Cosmic Ray Acceleration in the Galactic Center Region I: Gamma-Rays

S. Markoff[1], **W. Rhode**[2,3], **T. Enßlin**[4,5], **A. Donea**[6] **& P.L. Biermann**[4,7]
[1]*Physics Department, University of Arizona, Tucson, AZ 85719, USA*
[2]*Physics Department, University of California, Berkeley, CA 85720, USA*
[3] *Physics Department, University of Wuppertal, D-42097 Wuppertal, Germany*
[4] *Max-Planck Institute for Radio Astronomy, D-53121 Bonn, Germany*
[5] *Physics Department, University of Toronto, Ontario M5S1A7, Canada*
[6] *Astronomical Institute of the Romanian Academy, RO-75212 Bucharest, Romania*
[7]*Department for Physics and Astronomy, University of Bonn, Bonn, Germany*

Abstract

The measured Galactic cosmic ray spectrum can be explained as a superposition of injection from supernovae exploding into the interstellar medium and injection from supernovae that explode into their own stellar winds. This leads not only to predictions for the energy spectrum and chemical composition of the charged cosmic rays, but also to predictions for the observed or soon-to-be observed gamma-ray fluxes. We here present a comparison of the Galactic gamma-ray fluxes or limits for the diffuse inner disk data measured by EGRET and CASA-MIA respectively, using the GEANT/FLUKA Monte Carlo model for low energy and analytical approaches for high. We will also discuss the resultant constraints on the acceleration process.

1 Introduction:

Cosmic rays have provided many riddles to science since their discovery, and now with detections at energies far greater than what is reproducible with laboratory experiments, the challenge has only intensified. However, the origin of cosmic rays at even moderate energy (around GeV to TeV range) is not certain, and our understanding of the physics involved in their propagation is even less so. In this paper we wish to address the question of how to interpret the EGRET and CASA-MIA γ-ray data in the context of cosmic ray interactions, and to investigate what, if any, constraints on the spectrum and composition are provided by these data.

In the standard model for cosmic ray propagation, the average spectrum interacts with the interstellar medium (ISM), consisting of both matter and radiation, thus producing γ-ray emission via a combination of meson production and decays, inverse Compton (IC) upscattering of the ambient radiation field and bremsstrahlung. For photons above $\sim 1-10$ GeV, the spectrum is dominated by the meson (mainly pions and kaons) decay component and the spectrum will reflect the observed parent cosmic ray spectrum. This average spectrum in the conventional model has an injection spectrum of $E^{-2.1}$ near the source regions, which then decreases to $E^{-2.7}$ as the distribution undergoes diffusive losses in traveling away from the source. However, as shown in both Hunter et al. (1997) and Mori (1997), it is impossible to fit the EGRET inner Galaxy diffuse γ-ray data using the observed cosmic ray spectrum, which is too steep. An additional constraint comes from the CASA-MIA experiment (Borione et al. 1998), which measured the diffuse emission of the Galactic plane and set a very low upper limit in the $100-1000$ TeV range. Ong (1998) demonstrates that any straight extrapolation of fits to the inner Galaxy EGRET data overshoots the CASA-MIA γ-ray limits by a fair margin.

The question then remains, what realistic models exist which can simultaneously satisfy both sets of data? In this paper we will consider the two possibilities left to us within the current framework of our understanding of cosmic rays, and discuss whether they can satisfy the demands of the data, and what this implies for the original spectrum in terms of composition and spectral indices.

2 The Models

Since the observed cosmic ray spectrum is proving too steep to fit the EGRET data, it is possible that the interactions are occurring closer to the source, before diffusive losses have a chance to soften the spectrum. In the standard model, as mentioned above, the source distribution is proportional to $E^{-2.1}$, so we first consider this as the average interaction spectrum at lower energy. For the second case, we consider the possibility that most of the acceleration and subsequent interactions for photons and nuclei occur in the proximity of stars which have exploded into their own stellar winds (for an introduction to this theoretical scenario see, e.g., Wiebel-Sooth, Meyer & Biermann 1998, and references therein). In this framework, the source spectrum is proportional to $E^{-7/3}$.

These two simplistic models express the current favored range in spectral indices before the knee. What remains an open question is up to what energy either model can be extended.

3 To Knee or Not to Knee

Before considering the highest energies, we need some understanding of the knee region of the cosmic ray spectrum, where the overall spectrum turns down smoothly between $\sim 1 - 3 \times 10^{15}$ eV (Glasmacher et al. 1999). Fermi acceleration in supernova remnant (SNR) shocks is the classical and well-tested theory of cosmic ray acceleration. For a SNR exploding into the ISM, particles can only be energized to near 100 TeV (Lagage & Cesarsky 1983). This is above the knee, but Fermi acceleration by supernova shocks in stellar winds may provide the highest energies as well as the knee itself.

The origin of the highest energy particles is still unclear, as is their exact composition, but the trend is clearly that the composition becomes heavier through the knee region (Glasmacher et al. 1999b). One consequence of this latter wind model is that the composition of the spectrum is highly enriched by heavy elements which are amalgamated by the wind as the layers closer to the core are exposed, as compared to a typical SNR exploding into the ISM. In this picture, the relaxed spectra of all chemical elements is the same from He to Fe, with a slope of ≈ -2.67 before the knee and ≈ -3.07 beyond, where the location of the knee slides with increasing Z, where Z is the charge. In the wind-SN model, there is no hydrogen component and so the knee is visible only in He through Fe, with a range in location of about an order of magnitude in energy. Early tests with AGASA data are consistent with these predictions (Stanev, Biermann & Gaisser 1993).

The calculational possibilities corresponding to the two models are:

- The maximum case where the source spectrum dominates up to the highest energy, near 3×10^{18} eV. The existence of the knee in the source region is still an open question, so this gives rise to two alternatives: a) a spectrum with $E^{-2.1}$ all the way, or b) $E^{-2.1}$ to $\approx 5 \times 10^{15}$ eV, after which the spectrum steepens by ≈ 0.4. Here also two alternatives are to use an electron spectrum with single index to the maximum energy also, or to use a steeper relaxed spectrum above ~ 10 GeV. The spectral abundances should correspond to the ISM.

- The same two cases for the wind model, where the source spectrum goes as $E^{-2.33}$ to the knee, which scales as roughly $400 - 700\ Z$ TeV and then steepens again by ≈ 0.4 until the maximum energy. Such an attempt should include chemical abundances corresponding to data such as JACEE (see, e.g., Parnell et al. 1989).

In order to test the necessity for the knee in the context of the source model, and to gauge the effect of composition at high energy, we create a toy model for the cosmic-ray spectrum which is a weighted superposition of the various nucleic spectra, following the elemental grouping in Stanev, Biermann & Gaisser (1993), and using as the relative weights the normalizations of the various spectra at ~ 1 TeV found in Table 4 of Wiebel-Sooth & Biermann (1999). As each element crosses its individual knee, its spectrum steepens, so the combined spectrum is dominated by only the heaviest elements at the highest energy. To calculate the γ-ray flux, we convert the spectrum from particle energy to energy per nucleon, approximating the cross-section compared to the p-p inelastic cross section by scaling to the nucleon number as described in Ginzburg & Syrovatskii (1964), and follow the analytical model for nucleon collisions described in, e.g., Markoff, Melia & Sarcevic (1999). Because the heaviest nucleus that our Monte Carlo (GEANT/FLUKA) uses is He, for the low energy calculation, it is currently difficult for us to assess the uncertainty introduced by this model as compared to one which can account for the nuclei collisions more exactly. At least for He, this method overestimates the photon spectrum by a factor of ~ 2. For heavier nuclei and higher energy, this factor will only increase, as it does not account for energy lost when nuclei collide as compared to simply nucleons. Therefore this calculation can only provide an upper limit to the expected flux at high energy.

4 Results and Discussion

Our calculations at low energy (EGRET) were done using the Monte Carlo and at higher energies using an analytic code. As a crude estimate for the systematic errors of the EGRET data, we adopt a nominal value of 5%.

We find the first possibility, that of a source spectrum of $E^{-2.1}$, fails in both cases (a) and (b) to provide a reasonable fit to the EGRET data, and no realistic steepening will bring the spectrum close to the CASA-MIA points. On the other hand, the wind model does give such a realistic fit (Figure 1) to the EGRET points, which is shown for a cosmic ray (H only) spectral index of -2.34 and electron index of -2.7 for the IC calculation which cuts off at $\sim$ 10 GeV. Figure 2 shows an example of the differential γ-ray spectrum from the wind-SN model compared to the EGRET and CASA-MIA data, with spectral indices of -2.34 and -2.75 below and above the knee, respectively, and a knee at $400Z$ TeV. The data were taken from Ong (1998), which were in integrated units. Since we do not know the source spectrum used, we simply divided each point by its energy to get a rough idea of the differential value. This means these points are slightly underestimated.

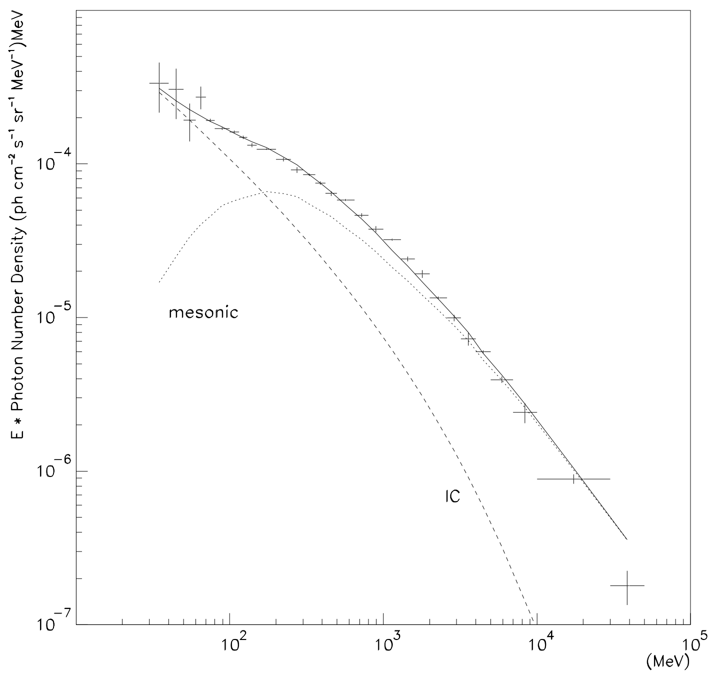

Figure 1: Comparison between the photon flux multiplied by energy for EGRET inner Galaxy data (crosses) and a typical fit. The two dominating components, mesonic and IC, and the total spectrum are shown. The parameters are: $\gamma_p = 2.34$, $\gamma_e = 2.75$ with an exponential cutoff at 30 GeV to represent the steepening, and He=0%.

We find that a superposition model based on the elemental abundances measured at ~ 1 TeV is the only possibility considered that can explain the inner Galaxy data from EGRET. However, it will only satisfy the upper limits from CASA-MIA provided that the correction factor introduced by the superposition cosmic ray spectrum overestimates the photon flux at highest energy by about an order of magnitude. A much better understanding of the correction factor introduced by converting to a purely nucleonic spectrum is required for a conclusive result. The presence of a knee is required in order to satisfy the CASA-MIA limits for the context of interactions near the source. Given the present favored ranges in the spectral indices, the wind-SN model is optimized with a knee which begins at the lower end of the possible range. The fit to EGRET at low energies also necessitates considerable γ-ray and neutrino production in the ~ 10 TeV range.

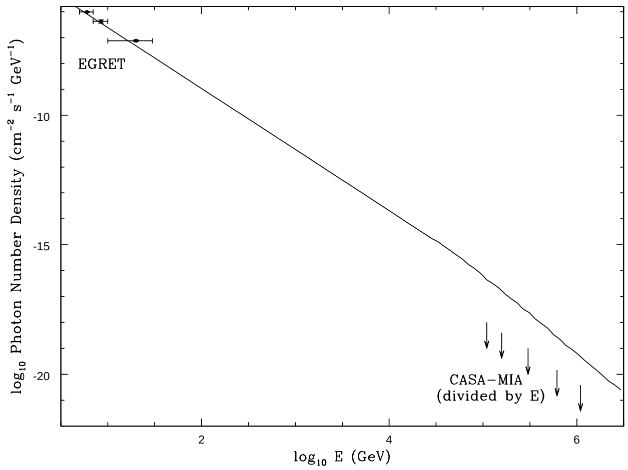

Figure 2: SN-Wind model compared with EGRET and CASA-MIA fluxes for cosmic ray spectral indices of -2.34 and -2.75, and a knee at $400Z$ TeV.

In the coming year we expect better confirmation of this limit from CASA-MIA, as well as new results from Milagro (see references in Ong 1998), which should be even more stringent. As a final note, for the wind model the positrons are all produced in the wind-SN zone, so this model can also be tested by its predictions for the positron fraction and spectrum, as well as with neutrino and γ ray fluxes in the TeV range.

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