Modeling the Diffuse Gamma ray Spectrum with Cosmic Rays

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Introduction

Most galactic cosmic rays (CRs) are accelerated in shocks (Fig. 1), which should make their spectrum a power-law with momentum. The spectrum below a few 100 GeV has been studied in detail at Earth.

However, because of solar wind effects, the true local interstellar spectrum (LIS) below ~10 GeV is uncertain. Cosmic ray interactions with the interstellar medium (ISM) produce a similar spectrum of diffuse gamma rays (γ-rays; Fig. 1), making GeV γ-rays a powerful probe of the LIS. Indeed, γ-ray data from Fermi-LAT points to a possible spectral break around a few GeV in the CR spectrum [1]. This is evidence for a break at the CR accelerator, and/or effects of CR propagation in the interstellar medium [2].

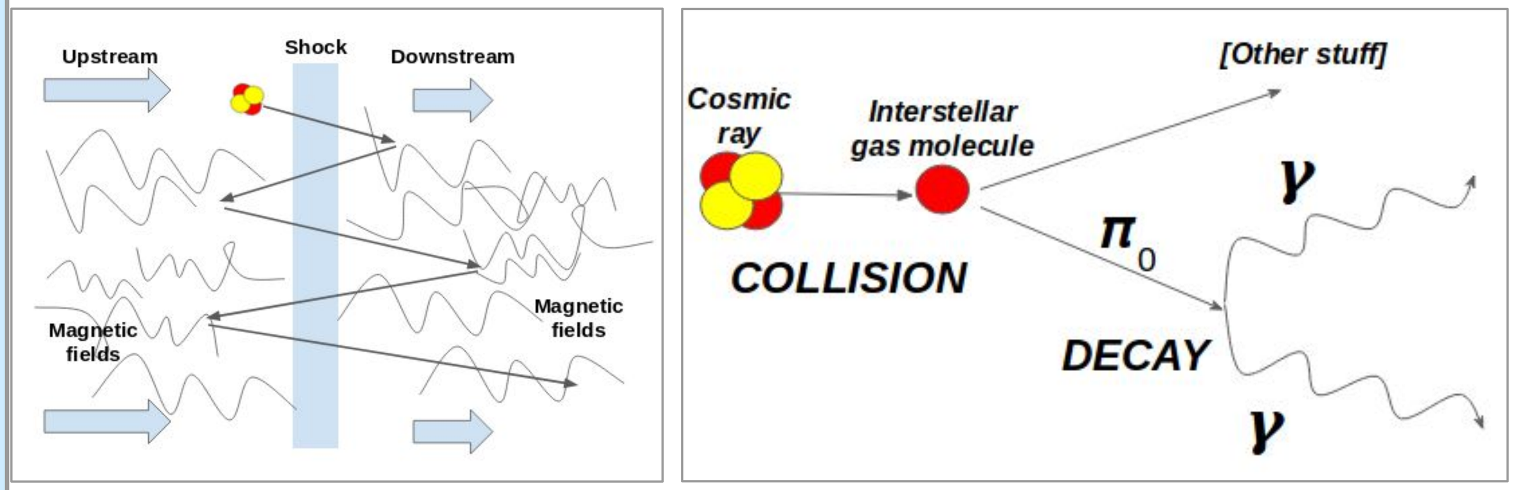

Fig 1. Left: CR acceleration at a shock front.
Right: γ-ray production through CR interactions with interstellar gas

Motivated by these previous works, we fit the CR (Earth-based & Voyager) and γ-ray data together using single and broken power-law models.

Method: cosmic ray fluxes

For the single power-law model, we assume the flux is a power law with momentum. For the broken power-law model, the flux is a power law with momentum at high energies with index α_1 and at low energies with index α_2, with a soft transition at break momentum p_{br} (eq. 1). To account for solar effects on CR fluxes, we modulate fluxes according to the force field model [3], where the wind "strength" is given by a parameter φ whose values over time have been evaluated and published from neutron monitor data [4]. We place gaussian priors on each experiment's φ from the published values. The Voyager1 φ is given a prior of 0 ± 100 since it has left the heliosphere.

These modulated fluxes are compared with the CR data, which is taken from the Database of Charged Cosmic Rays [5].

$$N(p) = A\left[\left(\frac{p}{p_{br}}\right)^{-\alpha_1/\delta} + \left(\frac{p}{p_{br}}\right)^{-\alpha_2/\delta}\right]^{\delta}$$

Eq. 1. CR flux formula used for broken power-law model.

Method: fitting procedure

We carry out Markov Chain Monte Carlo fits to sample the space of LIS and φ parameters. Our log-likelihood function is proportional to the -χ^2 of the model with the data (Fig. 2). The code for this framework can be found at https://github.com/jessicametzger/grcrfit/.

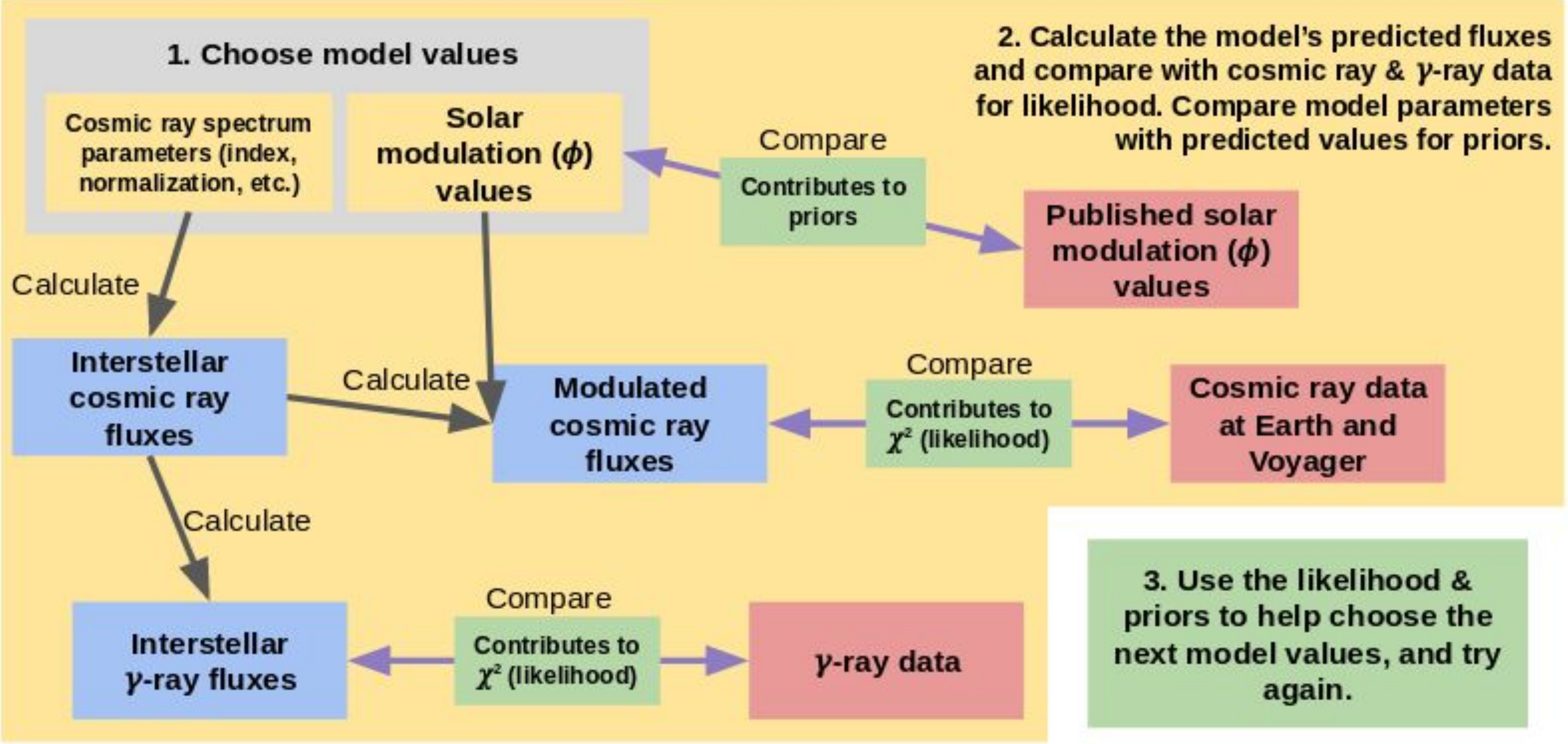

Fig. 2. The pipeline followed by each walker at each step, repeated until convergence.

Method: γ-ray fluxes

~1/2 the diffuse γ-rays in these energies are produced by CR protons interacting with ISM hydrogen, so this interaction is the only one we explicitly calculate. We use [6]'s framework to get this proton-proton flux, then use [7]'s method to calculate an "enhancement factor," which scales up the proton-proton flux to account for all other interactions. This is compared with the γ-ray data [8].

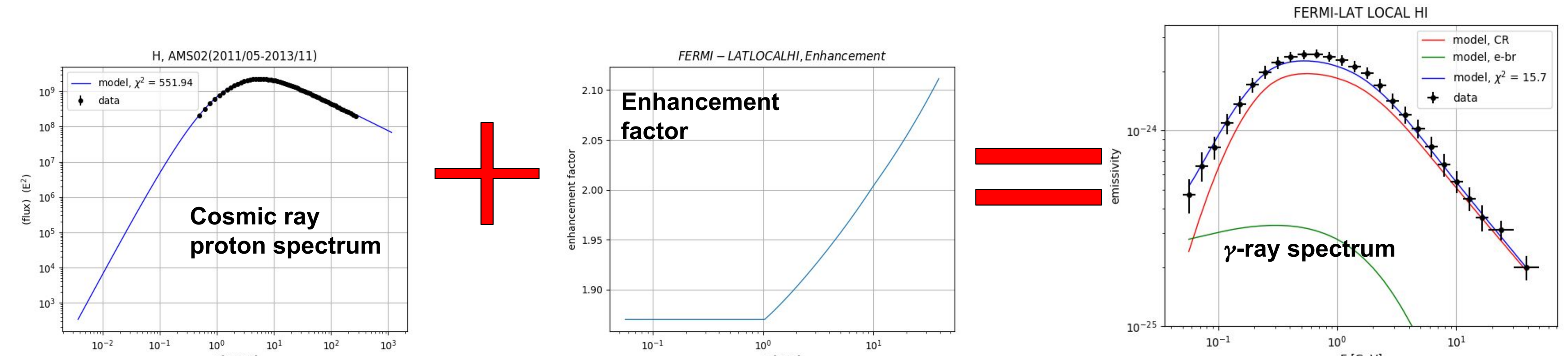

Fig. 3. Calculation of γ-ray fluxes, from cosmic rray fluxes.

Results

The single power law model was unable to describe the CR or γ-ray data. There is a mismatch at low energies, where the spectrum is too steep to describe the data (Fig. 4), evidence of a spectral break.

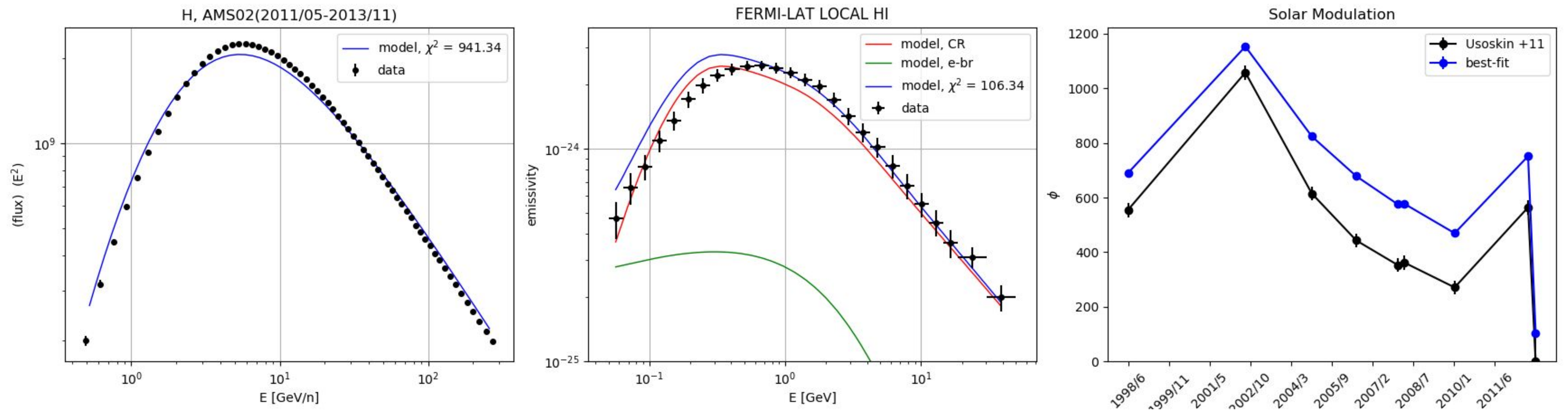

Fig. 4. Single power law best fits. Left: best-fit to AMS-02 fluxes. Middle: best-fit to gamma ray data. Right: best-fit solar modulation values, which are systematically too high, supporting a low-energy spectral break.

The broken power law model successfully describes all datasets (Fig. 5, Table 1). The fit supports a lower than expected break rigidity (momentum/charge) of ~1 GV. It also supports a much softer break than expected, and a much lower than expected low-energy spectral index.

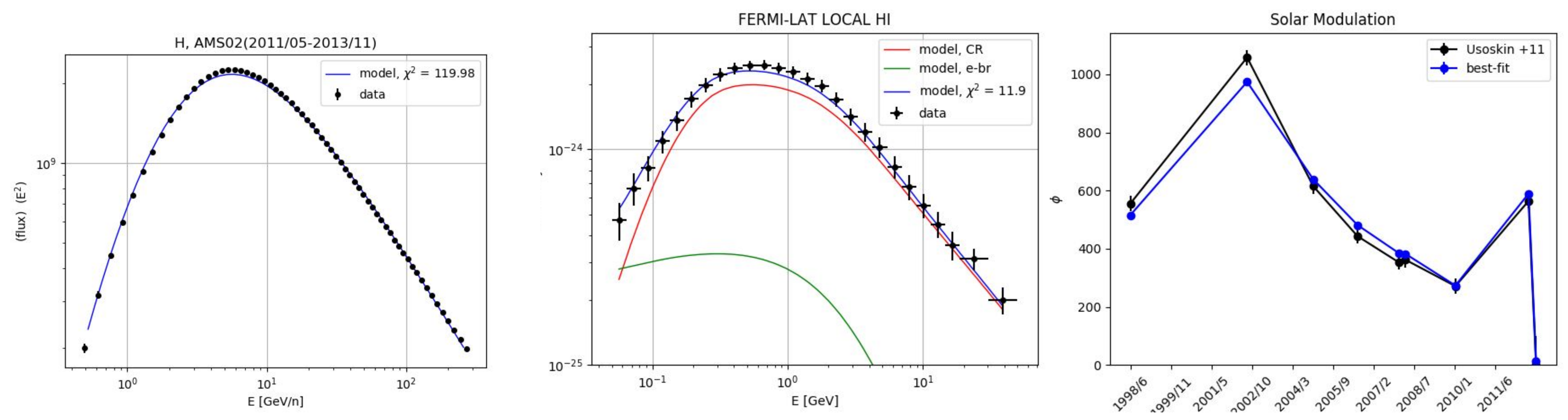

Fig. 5. Broken power law best fits, which are much closer to the data. Left: best-fit to AMS-02 fluxes. Middle: best-fit to gamma ray data. Right: best-fit solar modulation values, which now match the published values.

To see the effect of the Voyager data on the fit, we also tried a fit excluding Voyager data. In this fit, the break parameters were closer to their expected values based on previous fits without the Voyager data [1] (Table 1, blue text). The CR spectra for the two fits (with and without Voyager) are compared in Fig. 6; note the difference at low energies. (The γ-ray and modulation data was roughly the same in both fits.) Clearly, a fit with the Voyager data requires another low-energy break to describe all datasets.

Conclusion

Based on unified MCMC fits to the CR and γ-ray data, we find strong evidence for a low-energy break in the CR spectrum occurring during acceleration or propagation. Either the Voyager data is consistent with the LIS and there is a break around 1 GV rigidity, or it is observing some other phenomenon (e.g. another lower-energy break due to ionization) and the break is around 3-4 GV, as was expected.

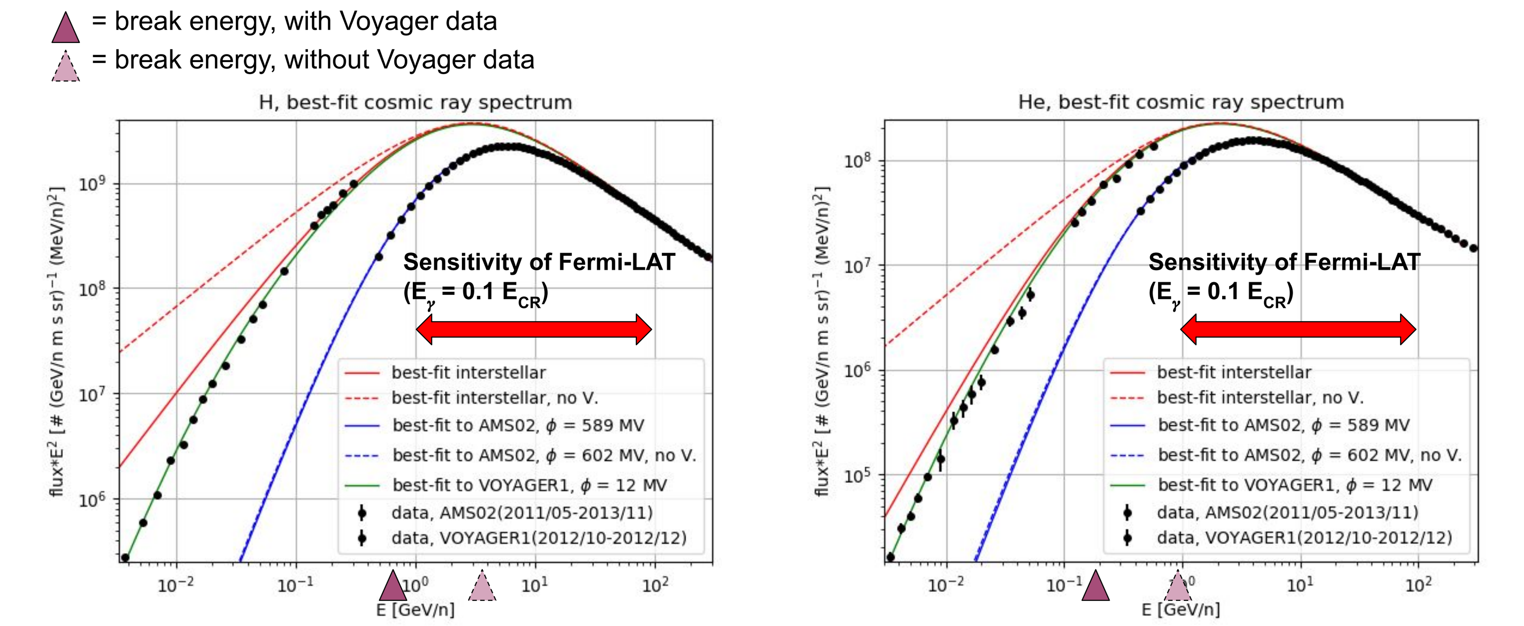

Fig. 6. Best-fit CR spectrum (solid: with Voyager data, dashed: without) including the LIS (red) and the LIS with solar modulation to match the AMS-02 and Voyager data. The Voyager data is the only probe of energies below 0.1 GeV.

Reduced χ^2: 2.16 (1.77) (single power law: 12.5)
Voyager modulation (ϕ): 12.72 ± 0.44 (none) (SPL: >100)
Softening parameter (δ): 1.48 ± 0.03 (0.32 ± 0.06)

Black = with Voyager data
Blue = without Voyager data
Red = best fit from Strong 2015 (based on γ-ray data)

Element	CR high-energy index (α_1)	CR low-energy index (α_3)	Break energy [GeV/nucleon]	Break rigidity (p_{br}/charge) [GV]	Flux at 10 GeV/nucleon
Hydrogen w/out V. Strong 15	2.875 ± 0.003 2.861 ± 0.003 2.82 ± 0.05	0.96 ± 0.03 2.16 ± 0.07 2.37 ± 0.09	0.671 ± 0.022 3.40 ± 0.35 5.87 ± 2.20	1.31 ± 0.03 4.26 ± 0.36 6.75 ± 2.20	25.26 ± 0.06 25.67 ± 0.12 26.73 ± 3.53
Helium w/out V.	2.759 ± 0.002 2.764 ± 0.003	0.01 ± 0.01 2.11 ± 0.09	0.173 ± 0.005 0.917 ± 0.140	1.19 ± 0.02 3.20 ± 0.33	1.383 ± 0.003 1.393 ± 0.004

Table 1. Best-fit parameters for the broken power-law model.

References

[1] Strong 2015 (2015ICRC...34..506S)
[2] Ptuskin et al. 2006 (2006ApJ...642..902P)
[3] Gleeson & Axford 1968 (1968ApJ...154.1011G)
[4] Usoskin et al. 2011 (2011JGRA..116.2104U)
[5] Maurin et al. 2014 (2014A&A...569A..32M)
[6] Kamae et al. 2006 (2006ApJ...647..692K)
[7] Kachelriess et al. 2014 (2014ApJ...789..136K)
[8] Casandjan 2015 (2015ApJ...806..240C)