OBSERVED ANTIPROTONS AND ENERGY DEPENDENT CONFINEMENT OF COSMIC RAYS: A CONFLICT?

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ABSTRACT

In the frame work of energy dependent confinement for cosmic rays, the energy spectrum inside the source is flatter than that observed. Antiproton ($\bar{p}$) observation suggests large amount of matter is being traversed by cosmic rays in some sources. As a result, secondary particles are produced in abundance. We have calculated their spectra and it is shown that the energy dependent confinement model is in conflict with some observations.

1. Introduction. The observed secondary to primary nuclei in cosmic rays decrease with energy suggesting that matter traversed by cosmic rays depends upon energy. Therefore, it was postulated (Eg. Juliusson et al. [1]) that the confinement of cosmic rays in the Galaxy is energy dependent. Recent observations show that the behaviour of this dependence is $\alpha R^{-\delta}$ above ~ 2 GV/c with δ = 0.6 to 0.7 [2,3]. This would mean that the accelerated spectrum of cosmic rays has a spectral index β = 2.15 to 2.05. $\bar{P}$ observations show that cosmic rays traverse a large amount of matter inside some sources. Because of the flatness of source spectrum, secondary particles are copiously produced [4], and the effect of energy loss processes is less felt by the particles. Recently, it is shown that supernova (SN) explosion in dense cloudlets can explain $\bar{p}$ observations [5]. This work was based on the Nested Leaky Box Model [6], in which cosmic ray source spectrum has β = 2.75. In this paper, we calculate the secondary particle production in SN, which explode in dense cloudlets, in the framework of energy dependent confinement model. We then compare the spectra of γ-rays, electrons and positrons with observation.

2. γ-ray Emission from Sources. We have established a set of coupled differential equations to describe the propagation of protons, $\bar{p}$, $e^{\pm}$ inside SN envelope, by taking into account all energy loss processes including adiabatic cooling during expansion [7]. The initially accelerated spectra is obtained by normalizing the interstellar spectra at 2 GV/c and thus we obtained $1.65\times10^4\ R^{-2.15}/(m^2.sr.s.GV/c)$ for nucleons and 90 $R^{-2.15}/(m^2.\ sr.\ s.\ GV/c)$ for electrons. We consider that the SN expansion continues in the cloudlet till about 50 $g.cm^{-2}$ matter is being traversed by cosmic rays. Because of the flat spectrum of nucleons, it is found that only 10% of the observed nucleons in cosmic rays have to come from such sources in order to account for the observed $\bar{p}$; the corresponding value for β=2.75 is 30% [8]. The effect of synchrotron radiation on electron spectrum is also small and the spectrum

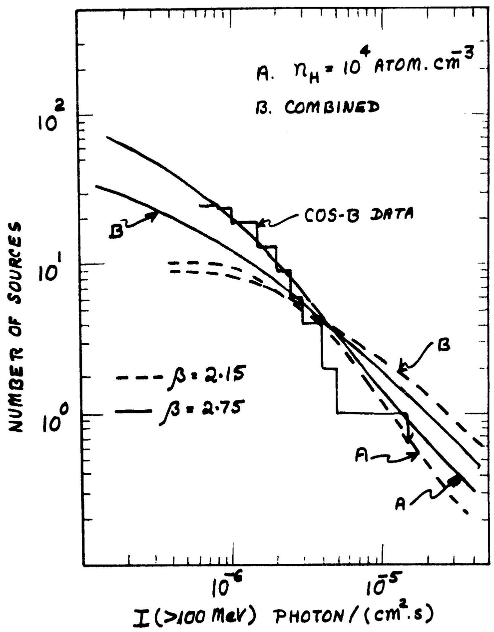

Fig.1 Integral distribution of γ-ray sources is shown as a function of intensity above 100 MeV. The dashed curves are for energy dependent model and the solid curves are for Nested Leaky Box model.

at high energies is not much depleted.

We have calculated the spectrum of γ-rays resulting from π° decay and bremsstrahlung processes. If 90% of the observed cosmic rays come from SN exploding in normal interstellar medium, the scaling required to estimate the total brightness of the source from the normalized interstellar spectrum is $\approx 10^{62}$. In order to calculate this number, we consider a galactic volume of R = 15 kpc and h = 0.5 kpc, in which cosmic rays are stored for 3×10^7 yrs. In this volume, the rate of SN explosion in interstellar medium is one in 30 yrs. We assume that acceleration is complete in ~200 yrs and the adiabatic cooling effective during the adiabatic phase. The number of SN required in cloudlets to account for the observed $\bar{p}$ is calculated and the relative number to that explode in interstellar space is found to be 0.129, 0.093, 0.075 and 0.061 for $n_H = 10^4$, 4×10^4, 10^5 and 2.5×10^5 atom.cm^{-3} respectively. Making use of these parameters, we have calculated the luminosity distribution of γ-ray sources in the Galaxy as described elsewhere [9].

We have shown in Fig. 1, the luminosity distribution of γ-ray sources for energies 100 MeV, assuming that the distribution of SN in the Galaxy is similar to the molecular hydrogen [10]. The dashed Curve A is calculated for $n_H = 10^4$ cm^{-3} and Curve B after folding in the observed density distribution of clouds [11]. These are compared with the Cos-B distribution [12], which is shown by the histogram. It is clear from this figure that there is no serious conflict with the data. For comparison, we have shown by solid curves the predictions with β = 2.75 [9]. We have also estimated the spectral hardness of γ-ray sources, which is defined as I (> 300 MeV)/ I(> 100 MeV). It is found that over the life of the SN, this varies only by small amount from

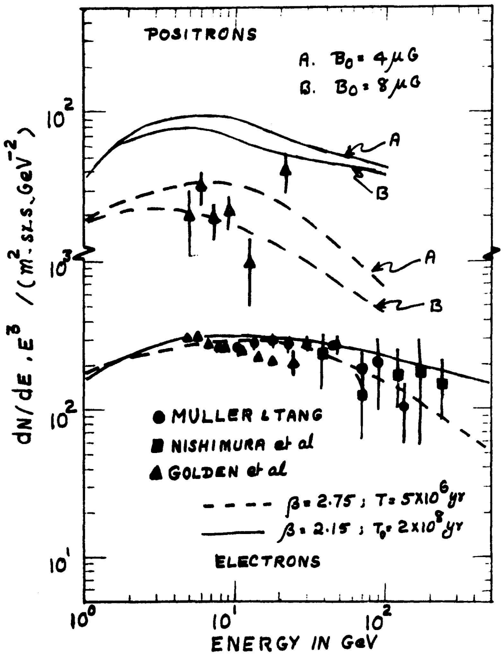

Fig. 2 *Electron spectrum is shown in the lower part and positron spectrum in the upper part. The solid curves are for energy dependent model and the dashed curves for Nested Leaky Box model.*

0.475 to 0.46, due to the flat input spectrum. This value is indeed in conflict with the observed values [12], most of which are much smaller.

3. Electron Spectrum. We have calculated the equilibrium spectrum of electrons and positrons in interstellar space by considering two kinds of source spectra $Q_{e^\pm}$. One of them is from SN exploding in dense cloudlets, which contribute ≈ 10% of the observed nucleons, and the other from SN explosion in normal interstellar medium. The equilibrium spectrum is obtained by solving the equation.

$$\frac{dJ_{e^\pm}}{dt} = \frac{\partial}{\partial E}\left(J_{e^\pm}\frac{dE_{e^\pm}}{dt}\right) + Q_{e^\pm} - J_{e^\pm}/T(E) \quad \ldots \quad (1)$$

in which T(E) is taken to be $T_0E^{-\delta}$, and T_0 is varied to obtain a good fit to the data. We have plotted in the lower part of Fig. 2, the observed flux values from recent experiments [13-15]. The solid curve is the calculated spectrum using a value of $T_0 = 2\times10^8$ yrs. This value of T_0 is inconsistent with 1.4×10^7 yrs obtained from ^{10}Be data at low energies [16]. We have also shown the calculated equilibrium spectrum for $\beta = 2.75$ [17] with $T = 5\times10^6$ yrs, which is consistent with the observed value within errors.

Making use of the same value of T_0 obtained from the study of electrons, we have calculated the equilibrium spectrum of positrons. This spectrum is shown in the upper part of Fig. 2 by solid curves. The two curves A and B correspond to magnetic fields in the dense cloudlets assuming that the field strength scales as $(B_0\sqrt{n_H})$ with B_0 = 4 and 8 μG respectively. It is clear that the observed spectrum [18] is not in agreement with the calculations. If one reduces the value of B_o or T_o, the deviation from the data would increase further. We have also shown the calculated positron spectrum for $\beta = 2.75$ [18] and one notices a good agreement with the observation.

4. Discussion. Many difficulties associated with the energy dependent confinement model have been pointed out earlier [19]. They include power requirement, streaming velocity at high energies and the smooth spectral shape extending to very high energies. We have shown here that, though the expected luminosity distribution of sources is not in conflict with the Cos-B data, the observed spectral hardening of γ-ray sources is not in agreement with the expectation. Secondly, the observed electron spectrum is clearly in conflict with the expectation [13]. Thirdly, the model predicts too large a flux of positrons. The above conclusions are further strengthened if the value of δ is indeed 0.7 [2].

The analysis made here is based on the hypothesis that antiprotons are produced in sources as secondary particles. However, if $\bar{p}$ comes from external galaxies [20], one may perhaps circumvent the present inconsistencies. However, it has been shown by Stephens [21] from a study of muon charge ratio at sea level that the extragalactic hypothesis and energy dependent confinement model cannot co-exist.

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