Diffuse Galactic Gamma Rays from Shock-Accelerated Cosmic Rays

Charles D. Dermer

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Charles D. Dermer
Space Science Division, Code 7653, Naval Research Laboratory,
Washington, DC 20375-5352; charles.dermer@nrl.navy.mil

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*-LAT 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, & Taylor (*PRL*, **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.

Introduction.—One hundred years after the discovery of cosmic rays by Victor 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 $p + p \to \pi^0 \to 2\gamma$ 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 $\pi^0 \to 2\gamma$ 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 multi-zone effects [5], and finding out if the nonthermal particles found in middle-aged SNRs as inferred from their SED 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 $T_{k,br} = 9^{+3}_{-5}$ 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 (s-GeV)$^{-1}$, by

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

Here and below, $j(T_p)$ is the cosmic-ray proton intensity in units of cosmic-ray protons (cm^2-s-sr-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 $d\sigma_{pp\to\pi^0\to 2\gamma}(T_p,\epsilon_\gamma)/d\epsilon_\gamma$ 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 $r \to 4$ [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

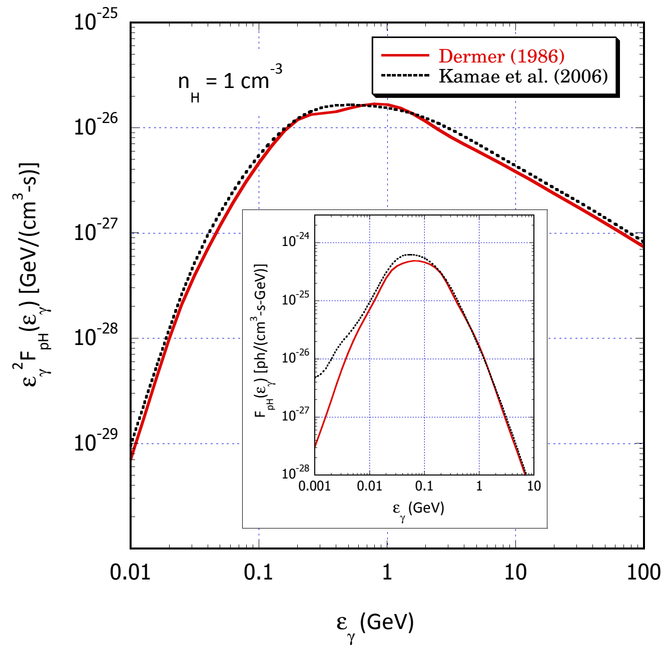

FIG. 1: Production spectra of secondary γ-rays made in p-p collisions from the models of Dermer [15] and Kamae et al. [17], using the empirical demodulated cosmic-ray proton spectrum given by eq. (3).

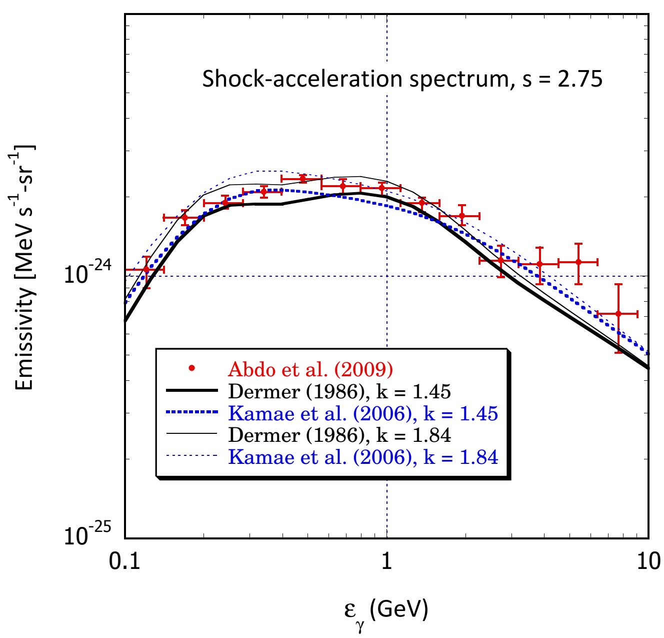

FIG. 2: Fits to the *Fermi*-LAT spectrum of the differential γ-ray emissivity of local neutral gas [7], employing a shock-acceleration spectrum, Eq. (4), with $s = 2.75$, for the cosmic-ray proton spectrum, and the models of Dermer [15] and Kamae et al. [17] for γ-ray production. The nuclear enhancement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

$\delta \approx 0.5 - 0.6$ 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

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

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.

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

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

[15]. 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.

Fig. 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 $-$ 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 bases for the models, and no improvement in nuclear data bases 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

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

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

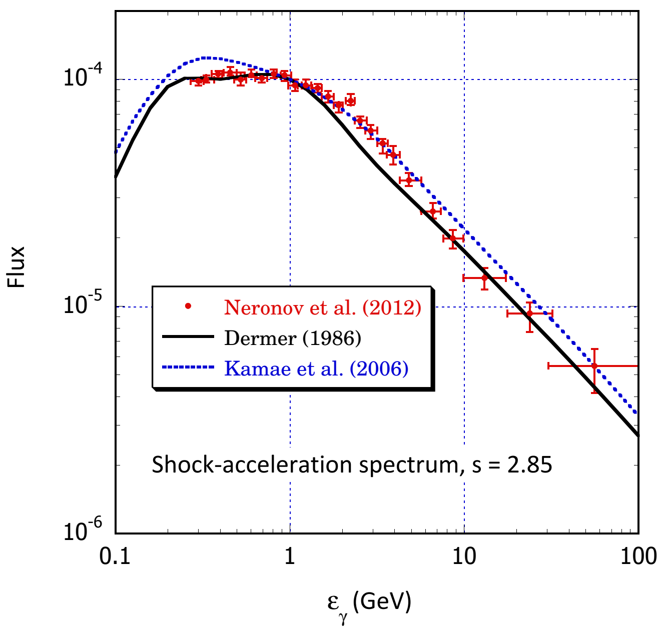

FIG. 3: *Fermi*-LAT spectrum of the differential γ-ray emissivity of Gould belt clouds [8], as analyzed by NST12. It is fit with a shock-acceleration model for the cosmic-ray proton spectrum with $s = 2.85$, using the models of Dermer [15] and Kamae et al. [17] for γ-ray production. The models are normalized to the flux at 1 GeV.

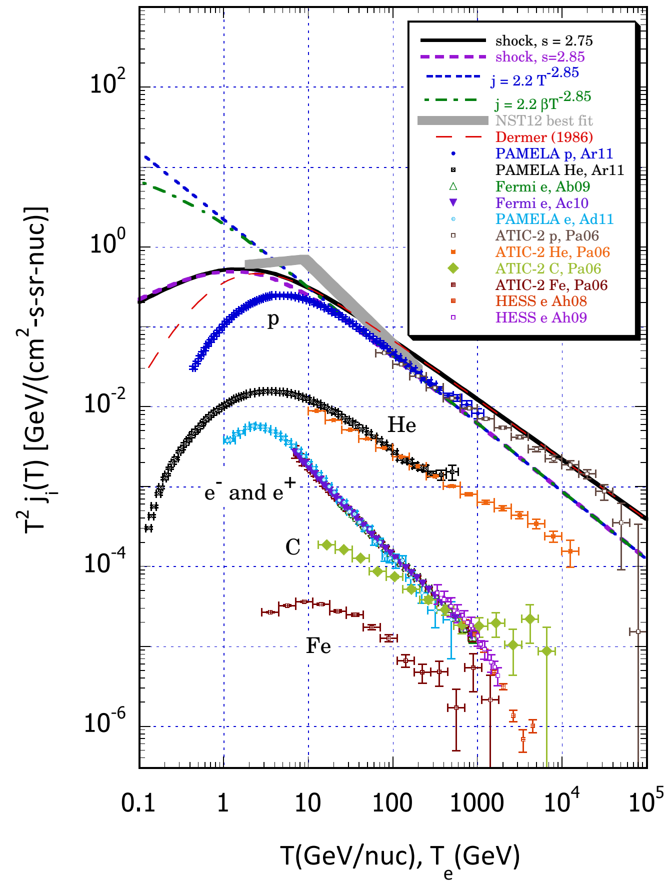

FIG. 4: Theoretical cosmic-ray proton fluxes compared with recent PAMELA, *Fermi*-LAT, ATIC-2, and HESS measurements of cosmic-ray p, He, C, Fe, and electron and positron fluxes [20]. The shock acceleration spectra are given by Eq. (4) with $s = 2.75$ and $s = 2.85$, a power-law kinetic energy flux $j \propto T^{-2.85}$, 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 [20] report systematic errors for different experiments.

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 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, agrees with the spectrum of 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. (2) 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.

This cosmic-ray proton flux is compared in Fig. 4 with one for a shocked flux with $s = 2.85$ in Eq. (2), 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.—Fig. 4 compares theoretical and empirical local interstellar spectrum of cosmic-ray protons with recent measurements of the fluxes of cosmic-ray protons, He, C, Fe and electrons. The small fluxes of the heavier cosmic rays and electrons imply that γ-ray emission from these channels make 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 [21]. The combination of a power-law momentum injection spectrum and the observationally similar local interstellar spectrum potentially puts constraints on propagation models which 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 $\pi^0 \to 2\gamma$ 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 [22], 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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