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II. Spectral Signatures of Discrete Cosmic-Ray Sources

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USE OF THE EGRET INSTRUMENT IN STUDIES OF THE ORIGIN OF THE COSMIC RADIATION:
II. SPECTRAL SIGNATURES OF DISCRETE COSMIC-RAY SOURCES

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Abstract

This is a continuation of previous studies (Dermer 1989a,b) aimed at predicting spectral signatures of discrete cosmic-ray sources. In this paper, a formalism is developed for calculating gamma-ray spectra observed at Earth from the decay of neutral pions formed in collisions of cosmic-ray protons and ions with galactic gas and dust. The cosmic rays are assumed to be emitted by discrete sources, and their intensities and spectra are described by solutions to a diffusion equation. Calculations of spectral signatures expected from these hypothetical point sources of cosmic rays are presented. In particular, a steady source of cosmic rays could show a harder gamma-ray spectrum than the spectrum of the diffuse galactic background, whereas an impulsive source of cosmic rays could show a much softer spectrum. Observations of the angular variations of gamma-ray intensities and spectra near point sources will provide information on cosmic-ray propagation in other parts of our galaxy, as well as on the nature of the discrete sources themselves. Capabilities of the Egret telescope in mapping spectra from cosmic-ray point sources are briefly discussed.

Introduction Our main sources of information about the cosmic radiation comes from direct observations of cosmic-ray particles near Earth, and from observations of secondary radiations resulting from the interactions of cosmic rays throughout the galaxy. Although a consensus has emerged that supernovae figure prominently in the origin of the cosmic rays (e.g. Ginzburg 1988), the full details of the acceleration mechanism and acceleration sites have yet to be clarified. Egret, the Energetic Gamma-Ray Experiment Telescope onboard the *Gamma Ray Observatory*, should provide a considerable wealth of data to help answer these questions.

It is of interest to determine the spectral signatures expected if cosmic-ray acceleration takes place at discrete sources. Arguments were presented elsewhere (Dermer 1989a) that measurements of the antiproton flux in the cosmic radiation can be taken as evidence for discrete sources of cosmic-ray production. This is because at energies between ~ 1 and 15 GeV, the ratio of antiprotons to protons in the cosmic radiation is ~ 5 times greater than would be expected on the basis of the leaky-box model of cosmic-ray propagation. A compact source of cosmic rays could produce this excess and not conflict with the cosmic-ray isotopic compositions if only neutral particles, namely antineutrons and neutrons, escape from these sources (Dermer and Ramaty 1986), as might be expected if the compact source were strongly magnetized (cf. Kazanas and Ellison 1986). The antineutrons would decay into antiprotons, giving the observed excess flux, and the prime signature of the neutrons would be neutral pion-decay gamma radiation resulting from collisions of the neutron-decay protons with diffuse gas near the compact source.

In a subsequent paper (Dermer 1989b), solutions to the cosmic-ray propagation equation (Syrovatskii 1959; Ramaty and Lingenfelter 1971) in a cylindrically symmetric geometry with absorbing boundary conditions were used to describe the essential features of the energy spectra of cosmic-ray protons emitted by point sources. Energy-dependent mean-free paths $\propto E^{0.4}$ were used in accordance with the conclusions of Protheroe et al. (1981). It was found that the spectra of cosmic rays emitted by a steady source could be harder than the ambient cosmic-ray proton flux provided they were injected with spectral index ≤ 2.3, whereas spectra softer than the ambient flux could be produced by impulsive injection due to rapid streaming of the energetic particles away from the source. However, gamma-ray spectra from interactions of cosmic rays emitted by these discrete sources were not calculated in that paper.

Analysis Here we provide a formalism for calculating gamma-ray spectra from the decay of neutral pions formed in collisions of cosmic-ray protons with gas and dust in the galaxy. The cosmic-ray protons are assumed to be emitted by a discrete source located at point P in Fig. 1. The positions of the Galactic Center and Sun are identified by the symbols GC and S, respectively, and the distance between them is $R_o = 7.1\ (\pm 1.5)$ kpc (Moran et al. 1987).

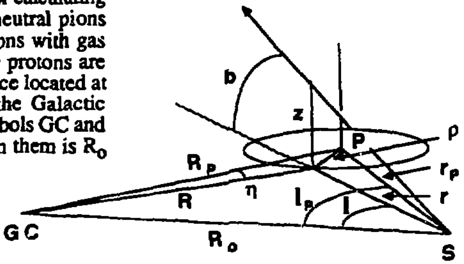

Fig. 1. Geometry of the model. GC, S, and P denote the location of the Galactic Center, Sun, and cosmic-ray point source, respectively.

Suppose that measurements are to be made in the direction (l,b), where l is the galactic longitude and b is the galactic latitude. A point source of cosmic rays is assumed to be located at distance r_p from the Sun and at galactic longitude l_p. For simplicity, we let the point source reside on the galactic midplane, so that $b_p = 0°$, although the treatment can easily be generalized to the case $b_p \neq 0°$. The differential flux [$\mathrm{cm^{-2}\ s^{-1}\ GeV^{-1}}$] of photons with energy between ε and ε + dε originating from the solid-angle element d sin b dl is given by

$$d\Phi(\varepsilon; l, b) = (4\pi)^{-1} \int_0^{\infty} ds\, F_\pi(\varepsilon; x)\, d \sin b\, dl \tag{1}$$

(e.g., Harding 1981), where s is the distance along the line of sight, and x denotes the coordinate (s,l,b). The gamma-ray emissivity F(ε;x) [photons $\mathrm{cm^{-3}\ s^{-1}}$] from neutral pion production and decay is found from the relation

$$F_\pi(\varepsilon; x) = c\, n_H(x)\, \zeta(x) \int_{E_p^{\min}(\varepsilon)}^{\infty} dE_p\, \beta(E_p)\, n_p(\rho, z, E_p)\, \frac{d\sigma_\pi(\varepsilon; E_p)}{d\varepsilon}\ , \tag{2}$$

where E_p is the kinetic energy of a cosmic-ray proton and βc is its speed. The neutral hydrogen gas density at x is denoted by $n_H(x)$, and ζ(x) is a correction factor collisions involving helium and heavier elements, and ionized and molecular form of matter. We take $\zeta(x) = \zeta = 1.45$ (Dermer 1986). The term $d\sigma_\pi/d\varepsilon$ is the differential cross section for the production of neutral pion-decay gamma-ray photons with energy ε between ε and ε + dε due to collisions between a cosmic-ray proton with energy E_p and a hydrogen atom. The results of Murphy et al. (1987) are used for this quantity.

The cosmic-ray proton density $n_p(\rho,z,E_p)$, is referred to the set of coordinates (ρ,z) defined with respect to point P (Fig. 2). These coordintes must be related to the coordinates (s,l,b). The distance of the GC from P is

$$R_p = (R_o^2 + r_p^2 - 2\, R_o\, r_p \cos l_p)^{1/2}\ .$$

The quantity s ranges from 0 to ∞ in the integration (1). For a given value of s, the following relations hold:

$$z = s \sin b;\quad r = s \cos b;\quad R = (R_0^2 + r^2 - 2\, R_0\, r \cos l\,)^{1/2};$$

$$\rho = (R^2 + R_p{}^2 - 2\, R\, R_p \cos \eta\,)^{1/2}.$$

The angle η is given by

$$\eta = \sin^{-1}\left(\frac{r_p}{R_p}\sin l_p\right) - \sin^{-1}\left(\frac{r}{R}\sin l\right) .$$

In the present calculations, the neutral hydrogen gas density n_H is assumed to be uniform throughout the galactic disk. Substituting eq. (2) into eq. (1) therefore gives

$$\frac{d\Phi(\varepsilon; l, b)}{d \sin b\, dl} = \frac{c\, n_H \zeta}{4\pi} \int_0^{s_{max}} ds \int_{E_p^{min}(\varepsilon)}^{\infty} dE_p\, \beta(E_p)\, n_p(\rho, z, E_p)\, \frac{d\sigma_\pi(\varepsilon; E_p)}{d\varepsilon} , \qquad (3)$$

where the maximum value s_{max} in the integration over s results from the finite extent of the disk.

Results The steady-state solution to the cosmic-ray diffusion equation in the galaxy with absorbing boundary conditions, given by eqs. (2) and (3) of Dermer (1989b), was used as the source function $n_p(\rho,z,E_p)$ in eq. (3). Examination of those equations shows that they are separable in energy and position variables, leading to the result that the spectral index of the cosmic ray protons emitted by a steadily radiating point source is independent of position. Thus, eq. (3) can be divided into a part that depends only on the energy spectrum of the protons, and a part that depends only on the position variables. Integrating over s in eq. (3) leads to the results shown in Fig. 2.

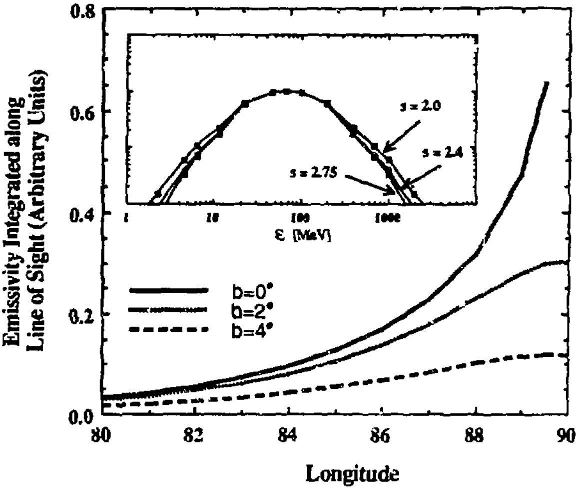

Fig. 2. Longitude and latitude dependence of the gamma-ray emissivity integrated along a line of sight. The hypothetical discrete source of cosmic rays is assumed to be 3 kpsc away from the Sun in the direction $b_P = 0°$, $l_P = 90°$. The inset shows the gamma-ray spectrum from power-law distributions of cosmic-ray protons with spectral indices s = 2.0, 2.4 and 2.75.

The model shown in Fig. 2 involves a hypothetical discrete source of cosmic rays located at 3 kpsc from the Sun in the direction $b_P = 0°$, $l_P = 90°$. The mean-free-paths parallel and perpendicular to the galactic plane were chosen to be 0.06 psc, and the size of the absorbing boundary, corresponding to the height of the galactic disk, was taken to be 300 psc. As can be seen from Fig. 2, the extent of the gamma-ray emission from the point source is a few degrees. If the source radiated a cosmic-ray spectrum $\propto E_p^2$, as predicted from diffusive shock acceleration models for a compression ratio of 4 (corresponding to strong shocks), the spectral index s of the proton spectrum after losses would be 2.4. The neutral pion-decay gamma-ray spectrum from such a cosmic-ray proton spectrum is not very different from the spectrum of the diffuse galactic background radiation when 100 MeV $\lesssim \varepsilon \lesssim$ 1 GeV, as shown by the inset to Fig. 2. It would therefore be difficult to distinguish spectral variations from such a source, even if the source were bright enough to be seen above the diffuse galactic gamma-ray background emission.

The second COS-B catalog of gamma-ray sources (Swanenburg et al. 1981) shows, however, a wide range of spectral variations. Ormes et al. (1988) give a method for determining the associated cosmic-ray nucleon source spectral index, and find that $s \lesssim 2$ in a number of cases. This could be reconciled by the steady, discrete source model described above if the escape of the protons or neutrons were energy-dependent. Thus, although shock-acceleration gives $s \geq 2$, the spectra of particles escaping from the source would be hardened by energy-dependent losses (gamma-ray emission in the source itself could be degraded by γ-γ or γ-B absorption processes). Observations of angular variations of the intensity and spectra near gamma-ray sources could provide evidence for this model since these variations would suggest the existence of a diffusing cosmic ray halo. If, instead, the source were coincident with a point source, this would imply that the emission is directly associated with the compact source itself.

Calculations of the gamma-ray spectra from impulsive compact sources of cosmic rays, using eq. (3), and eq. (4) in Dermer (1989b), could explain the appearance of soft gamma-ray sources. Again, observations of angular variations of gamma-ray spectra would help decide whether such a model is viable. The Egret instrument onboard GRO will provide maps of the galaxy with angular resolution < 1° and with sensitivities an order of magnitude better than COS-B, and will help resolve the question of the existence of compact sources of cosmic rays.

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