18.01 Inverse Compton scattering on solar photons, heliospheric modulation, and neutrino astrophysics (Evaluation of the celestial foreground in determination of the extragalactic diffuse γ-ray emission)

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Abstract

We study the inverse Compton scattering of solar photons by Galactic cosmic-ray electrons. We show that the gamma-ray emission from this process is substantial with the maximum flux in the direction of the Sun; the angular distribution of the emission is broad. This previously-neglected foreground should be taken into account in studies of the diffuse Galactic and extragalactic gamma-ray emission. Furthermore, observations by GLAST can be used to monitor the heliosphere and determine the electron spectrum as a function of position from distances as large as Saturn's orbit to close proximity of the Sun, thus enabling unique studies of solar modulation. This paves the way for the determination of other Galactic cosmic-ray species, primarily protons, near the solar surface which will lead to accurate predictions of gamma rays from pp-interactions in the solar atmosphere. These albedo gamma rays will be observable by GLAST, allowing the study of deep atmospheric layers, magnetic field(s), and cosmic-ray cascade development. The latter is necessary to calculate the neutrino flux from pp-interactions at higher energies (>1 TeV). Although this flux is small, it is a "guaranteed flux" in contrast to other astrophysical sources of neutrinos, and may be detectable by km^3 neutrino telescopes of the near future, such as IceCube. Since the solar core is opaque for very high-energy neutrinos, directly studying the mass distribution of the solar core may thus be possible.

Anisotropic Inverse Compton Scattering on Solar Photons

$$\frac{dF_\gamma}{d\epsilon_2} = \frac{1}{4}\int_L dr \frac{R_\odot^2}{r^2} \int d\gamma_e \frac{dJ_e(r,\gamma_e)}{d\gamma_e} \times \int d\epsilon_1 \frac{dn_{ph}(\epsilon_1, T_\odot)}{d\epsilon_1}\frac{dR(\gamma_e,\epsilon_1)}{d\epsilon_2}$$

Head-on collision: $E_\gamma \sim \gamma^2 \epsilon_\nu$

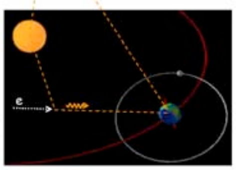
10 GeV e's → 100 MeV γ's

Target photons:

$\rho = 0.25 n_{ph} (R_\odot/r)^2$

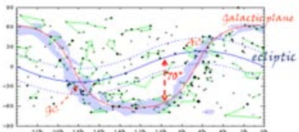
$T_\odot = 6000$ K

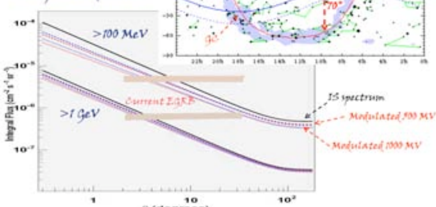
Following collision: $E_\gamma \sim (1/\gamma)\gamma\epsilon_\nu \sim \epsilon_\nu$



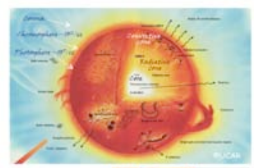
The Ecliptic Stripe

Averaged over one year, the ecliptic will be seen as a bright stripe on the sky, but the emission comes from all directions





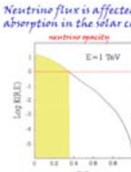
Solar Atmosphere and Interior



CR cascade development in the solar atmosphere depends on:

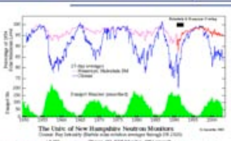
- the gas density profile
- underlying B-field structure

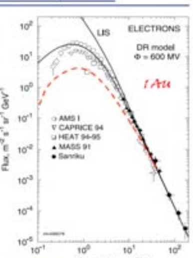
Neutrino flux is affected by absorption in the solar core



Solar magnetic field tubes

Local Interstellar Electron Spectrum & Heliospheric Modulation





Modulation: force-field approximation (+Voyager & Pioneer data)

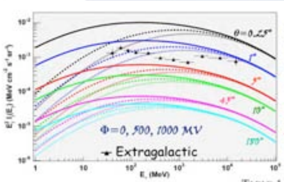
$$\Phi(r,t) = \int_r^{r_b(t)} dx \frac{V(x,t)}{3\kappa_1(x,t)} \quad \begin{cases} \kappa_1 \propto r^s, \text{ and } V = \text{const}, \\ \Phi(r,t) \propto r^{-s+1} - r_b^{-s+1}. \end{cases}$$

$$\Phi_1(r) = \frac{\Phi_0}{1.88}\begin{cases} r^{-0.4} - r_b^{-0.4}, & r > r_0, \\ 0.24 + 8(r^{-0.1} - r_0^{-0.1}), & r < r_0, \end{cases}$$

$$\Phi_2(r) = \Phi_0(r^{-0.1} - r_b^{-0.1})/(1 - r_b^{-0.1})$$

$r_0 = 10$ AU, $r_b = 100$ AU

Differential Spectrum



IC spectrum <1 GeV shows strong dependence on the modulation level

→ variations of γ-ray flux over the solar cycle

IC integral flux

$F(>100 \text{ MeV}, \theta<2.5°) \sim 2\times10^{-7}$ cm^{-2} s^{-1}

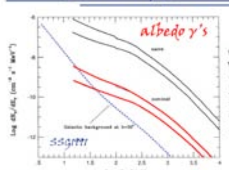
EGRET upper limit $= 2\times10^{-7}$ cm^{-2} s^{-1}

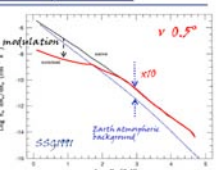
TABLE 1. ALL-SKY AVERAGE INTEGRAL FLUX

E	$\Phi_0 = 0$	500 MV	1000 MV
>10 MeV	5.6	3.4	2.4
>100 MeV	0.69	0.56	0.47
>1 GeV	0.05	0.04	0.04

NOTE. — Flux units 10^{-6} cm^{-2} s^{-1} sr^{-1}.

Gamma Rays & Neutrino Flux from the Sun



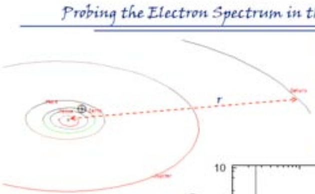


$F_\gamma(>0.1 \text{ GeV}) \sim (0.2\text{–}0.7)\times10^{-7}$ cm^{-2} s^{-1}

~20 ν/yr (>0.1 TeV) in a km^3 detector

- Seckel, Stanev, Gaisser 1991, ApJ 382, 652 (γ,ν)
- IM, Karakula, Tkatzyk 1991, A&A 248, L5 (ν)
- IM, Karakula 1993, J.Phys.G 19, 1399 (ν)
- Ingelman, Thunman 1996, PRD 54, 4385 (ν)

Probing the Electron Spectrum in the Heliosphere

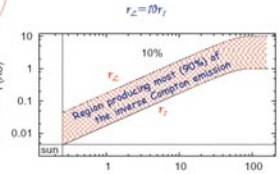


$Flux_{IC} \sim 1/r$

r_1 (AU) $= \sin\theta$, $\theta<90°$

r_1 (AU) $= 1$, $\theta>90°$

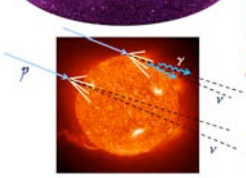
$r_2 = 10 r_1$



Looking in different directions one can probe the e-spectrum at different distances from the sun!

Why It Is So Interesting & What GLAST Can Do

Simulated GLAST skymap >1 GeV



- GLAST will resolve 1000s of blazars, main contributors to the extragalactic diffuse γ-emission; 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 $pp\to\pi^0\to2\gamma$ $F(>100 \text{ MeV}) \sim 0.5\times10^{-7}$ cm^{-2} s^{-1}
  - CR cascade development
  - B-field & density profile
- Neutrino flux >1 TeV: $pp\to\pi\to\mu\to\nu$

GLAST Perspective

Based on the expected sensitivity of the LAT:

- A source with flux 10^{-7} cm^{-2} 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

For more details see astro-ph/0607521 (ApJL, in pr