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COMPACT SOURCE ORIGIN OF COSMIC RAY ANTIPROTONS

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The flux of cosmic ray antiprotons with kinetic energies between ~1 and 15 GeV is ~5 times greater than the flux predicted on the basis of the leaky-box model.[1] This excess is attributed to secondary antineutron production in compact sources.[2,3] Because the antineutrons are not confined by the magnetic field of the compact source, they leave the interaction site, decay in interstellar space and account for the apparent excess cosmic ray antiproton flux. The escape and decay of neutrons produced in association with the antineutrons is a source of cosmic ray protons. Observations of the angular variation of the intensity and spectral shape of 100 MeV γ-rays produced by neutron-decay protons in the reaction $p+p \rightarrow \pi^0 \rightarrow 2\gamma$ could reveal compact-source cosmic ray production sites. COS-B observations of spectral hardening near point sources,[4] and future high-resolution observations of galactic point sources by Gamma-1 and the Egret telescope onboard the *Gamma Ray Observatory* may provide supporting evidence for this model.

Measurements of the ratio of the cosmic ray antiproton (CR p-) flux to the cosmic ray proton flux are shown in Fig. 1. Also plotted is the predicted flux of secondary CR p- expected from the leaky-box model of galactic cosmic ray propagation.[5] This model, developed to explain the observed cosmic ray isotopic compositions, attributes all CR p- as secondary products of collisions between cosmic rays and diffuse galactic gas and dust. The deficiency in the integrated flux between 1 and 15 GeV, coupled with the lack of observations of CR antinuclei, is interpreted here as evidence for an additional CR secondary production source. This interpretation has the virtue that the chemical composition of the CR is unaffected by the existence of these sources, since the magnetic field at the interaction site inhibits the escape of charged nuclei but permits neutral species to freely escape.

We estimate the discrete source neutron production rate by normalizing to the CR p- excess, giving the fit through the data shown in Fig. 1. The normalization is carried out by noting that secondary antineutrons with E<12 GeV are produced primarily by energetic protons with $E \lesssim 250$ GeV in the reaction $p+p \rightarrow p+p+n+\bar{n}$. Neutron production proceeds predominantly through pion-associated reactions such as $p+p \rightarrow p+n+\pi^+$ and related multi-prong reactions. We approximate the inclusive differential cross section for neutron production in proton collisions by the expression $d\sigma_{p+p\rightarrow nX}/dE_n = 25$ mb $\delta(E_n-E_p/2)$, where E_p and E_n refer to proton and neutron kinetic energy, respectively. For the neutron production rate per discrete source, we obtain

$$\frac{dN_n}{dE_n dt} = \begin{cases} 1.3\text{x}10^{41}\ g\,(2E_n + m_p)^{-2.2}, & s=2.2 \\ 2.8\text{x}10^{41}\ g\,(2E_n + m_p)^{-2.75}, & s=2.75 \end{cases}$$

where m_p =0.94 GeV, and the spectral index of the assumed nonthermal ion flux in the compact sources is denoted by s. The term $g=n_{0.2}V_{67}f_5/N_{100}$, where the diffuse galactic disk hydrogen density $n_H=0.2n_{0.2}\,cm^{-3}$, the galactic disk volume $V=10^{67}V_{67}$ cm^3, the integrated CR p- excess is $5f_5$ times greater than the leaky box model prediction, and the number of discrete sources in the galaxy is given by $100N_{100}$.

Neutrons follow a straight-line escape from the compact sources unless they collide with intervening matter (within $\sim10^{-4}$ psc of the source for a 10 GeV neutron). After decaying, the neutron-decay protons diffuse in the galactic magnetic field. Except for extremely strong sources, the flux of neutron β-decay electrons and knock-on electrons from neutron-decay protons is small compared to the flux of ambient galactic CR electrons. This is also usually the case for secondary electrons and positrons resulting from pion production. Except possibly for the 2.2 MeV line formed by neutron capture on protons in the atmosphere of a binary stellar compaion,[3] the most pronounced signature of a compact source origin of antiprotons would be neutral pion production and decay from collisions of neutron-decay protons with galactic matter.

The intensity of the proton flux near a compact source can be obtained by solving the transport equation[6,7] for cosmic ray propagation and energy loss. Neglecting the energy loss term, and assuming a steady point source radiating at the origin of the radial (ρ) and z coordinates, the differential density of neutron-decay protons in a geometry with absorbing boundaries at z= ±a is given by

$$n(\rho,z,E_p) = \frac{3(dN_n/dE_n dt)}{4\pi c\, l_\perp^{1/2}\, l_\parallel} \sum_{n=-\infty}^{n=\infty} (r_n - t_n) \ ,$$

where $l_\perp$ and $l_\parallel$ are the mean free paths of the neutron-decay protons perpendicular and parallel to the galactic plane, and

$$r_n^{-2} = \frac{\rho^2}{l_\parallel} + \frac{(z-4na)^2}{l_\perp} \quad ; \quad t_n^{-2} = \frac{\rho^2}{l_\parallel} + \frac{(z+4na-2a)^2}{l_\perp} \ .$$

Fig. 2 shows model results for neutron-decay proton fluxes in the vicinty of a compact source, assuming s=2.2, a=300 psc, $l_\perp$=0.06 psc, and $l_\parallel = l_\perp/2$, $l_\perp$, and $2l_\perp$. These values pertain to protons with 2 GeV kinetic energies; a dependence of $l \propto E_p^{0.5}$ at higher energies is expected from energy-dependent diffusion. As can be seen, an enhanced CR proton flux is found in the vicinity of discrete sources, which would reveal itself through an enhancement in the neutral pion decay gamma radiation. Detailed information about the propagation characteristics of the galaxy and the time dependence and spectra of the injected nonthermal neutrons depend on high sensitivity imaging observations near point sources at photon energies ε~100 MeV. For example, angular resolution << 5° is required to map the presumed CR proton halo around Cyg X-3, if the halo is ~150 psc in radial extent. Both Gamma-1 and Egret onboard GRO have ~1.5° single-photon direction determination at ε=100 MeV, and are capable of mapping variations in the diffuse galactic gamma-ray emission on scales of a fraction of a degree.[8] Investigation of CR halos near magnetized, accreting neutron stars, such as the X-ray sources Cyg X-3, Her X-1, or Vela X-1, should be a high priority of these missions.

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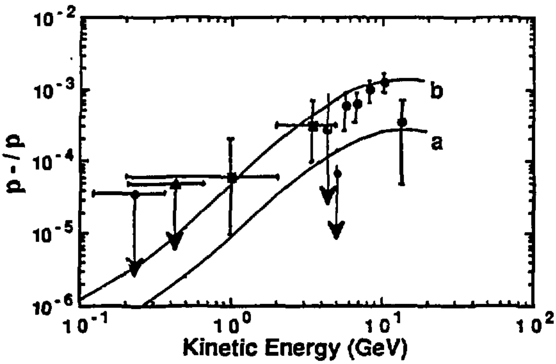

Fig. 1. Ratio of the fluxes of antiprotons to protons in the cosmic radiation. Data are from Ref. 9 (diamond), Ref. 10 (triangle), Ref. 11 (squares), and Ref. 12 (circles). Curve a is the leaky box model prediction of Ref. 5, and curve b, used to normalize the compact source neutron production rate, is 5 times the magnitude of curve a.

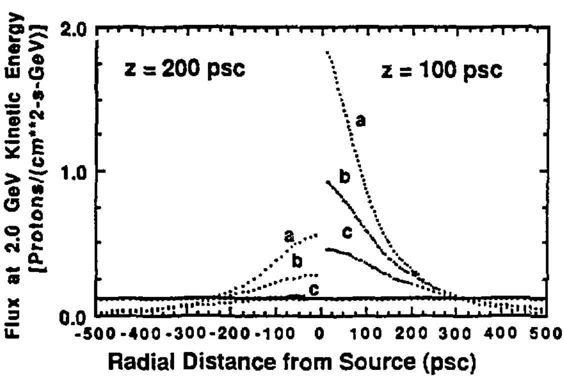

Fig. 2. Radial dependence of the flux of 2 GeV protons at 100 and 200 psc above the z=0 galactic plane, for a diffusive propagation model with absorbing boundaries at z=±300 psc. The source of nonthermal energetic neutrons, located midway between the boundaries, is assumed to emit neutrons continuously. The perpendicular diffusion mean free path is 0.06 psc, and the ratios of the parallel and perpendicular mean free paths are given by 0.5, 1.0, and 2.0 in curves a, b, and c, respectively. Solid line shows the local value of the cosmic ray proton flux at 2 GeV.