981)
[4] S.A. Stephens, Proc. 17th ICRC (Paris), 13, 89 (1981)
[5] B.G. Mauger and S.A. Stephens, Proc. 18th ICRC (Bangalore), 9, 171 (1983)
[6] V.L. Ginzburg and V.S. Ptuskin, J. Ap. Astron. 5, 99 (1984)
[7] G.D. Badhwar and S.A. Stephens, Proc. 15th ICRC (Plovdiv), 11, 149 (1977)
[8] S.A. Stephens and B.G. Mauger, Proc. 19th Rencentre de Moriond Astrophysics Meeting, 217 (1984); Ap.Sp.Sci. (1985) in press.
[9] S.A. Stephens and G.D. Badhwar, Ap.Sp.Sci., 76, 213 (1981)
[10] J. Nishimura, Handbuch der physik, XLVI/2, 1 (1967)
[11] W. Hermson, Ph.D. Thesis, University of Leiden (1980).