Inverse Compton scattering on stellar photons (heliospheric modulation, and neutrino astrophysics)

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Diffuse γ-ray Emission

**Galactic:** CR interactions in ISM ($\pi^0$, brem) and with ISRF (IC) - interesting

**Extragalactic (EGRB):** unresolved sources, true diffuse emission (DM?) - very interesting

After extracting foregrounds can get at 'background'

**Galactic:** GalProp + other approaches

What about other 'celestial' sources?

Today's talk
Outline

• Inverse Compton scattering in Galaxy

• Study of 'local' heliosphere
  - Foreground for EGRB
  - Using GLAST as a solar modulation probe
  - Implications for other studies (gammas and neutrinos from Sun, etc.)

• Other stars
  - Electron spectrum in ISM?
Inverse Compton Scattering

Most familiar: diffuse Galactic emission
Large scale Galactic ISRF + CR electron distribution

Inverse Compton scattering

High energy e- initially e- loses energy

\[ \gamma' > \gamma \]
In Inverse Compton Scattering Continued,

Solar photons stream outward from Sun - anisotropic

CR electrons distributed throughout heliosphere - isotropic

`Close' to stars, local radiation field dominant

Star nearby called the 'Sun'
**Anisotropic ICS**

**Intensity:**

\[
\frac{dF_\gamma}{d\varepsilon_2} = \frac{1}{4} \int_L dx \frac{R_\odot^2}{r^2} \int d\gamma_e \frac{dJ_e(r, \gamma_e)}{d\gamma_e} \times \int d\varepsilon_1 \frac{dn_{bb}(\varepsilon_1, T_\odot)}{d\varepsilon_1} \frac{dR(\gamma_e, \varepsilon_1)}{d\varepsilon_2}
\]

\[E_\gamma/m_e c^2 = \varepsilon_2, \quad \varepsilon_\nu/m_e c^2 = \varepsilon_1\]

Target photons distributed radially outward from Sun:

\[\rho \sim n_{bb}(R_{Sun}/r)^2\]

\[T_{Sun} \sim 6000 K \text{ BB}\]

**Following collision:**

\[E_\gamma \sim (1/\gamma_e) \gamma_e \varepsilon_\nu \sim \varepsilon_\nu\]

**Head-on collision:**

\[E_\gamma \sim \gamma_e^2 \varepsilon_\nu\]

10 GeV Electrons \sim 100 MeV gammas
GLAST LAT Project

Interplanetary B-field and Solar Wind
Solar modulation refers to the influence the Sun exerts upon the intensity of galactic cosmic rays. As solar activity rises (top panel), the count rate recorded by a neutron monitor in McMurdo Antarctica decreases (bottom panel).

**Force-field approximation (Voyager & Pioneer data):**

\[
\Phi(r, t) = \int_r^{r_b(t)} dx \frac{V(x, t)}{3K_1(x, t)} \begin{cases} 
\kappa_1 \propto r^3, \text{ and } V = \text{const}, \\
\Phi(r, t) \propto r^{-\delta+1} - r_b^{-\delta+1}.
\end{cases}
\]

\[
\Phi_1(r) = \frac{\Phi_0}{1.88} \begin{cases} 
0.24 + 8(r^{-0.1} - r_0^{-0.1}), & r \leq r_0, \\
0.24 + 8(r_0^{-0.1} - r_0^{-0.1}), & r > r_0,
\end{cases}
\]

\[
\Phi_2(r) = \Phi_0(r^{-0.1} - r_b^{-0.1})/(1 - r_b^{-0.1}) \quad r_0 = 10 \text{ AU}, \quad r_b = 100 \text{ AU}
\]
Probing the Electron Spectrum in the Heliosphere

Looking in different directions can probe the electron spectrum at different distances from the Sun.

$$\text{Flux}_{IC} \sim 1/r$$

$$r_1 \text{ (AU)} = \sin \theta, \quad \theta < 90^\circ$$

$$r_1 \text{ (AU)} = 1, \quad \theta > 90^\circ$$

$$r_2 = 10r_1$$
Averaged over one year, the ecliptic will be seen as a bright stripe on the sky, but the emission comes from all directions.
Spectrum < 1 GeV shows variation dependent on modulation level
⇒ Variations of γ-ray flux over solar cycle

Table 1. All-sky average integral flux

<table>
<thead>
<tr>
<th>$E$</th>
<th>$\Phi_0 = 0$</th>
<th>500 MV</th>
<th>1000 MV</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt;10 MeV</td>
<td>5.6</td>
<td>3.4</td>
<td>2.4</td>
</tr>
<tr>
<td>&gt;100 MeV</td>
<td>0.69</td>
<td>0.56</td>
<td>0.47</td>
</tr>
<tr>
<td>&gt;1 GeV</td>
<td>0.05</td>
<td>0.04</td>
<td>0.04</td>
</tr>
</tbody>
</table>

EGRB from SMR2004

$F_{IC}(>100\text{MeV}) < 6^\circ \sim 2 \times 10^{-7} \text{cm}^{-2} \text{s}^{-1}$

EGRET: $F(>100\text{MeV})$ UL = $2 \times 10^{-7} \text{cm}^{-2} \text{s}^{-1}$

Note. — Flux units $10^{-6} \text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1}$. 
Why it is interesting

- GLAST will resolve 1000s of blazars, main contributors to the EGRB; thus solar IC becomes more important
- Studies of heliospheric modulation and monitoring of the heliosphere 0-10 AU
- Determination of the CR proton flux near the solar surface:
  - albedo gammas $pp \rightarrow \pi^0 \rightarrow 2\gamma$
  - $F(>100 \text{ MeV}) \sim 0.5 \times 10^{-7}$ cm$^{-2}$ s$^{-1}$
  - CR cascade development
Solar Atmosphere and Interior

CR cascade development in the solar atmosphere depends on:

- the gas density profile
- underlying B-field structure

Neutrino flux is affected by absorption in the solar core

Magnetic flux tubes

Chromosphere $\sim 10^{12}/cc$

Photosphere $\sim 10^{17}/cc$
Gamma rays and neutrinos from the Sun

F_ν(>100 MeV) ~ (0.2-0.7) x 10^{-7} cm^{-2} s^{-1}

- Ingelman, Thunman 1996, PRD 54, 4385 (ν)

~20 ν/yr (>100 GeV) in a km^3 detector
Based on the expected sensitivity of the LAT:

- A source with flux $10^{-7} \text{ cm}^{-2} \text{s}^{-1}$ and the hardness of the solar IC emission will be detectable on a daily basis when the Sun is not close to the Galactic plane, where the diffuse emission is brightest.

- Sensitive variability studies of the bright core of the IC emission surrounding the Sun should be possible on weekly time scales.

- With exposure accumulated over several months, the Sun should be resolved as an extended source and potentially its IC and pion decay components separated spatially.

Shameless advertising: astro-ph/0607521
What about other stars?
Look at luminous stars since their radiation field is more extensive.

Probing electron spectrum at locations other than 'local'.

\[ L_{IC} \sim r L_{Star}, \quad F_{IC} \sim \frac{L_{IC}}{d^2}, \quad \theta \sim \frac{r}{d} \Rightarrow F_{IC} \sim \frac{L_{Star}}{\theta / d} \]
Source @ 100 pc:

\[ \text{Source @ 100 pc:} \]

\[ \text{gamma spectrum} \leq 5^\circ \]

\[ \text{gamma flux} \]

\[ E^2 \text{ Flux (cm}^{-2} \text{s}^{-1} \text{MeV)} \]

\[ 10^{-13} \text{ to } 10^{-10} \text{ (cm}^{-2} \text{s}^{-1} \text{MeV)} \]

\[ 1 \text{ to } 10^6 \text{ (MeV)} \]

\[ \text{Energy (MeV)} \]

\[ \text{Flux (cm}^{-2} \text{s}^{-1} \text{)} \]

\[ 10^{-11} \text{ to } 10^{-6} \text{ (cm}^{-2} \text{s}^{-1} \text{)} \]

\[ 2 \text{ to } 10 \text{ (Angular distance from the star in degree)} \]

\[ \text{Orlando & Strong astro-ph/0607563} \]
Candidates for Detection

Single Stars: 70 most luminous from Hipparcos

OB associations:

- e.g., Cygnus OB2
  - 1700 pc
  - ~100 O stars
  - ~2500 B stars

\[ F_{>100\text{MeV}} \text{ within } 1^\circ \approx 4 \times 10^{-9} \text{ cm}^{-2} \text{ s}^{-1} \]

Conservative, could be higher if CR spectrum different
Bottom Line ....

- **On-going work**
  - Trying methods on EGRET data but difficult ...
  - Good exercise for when GLAST is 'flying'

- **Practical**
  - Solar modulation
    - Using GLAST as a solar modulation probe is exciting
    - Multi-wavelength with other instruments
  - IC halos

- **Theoretical**
  - CR interactions in the Sun
    - Reduce uncertainty in flux at solar surface, feed in to CR cascade calculations
    - $\pi^0$ gammas + neutrinos
    - Neutrino detectors

- **The future is (γ-ray) bright for GLAST**