ELECTRONS AND POSITRONS FROM EXPANDING SUPERNOVA ENVELOPES IN DENSE CLOUDS

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ABSTRACT

If antiprotons ($\bar{p}$) in cosmic rays are produced as secondary particles in sources, it is expected that positrons are also created by the same process. In this paper we calculate the interstellar spectra of positrons and electrons by taking into account such sources, and compare them with observations.

1. Introduction. Large flux of $\bar{p}$, in excess of that expected on the basis of a few g.cm^{-2} of matter traversed by cosmic rays, has been observed [1-3]. This excess has been explained as being produced in the expanding envelopes of supernova (SN), which explodes in dense cloudlets in the Galaxy [4]. It is shown that if 30% of the observed cosmic ray nucleons come from such sources, $\bar{p}$ observations can be explained satisfactorily [5]. As $\bar{p}$ being produced in interactions of cosmic ray nucleons with gas, it is expected that pions and kaons are also produced in these interactions, which decay to electrons and positrons. In these sources initially accelerated electrons are depleted at high energies due to synchrotron process. As a result, high energy spectrum of the electron component from these sources are expected to be rich in positrons. In this paper, we evaluate the equilibrium spectra of positrons and electrons in the Galaxy by including the electron component from these sources.

2. Electron Spectrum in the Same Source. The evolution of electron component inside SN envelope is coupled to that of nucleonic component and therefore, one needs to solve the following coupled equations.

$$\frac{dJ_p}{dt} = \frac{\partial}{\partial E}\left(J_p \frac{dE_p}{dt}\right) - \frac{\rho v}{\lambda} J_p + \int_{E'} \frac{\rho v}{\lambda} J_p \frac{dE'}{E'} \quad \ldots \quad (1)$$

$$\frac{dJ_{e^\pm}}{dt} = \frac{\partial}{\partial E}\left(J_{e^\pm} \frac{dE_{e^\pm}}{dt}\right) + Q_{e^\pm} \quad \ldots \quad (2)$$

In the above equations, 1st term on the RHS describes continuous energy loss of particles. In the case of protons, this energy loss corresponds to ionization and adiabatic cooling. For electrons, in addition to the above, one needs to include bremsstrahlung and synchrotron processes; the loss due to inverse Compton process is small compared to synchrotron process except at a very early phase of SN. 2nd term in Eqn. 1 is the loss of nucleons due to interaction and 3rd term takes care of the finite inelasticity during collision. In these terms, v is the velocity of interacting particle, ρ the density and λ the interaction mean free path. The production term $Q_{e^\pm}$ is given as

$$Q_{e^\pm} = \iiiint \frac{dE_\mu}{\Psi_e} \cdot \frac{dE_\pi}{\Psi_\mu} \cdot \{J_p \rho v\} dE_p \cdot \{2\pi (E \frac{d^3\sigma}{d_p^3})\} \; p_\perp \; d\theta \; \ldots \qquad (3)$$

In this equation, integral over θ describes the production of pions, in which $p_\perp$ and θ are the transverse momentum and angle of emission of pions; the invariant cross-section $E(d^3\sigma/d_p^3)$ depends upon E_p and hence the integral over E_p. The integrals over E_π and E_μ take care of the energy distribution of decay products as pion decays to muon and muon to electron. The parameters relating to the production of pions and the evolution of SN are described elsewhere [5,6].

While evaluating Eqns. 1 and 2, we have set the initial condition that the energy spectra of nucleons and negatrons are simple power law in rigidity of the type $AR^{-2.75}$, where $A = 2.5\text{x}10^4$ and 150 particles/cm^2.sr. s.GV/c) for nucleons and electrons respectively. It is assumed that the initial acceleration is complete at the onset of the adiabatic phase and the remnant leaves the cloudlet when cosmic rays traverse ~ 50 g.cm^{-2} of matter. The magnetic field inside the cloud is expected to scale as $B^2 \alpha \rho n_H$, with $B_o = 4\mu G$ for $n_H = 1$ atom.cm^{-3}. The photon density corresponds to an outburst of optical photons of 10^{43} erg/s soon after the explosion, which decay with an e-folding time of 0.2 yrs.

3. Equilibrium Spectrum in Interstellar Space. The equilibrium spectrum of $e^\pm$ in interstellar space is evaluated by solving the continuity equation

$$\frac{dJ_{e^\pm}}{dt} = \frac{\partial}{\partial E} (J_{e^\pm} \frac{dE_{e^\pm}}{dt}) + Q_{e^\pm} - \frac{J_{e^\pm}}{T} \qquad \ldots \qquad (4)$$

In this equation, the source term $Q_{e^\pm}$ consists of 3 terms. (1) The electrons from SN, which explode in dense clouds. This is obtained from Eqn. 2 and normalized to the observed $\bar{p}$ flux value at 9 GeV [1]. The production term is then given by $J_{e^\pm}/T$. (2) The second term comes from sources in which cosmic rays traverse matter in an energy dependent manner [7]. It is assumed that at energies $\lesssim 2$ GV/c, the matter traversed is ≈ 4 g.cm^{-2} and above this energy it is proportional to $R^{-0.6}$. The secondary production of electrons is calculated using the equilibrium nucleon spectrum in the source and $Q_{e^\pm}$ is obtained after allowing for the energy dependent leakage. (3) The third term comes from the production of secondary electrons in interstellar space. In the case of negatrons, we have also included a term which is 70% of 150 $E^{-2.75}/T$. The resident time T in Eqn. 4 is considered to be free parameter and is adjusted to fit the observed electron spectrum.

4. Results. We have plotted in the lower part of Fig. 1, the observed flux values of electrons from recent experiments above 1 GeV [8-10]. For convenience, the flux scale is multiplied by E^3. The curve shown here is the calculated spectrum using a value of $5\text{x}10^6$ yrs for T. One finds

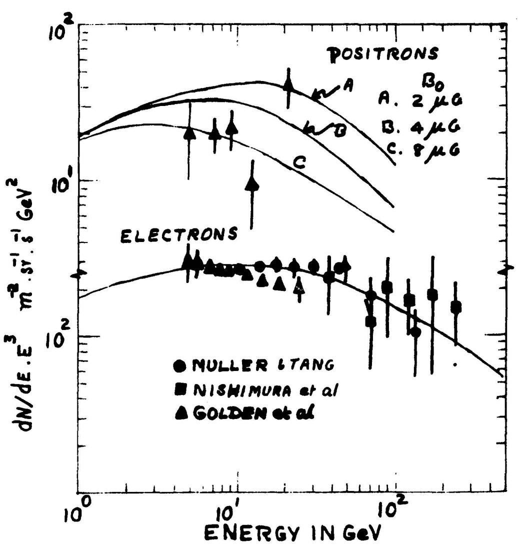

Fig. 1 *The spectrum of electrons is shown on the lower part of this figure and that of e^+ is shown on the upper part*

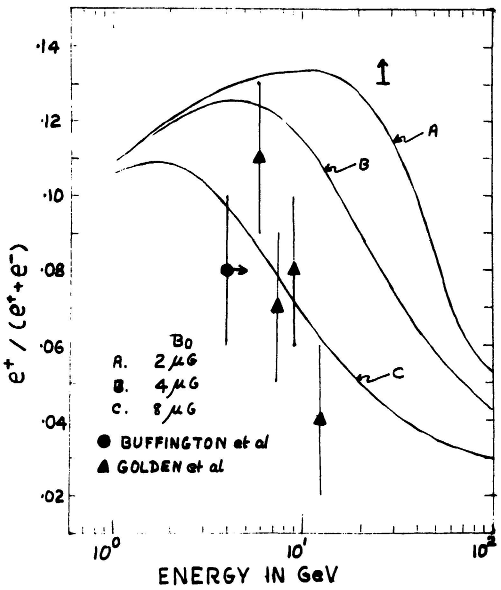

Fig. 2 *Positron fraction is plotted as a function of energy*

a good fit to the observed data points. We make use of the same interstellar parameters to calculate the positron spectrum from Eqn. 4.

The calculated positron spectrum in interstellar space is plotted in the upper part of Fig. 1. We have pointed out earlier that high energy electrons in SN envelopes are depleted by synchrotron energy loss process, and the positron spectrum is quite sensitive to the B_o value used in Eqn. 2. Three curves shown in Fig. 1 is based on different values of B_o. The spectral steepening noticed in this figure is due to the combined effect of energy loss processes and the energy dependent matter traversal in sources. The data points plotted here are from Golden et al. [11]. One notices from Fig. 1 that the positron spectrum is quite consistent with the model that major contribution comes from sources which produce antiprotons in cosmic rays. The spread in the data points is such that one cannot obtain a precise value of B_o, though a value between 4 and 8 μG could fit the data points well.

We have shown in Fig. 2, the fraction of positrons as a function of energy for 3 different values of B_o as in Fig. 1. The increase in this ratio with energy arises from the fact that initially accelerated electrons in SN, which explode in dense clouds are depleted due to synchrotron process and that the electron component at higher energies is dominated by secondary particles. The initial decrease in the ratio is primarily due to the depletion of secondary electrons through synchrotron process and later by the energy dependent source term in Eqn. 4. One also notices that the ratio attains an asymptotic value close to about 2% at very high energies. The absolute value of this ratio can be easily adjusted by about 20% by increasing the primary electron flux values by the same factor. In that case a small adjustment in the value of T could reproduce the good fit obtained for electrons in Fig. 1. We have also plotted the observed values of the fraction of e^+ [11,12]. One notices that the general trend of the data points are similar to the calculated values except for a normalization of about 20%, which is consistent with the errors in the results.

Thus we conclude that SN exploding in dense clouds seems to explain not only the $\bar{p}$ results but also the e^+ data. We have also shown elsewhere that the observed Cos-B γ-ray sources could also be explained [13].

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