Astrophysical Journal, **610**, 868-875 (2004) / astro-ph/0403138

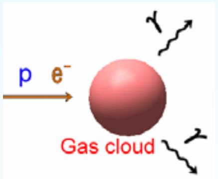
Gamma-Ray Spectra due to Cosmic-Ray Interactions with Dense Gas Clouds

Michiko Ohishi[1], Masaki Mori[1], and Mark Walker[2]
[1] Institute for Cosmic Ray Research, University of Tokyo, Japan
[2] School of Physics, University of Sydney and ATNF/CSIRO, Australia

Motivation

- Self-gravitating, cold, dense molecular hydrogen gas clouds—a possible form of baryonic dark matter (Ex. Walker and Wardle 1998, ApJ, 498 L125)
- Some Observational evidence
  - Can explain ESE (extreme scattering events) in the radio observation
- Dense gas irradiated by high-energy cosmic rays produce gamma-rays—could be a part of galactic diffuse gamma-ray emission
- Lack of detailed calculation of gamma-ray production from inter-action in dense gas

⇒ Monte-Carlo calculation of interaction process using modern high-energy simulator—GEANT4 (Ver. 4.5.1)

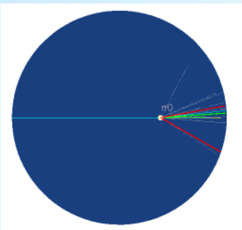


R~1AU
M~$10^{-4}M_{solar}$
T~10K

Gamma-ray production in dense matter

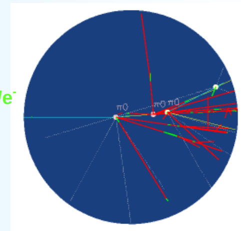
Examples of 10 GeV proton injection

In thin matter



Red : γ
Green : e^+/e^-

In dense matter



- Almost all gamma-rays are π^0 decay origin.
  $p+p \rightarrow \pi^0(\rightarrow 2\gamma)+X$
- Generated gamma-rays can easily escape the cloud.

- In addition to π^0 decay, Brems-strahlung by secondary electrons becomes major component, especially in the lower energy range.
- Generated gamma-rays also suffer from secondary interaction (and absorption) with matter.

Simulation model

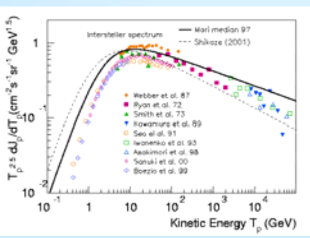
Gas sphere

Radius 1AU, molecular hydrogen, uniform
Mean column density $\Sigma = 2R\rho\langle\cos\theta\rangle = \frac{4}{3}R\rho$

with $\Sigma = 10^{-2}, 10^{-1}, \ldots, 10^{5}$ g/cm^2

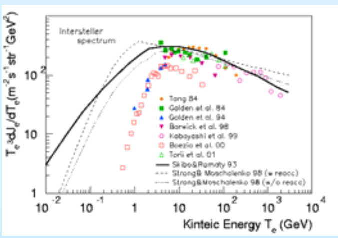
Injection cosmic-ray spectra

Protons



(Mori 1997, ApJ 478, 225)

Electrons

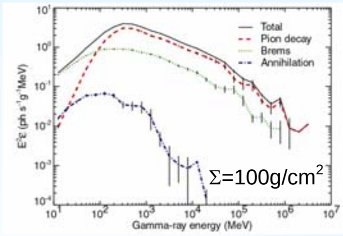


(Skibo&Ramaty 1993, AA Suppl. 97, 145)

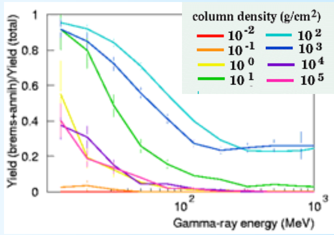
Results of simulation

Gamma-ray emissivity: $\varepsilon \equiv \frac{4\pi}{\Sigma} J_{CR}^{solar} \frac{dN_\gamma}{dE}$

Contributions of the three emission processes: pion decay, bremsstrahlung, annihilation



Proportion of the non-π^0 origin gamma-rays

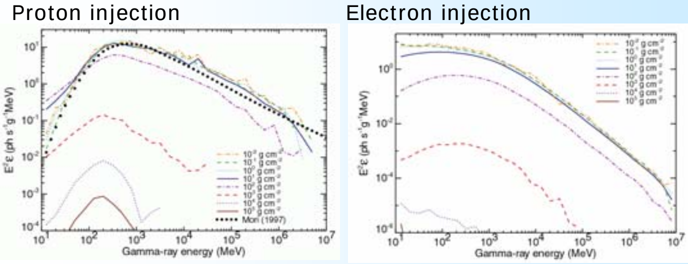


- Electron Brems component becomes dominant below 100 MeV for column density ~100g/cm^2.
- Contribution of Brems+annihilation get its maximum at Σ(column density)=100-1000g/cm^2.

Emissivity versus column density

Proton injection

Electron injection



As thin matter limit these calculations are consistent with one-interaction calculations (Mori 1997, ibid.)

Calculation of diffuse gamma-rays

Flux of diffuse gamma-rays from gas clouds

$$I_D = \frac{1}{\Sigma}\int_0^\infty ds\, \rho(s) J_{CR}(s) \frac{dN_\gamma}{dE} = \frac{1}{4\pi}\varepsilon Q, \quad Q \equiv \int_0^\infty ds\, \rho(s)\frac{J_{CR}(s)}{J_{CR}^{solar}}$$

Gas cloud distribution (Walker 1999, MNRAS 308, 551)

$$\rho(R,z) = \frac{\sigma^2}{2\pi G(R^2+z^2+r_c^2)}, \quad r_c = 6.2\text{kpc}, \sigma = 155\text{km/s}$$

Cosmic ray model (Webber et al. 1992 ApJ 390, 96)

$$\frac{J_{CR}(R,z)}{J_{CR}^{solar}} = \left(\frac{R}{R_0}\right)^2 \exp\left[\frac{R_0-R}{L} - \frac{|z|}{h}\right] \quad (R_0, L, h) = (8.5, 7, 1.5)\ \text{kpc}, \quad J_{CR}^{solar} = J_{CR}(R_0, 0)$$

Discussion

Comparison with EGRET data

- High Galactic latitudes (Kniffen et al. 1996, A&AS 120, 615)
  Observed I~1.5×10^{-5} ph/(cm^{2}s sr)
  → Unmodeled emission <6×10^{-6} ph/(cm^{2}s sr)
  → Low Σ gas: ≤ 20% of the total Galactic dark halo
  (~100% for Σ ≥ 200g/cm^2)
- Low Galactic latitudes (Hunter et al. 1997, ApJ 481, 205)
  Observed I~3×10^{-8} ph/(cm^{2}s sr MeV) at 1GeV (|ℓ|≤60°, |b|≤10°)
  → Galactic dark halo must be ε ≤ 4.6×10^{-6} ph/(s g MeV)
  with <Q>=3.28×10^{-2} g/cm^2
  → Low Σ gas: ≤ 30% of the total Galactic dark halo
  → Galactic dark halo to be made of dense gas, Σ ≥ 100g/cm^2

Summary

- Gamma-ray emissivity of dense gas declines substantially for E ≥ 100MeV photons for Σ ≥ 100g/cm^2.
- EGRET data do not exclude purely baryonic models for the Galactic dark halo for Σ ≥ 200g/cm^2 !