

Is the cosmic ray energy spectrum the same all over the Galaxy ?

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Abstract: Recent measurements of cosmic gamma ray intensities up to TeV energies have been used to estimate the spectral shape of the parent cosmic ray particles present in the interstellar medium. The case is made for the particle spectrum in the Inner Galaxy being flatter than both locally and in the Outer Galaxy. Of various possible explanations we make the case for the propagation of the particles being different in the more turbulent interstellar medium of the Inner Galaxy. The characteristic parameter α for the so called anomalous diffusion is expected to be less in the Inner Galaxy than locally by about 0.2 and the corresponding power law spectral exponent of the cosmic ray particles differs from that locally by about $\Delta\gamma \simeq 0.1$.

Keywords: Inner Galaxy, cosmic rays, energy spectrum

1 Introduction

In most of the models cosmic ray (CR) particles are generated by supernova remnants (SNR) within a few kpc of the Earth. To probe more distant sources techniques used in Gamma Ray and Neutrino Astronomy must be used.

Here, we examine the diffuse component and choose regions of the Galaxy (latitude range, $|b| < 2.5^\circ$), where CR interactions with gas in the interstellar medium (ISM) predominate. The interactions are primarily between CR protons and the ISM in which π^0 -mesons are produced, the π^0 - decaying into two gamma rays each. A non-negligible flux of gamma rays from CR electron-photon interactions (Inverse Compton, 'IC') is also generated and is relevant.

2 The data

The satellite data used here for the study of gamma rays in the Inner Galaxy are from Fermi LAT for the longitude and latitude ranges $|\ell| \leq 80^\circ$ and $|b| \leq 8^\circ$ respectively [1]. The Fermi LAT collaboration also presented the gamma ray spectrum in the Outer Galaxy for $80^\circ \leq \ell \leq 280^\circ$, $|b| \leq 8^\circ$, which we use here for comparison with our model (see §5). To compare measurements made at different angular ranges we convert them using our model [2]. The published Fermi LAT spectra are limited to the highest gamma ray energy of 10^2 GeV. Data from the TeV region come from the MILAGRO project: a water-Cherenkov detector, [3].

3 Analysis of the energy spectra

3.1 Derivation of the spectra

Figure 1 shows the integral spectrum for the angular range: $30^\circ < \ell < 65^\circ$, $|b| < 2.5^\circ$. The predictions come from our Monte Carlo model of SNR acceleration of CR [4, 5] with the target gas, H_I and H_2 from the summary [2].

As for π^0 -gamma rays, the proton injection spectrum with differential energy spectrum exponent of $\gamma \simeq 2.15$ comes out in our SNR acceleration model. Anomalous diffusion has been adopted with the parameter $\alpha = 1.0$ [6]. We prefer anomalous diffusion since it matches better the

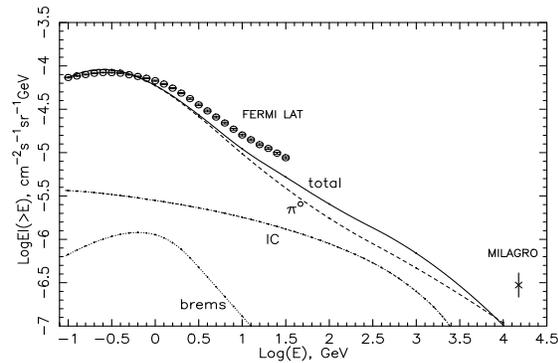


Fig. 1: Integral energy spectra of diffuse gamma rays in the Inner Galaxy. Experiment: open circles at $\log E, GeV < 1.5$ - Fermi LAT measurements at $|\ell| < 80^\circ, |b| < 8^\circ$, converted to the region covered by MILAGRO by increasing the Fermi LAT intensities by the factor $\Delta \log(EI(>E))$ which smoothly varies from 0.434 to 0.494 in the $\log E, GeV$ interval from -1 to 2 respectively based on calculations [2]; the cross at $\log E, GeV = 4.2$ is the MILAGRO measurement for the same region. Model calculations: dashed line - π^0 - gamma rays (π^0), calculated for anomalous diffusion with $\alpha = 1$, dash-dotted line - gamma rays from Inverse Compton scattering of electrons on the interstellar radiation field (ISRF) photons (IC), dotted line - gamma rays from the bremsstrahlung of electrons on the ISM gas, full line - total diffuse gamma rays. The calculated total diffuse π^0 gamma ray intensity is increased to normalize it to the experimental one at $\log E, GeV = -1$.

propagation in the highly non-uniform ISM. The parameter α in the description of anomalous diffusion is an exponent determined by the structure of the turbulent ISM. It determines the temporal dependence of the CR propagation and the shape of the diffusion front. The value $\alpha = 2$ is for the normal 'gaussian' diffusion in the relatively uniform ISM with small turbulence, such as that in the far Outer Galaxy or in the Galactic Halo. The smaller $\alpha = 1$ value corresponds to an asymptotically faster diffusion, which fits better the conditions in the local environment. Connection of the turbulence spectra with the diffusion characteristics let us make some predictions about steepening the

cosmic ray energy spectra with rising Galactocentric radius, the rise of the radial gradient of CR at higher energies etc. [7].

Turning to the IC contribution, the electron spectrum in the Inner Galaxy was taken equal to the local one but truncated at 10 TeV, following [5]. In any event, this narrow range of latitudes leads to IC gamma rays comprising only a minority component. The photon intensities in the interstellar radiation field (ISRF) were taken from [8].

3.2 Spectral features to be explained

It is evident that the calculated spectra do not fit the Fermi LAT and MILAGRO measurements. The concavity of the measured spectrum at about 10 GeV is stronger than that of the calculated spectrum. The Fermi LAT collaboration put forward three possible explanations [1]:(i) a contribution of undetected point sources; (ii) the presence of 'fresh' cosmic ray sources with harder injection spectra; (iii) different cosmic ray spectra in different parts of the Galaxy. We give stronger support to the last two mechanisms. We argue that both of them have the same physical origin - the higher frequency of SN explosions in the Inner Galaxy and hence a higher density of SNR.

It is known that CR measured locally come mostly from a relatively small number of sources at small distances from the solar system. On the other hand, measured gamma quanta are produced by CR interacting with the ISM all along the line of sight and therefore originating from many more sources. Gamma quanta coming from the Inner Galaxy contain a larger fraction of those produced in the region of higher frequency of SN explosions. The higher frequency means that the 'effective' age of SNRs is younger and the energy spectrum of their produced CR is harder than those nearby. Thus, the concave shape of the π^0 -gamma spectrum can be due to the contribution of many sources with different slopes of the power law spectra including relatively hard ones from young sources - the mechanism proposed in [7, 9], and also in [1] as item (ii).

In addition to the role of 'new' SNR sources in the Inner Galaxy there is a possibility of Inner Galaxy sources providing flatter injection spectra. Such a result could come from the different ISM characteristics such as magnetic fields, gas density etc. Clearly, if the mean exponent of the injection spectrum in the Inner Galaxy is reduced a better fit can be achieved. A change by $\Delta\gamma = 0.1$, i.e. from $\gamma = 2.15$ to 2.05 is possible, both by virtue of slightly flatter injection spectra and the increased probability of a line of sight penetrating a SNR 'bubble', within which the spectrum is flatter than outside.

However, it is seen in Figure 1 that in spite of our simulated spectra showing the concavity originating from this mechanism there is still an excess of the experimental intensities over our Monte Carlo simulations. Such an excess is also mentioned in [1]. The actual reduction of the exponent for the needed injection spectra is greater than $\Delta\gamma = 0.1$ and the explanation of the flattening by only this mechanism requires a more serious modification of the model for the CR acceleration in SNR, which seems to us less likely than the explanation given below.

4 Interpretation in terms of the higher turbulence in the ISM in the Inner Galaxy

A better explanation is in terms of the effect of propagation, as distinct from injection. In [7] it was pointed out

that the exponent of the ambient CR spectrum depends on the mode of the particle diffusion. In [7] the diffusive properties of the ISM were assumed to depend on the degree of turbulence of the medium caused by the frequency of SN explosions.

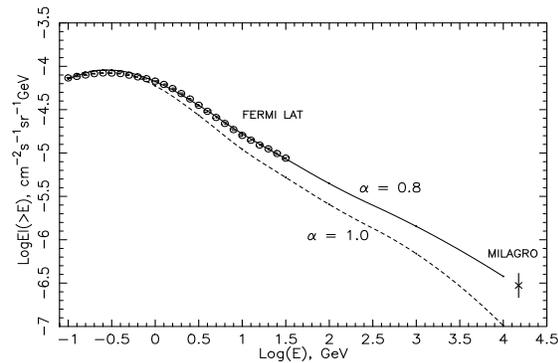


Fig. 2: Integral energy spectrum of diffuse gamma rays in the Inner Galaxy. Comparison of the Fermi LAT (open circles) and MILAGRO (cross) measurements with two versions of spectra calculated for anomalous diffusion with the parameter α equal to 1.0 (dashed line) or 0.8 (full line). The agreement of the experimental measurements with the spectrum calculated for the more turbulent ISM in the Inner Galaxy (with $\alpha = 0.8$) is quite good.

The higher frequency of SN explosions in the Inner Galaxy makes the ISM there more turbulent and the parameter α decreases [6]. The spectrum becomes flatter as α falls and we argue that with respect to its value at $R = 8.5$ kpc, the value of α at 6 kpc (the relevant 'Inner Galaxy' for $\ell : 30^\circ - 65^\circ$) is smaller by ~ 0.2 [7]. This value is just what is required as will be seen in Figure 2 where the reduction of α down to $\alpha = 0.8$ gives a good agreement with the Fermi LAT measurements.

5 Difference between the gamma-ray spectra in the Inner and Outer Galaxy

The smaller density of SNR in the Outer Galaxy and in the Galactic Halo leads us to predict that the smaller turbulence of the ISM there will give steeper CR energy spectra. The published Fermi LAT measurements cover the area of the whole Outer Galaxy with coordinates $80^\circ < \ell < 280^\circ$, $|b| < 8^\circ$ and the collaboration has already noticed that the excess of measured intensities above the model calculations at high energies is smaller in the Outer compared with the Inner Galaxy. It means that the energy spectrum of gamma quanta in the Outer Galaxy is steeper than in the Inner Galaxy. Figure 3 shows the measured spectra compiled from Figures 15 and 16 of [1].

Fitting them by power laws at energies above 10 GeV yields the values $\gamma = 2.401 \pm 0.009$ for the Inner Galaxy and $\gamma = 2.525 \pm 0.005$ for the Outer Galaxy. The difference is very significant. This supports the prediction of a steeper spectrum in the Outer Galaxy.

Inspired by the good agreement of our model calculations with the experimental data in the Inner Galaxy shown in Figure 2 we calculated the gamma ray spectrum for the Outer Galaxy $80^\circ < \ell < 280^\circ$, $|b| < 8^\circ$ at higher energies than published by Fermi LAT. The α parameter was taken as 0.8 for the Inner Galaxy and 1.0 for the Outer Galaxy. The comparison of these two spectra is shown in Figure 4.

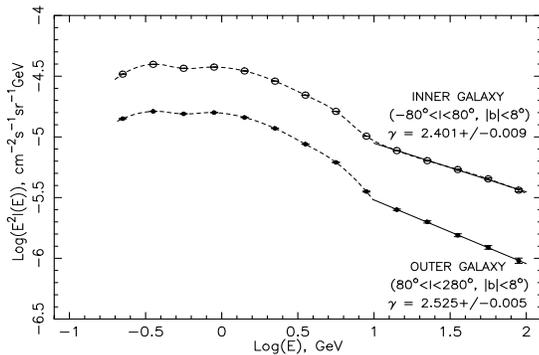


Fig. 3: Differential energy spectra of total gamma rays in the Inner Galaxy (open circles, $|\ell| < 80^\circ$, $|b| < 8^\circ$) and in the Outer Galaxy (full circles, $80^\circ < \ell < 280^\circ$, $|b| < 8^\circ$) compiled from Figures 15 and 16 of [1]. The dashed lines are the cubic splines drawn to guide the eye. The full lines above $\log E = 1$ are best linear fits, the slope of which confirms the steeper spectrum in the Outer Galaxy.

It is seen that the predicted spectrum in the Inner Galaxy at TeV energies is considerably flatter than in the Outer Galaxy and the expected difference between spectra in the Inner and Outer Galaxy is higher than at tens of GeV.

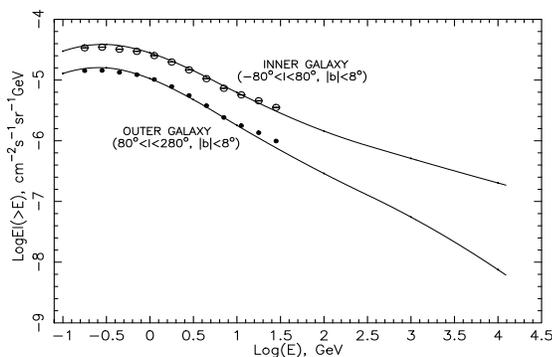


Fig. 4: Integral energy spectra of diffuse gamma rays in the Inner Galaxy (open circles, $|\ell| < 80^\circ$, $|b| < 8^\circ$) and in the Outer Galaxy (full circles, $80^\circ < \ell < 280^\circ$, $|b| < 8^\circ$) from Fermi LAT measurements. Upper full curve - calculations for the model of anomalous diffusion with $\alpha = 0.8$ in the Inner Galaxy. Lower full curve - calculations for the Outer Galaxy with the turbulence in the ISM equal to that locally ($\alpha = 1.0$). It is seen that at TeV energies the expected difference between spectra in the Inner and Outer Galaxy is higher than at tens of GeV. If the turbulence in the Outer Galaxy is smaller than that locally [10] then the predicted difference can be bigger still. It should be noted that the 'Outer Galaxy' results refer mainly to the near Outer Galaxy, in fact.

6 Comparison with the results of other studies

The Fermi LAT group themselves [1] acknowledge that there is a difference in gamma ray spectra between the Inner and Outer Galaxy but their possible explanations do not include 'anomalous diffusion'.

In [4] we examined the 'low energy' gamma ray spectra from [11], and used it to determine the dependence of the proton spectral exponent on Galactocentric distance. Al-

though an anomalous excess of gamma rays above several GeV reported by the EGRET team was not confirmed by the Fermi LAT measurements [1] this does not invalidate the conclusions. It was found that the differential exponent of the gamma ray spectrum increased from 2.40 ± 0.14 at $R = 5\text{kpc}$ to 2.88 ± 0.12 at $R = 15\text{kpc}$. Such a variation is of the order of that for the 'variable turbulence model' predictions referred to in §4.

In that work [4] it was shown that there was a simple relationship between the anomalous diffusion parameter, α , and the ensuing exponent of the differential proton spectrum, γ . The result was an increase in γ of 0.48 for an increase in α (ie a decrease in the degree of anomaly) of 0.5.

The MILAGRO group [3] interpret the spectral data from their own observations for $\ell : 30^\circ - 65^\circ$ in terms of the 'GALPROP' model of 'conventional' particle diffusion but with an artificially enhanced IC contribution, specifically by increasing the electron intensity by a factor 4. We consider that the explanation(s) advanced here are more physical and less ad hoc in the sense that increased turbulence should have an effect on particle propagation in some form, at least. However, a full treatment of the effect has not yet been made..

Finally, reference should be made to a new paper [12]. This study uses our work [4] on anomalous diffusion but concentrates on the latitude variation of the CR diffusion properties and examines the implications for primary particle spectra, secondary to primary ratios and latitudinal anisotropies. Thus, it is complementary to the present paper.

7 Other features in the Inner and Outer Galaxy

An interesting question is connected with the prominent feature of the CR measured at Earth - the well known 'knee' in the CR energy spectrum at several PeV. Is such a sharp or even sharper knee expected elsewhere in the Galaxy? Using data for [13]: distance $\sim 300\text{pc}$, age $\sim 100\text{year}$, and the usual rate of Type 2 SN, 10^{-2}year^{-1} , the probability of there being a SN so 'young' or younger and so close or closer is $\simeq 0.15f$, where f is the ratio of the SN rate (per unit area) at the location in question to that locally. Thus, for the Inner Galaxy, where f is ~ 2 the probability is $\simeq 0.3$ and the answer is 'probably'. Similarly, for the Outer Galaxy, where f is typically 0.3 the probability is $\simeq 0.05$ and the knee is unlikely. At present there seems to be no way of checking these answers.

8 Conclusion

In our view, the flattening of the gamma ray spectrum in the Inner Galaxy and the steeper spectrum in the Outer Galaxy find a natural explanation for CR accelerated in SNR in which particles are propagated in the increasingly turbulent region encountered as the Galactocentric distance is diminished.

As remarked already (in §6), further work is necessary to quantify the degree of anomalous diffusion expected. This work should include a more detailed spatial analysis of the diffusion properties of the ISM by way of comparisons of gamma ray spectra from active regions of the Galaxy (such as OB associations) and at various heights

above the Galactic Plane. In terms of other galaxies, it will be useful to study radio spectra (from CR electrons and magnetic fields) as a function of galaxy type and luminosities in other wavebands.

Acknowledgements

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