Cosmic Rays in the Inner Galaxy and the Diffusion Properties of the Interstellar Medium

A. D. Erlykin ¹,² and A. W. Wolfendale ²
(1) P N Lebedev Physical Institute, Moscow, Russia
(2) Department of Physics, Durham University, Durham, UK

May 5, 2014

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 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 $\alpha$ for the so called 'anomalous diffusion' is expected to be less in the Inner Galaxy than that locally and the corresponding power law spectral exponent of the cosmic ray particles $\gamma$ will differ from that locally. Arguments are presented favouring a value of $\alpha$ lower than the local one by $\Delta \alpha = 0.2$; the consequence is that $\Delta \gamma \sim 0.1$ for the parent particles.

1 Introduction

There is a wealth of information about those cosmic rays (CR) that are detected at Earth and satisfactory models involving acceleration by supernova remnants (SNR) have been put forward, at least for energies to some few TeV. The CR in question (particles, and mainly protons) are thought to be generated by SNR within a few kpc of the Earth but for more distant sources from which few, if any, particles arrive at Earth, other techniques must be used.

Insofar as Neutrino Astronomy is only about to start, recourse is made to Gamma Ray Astronomy, the gamma rays being generated by CR particles interacting with gas and photons. Some information about distant SNR sources has come from the detection of gamma ray sources [1], although here there are problems in distinguishing between electron-Inverse Compton interactions and CR nuclei-gas interactions as the source of the gamma rays.

The purpose of the analysis described in this paper is to study whether there is a difference between CR energy spectra in the different parts of the Galaxy. It is known that there is the spatial gradient of CR in the Galactic Disk which means that there
are more CR in the Inner Galaxy than in the Outer Galaxy. However, this gradient is found to be small and established only for low energy CR in the GeV region \[2, 3, 4, 5\]. Its existence at TeV energies is not known and we try to find it studying the CR energy spectrum in the Inner Galaxy in comparison with that locally and in the Outer Galaxy.

The form of the paper is as follows. Experimental data are taken and corrected by removal of the extragalactic component and the contribution of discrete gamma ray sources. The remainder, which is the bulk of the measured intensity, is then compared with our model predictions and conclusions drawn about the mode of CR propagation.

2 The data

There is a long history of cosmic gamma ray data from a series of satellites and ground based telescopes of ever improving collecting power and resolution. The satellite data used here for the study of gamma rays in the Inner Galaxy are from Fermi LAT \[6\]. In this paper the Fermi LAT collaboration concluded that there is an excess of high energy gamma rays detected in the Inner Galaxy over the expectation assuming CR energy spectra there are the same as locally ( GALPROP model ). It means that the CR energy spectra in the Inner Galaxy are flatter than that locally. This conclusion was based on the analysis of the observed total energy spectrum including the contribution of discrete sources as well as the isotropic background. The analysed energy range was limited by the maximum energy of 0.1 TeV.

Here, we examine not the total, but the so called diffuse component of gamma rays and choose regions of the Galaxy \(30^\circ < \ell < 65^\circ, |b| < 2^\circ\), where CR interactions with gas in the interstellar medium (ISM) predominate. The interactions are primarily between CR protons and the ISM, in which \(\pi^0\)-mesons are produced, the \(\pi^0\) - decaying into two gamma rays each. In what follows these gamma rays are referred to as \(\pi^0\)-gamma rays. A non-negligible flux of gamma rays from CR electron interactions with photons and ISM gas ( Inverse Compton, 'IC' and bremsstrahlung, 'BR' ) is also generated and is relevant. We subtract the contribution of the discrete sources where gamma rays are generated by the interactions of accelerated CR ( protons, nuclei and electrons ) with the gas, photons and magnetic fields inside these sources ( SNR, pulsars etc ) using the published Fermi LAT estimates. We also subtracted the contribution of the isotropic gamma ray background, because it is mainly extragalactic and we are interested and restrict ourself only to the spatial distribution of the Galactic CR.

In order to check the Fermi LAT indication of the gamma ray excess we introduced two new subjects: a) for the comparison of the observation with the expectation we used our own model of the CR acceleration and propagation ( anomalous diffusion model ) \[7, 8\] and b) to extend the analysed energy range we included experimental data of the MILAGRO collaboration which gave an estimate of the diffuse gamma ray flux at 15 TeV \[9, 10\].

MILAGRO is a ground based water-Cherenkov detector. The collaboration measured the gamma ray flux in the region with Galactic coordinates \(30^\circ < \ell < 65^\circ, |b| < 2^\circ\). Recognized 'discrete' gamma ray sources have been removed, these amounted to about 25% of the flux. There are also data for the region with \(65^\circ < \ell < 85^\circ, |b| < 2^\circ\) but we
did not use them since this region is at the very far periphery of the Inner Galaxy and includes the intensive gamma ray source in the Cygnus region which was evidently not completely removed from the data. Unfortunately, the MILAGRO collaboration gave only the upper limits for the gamma ray flux from the Outer Galaxy which was rather high and not useful for our analysis.

The adopted Fermi LAT data are for the longitude and latitude ranges $|\ell| \leq 80^\circ$ and $|b| \leq 8^\circ$ respectively. Besides diffuse gamma rays they included contributions from discrete sources and isotropic background. We decided to use only diffuse gamma rays due to three reasons: a) as has been already mentioned, diffuse gamma rays are directly connected with Galactic CR via their interactions with the ISM; b) in the analysis of the data we used our calculations [11] which were made for the diffuse component of the total gamma ray flux; c) the MILAGRO flux used for the comparison with Fermi LAT included only diffuse gamma rays. We removed from the published gamma ray flux contributions from detected gamma ray sources and isotropic background using their calculations with the GALPROP model $SS4R20^T150^C5$ presented in the publication. The corrections were not big and reduced the total intensities by $\Delta(\log I) = 0.067$ at $\log E, \text{GeV} = -1$ and by $\Delta(\log I) = 0.117$ at $\log E, \text{GeV} = 2$.

In order to make a direct comparison between MILAGRO and Fermi LAT data the latter measurements were converted to the region of $30^\circ < \ell < 65^\circ, |b| < 2^\circ$ using our calculations [11]. The mean intensity in the latter region was found to be higher compared with the former one. According to these calculations the conversion factor $R$ was nearly independent of the energy, increasing smoothly from $\log R = 0.434 \pm 0.002$ at $\log E, \text{GeV} = -1$ to $0.494 \pm 0.004$ at $\log E, \text{GeV} = 2$. Its uncertainty was calculated from the sampling errors of the mean intensity in the regions of $|\ell| < 80^\circ, |b| < 8^\circ$ and $30^\circ < \ell < 65^\circ, |b| < 2^\circ$ averaged over $161 \times 9$ and $36 \times 3$ points separated by $\Delta \ell = 1^\circ$ and $\Delta b = 2^\circ$ respectively. Calculations included 50 samples of simulated space-time configurations of 50000 SNR. The shape of the experimental energy spectrum after the conversion has not been distorted significantly.

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 also use here for comparison with our model (see §5). Since for the comparison of the spectral shapes in the Inner and Outer Galaxy the absolute intensities are not important, we made a direct comparison of the data for the Inner ($|\ell| < 80^\circ, |b| < 8^\circ$) and Outer ($80^\circ < \ell < 280^\circ, |b| < 8^\circ$) Galaxy without any corrections.

The MILAGRO collaboration published the integral (rather than the differential) gamma ray intensity and since we are going to use both MILAGRO and Fermi LAT data to derive the spectral shape above the Fermi LAT maximum energy, we integrated the Fermi LAT intensities, too.
3 Analysis of the energy spectra of gamma rays

3.1 Derivation of the spectra

Figure 1 shows the integral spectrum for the region with Galactic coordinates $30^\circ < \ell < 65^\circ$, $|b| < 2^\circ$. The predictions come from our Monte Carlo model of SNR acceleration of CR $[7, 8]$ with the target gas, $HI$ and $H_2$ from the summary $[11]$.

![Figure 1: Integral energy spectra of diffuse gamma rays in the Inner Galaxy. Experiment: open circles at $logE, GeV < 1.5$ - 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 $logE, GeV$ interval from -1 to 2 respectively based on calculations $[11]$; the cross at $logE, GeV = 4.2$ is the MILAGRO measurement for the same region. Model calculations: dashed line - $\pi^\circ$ - gamma rays ($\pi^\circ$), 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 $\pi^\circ$ gamma ray intensity is increased to normalize it to the experimental one at $logE, GeV = -1$. As for $\pi^\circ$-gamma rays, the proton injection spectrum with differential energy spectrum exponent of $\gamma = 2.15$ comes from our SNR acceleration model. Insofar as we normalize the prediction to observation at the lowest energy ($logE, GeV = -1$), no 'metallicity correction' has been applied to the $H_2$ column densities. Anomalous diffusion ('superdiffusion') has been adopted with the parameter $\alpha = 1.0$, which gives the best description of the CR spectrum observed locally $[12]$. The case for anomalous diffusion is considered here and strengthened later, in §4.
Mathematical apparatus for anomalous diffusion of CR was developed by two groups in Russia \cite{13, 14, 15, 16}. It was applied for the analysis of various characteristics of CR (energy spectra, mass composition, anisotropy, electrons and positrons etc.) \cite{17, 18, 19, 20, 21, 22, 23}. We prefer anomalous diffusion since it matches better the expected mode of propagation in the highly non-uniform ISM. It also helps to understand the formation of the huge Galactic Halo and the small radial gradient of CR in the Galaxy \cite{12, 24} following from the analysis of Fermi LAT data \cite{25} and previous measurements. The parameter $\alpha$ in the description of anomalous diffusion is 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 (and in the near Outer Galaxy). The distinction between near and far Outer Galaxy arises because many of the 'Outer Galaxy' CR come from within a few kpc of the Sun and here the turbulence is still quite high ($\alpha = 1$) compared with our presumed $\alpha = 2$ for the far Outer Galaxy.

The connection of the turbulence spectra with the diffusion characteristics let us make some predictions about the steepening of the CR energy spectra with increasing Galactocentric radius, the rise of the radial gradient of CR at higher energies etc. Some of these predictions were already checked and confirmed by our analysis of EGRET data \cite{24}, others can be checked by further analysis of Fermi LAT data, and will be done so in what follows.

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 \cite{8}. Interestingly, it is likely that because of the greater electron density losses in the Inner Galaxy (due to the higher energy densities of the magnetic field and starlight there) the electron cut-off energy will be significantly less than 10 TeV and the slight convexity of the 'total' in Figure 1 centred on $\log E, GeV \simeq 2.5$ will be largely removed. 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 \cite{26} which confirmed those from \cite{27}.

The same electron spectrum as for the case of IC and the same ISM gas as for the case of $\pi^0$ gammas have been used to calculate the spectrum of bremsstrahlung gamma rays. Figure 1 shows that its contribution does not exceed several percent.

The dominant contribution in the GeV region is from $\pi^0$ gamma rays. Inverse Compton and bremsstrahlung processes do not contribute more than 5% of the total gamma ray flux. Hence, in order to visualize the possible difference of the shapes for the observed and calculated spectra the dominant $\pi^0$ spectrum has been increased to normalize the total calculated intensity at $\log E = -1$ to the experimental one.

3.2 Gamma ray spectral features to be explained

It is evident that the calculated (conventional) spectra do not fit the Fermi LAT and MILAGRO gamma ray measurements. The concavity of the measured spectrum at...
about 10 GeV is stronger than that of the calculated spectrum. This feature has been examined by us in [30] where it is argued that a 'New Component' can be involved at energies below 10 GeV. At this stage it can be remarked that the Fermi LAT work [6] shows an even more dramatic feature just below 10 GeV. Specifically, they appear to show a statistically significant change of the fractional intensity difference, (data-model)/data, in going from 6 to 9 GeV (although, as usual, this is presumably diluted by systematic errors). This feature gives support to the idea of a new component but this component should cease for energies much above 10 GeV which are mainly the concern of the present work.

The Fermi LAT collaboration put forward three possible explanations for the feature [6]: (i) a contribution of undetected gamma ray point sources: pulsars, pulsar wind nebulae, SNRs; (ii) the presence of 'fresh' cosmic ray sources with a harder injection spectrum; (iii) different cosmic ray particle spectra in different parts of the Galaxy, particularly that in the Inner Galaxy being harder than locally. Having no arguments against the possible contribution of undetected gamma ray point sources we give stronger support to the last two mechanisms (as mentioned in our earlier work [24]). We argue that both of them have the same physical origin - the higher frequency of SN explosions in the Inner Galaxy and hence the higher density of SNR.

It is known that CR particles measured locally come mostly from a relatively small number of CR sources at small distances from the solar system (mainly within ∼1kpc). On the other hand, measured gamma rays are produced by CR interacting with the ISM all along the line of sight and therefore originating from many more sources. Gamma rays 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 therefore the energy spectrum of their produced CR is harder than those nearby. The concave shape of the $\pi^0$-gamma spectrum can be due both to the contribution of many sources with different slopes of the power law spectra including relatively hard ones and the generally harder spectra near to young sources - the mechanism proposed in [29] [30] and mentioned as item (ii) in [6].

In addition to the role of young SNR sources in the Inner Galaxy (from which CR have not diffused very far) there is the possibility of Inner Galaxy SNR providing flatter injection spectra than those elsewhere. Such a result could come from the different ISM characteristics, such as magnetic fields, gas density, smaller remnants at the time of particle escape, etc. Clearly, if the mean exponent of the injection spectrum of CR particles in the Inner Galaxy is reduced a better fit can be achieved. A (not unlikely) 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 the remnant of a SN before it has had time to 'release' its accelerated CR into the ISM.

However, it is seen in Figures 1 that in spite of the fact that our simulated spectra show the concavity, followed by the flatter slope at high energies originating from this mechanism there is still an excess of the experimental intensities over our Monte Carlo simulations, so that we confirm the Fermi LAT conclusion about the existence of this excess. The actual reduction of the exponent for particle injection spectra needed is greater than $\Delta \gamma = 0.1$ and the explanation of the flattening by this mechanism alone requires a more serious modification of the model for CR acceleration and propagation,
as considered below.

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

4.1 Cosmic Ray Diffusion

In our view, a better explanation of the spectral feature is in terms of the effect of propagation, as distinct from injection, as put forward by us in [24]. In that work it was pointed out that the exponent of the ambient CR particle spectrum depends on the mode of the particle diffusion. We are not disputing ‘diffusion’ as the mechanism responsible for CR transport but, rather, its mathematical form. It would be remarkable if this form were the same everywhere. In [24] it was pointed out that the diffusive properties of the ISM depend on the degree of turbulence of the medium which, in turn, depends on the position in the Galaxy. This aspect will now be examined in a more detailed way than has been done hitherto.

4.2 Turbulence in the Galaxy

Turbulence in the ISM arises from energy input from a variety of sources, such as supernovae (SN), SNR, pulsars, stellar winds, jets etc. A useful summary of the surface densities of ‘energy sources’ as a function of Galactocentric distance is given in [31]. In going from locally to a Galactocentric distance of 3 kpc the increase in input energy density due to the higher density of sources is about 3.

Confirmation that there is an increase in turbulence as one approaches the Galactic Centre, as distinct from the energy input, is provided by many indicators. Specific ones are the magnetic field [32], where the factor of increase for \( R = 3 \text{ kpc} \) compared with locally is \( \sim 2.8 \) ( for the total field, regular and irregular ) and thermal bremsstrahlung: \( \sim 4 \) [33].

4.3 Diffusive characteristics as a function of the degree of turbulence

Ideally, it should be possible to determine the expected value of \( \alpha \) as a function of the degree of turbulence but there are many factors which make this impossible, so far. Nevertheless, the data given in [12] allow a very approximate result: \( \alpha \) changes from 1.0 to 0.5 for a change in turbulent energy by a factor 3. Thus, we would expect a change in \( \alpha \) of about 0.5 in going from locally to \( R = 3 \text{ kpc} \) or a change by \( \sim 0.25 \) averaged over a line of sight through the Inner Galaxy ( at \( \ell = 0^\circ \)).

4.4 Determination of the experimental value of \( \alpha \)

Figure 2 gives the result of fitting the Inner Galaxy gamma ray spectrum ( \( 30^\circ < \ell < 65^\circ, |b| < 2^\circ \) ) with a reduced value of \( \alpha \): 0.8, such as to give a fit to the data. Although
we are probing the Inner Galaxy, in fact the closest distance the line of sight gets to
the Galactic Centre (for \( \ell = 30^\circ \)) is about 4 kpc. The result is that if the value in the
true Inner Galaxy, at \( R \sim 3 \) kpc were 0.5, that relevant to the present range would be
\( \alpha \simeq 0.9 \). Thus, the observed value of \( \alpha \) is in the region of expectation.

Figure 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 \( \alpha \) 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 conversion of the gamma ray energy spectrum observed in the region with
Galactic coordinates \( |\ell| < 80^\circ, |b| < 8^\circ \) to the region of \( 30^\circ < \ell < 65^\circ, |b| < 2^\circ \) described
in §2 and illustrated in Figure 1 has been made for \( \alpha = 1 \). The same conversion
made using \( \alpha = 0.8 \) gives the spectrum still flatter than that for \( \alpha = 1 \). It makes our
conclusion about the flatter CR energy spectrum in the Inner Galaxy stronger still.

At the present stage of the study we do not pretend to specify the precise value of \( \alpha \).
The important point is the qualitative conclusion about the flatter CR energy spectrum in the Inner Galaxy than locally, which gives the support to the general contention on
the non-uniformity of CR characteristics all over the Galaxy.
5 Difference between the gamma-ray spectra in the Inner and Outer Galaxy

The reduced turbulence in the Outer Galaxy compared with that in the Inner Galaxy leads us to predict steeper CR energy spectra in the Outer Galaxy although the wide range of latitude (|b| < 8°) means that the far Outer Galaxy is not reached in the used Fermi LAT observations. The published Fermi LAT measurements cover the area of the whole Outer Galaxy with coordinates 80° < l < 280°, |b| < 8° 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 rays in the Outer Galaxy is indeed steeper than in the Inner Galaxy. Figure 3 shows the measured spectra compiled from Figures 15 and 16 of [6]. Fitting them by power laws at energies above 10 GeV yields values for the differential exponents of 2.401 ± 0.009 for the Inner Galaxy and 2.525 ± 0.005 for the Outer Galaxy. Taken at face value the difference is very significant but it is appreciated that systematic errors degrade the results. Presumably some, at least, of the systematic errors are the same for the measurements towards, and away from, the Galactic Centre so that their effect is not large; nevertheless, it could be appreciable. Thus, the conservative statement: 'this supports the prediction of a steeper gamma ray spectrum in the Outer Galaxy compared with the Inner' is appropriate.

Both spectra shown in Figure 3 are for the total gamma ray flux including contributions from discrete sources and the isotropic background. In §2 it was shown that the subtraction of these contributions increases the exponent of the spectrum in the Inner Galaxy by (0.117-0.067)/3 = 0.017. It is not enough to remove the difference between the calculated exponents of the two spectra in the Inner and Outer Galaxy.

Inspired by the acceptable agreement of our model calculations with the experimental data in the Inner Galaxy shown in Figure 2 we have calculated the gamma ray spectrum for the Outer Galaxy 80° < l < 280°, |b| < 8° 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. It is seen that the predicted spectrum in the Inner Galaxy at TeV energies is considerably flatter than in the Outer Galaxy. Since upper limits for the gamma ray intensity in the Outer Galaxy, given by the MILAGRO collaboration are rather high, they do not help the comparison.

6 Comparison with the results of other studies

The Fermi LAT group themselves [6] 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 [24] we examined the 'low energy' gamma ray spectra from [34], and used it to determine the dependence of the proton spectral exponent on Galactocentric distance. Although an anomalous excess of gamma rays above several GeV reported by the EGRET team was not confirmed by the Fermi LAT measurements [6] this does not
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 [6]. 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.

Invalidate the conclusions. It was found that the differential exponent of the gamma ray spectrum increased from \(2.40 \pm 0.14\) at \(R = 5\) kpc to \(2.88 \pm 0.12\) at \(R = 15\) kpc. Such a variation is of the order of that for the `variable turbulence model' predictions referred to in §4.

In that work [24] it was shown that there was a simple relationship between the anomalous diffusion parameter, \(\alpha\), and the ensuing exponent of the differential proton spectrum, \(\gamma\). The result was an increase in \(\gamma\) of 0.48 for an increase in \(\alpha\) (ie a decrease in the degree of anomaly) of 0.5.

The MILAGRO group [9, 10] 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 to be made to a paper [35] which appeared after the present work had been submitted. The study uses our work [24] 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 Conclusions and Future Work

The flattening of the gamma ray spectrum for the Inner Galaxy in comparison with that in the Outer Galaxy seems well established (although, because of the possibility of systematic errors, confirmation by independent precision measurements is needed) and, in our view, finds 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. Further work will 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.

Although getting away from the main thrust of the paper, an aspect of potentially considerable importance is the role of Gamma Ray Astronomy (via Fermi LAT) in determining the foreground to be subtracted from the map of Cosmic Microwave Background (CMB). In an early work using the 'WMAP' and the EGRET gamma ray data (see [36]) it was claimed that the 'cleaned' CMB map still contained signatures due to CR effects in the Galactic Halo. The relevance to the paper is that whereas we have concentrated on large-scale differences in the diffusion properties of the Inner and Outer Galaxy there is the likelihood of such differences on smaller scales, too. Such changes at higher Galactic latitudes are germane to the CMB foreground problem.

Acknowledgements

The Kohn Foundation is thanked for supporting this work. We are grateful to Dr. Andrew Strong for his ready advice and to the referee for numerous helpful suggestions.

References

[1] Funk S., 2011, Rapporteur talk at 32nd Int. Cosm. Ray Conf., Beijing, China; arXiv:1204.4529
[2] Dodds, D. et al., 1975, Mon. Not. Roy. Astro. Soc., 171, 569
[3] Strong, A.W. et al., 1978, Mon. Not. Roy. Astro. Soc., 182, 751
[4] Issa, M.R. et al., 1981, J. Phys. G, 7, 565
[5] Bloemen, JBJM et al., 1984, Astron. Astrophys., 135, 12
[6] Ackermann, M. et al., 2012, Astrophys.J., 750:3(35pp)
[7] Erlykin, A.D. and Wolfendale, A.W., 2001, J. Phys. G: Nucl. Part. Phys., 27, 941
[8] Erlykin, A.D. and Wolfendale, A.W., 2002a, J. Phys. G: Nucl. Part. Phys., 28, 359
[9] Abdo, A.A. et al., 2007, Astrophys. J., 658, L33
[10] Abdo, A.A. et al., 2008, Astrophys. J., 688, 1078
[11] Erlykin, A.D. et al., 2003, 28th ICRC, Tsukuba, Japan, 4, 2281
[12] Erlykin, A.D. et al., 2003, Astropart. Phys., 19, 351
[13] Lagutin, A.A. and Uchaikin, V.V., 2001a, Proc. 27th Int.Cosm.Ray Conf., Hamburg, Germany, 5, 1900
[14] Lagutin, A.A. et al., 2001b, Proc. 27th Int.Cosm.Ray Conf., Hamburg, Germany, 5, 1889
[15] Uchaikin, V.V., 2003, Physics Uspekhi, 46, 821
[16] Lagutin, A.A. and Uchaikin, V.V., 2003, Nucl. Instr. Meth. B201, 212
[17] Lagutin, A.A. et al., 2003a, Proc. 29th Int.Cosm.Ray Conf., Pune, India, 3, 197
[18] Lagutin, A.A. et al., 2001c, Proc. 27th Int. Cosm. Ray Conf., Hamburg, Germany, 5, 1896
[19] Lagutin, A.A. et al., 2001d, Nucl. Phys. B (Proc. Suppl.), 97, 267
[20] Lagutin, A.A. et al., 2003b, Proc. 28th Int. Cosm. Ray Conf., Tsukuba, Japan, 2/7, 675
[21] Lagutin, A.A. et al., 2005, Int. J. Mod. Phys., A20, 6834
[22] Bugayov, V.V. et al., 2007, Proc. 30th Int.Cosm. Ray Conf., Merida, Mexico, 2, 527
[23] Yushkov, A.V. et al., 2009, Proc. 31st Int.Cosm. Ray Conf., Lodz, Poland, ID0920
[24] Erlykin, A.D. and Wolfendale, A.W., 2002b, J. Phys. G: Nucl. Part. Phys., 28, 2329
[25] Ackermann, M. et al., 2011, Astrophys. J., 726:81
[26] Porter, T.A. et al., 2011, http://galprop.stanford.edu/workshop2011.php
[27] Chi, X. and Wolfendale, A.W., 1991, J. Phys. G: Nucl. Part. Phys., 17, 987
[28] Ackermann, M. et al., 2012, Astron. Astrophys., A71, 538
[29] Qiang Y. et al., 2011, Proc. 32nd Int. Cosm. Ray Conf., Bejing, China, 6, 21; arXiv:1109.0076
[30] Erlykin, A.D. and Wolfendale, A.W., 2012, Astropart. Phys., 35, 449
[31] Fatemi, S.J. and Wolfendale, A.W., 1996, J. Phys. G: Nucl. Part. Phys., 22, 1089
[32] Beck, R., 2009, Astrophys. Space Sci. Trans., 5, 43
[33] Abergel, A. et al., 2011, Astron. Astrophys., 536, A21
[34] Hunter, S.D. et al., 1997, Astrophys. J., 481, 205
[35] Tomassetti, N., 2012, Astrophys. J. Lett., 752, L13
[36] Wibig, T. and Wolfendale, A.W., 2005, Month. Not. Roy. Astron. Soc., 360, 236