Diffuse Galactic Gamma Rays at Intermediate and High Latitudes, Constraints on the ISM Properties

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DESY September 29, 2011 The diffuse Galactic $\gamma\text{-rays}$ are produced by

• Decay of π^0 's produced by inelastic interactions of cosmic ray (CR) proton and helium with interstellar gas (ISG)

• Bremsstrahlung of CR e^{\pm} in the ISG

• Inverse Compton scattering (ICS) of CR e^{\pm} of interstellar radiation field (ISRF)

Dark matter (?) annihilation/decay

The diffuse γ -ray emission can be used to probe and constrain the properties of CR propagation, CR sources, ISG and ISRF.

It may have implications on indirect DM detection.

We use high latitude ($|b| > 10^{\circ}$) diffuse γ -ray spectrum at energies between $100 \ MeV$ and $100 \ GeV$ measured by Fermi space telescope.

CR Propagation

The propagation of CRs in the Galaxy is described by:

$$\frac{\partial \psi(\vec{r}, p, t)}{\partial t} = q(\vec{r}, p, t) + \vec{\nabla} \cdot (D_{xx} \vec{\nabla} \psi) + \frac{\partial}{\partial p} \Big[p^2 D_{pp} \frac{\partial}{\partial p} (\frac{\psi}{p^2}) \Big] \\ - \frac{\partial}{\partial p} (\dot{p} \psi) - \vec{\nabla} \cdot (\vec{V} \psi) + \frac{\partial}{\partial p} \Big[\frac{p}{3} (\vec{\nabla} \cdot \vec{V}) \psi \Big] \\ - \frac{\psi}{\tau_{frag}} - \frac{\psi}{\tau_{decay}}$$

We use the publicly available DRAGON code to numerically solve the propagation equation in the steady state approximation.

Primary Sources of CRs

Supernova Remnants:

CR primary sources up to energies of \sim 100TeV, are mainly supernova remnants (SNRs).

$$q_i(r, z, E) = q_{0,i}f_s(r, z)(\frac{R(E)}{R_0})^{-\gamma^i}$$

 $f_s(r, z)$ traces the spatial distribution of SNRs. [Ferriere (2001)]

Pulsars:

Electrons and positrons accelerated between a pulsar and the termination shock of the wind nebula, may also contribute to the high energy e^{\pm} spectrum.

$$Q_p(r,z,t,E) = J_0 f_p(r,z) E^{-n} e^{-E/M}$$

 $f_p(r, z)$: Spatial distribution of middle aged pulsars in the Galaxy [Giugere & Kaspi (2006)]

Diffusion and Magnetic Fields

The scattering of CRs on randomly moving magneto-hydro-dynamic (MHD) waves leads to diffusion in physical and momentum space.

The large scale Galactic magnetic field is generally assumed to be a bi-symmetrical spiral with small pitch angle.

We assume a purely azimuthal regular magnetic field with the form:

$$B_0 = B_h \exp\left(-\frac{r - r_{\odot}}{r_h}\right) \exp\left(-\frac{|z|}{z_h}\right)$$

Phenomenologically, the weaker magnetic field, the stronger spatial diffusion.

$$D(r, z, R) = D_0 \beta^{\eta} \left(\frac{R}{R_0}\right)^{\delta} \exp\left(\frac{r - r_{\odot}}{r_d}\right) \exp\left(\frac{|z|}{z_d}\right)$$
$$D_{pp} \propto \frac{p^2 v_A^2}{D_{xx}}$$

Methodology



The injection spectral index of protons, γ^p , is fitted to the PAMELA and CREAM data.

Proton flux has a broken power-law.

For the set of values of (δ, z_d, r_d) we derive the other propagation parameters (D_0, η, v_A) by minimizing the χ^2 of B/C data.



Methodology



We fit the electron spectral index, γ^e , to the low energy $e^- + e^+$ spectrum.

The averaged properties of pulsars are determined by high energy spectrum.

The predicted anti proton flux is consistent with local data.



Diffuse Galactic Gamma Rays

The Reference model :

 $\delta = 0.5$

$$z_d = 4 \ kpc$$
 $r_d = 20 \ kpc$

A good combined fit to the local CR data and diffuse γ -ray.





Constraining the Diffusion Properties

Different diffusion spectral indices:

 $\delta = 0.5(Kraichnan), \quad \delta = 0.4, \quad \delta = 0.33(Kolmogorov)$ 10^{-2} 10^{-2} = 1.11RUN4-20 = 0.51RUN4-20 1.33 K0I4-20 KOL4-20 $E^{2}dN/dE$ (MeV cm⁻²s⁻¹sr⁻¹) $E^{2}dN/dE$ (MeV cm⁻²s⁻¹sr⁻¹) ||||||∎|||⊔ 0<l<360, 10<|b|<20 0<1<360, 60<1b1<90 10⁻³ 10⁻³ 10^{-4} 10^{-4} Fermi-LAT Fermi-LA7 Total Total EGB Point Sources Point Sources Fotal Model Total Model Pion decav Pion decay Inverse Compton Inverse Compton Bremsstrahlung Bremsstrahlung 10^{-5} 10^{-5} 0.1 100.0 1.0 10.0 0.1 1.0 10.0 100.0 E (GeV) E (GeV)

• The bigger δ , the faster diffusion, the greater ICS at very high energies. • Different v_A `s, different Bremsstrahlung emissions at low energies.

Including anti-protons data Kraichnan model is slightly prefered.

Constraining the Diffusion Properties



Different radial scales:

 $r_d = 5, 10, 20 \ kpc$

The differences are too small.

Different scale heights: $z_d = 1, 4, 10 \ kpc$

The thicker diffusion zone, the less confined CR distribution, the greater flux.

Convection

Galactic winds produce the convective transport of CRs outward the Galactic disk as well as adiabatic energy losses.

 $v_C = 50.z \ km/s$

A strong convective wind in the Galaxy is not favoured by $\gamma\text{-ray}$ data in the lower latitudes.



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Rigidity Break in Injection or Diffusion

PAMELA has observed a break at $R\,{\sim}\,230$ GV in p and He spectra.



Scenario A: break in injection index γ^p

• SNRs studies [Caprioli]

 diffusive shock acceleration semianalytical calculations [Amato,Blasi,Volk, Malkov]

 the emergence of a population of SNRs with a harder injection index

Scenario B: break in diffusion index δ

transition from Kraichnan type
turbulence at low R to Kolmogorov
type at high R

Rigidity Break in Injection or Diffusion

The maximal difference between scenarios A and B, is up to O(0.1) in both ICS and π^0 spectra, but of opposite sign.

It results in a difference less than $O(10^{-2})$ in the total diffuse γ spectra in all three regions of interest.



Interstellar Gas

Hydrogen: observed in three states

- Atomic (HI) [Nakanishi & Sofue (2003)]
- Molecular (H2) [Nakanishi & Sofue (2006)]
- Ionized (HII)

Helium: follows the hydrogen distribution with a factor $He/H \sim 0.11$



H2 distribution in Galaxy has large uncertainties.

Different Gas Distributions



For each gas model we fit the propagation parameters to CR spectra.

The greater gas density, the larger number of targets, the more π^0 and Bremsstrahlung emissions.

A combined analysis of CRs and diffuse γ -rays can be used to constrain the large scale gas distributions.

Summary I

The study of non spatially uniform diffusion in the Galaxy suggests
a weak dependence on radial variation of spatial diffusion
a slight preference for thicker diffusion zones

AMS-02 measurments of the local flux of radioactive isotopes will constrain the thickness of the diffusion region.

It breaks the degeneracy between thicker regions of emissivity populated by CRs diffusing out of the Galactic disk and contribution of exotic sources such as DM.

 \checkmark Thanks to the diffuse γ -ray spectra and combining them with CR data we can discriminate and even constrain ISG profiles.

Summary II

 \checkmark CR and γ -ray data do not constrain strongly the diffusion spectral index within the range we have considered.

 \checkmark To interpret the rigidity break in p and He spectra, we have discussed the possibilities of break in the injection or diffusion indices. Diffuse γ -ray emission can not be used to discriminate them.

A better understanding of the contributions of the astrophysical components to the diffuse γ -rays may be applied to place limits on a possible exotic contribution to the diffuse γ -ray flux. (work in prep)