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A possible explanation of the GeV excess

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Abstract. Acceleration of particles at supernova remnant (SNR) shock waves is regarded as the most probable mechanism to produce galactic cosmic rays up to 10^{15} eV. In this picture the galactic cosmic ray hadron component would result from the injection of relativistic particles from many SNRs. The superposition of individual power law source spectra with dispersion in the spectral index value, which is observed in the synchrotron radio spectra of shell SNR, shows a positive curvature in the total spectrum, in particular a hardening at higher energies.

Recent EGRET observations of the diffuse Galactic γ-ray emission reveal a spectrum which is incompatible with the assumption that the cosmic ray spectra measured locally hold throughout the Galaxy: the spectrum above 1 GeV, where the emission is supposedly dominated by π^0-decay, is harder than that derived from the local cosmic ray proton spectrum. We demonstrate that in case of a SNR origin of cosmic ray nucleons part of this γ-ray excess may be attributed to the dispersion of the spectral indices in these objects. In global averages, as are γ-ray line-of-sight integrals, this dispersion leads to a positive curvature in the composite spectrum, and therefore to modified π^0-decay γ-ray spectra.

1 Introduction

The recent detections of non-thermal X-ray synchrotron radiation from the supernova remnants (SNRs) SN1006 (Koyama et al., 1995), RX J1713.7-3946 (Koyama et al., 1997), IC443 (Keohane et al., 1997; Slane et al., 1999), Cas A (Allen G.E. et al., 1997), and RCW86 (Borkowski et al., 2001) and the subsequent detections of SN1006 (Tanimori et al., 1998) and RX J1713.7-3946 (Muraishi et al., 2000) at TeV energies support the hypothesis that at least Galactic cosmic ray electrons are accelerated predominantly in SNR. To date, there is still no unambiguous proof that cosmic ray (CR) nucleons are similarly produced in SNR.

The γ-ray spectrum observed with EGRET below 1 GeV is in accord with, and supports, the assumption that the cosmic ray spectra and the electron-to-proton ratio observed locally are uniform. However, the spectrum above 1 GeV, where the emission is supposedly dominated by π^0-decay, is harder than that derived from the local cosmic ray proton spectrum.

In the following we will demonstrate that in case of a SNR origin of cosmic ray nucleons part of the γ-ray excess may also be attributed to the dispersion of the spectral indices in these objects. In global averages, as are γ-ray line-of-sight integrals, this dispersion leads to a positive curvature in the composite spectrum, and hence to modified π^0-decay γ-ray spectra.

2 The dispersion of cosmic ray spectra in SNR

The synchrotron spectra of shell SNRs show power law behaviour $I_\nu \propto \nu^{-\alpha}$ (Clark and Caswell, 1976; Milne, 1979; Green, 2001) with $<\alpha>\simeq 0.5$, with significant dispersion σ_α in the spectral index. We therefore assume a power law energy distribution for cosmic ray hadrons leaving the SNR, which is modified by the propagation through the Galaxy due to a moment-dependent diffusion coefficient $D \propto p^b$

$$N(p) = N_0 \left(\frac{p}{mc}\right)^{-s} \tag{1}$$

with a spectral index having a mean value $< s >= 1 + b + 2 < \alpha > \simeq 2.7$ and dispersion $\sigma = 2\sigma_\alpha$. This is justified, because the age of the SNRs is much smaller than the characteristic radiative loss times of both cosmic ray nucleons and GeV electrons in the remnant, and because both the particle acceleration processes and the spatial propagation scale with rigidity. So the relativistic hadrons should have the same momentum spectrum as the relativistic electrons. We represent the distribution of hadron spectral indices by the Gaussian

$$n(s) = \frac{1}{\sqrt{2\pi}\sigma}\ \exp\Big[-\frac{(s-<s>)^2}{2\sigma^2}\Big] \tag{2}$$

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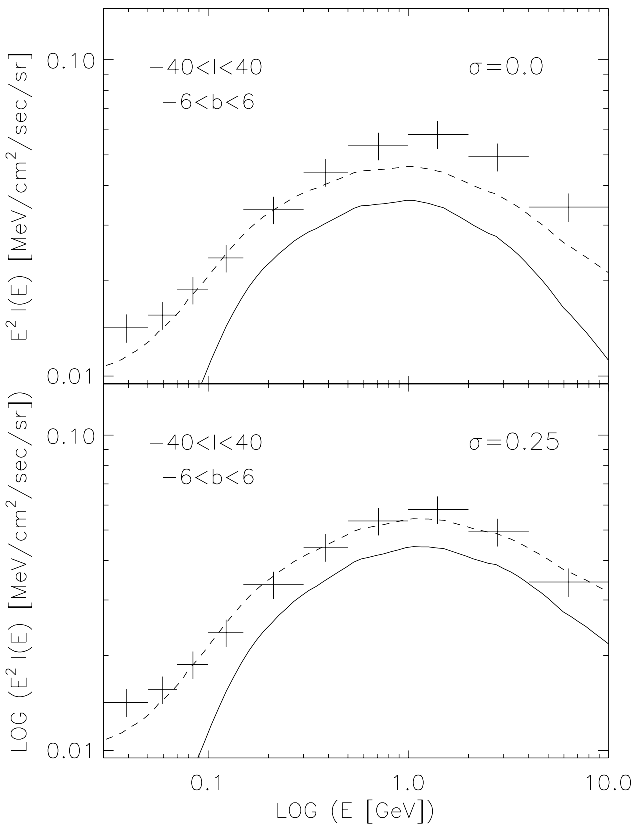

Fig. 1. The observed intensity spectrum from the inner Galaxy shown in comparison with π^0-decay spectra with (bottom panel) and without (top panel) dispersion in the cosmic ray spectrum. The solid lines display the π^0-decay spectra, and the dashed lines are the total γ-ray spectra including the leptonic contribution, which here is simply given as a power law $\propto E^{-2}$ with an intensity determined by the data for $E \leq 100\,\mathrm{MeV}$. Whereas in the top panel, i.e. without dispersion, the GeV excess can be clearly seen, the bottom panel proves that a dispersion with $\sigma = 0.25$ can in fact explain the data and remove the GeV excess.

and obtain from Eq. (1) for the averaged hadron spectrum in the Galaxy

$$\begin{aligned} < N(p) > &= \int_{-\infty}^{\infty} ds\, N(p,s)\, n(s) \\ &= N_0 \left(\frac{p}{mc}\right)^{-<s>+\frac{\sigma^2}{2}\ln\left(\frac{p}{mc}\right)} \end{aligned} \qquad (3)$$

3 Pion decay gamma rays

To compare our model with recent observations of the diffuse Galactic γ-emission, the pion source spectrum is calculated using the cosmic hadron distribution function in Eq. (3) as input for the Monte-Carlo code DTUNUC (V2.2) (Möhring et al., 1991; Ranft et al., 1994; Ferrari et al., 1996; Engel et al., 1997), which is based on a dual parton model (Capella et al. , 1994).

We compare the γ-ray spectra thus derived with the spectra of diffuse γ-ray emission from the inner Galaxy observed by EGRET. The data of all viewing periods of phases 1-4, corresponding to observations between 1991 April and 1995 October are used. We subtract from the observed intensity the extragalactic background (Sreekumar et al., 1998) and the point-spread functions of all sources in the Third EGRET Catalogue (Hartman et al., 1999).

As can be seen in Fig. 1, a dispersion in the index of the cosmic ray source spectra of $\sigma \simeq 0.25$ is sufficient to explain the observed intensity spectrum and remove the GeV excess. We can therefore conclude that, if dispersion is to be made responsible for the GeV excess, it must be at a level of $\sigma \simeq 0.25$.

4 Compatibility with upper limits at higher gamma ray energies

A dispersion in the cosmic ray source spectra – and thus in the cosmic ray flux throughout the Galaxy – has impact also on the resultant γ-ray spectra at higher energies, both for the diffuse emission and for individual SNRs.

To date, observations of TeV γ-ray emission from individual SNR have yielded only a few detections, one of which (Cas A, Aharonian et al. (2001)) is presumably (Atoyan et al., 2000) and the others are clearly caused by leptonic emission. Also, upper limits for the diffuse galactic γ-radiations at 500 TeV have been recently derived by the Whipple-team (LeBohec, 2000).

To investigate the compatibility of our model to this observational facts, we use an analytical approximation for high CR proton energies. We approximate the differential cross-section by the total cross section $\sigma^{\pi}_{\mathrm{pp}} \simeq \sigma_{\mathrm{p,inel}} \simeq 3{\cdot}10^{-26}\,\mathrm{cm}^2$, the multiplicity $\xi \simeq E_p^{1/4}$ (GeV), and a δ-function in energy, centered at the mean pion Lorentz factor $\bar{\gamma}_\pi \simeq \gamma_p^{3/4}$ (Mannheim and Schlickeiser , 1994). The differential cross-section for pion production then is

$$\begin{aligned} \sigma^{\pi^0}(\gamma_\pi, \gamma_p) &\simeq 3 \cdot 10^{-26}\,((\gamma_p - \gamma_{\mathrm{thr}})\,0.938)^{1/4} \\ &\quad \times \delta(\gamma_\pi - \gamma_p^{3/4})\,\frac{\mathrm{cm}^2}{GeV} \end{aligned} \qquad (4)$$

As can be seen in Fig. 2, a dispersion of $\sigma = 0.25$ clearly violates the upper limit at 500 GeV derived by the Whipple team, if hadrons are accelerated in the sources up to $\gamma_{\max} = 10^6$, but the upper limit is clearly satisfied, if $\gamma_{\max} = 10^5$. Therefore, if a spectral dispersion exists at the level required to explain the GeV excess, there must be a high energy cut-off in the cosmic ray source spectra somewhere between $\gamma_{\max} = 10^5$ and $\gamma_{\max} = 10^6$.

5 Discussion

We have calculated the high energy diffuse Galactic γ-ray emission produced by the hadronic component of cosmic rays

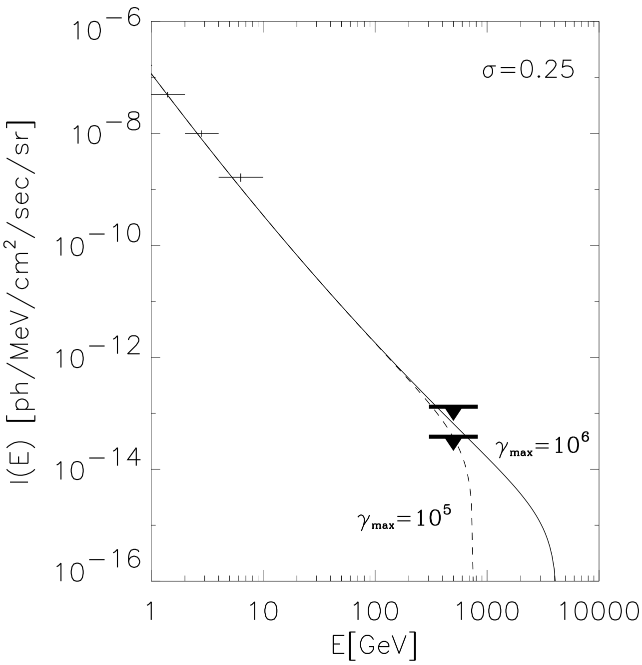

Fig. 2. Composite spectrum between 1 GeV and 1 TeV of the diffuse Galactic γ-ray emission from the Galactic plane at $l \approx 40^o$ based on EGRET and Whipple data. The upper limit at 500 GeV, which is at the 99.9% confidence level, depends on the γ-ray spectrum. The lower mark applies for a γ-ray spectral index $s = 2.0$ whereas the upper mark is appropriate for a spectral index $s = 2.6$. The data are compared with π^0-decay spectra calculated for a cosmic ray spectrum produced by individual sources with mean spectral index $< s >= 2.7$ and dispersion $\sigma = 0.25$. The solid line refers to a high energy cut-off in the cosmic ray proton spectrum at $\gamma_{\max} = 10^6$. It should be compared with the lower mark for the upper limit at 500 GeV, which it clearly and significantly exceeds. For $\gamma_{\max} = 10^5$ the dashed line shows no contradiction with the Whipple data, when compared to the upper mark for the upper limit at 500 GeV.

under the assumption that the interstellar cosmic ray spectrum is a superposition of individual power-law spectra with a dispersion in the spectral index as a result of cosmic ray production in SNR. We have shown that a diffuse γ-ray spectrum thus derived can in fact explain the GeV excess, provided the dispersion in the individual SNR production spectral indices is $\sigma \simeq 0.25$. To comply with data in the TeV energy range both for individual SNR and for the diffuse emission, the existence of a high energy cut-off in the cosmic ray source spectra at proton energies not higher than somewhere between Lorentz factors $\gamma_{\max} = 10^5$ and $\gamma_{\max} = 10^6$ is required.

The hypothesis presented here has a number of consequences for observable quantities which can be used to test the viability of the scenario.

Is this model compatible with the SNR radio synchrotron spectra? A χ^2 analysis of radio spectral indices of shell SNR gives a dispersion justifying the required $\sigma = 0.25$. Taking the radio spectral index data for Galactic shell SNR from Green (2001) and performing a χ^2-test one sees, that this sample of measuremets is inconsistent with an uniform source spectral index of 0.5 (Büsching et al., 2001). Assuming a distribution in the spectral index we get a reduced χ^2 of unity for a dispersion $\sigma_\alpha = 0.10$ and $< \alpha >= 0.53 \pm 0.02$. This analysis indicates that a dispersion in the radio spectral indices of shell SNR exists a a level corresponding to $\sigma_s = 0.2$ which falls marginally short of $\sigma = 0.25$ required to explain the GeV excess. Therefore, given the uncertainties, we conclude that $\sigma = 0.25$ is compatible with the radio synchrotron spectra of SNR.

Why don't we observe a dispersion in the local CR spectrum? Taking the local supernova rate of about $S = 30$ $\mathrm{Myr}^{-1}\,\mathrm{kpc}^{-2}$ and the life time identical to the escape time $\tau \simeq 20\,\gamma^{-0.6}$ Myr, the number of SNR contributing to the local cosmic ray (proton) flux is then $N = \pi\,H^2\,\tau\,S \simeq 17000\,\gamma^{-0.6}$. This means while at a proton energy of 50 GeV some 1600 SNR would contribute, above 100 TeV the number would be down to 17 SNR. In this case the local cosmic ray spectrum could strongly deviate from the average spectrum in Eq. 3. A similar effect affects the cosmic ray electron spectrum at much smaller energies of 100 GeV, which is the basis for the inverse Compton models of the GeV excess (Pohl and Esposito, 1998).

What about deviations from power law behaviour in CR sources? We have found that there must be a cut-off at proton energies not higher than a few hundred TeV. This can be established as a sharp cut-off, or alternatively in the form of a spectral steepening at somewhat smaller energies, which behaviour is predicted in models of non-linear shock acceleration (e.g. Baring et al. (1999)). As a result the average spectrum at higher energies would be softer. This would not change the expected GeV γ-ray spectrum, but the local cosmic ray proton spectrum above 10 TeV, which is observed to be slightly softer than that obtained by direct measurements at lower energies (Asakimori et al., 1998; Amenomori et al., 2000). All in all the lack of dispersion in the local cosmic ray proton spectrum does not seem to contradict the hypothesis presented in this paper.

Is the high energy limit in the cosmic ray proton source spectra compatible with the observed all-particle spectra near the "Knee"? We have not investigated the composition and in particular not studied the possibility of different source spectra for different species. This issue remains for further investigations.

Since there is observational evidence for a dispersion in the spectral indices of the cosmic ray spectra in SNR, the composite cosmic ray spectrum must be curved, if the cosmic rays are predominantly produced in SNR. We have shown that if the dispersion is as strong as $\sigma = 0.25$, its effect on the interstellar cosmic ray spectrum would explain the GeV excess in the diffuse Galactic γ-ray spectrum. If the actual dispersion is weaker than this, it would still contribute to the GeV excess and therefore should not be neglected. There are other viable models for the GeV excess and it may well be that it is a combined effect of the spectral dispersion and, e.g., a hard inverse Compton spectrum (Pohl and Esposito, 1998).

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