SOURCES OF COSMIC RAYS AND GALACTIC DIFFUSE GAMMA RADIATION

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ABSTRACT

The diffuse galactic gamma-ray spectrum measured by the EGRET experiment [Hunter et al. 1997] are interpreted within a scenario in which cosmic rays (CRs) are injected by three different kind of sources, (i) supernovae (SN) which explode into the interstellar medium (ISM), (ii) Red Supergiants (RSG), and (iii) Wolf-Rayet stars (WR), where the two latter explode into their pre-SN winds [Biermann et al. 2001; Sina et al. 2001].

Key words: cosmic ray sources; gamma-rays; diffuse; galactic.

1. INTRODUCTION

Conventional models of diffuse galactic gamma-ray production are based on three main processes. Gamma-rays are produced through the decay of π⁰ as secondary particles of hadronic collisions of CRs with the ISM, such as proton-hydrogen or proton-helium collisions, in bremsstrahlung processes of CR electrons with the ISM, and through inverse Compton scattering of CR electrons with interstellar radiation fields. These models can explain a wide range of observations like the energy spectra below ≈1 GeV or the integrated flux from the outer parts of our Galaxy. Nonetheless the diffuse galactic gamma-rays observed by the EGRET experiment from the inner Galaxy above ≈1 GeV exceeds by about 60% the intensity predicted by these calculations (the measured spectrum is too hard).

In this contribution we shall present first results on the diffuse gamma-ray production expected in the model by [Biermann et al. 2001]. In this model, in addition to the aforementioned processes, interactions of hadrons of the relatively hard CR injection spectrum (see Tab. 1) with the pre-SN winds are considered as further possible sources of diffuse galactic gamma-rays [Biermann et al. 2001].

Table 1. Interaction spectra for the different type of supernovae. \( E_{\text{knee}} \) and \( E_{\text{cut-off}} \) are in GeV. \( \gamma_1 \) and \( \gamma_2 \) are the spectral indices (\( \Phi = \Phi_0 E^{\gamma} \)) below and above \( E_{\text{knee}} \). \( Z \) is the charge of the nucleus.

| SN type | \( E_{\text{knee}} \) (GeV) | \( E_{\text{cut-off}} \) (GeV) | \( \gamma_1 \) | \( \gamma_2 \) |
|---------|-----------------|-----------------|-----------|-----------|
| ISM     | 3 \( Z 10^3 \)  | 2 \( Z 10^5 \)  | -2.75     | -2.33     |
| RSG     | 3 \( Z 10^3 \)  | 2 \( Z 10^5 \)  | -2.75     | -2.33     |
| WR      | 2 \( Z 10^8 \)  | 2 \( Z 10^8 \)  | -2.88     | -3.21     |

Figure 1. The log of the mean energy of the CR particles versus the number of shock crossings for \( V_{sh} = 0.01c \). Starting from the bottom for \( 5^\circ, 25^\circ, 65^\circ, 80^\circ \) and \( 85^\circ \) respectively. We see the difference in the energy gain of CR particles for the almost perpendicular case compared to smaller shock inclinations. An effect that [Jokipii 1987] pointed out as well.
introduce all necessary input parameters. In section 4 and 5, we present our results, compared to EGRET, CASA-MIA and KASCADE data. In section 6, we summarize our findings and discuss some further improvements in our models.

2. SOURCES OF COSMIC RAYS

Jokipii (1985) investigated the rate of the energy gain and the maximum energy in non-relativistic shocks, which can be attained in given conditions, such as the effect of a highly oblique magnetic field to the scattering of the CR particles. Briefly, he showed that if the perpendicular diffusion ($k_\perp$) is much smaller than the parallel one ($k_\parallel$), CR particles can gain considerable energy in quasi-perpendicular shocks compared to quasi-parallel ones.

We have constructed a Monte Carlo code in order to simulate non-relativistic near parallel and oblique shocks with $0^\circ \lesssim \psi \lesssim 90^\circ$ where $\psi$ is the angle between the shock normal and the magnetic field, seen in the shock frame. The velocities of the upstream plasma flow are kept between 0.001$c$ and 0.01$c$, which correspond to astrophysical environments with non-relativistic shocks such as in WR winds, RSG winds, etc. In order to investigate the behavior of the particle scattering, between the quasi-parallel and oblique shock configurations, a cross-field diffusion is also allowed. Briefly, our Monte Carlo simulations in comparison to the Jokipii’s theoretical work show the same trend (see Fig. 1). Furthermore, for realistic environments, such as RSG and WR stars, our calculations suggest that WR winds could provide large enough radii for protons to reach enough energy in the available time and space, and we claim that the maximum energy (for $Z=1$) reached could be $\sim 10^{17}$ eV, in about $10^{10}$ sec ($\sim 10^4$ yrs), which corresponds to $10^{19}$ cm ($\approx 10$ pc). On the other hand in RSG winds we may find the conditions (smaller radii and corresponding time) where the maximum energy could be about $3 \times 10^{14}$ eV. There is further work under way which calculates the real time versus energy, attainable in highly oblique non-relativistic shocks found in WR and RSG stars and investigates in detail the constraints put in these models, following ‘limits’ that may apply (e.g. $k > r_{sh} V_{sh}$) (Meli & Biermann 2004).

3. MODELS FOR GAMMA-RAY PRODUCTION

The gamma-ray spectrum is computed using a three-dimensional spatial distribution of matter and radiation fields in our Galaxy. In this model the ISM is composed of atomic ($\approx 1 \times 10^6 M_\odot$), molecular ($\approx 3 \times 10^5 M_\odot$) and ionized hydrogen ($\approx 10^8 M_\odot$) as well as 10% He. Its spatial distribution is taken from Launhardt et al. (2002); Kalberla et al. (1998). A logarithmic spiral arm model based on COBE/DIRBE data is also incorporated (see Fig. 2) (Drimmel & Spergel 2001). The interstellar photon densities of interest have been approximated by three diluted blackbody spectra from the interstellar radiation field (ISRF) plus the 2.7K microwave background (CMB) (Bloemen 1983).

CR spectra and their spatial distributions are another input for the calculations. We assume CR protons and electrons to be radially distributed with a radial exponential scale height $h_{CR}$ are 0.5 kpc for protons and 2 kpc for electrons (Bloemen 1985; 1989). The spectral indices are approximated by constants throughout the Galaxy and the normalization of the flux is taken from the review of Wiebel-Sooth et al. (1998).

The number of gamma-rays from a certain direction $(i, b)$ with an energy $E_\gamma$ per unit of time can then be

![Figure 2. Model of the ISM density based on COBE/DIRBE data (Drimmel & Spergel 2001). The logarithmic spiral structure is superimposed on a purely radial distribution of molecular and ionized hydrogen (Launhardt et al. 2003; Kalberla et al. 1998).](image)

![Figure 3. Gamma-ray production spectra, see Eq. (1). The spectra are shown in units of photons per atom, or cm$^{-3}$ in the case of inverse Compton.](image)
calculated using
\[
\frac{dn_\gamma(E_\gamma,l,b)}{dtdE_\gamma d\Omega} = \int dL(l,b) \int dE_k \Phi_k(E_k,r,l,b) \sigma_i(E_k,E_\gamma)n_T(r,l,b)
\]
where \(\int dL(l,b)\) is the line-of-sight integral along the direction \((l,b)\), \(E_k\) and \(\Phi_k(E_k,r,l,b)\) are energy and flux at position \((r,l,b)\) of the CR particles of type \(k\), \(\sigma_i(E_k,E_\gamma)\) is the cross section of the gamma-ray production process \(i\), and \(n_T(r,l,b)\) is the density of target particles of type \(T\) (either components of the ISM, photons of a radiation fields or particles of a SN-wind). In the case of IC it is also necessary to integrate over the energy distribution of the photon gas \(\epsilon\). If we use the assumed independence of CR energy spectra from the position in our galaxy
\[
\Phi_k(E_k,r,l,b) = \Phi_k^E(E_k) \cdot \Phi_k^N(r,l,b),
\]
the integral can get factorized into one integral over energy and one over the line-of-sight:
\[
\frac{dn_\gamma(E_\gamma,l,b)}{dtdE_\gamma d\Omega} = I_E(E_\gamma) \cdot I_L(b,l),
\]
with
\[
I_E(E_\gamma) = \int dE_k \Phi_k^E(E_k) \sigma_i(E_k,E_\gamma)
\]
and
\[
I_L(b,l) = \int dLn_T(r,l,b) \Phi_k^N(r,l,b).
\]

The cross sections \(\sigma_i\) for Bremsstrahlung and inverse Compton effect have been numerically computed using the formulae given by Blumenthal & Gould (1970). For nuclear reactions they have been simulated with DPMJET3 (Roesler et al. 2001). The independent solution for \(I_E\) and \(I_L\) are shown in Fig. 3 and Fig. 4.

4. SPECTRAL ANALYSIS OF THE GAMMA-RAY EMISSION

The emission from the inner Galaxy and from the outer Galaxy, predicted by our model calculations, are shown in Fig. 4 (A) and (B), respectively, where the predicted spectra are compared to EGRET (Hunter et al. 1997), Whipple (LeBohec et al. 2000), CASA-MIA (Borione et al. 1998) and KASCADE (Schatz et al. 2003) data. The contributions to the gamma-ray spectrum from the three kind of supernovae, from Bremsstrahlung and from inverse Compton scattering, as well as their sum, are explicitly indicated. The contribution to the diffuse gamma emission due to the collisions of CR protons with protons and helium in the interstellar medium explains the spectrum above 0.1 GeV and below 1 GeV. Around 1 GeV the observed flux of diffuse galactic gamma-rays stems mainly from interactions of CRs injected by both ISM and RSG supernovae. Above 1 GeV it is produced essentially by interactions of protons injected by exploding RSG with the protons in the local strong and enriched winds. Finally we remark that a change in the spectral index of the gamma-ray emission is evident from Fig. 5 (A) at photon energy above 1 GeV. Within our model the change in the gamma-ray spectral index arises naturally from the assumption that the two different regimes in the gamma-ray emission, corresponding to gamma-rays emitted by different supernovae types.
5. DIRECTIONAL ANALYSIS OF THE INTEGRATED FLUX

The predicted longitude intensity distributions of diffuse galactic gamma radiation are shown in Fig. 6. As can be seen in Fig. 6 (a) the used 3D models for ISM, photons and CR particles could be further optimized to reproduce the EGRET data even better in this energy range. More importantly, it is apparent (Fig. 6 (b)-(d)) that for higher energies the flux coming from the Galactic center is getting more and more underestimated while the flux from the antiparticle center stays relatively well reproduced. The discrepancy between the calculation and the EGRET data supports the picture of an additional contribution from CR sources (SN) that are much more abundant in the inner Galaxy than in the outer.

6. DISCUSSION AND OUTLOOK

The presented model is very promising in explaining the measured diffuse gamma-ray flux. Also it seems to be capable to reproduce the C/B ratio as well as the antiproton flux (Sina et al. 2001). It is quite a plausible scenario in which the CR interact mostly in the environment close to their sources. Some stars, like RSG or WR, provide sufficient material, ejected as powerful winds at the end of their lives, before they explode as supernovae. This wind material provides most of the grammage crossed by CR particles seen at Earth. We expect the data in the TeV range from MAGIC and HESS experiments to allow further insight or put constraints on the present model. More detailed studies are planned to calculate the various predictions of the model by Biermann et al. (2001) and improve the 3D of the interstellar matter, cosmic ray, and radiation field distributions.

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