Diffuse Galactic Gamma Rays from Shock-Accelerated Cosmic Rays

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A shock-accelerated particle flux $\propto p^{-s}$, where p is the particle momentum, follows from simple theoretical considerations of cosmic-ray acceleration at nonrelativistic shocks followed by rigidity-dependent escape into the Galactic halo. A flux of shock-accelerated cosmic-ray protons with $s \approx 2.8$ provides an adequate fit to the Fermi Large Area Telescope γ-ray emission spectra of high-latitude and molecular cloud gas when uncertainties in nuclear production models are considered. A break in the spectrum of cosmic-ray protons claimed by Neronov, Semikoz, and Taylor [Phys. Rev. Lett. **108**, 051105 (2012)] when fitting the γ-ray spectra of high-latitude molecular clouds is a consequence of using a cosmic-ray proton flux described by a power law in kinetic energy.

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Introduction.—One hundred years after the discovery of cosmic rays by Hess in 1912 [1], the sources of the cosmic radiation are still not conclusively established. Theoretical arguments developed to explain extensive observations of cosmic rays and Galactic radiations favor the hypothesis that cosmic-ray acceleration takes place at supernova remnant (SNR) shocks [2]. A crucial prediction that follows from this hypothesis is that cosmic-ray sources will glow in the light of γ rays made by the decay of neutral pions created as secondaries in collisions between cosmic-ray protons and ions with ambient matter. The $p + p \rightarrow \pi^0 \rightarrow 2\gamma$ spectrum formed by isotropic cosmic rays interacting with particles at rest is hard and symmetric about $\epsilon_\gamma = m_{\pi^0}/2 = 67.5$ MeV in a log-log representation of photon number spectrum vs energy [3].

The AGILE and Fermi γ-ray telescopes have recently provided preliminary evidence for a $\pi^0 \rightarrow 2\gamma$ feature in the spectra of the W44, W51C, and IC 443 SNRs [4]. Whether this solves the cosmic-ray origin problem depends on disentangling leptonic and hadronic emission signatures, including multizone effects [5], and finding out if the nonthermal particles found in middle-aged SNRs as inferred from their spectral maps have the properties expected from the sources of the cosmic rays.

Supporting evidence that cosmic rays are accelerated at shocks comes from the diffuse Galactic γ-ray emission. High-latitude Galactic gas separate from γ-ray point sources, dust, and molecular gas provides a "clean" target for γ-ray production from cosmic-ray interactions. Because the cosmic-ray electron and positron fluxes are $\gtrsim 20$ times smaller than the cosmic-ray proton flux at GeV energies [6], the π^0-decay γ-ray flux strongly dominates the electron bremsstrahlung and Compton fluxes. The diffuse Galactic γ-ray spectrum can be deconvolved to give the cosmic-ray proton spectrum, given accurate nuclear γ-ray production physics. Data from the Fermi Large Area Telescope (LAT) offer an opportunity to derive the interstellar cosmic-ray spectra unaffected by Solar modulation [7,8].

This problem is revisited in order to address a recent claim [8] that fits to the diffuse Galactic γ-ray emission of Gould belt clouds imply a break at $T_{k,\mathrm{br}} = 9^{+3}_{-5}$ GeV in the cosmic-ray proton spectrum that represents a new energy scale. Note that a break in the kinetic-energy representation of the proton spectrum has been reported before [9]. In this Letter, we show that when uncertainties in nuclear production models are taken into account, a power-law momentum spectrum favored by cosmic-ray acceleration theory provides an acceptable fit to Fermi LAT γ-ray data of diffuse Galactic gas and produces a break in a kinetic energy representation at a few GeV from elementary kinematics. Comparison of theoretical γ-ray spectra with data supports a nonrelativistic shock origin of the cosmic radiation, consistent with the SNR hypothesis.

Production spectrum of γ rays from cosmic-ray collisions.—The γ-ray production spectrum divided by the hydrogen density n_H is given, in units of $(\mathrm{s}\cdot\mathrm{GeV})^{-1}$, by

$$\frac{F_{pH}(\epsilon_\gamma)}{n_H} = 4\pi k \int_{T_{p,\min}(\epsilon_\gamma)}^{\infty} dT_p j_p(T_p) \times \frac{d\sigma_{pp\rightarrow\pi^0\rightarrow 2\gamma}(T_p, \epsilon_\gamma)}{d\epsilon_\gamma}. \quad (1)$$

Here and below, $j(T_p)$ is the cosmic-ray proton intensity in units of cosmic-ray protons $(\mathrm{cm}^2\,\mathrm{s}\,\mathrm{sr}\,\mathrm{GeV})^{-1}$, and k, the nuclear enhancement factor, corrects for the composition of nuclei heavier than hydrogen in the cosmic rays and target gas [10]. The term $d\sigma_{pp\rightarrow\pi^0\rightarrow 2\gamma}(T_p, \epsilon_\gamma)/d\epsilon_\gamma$ is the differential cross section for the production of a photon with energy ϵ_γ by a proton with kinetic energy T_p, in GeV, and momentum p in GeV/c.

The much studied and favored model for cosmic-ray acceleration is the first-order Fermi mechanism, which was proposed in the late 1970s [11]. Test particles gain energies by diffusing back and forth across a shock front

while convecting downstream. The downstream steady-state distribution function is given by $f(p) \propto p^{-3r/(r-1)}$, where p is the momentum and r is the compression ratio. Consequently, the particle momentum spectrum $\propto p^2 f(p) \propto p^{-A}$, where $A = (2 + r)/(r - 1)$ is the well-known test-particle spectral index that approaches 2 (equal energy per decade) in the limit of a strong nonrelativistic shock with $r \rightarrow 4$ [12]. After injection into the interstellar medium with $A \cong 2.1$–2.2, characteristic of SNR shocks, cosmic-ray protons and ions are transported from the galactic disk into the halo by rigidity-dependent escape [13], which softens their spectrum by $\delta \approx 0.5$–0.6 units, leaving a steady-state cosmic-ray spectrum $dN/dp \propto p^{-s}$, where $s = A + \delta \cong 2.7$–2.8. Thus, we consider a cosmic-ray flux

$$j_{\rm sh}(T_p) \propto \beta(T_p)\left(\frac{dN}{dT_p}\right) \propto \beta(T_p)\left|\frac{dp}{dT_p}\right|\left(\frac{dN}{dp}\right) \propto p(T_p)^{-s}. \quad (2)$$

Gamma-ray production from cosmic-ray–matter interactions.—Secondary nuclear production in proton-proton collisions is described by isobar formation at energies near threshold $T_p = 0.28$ GeV [3] and scaling models at high-energies $T_p \gg m_p$. Uncertainties remain in the production spectra at $T_p \approx$ few GeV, where most of the secondary γ-ray energy is made in cosmic-ray collisions.

Figure 1 compares two models for γ-ray production from p-p collisions using an empirical fit to the demodulated cosmic-ray flux measured [14] in interstellar space given by [15]

$$j_{\rm dem}(T_p) = 2.2(T_p + m_p)^{-2.75}. \quad (3)$$

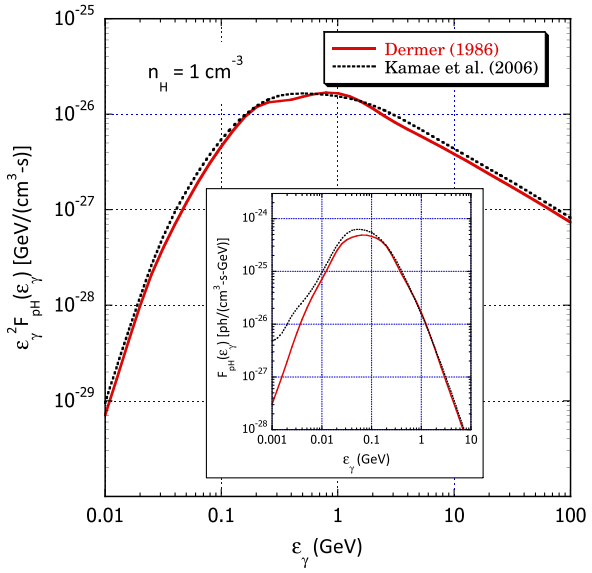

FIG. 1 (color online). Production spectra of secondary γ rays made in p-p collisions from the models of Dermer [15] and Kamae *et al.* [17], using the empirical demodulated cosmic-ray proton spectrum given by Eq. (3).

The model of Dermer [15] describes low-energy resonance production in terms of the $\Delta(1232)$ resonance through Stecker's model [3], and high-energy production by the scaling model of Stephens and Badhwar [16], with the two regimes linearly connected between 3 and 7 GeV. The model of Kamae *et al.* [17] is a parametric representation of simulation programs and includes contributions from the $\Delta(1232)$ isobar and $N(1600)$ resonance cluster, non-scaling effects, scaling violations, and diffractive processes. This model is represented by functional forms that are convenient for astrophysical calculations.

Figure 1 shows that the two models agree within 20% at $\epsilon_\gamma > 100$ MeV, but display larger differences at $\epsilon_\gamma \lesssim 10$ MeV, where the γ-ray production is energetically insignificant. Both models are in general agreement in the high-energy asymptotic regime, with the Kamae *et al.* model giving fluxes larger by $\approx 13\%$ due to the inclusion of diffractive processes. The spectral peak in a νF_ν representation occurs at 500 MeV to 1 GeV for this proton spectrum. The most significant discrepancy in the two models is by $\approx 30\%$ at the pion production peak near 67.5 MeV [18]. Because of the different approaches of the models and little improvement in nuclear databases from laboratory studies between model development, this comparison indicates that our knowledge of the γ-ray production spectrum in p-p collisions is uncertain, at worst, by 30% near the pion-production peak and is better than 15% at $\epsilon_\gamma \gtrsim 200$ MeV.

Fits to Fermi LAT γ-ray data.—The Fermi LAT data [7] of the diffuse galactic γ radiation are fit using a shock spectrum given by Eq. (2). Guided by the high-energy asymptote of Eq. (3), we let

$$j_{\rm CR}(T_p) = 2.2p^{-s}, \quad (4)$$

with $s = 2.75$. The data shown in Fig. 2 are from regions in the third quadrant, with Galactic longitude from 200° to 260°, and galactic latitudes $|b|$ ranging from 22° to 60°. There are no molecular clouds in these regions, the ionized hydrogen column density is small with respect to the column density of neutral hydrogen, and γ-ray emission from point sources is removed. The linear increase of the emissivity as traced by 21 cm line observations allows residual galactic and extragalactic γ radiation to be subtracted, leaving only the γ-ray emission resulting from collisions of cosmic rays with neutral gas, allowing for an absolute normalization to be derived for the emissivity. As can be seen, the shock-acceleration spectrum gives an acceptable fit to the data and restricts the value of k to be $\lesssim 1.8$. Given that there must be some residual cosmic-ray electron-bremsstrahlung and Compton radiations at these energies, the restriction on k could be larger.

The spectrum in Fig. 3 from the analysis of Fermi LAT data given in Ref. [8] shows the averaged γ-ray flux from molecular clouds in the Gould belt. The derived flux, which extends to ≈ 100 GeV, matches the spectrum of

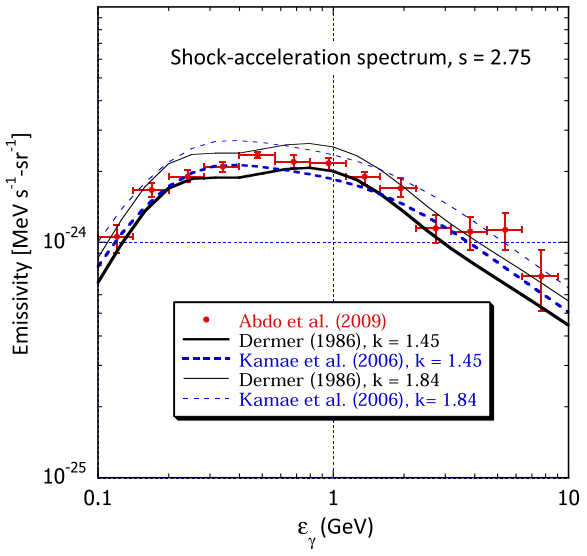

FIG. 2 (color online). Fits to the Fermi LAT spectrum of the differential γ-ray emissivity of local neutral gas [7], employing a shock-acceleration spectrum, Eq. (4), with $s = 2.75$, for the cosmic-ray proton spectrum, and the models of Dermer [15] and Kamae *et al.* [17] for γ-ray production. The nuclear enhancement factor k takes the values of 1.45 and 1.84, as labeled.

diffuse Galactic gas emission used by the Fermi team in their analysis of the extragalactic diffuse γ-ray intensity [19], supporting the assumption that the clouds are porous to cosmic rays. The cosmic-ray proton shock acceleration spectrum given by Eq. (4) with $s = 2.85$ is seen to give an adequate fit to the data in Fig. 3, given the nuclear physics uncertainties in γ-ray production.

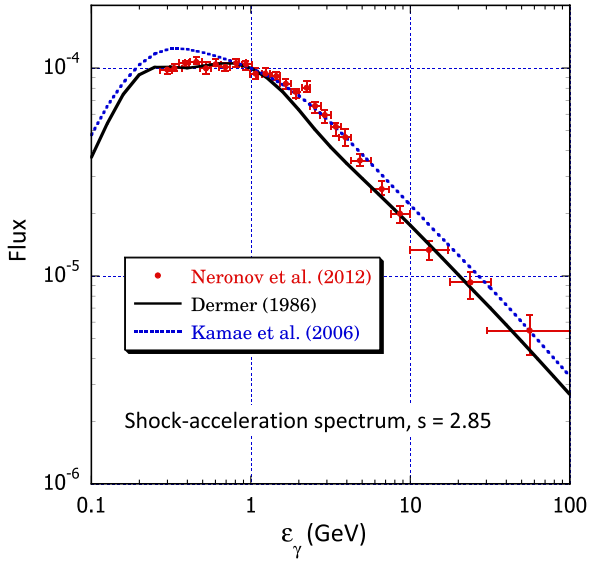

FIG. 3 (color online). Fermi LAT spectrum of the differential γ-ray emissivity of Gould belt clouds [8]. It is fit with a shock-acceleration model for the cosmic-ray proton spectrum with $s = 2.85$, using the models of Dermer [15] and Kamae *et al.* [17] for γ-ray production. The models are normalized to the flux at 1 GeV.

This cosmic-ray proton flux is compared in Fig. 4 with a shocked spectrum given by Eq. (4) with $s = 2.85$, with two power-law kinetic energy spectra (one multiplied by β), and the spectrum, Eq. (3), assumed to represent the demodulated local cosmic-ray proton spectrum. The best fit of the functional form used by Neronov *et al.* (2012) [8] is also plotted and is in accord with the shock spectrum, Eq. (4), when allowance is made for the large uncertainties in derived parameters. Indeed, the allowed spectrum would be further limited by the Fermi LAT data of Fig. 2 unless $k \lesssim 1.2$. The reduced χ^2 to determine goodness of fit should take into account uncertainties in nuclear production, and firm conclusions about a break depend on improved cross sections.

Summary.—Figure 4 compares theoretical and empirical local interstellar spectrum of cosmic-ray protons with recent measurements of the fluxes of cosmic-ray protons, He,

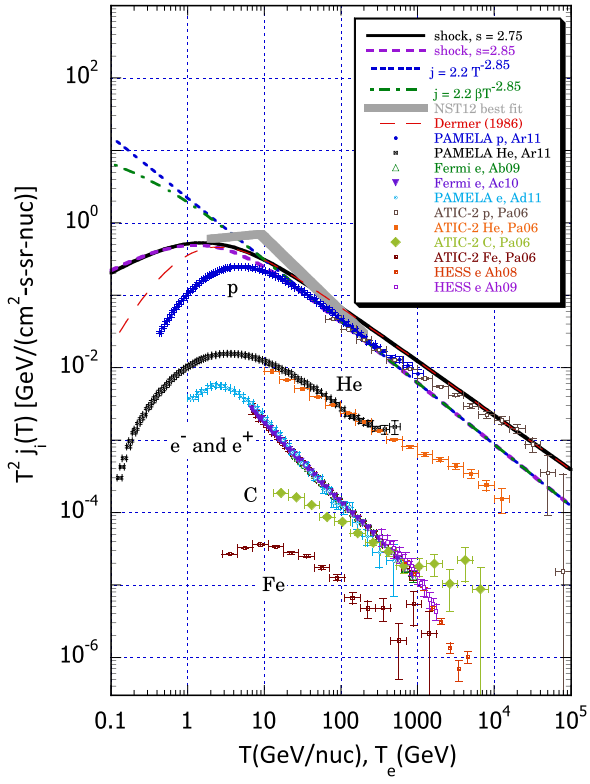

FIG. 4 (color online). Theoretical cosmic-ray proton fluxes compared with recent PAMELA, Fermi LAT, ATIC-2, and HESS measurements of cosmic-ray p, He, C, Fe, and electron and positron fluxes [22]. The shock acceleration spectra are given by Eq. (4) with $s = 2.75$ and $s = 2.85$, a power-law kinetic energy flux $j \propto T^{-2.85}$, and a flux $j \propto \beta T^{-2.85}$ are shown, in addition to the demodulated cosmic-ray proton spectrum, Eq. (3), and the best-fit spectrum of Ref. [8]. Solar modulation accounts for the difference between the measured and theoretical cosmic-ray proton fluxes at $T \lesssim 10$ GeV/nuc. Papers cited in Ref. [22] report systematic errors for different experiments.

C, Fe, and electrons. The small fluxes of the heavier cosmic rays and electrons imply that γ-ray emission from these channels makes a minor, but non-negligible contribution to the γ-ray flux.

The favored model for the origin of cosmic rays is nonrelativistic shock acceleration by SNRs in the Galaxy. The simplest possible shock-acceleration model with proton flux $\propto p^{-s}$ gives an adequate fit to Fermi LAT data of high Galactic latitude gas and clouds and is in accord with expectations of a SNR origin for the cosmic rays. The use of a shock spectrum for the cosmic-ray flux allows a range of calculations to be made that depend on knowing the low-energy cosmic-ray spectrum [20]. The combination of a power-law momentum injection spectrum and the observationally similar local interstellar spectrum potentially puts constraints on propagation models that have a large effect on the primary spectra, such as those involving strong reacceleration [6].

If cosmic rays are indeed accelerated by SNR shocks, then the $\pi^0 \rightarrow 2\gamma$ feature from shock-accelerated cosmic rays should be observed in the spectra of individual SNRs. Indications for such a feature are found in a few middle-aged SNRs [4], but final confirmation of cosmic-ray sources will require detailed spectral calculations involving both shock-accelerated protons and leptons [21], including radiative losses and escape and comparison with improving Fermi LAT data resulting from increasing exposure and development of better analysis tools.

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Note added in proof.—A recent Letter by Blasi, Amato, and Serpico [23] explains a supposed low-energy break in a power-law injection momentum spectrum as a result of advective effects on cosmic-ray propagation (compare Ref. [13]). Kachelriess and Ostapchenko [24] claim to find deviations from a cosmic-ray power-law momentum spectrum at low energy, but their treatment is susceptible to some of the same criticisms as presented here.

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