Galactic Diffuse Gamma-ray Emission, the EGRET Model, and GLAST Science

Stanley D. Hunter
NASA/GSFC Code 661
sdh@gamma.gsfc.nasa.gov
The Galactic Diffuse Gamma-ray Emission

... the dominant feature of the gamma-ray sky and a probe of the *Galactic ISM* and the *CR distributions*
EGRET/GLAST Diffuse Emission Model

• Relation to the EGRET/GLAST Science:
  – Study the physical structure of the interstellar medium (ISM) in the Milky Way and the distribution of matter and CRs that pervade it
  – ‘Background’ model for point source analyses

• EGRET model - Calculation from first principles
  – Two components
    Galactic Diffuse, $|b| < 10^\circ$ + Isotropic Diffuse model, $|b| > 10^\circ$
  – Model used for all EGRET Source Catalogs
    (e.g. Hartman, 1999, ApJS, 123, 79)
  – Common CR distribution, emission discontinuous at $|b| = 10^\circ$
    • ‘Eliminated’ by PSF convolution
  – GALDIF model extended to all-sky for GLAST model
    • GLAST 2\textsuperscript{nd} Data Challenge - Feb. 2005
EGRET/GLAST Diffuse Emission Model

• Inputs to model:
  – Gamma-ray production processes in the ISM
    • Pion production, Bremsstrahlung, inverse Compton scattering
  – Tracers of the ISM (matter and radiation)
    + Galactic rotation curve → 3-D ISM distribution
      • HI (21 cm), H₂ (115 GHz CO), HII (pulsar dispersion), low-energy photon density
  – Physical parameters:
    • N(HI)/W_{HI} conversion factor, CR spectrum, e/p ratio, interaction cross-sections, Galactic rotation curve, etc.
  – Model assumptions:
    • Assume the CRs are in dynamic balance with ISM
  • There are only two adjustable parameters in this calculation!
    – Molecular mass ratio, X=N(H₂)/W_{CO}, CR coupling scale
  • Discrepancies between model and observation are directly interpretable in terms of model inputs and parameters.
Composition of the ISM - Matter & Radiation

• Interstellar Clouds $0.011M_\odot/pc^3$, ~90% of ISM
  – Bright Nebulae, e.g. Orion (M42)
  – HI 8 H-atoms/cm$^3$, 0.01 elec/cm$^3$
  – All other elements
  – Dark Nebulae, e.g. Ophiuchus
  – $H_2$ 1 H-mol/cm$^3$
  – HII ~8 elec/cm$^3$

• Interstellar Gas
  – Mean density between clouds 0.1 H-atoms/cm$^3$, 0.035 elec/cm$^3$

• Interstellar Grains $0.0015 M_\odot/pc^3$, ~10% of ISM
  – Number density $0.5 \times 10^{-12}$ cm$^{-3}$
  – Mass density ~1g/cm$^3$

• Stellar radiation $7 \times 10^{-13}$ erg/cm$^3$
  – CMB (2.7 °K) $4 \times 10^{-13}$ erg/cm$^3$
  • Turbulent gas motion $5 \times 10^{-13}$ erg/cm$^3$
  • Cosmic rays $16 \times 10^{-13}$ erg/cm$^3$
  • Magnetic field $15 \times 10^{-13}$ erg/cm$^3$

• Should this list also include dark matter?
Cosmic Rays and Matter - Dynamic Balance

• Cosmic rays are Galactic, not universal (Sreekumar et al. 1992; 1993)
• The cosmic ray and magnetic fields are in a quasi-stationary state, *dynamic balance* (Parker 1969)
  – The CR pressure may not exceed the magnetic field pressure (Parker 1968) and appears to be close to the maximum
• The Galactic magnetic field is confined to the disk by the weight of the interstellar gas
• CRs (at least < 10^{16-17} eV per nucleon) are bound to the lines of force and the lines of force are normally closed
• CR age, based on isotopic abundance, is slightly more than 10^7 years
  – Consistent with secondary abundance and Galactic matter density
  – Slow diffusion rate in magnetic field and small anisotropy
• ⇒ Energy density of the cosmic rays is larger where the matter density is larger on some coarse scale - *Dynamic Balance*
• Unanswered questions:
  – *What is the CR/matter coupling scale? What is the vertical scale height?*
CR Distribution from Dynamic Balance

- Derive 3-D distributions of HI, H₂, and HII
- Determine Galactic mater surface density, normalize total Solar density to unity,
  \[ c_e = c_n = c(l,\rho) \]
- CR density at \( l,\rho \) is then Solar CR density \( \times c(l,\rho) \)
- The diffuse emission is \( \propto (\text{Matter density})^2 \)
- CR scale height assumed to be large compared to matter scale height
The Galactic Diffuse Emission

Straight forward integral over the line-of-sight:

$$j(E_\gamma, l, b) = \frac{1}{4\pi} \int (c_e \cdot q_{eb} + c_n \cdot q_{mn}) \times (n_{H\text{I}} + n_{H\text{II}} + n_{H\text{I}\text{I}}) \, d\rho +$$

$$\frac{1}{4\pi} \sum_i \int c_e \cdot q_{ic,i} \cdot u_{ic,i} \, d\rho$$

[ph cm$^{-2}$ s$^{-1}$ sr$^{-1}$ GeV$^{-1}$]

Gamma-ray production functions
electron bremsstrahlung, nucleon-nucleon ($\pi^0$), and inverse Compton
Synchrotron emission is not significant

Galactic cosmic-ray distribution of electrons and nucleons (+ He, heavies)

Galactic matter distribution of atomic, molecular, and ionized hydrogen

Low-energy photon energy density
cosmic microwave background, infra-red, visible, and ultraviolet

The hard part: determining the 3-D matter, ISR, and CR distributions.
Comparison with EGRET Observation - 1
Comparison with EGRET Observation - 2

EGRET data from Phases I+II
Source subtraction by J. Cattelli, 1995
Galactic Pole Emission

North Galactic Pole

\[
\frac{(1.18 \pm 0.33)}{\sin(\theta)} + 0.90 \pm 0.43
\]

South Galactic Pole

\[
\frac{(1.65 \pm 0.33)}{\sin(\theta)} + 0.07 \pm 0.43
\]

Extra-galactic diffuse
Conclusions

• Some adjustments still needed:
  – CR electron scale height or low-e photon density too low
  – Extension of emission above ± 30º to ± 90º

• GALDIF, all-sky calculation provides an accurate, easy to use model of the Galactic Diffuse Emission
  – Discrepancies are directly interpretable in terms of calculation inputs and assumptions

• *Preliminary FITS files are available now!*