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Extended inverse-Compton gamma-ray emission from the Sun seen by EGRET

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Abstract: We study the Sun as an extended source of gamma-ray emission, produced by inverse-Compton scattering of cosmic-ray electrons with the solar radiation. This emission contributes to the diffuse gamma-ray background even at large angular distances from the Sun. While this emission is expected to be readily detectable by the upcoming gamma-ray satellite GLAST, the situation for available EGRET data is more challenging. Analyzing the EGRET database, we find clear evidence for the emission from the Sun and its vicinity, compatible with our predictions. Our model for solar gamma-ray production has been implemented taking into account the solar modulation of cosmic-ray electrons, and observations of this process are promising to study the solar modulation of electrons as a function of distance from the Sun.

The extended solar emission model

The heliosphere has been studied as an extended source of gamma-ray emission, produced by inverse-Compton scattering of cosmic-ray electrons with the solar photon field [1,2, 3]. For this analysis our model [1] has been improved using the anisotropic inverse-Compton scattering formalism [4], taking into account the formulation given in [5] for the electron modulation and using the studies of the radial distribution of cosmic rays in the heliosphere at solar maximum and minimum [6]. Since the biggest uncertainties in the inverse-Compton emission come from the cosmic-ray electron spectrum close to the Sun, in our model we considered two possible configurations of the solar modulation within 1AU. The naïve approximation is to assume that the cosmic-ray flux towards the Sun equals the observed flux at Earth, since there is evidence that modulation by solar wind does not significantly alter the spectrum once cosmic rays have penetrated as far as Earth [7,8]. This gives an upper limit on the modelled inverse-Compton flux. The other approach is to assume that the electron spectrum varies due to solar wind effects within 1 AU. With this nominal approximation we assume that the formulation for solar modulation from 100 AU to 1 AU can be extrapolated also below 1 AU. This will give a lower limit in our model.

Fig 1 shows the spectrum of the emission for two different angular distances from the Sun and for two levels of solar modulation (500 MV and 1000 MV, respectively for solar minimum and solar maximum) and for the naïve and the nominal approximation to the electron modulation. The angular profile of the emission is shown in Fig 2. The inverse-Compton emission is shown as a function of the angle from the Sun above 100 MeV without modulation, again for two levels of solar modulation and for the naïve and nominal cases. The emission is extended and is significant compared to the extragalactic background (around 10^{-5} $cm^{-2}s^{-1}sr^{-1}$, value taken from [9]) even at large angles from the Sun.

Since the inverse-Compton emission from the heliosphere is significant compared to the diffuse background, it can be strong enough to be a confusing background for other sources and has to be taken into account for diffuse background studies.

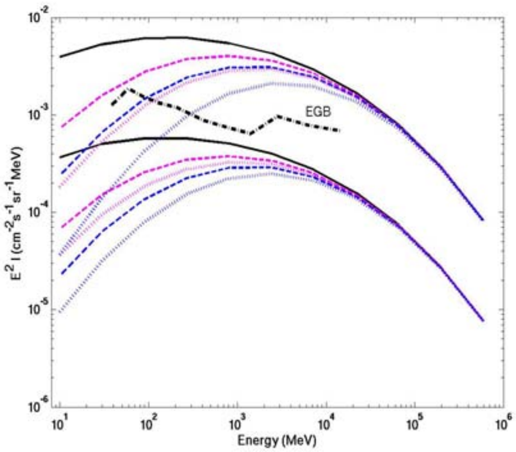

Figure 1: Spectrum of the emission for (top to bottom) 0.5° and 5° angular distance from the Sun and for different levels of solar modulation. Solid lines: no modulation, interstellar electron spectrum; pink lines: 500 MV modulation (solar minimum); blue lines: 1000 MV modulation (solar maximum); dashed line: naïve model; dotted lines: nominal model. EGB: extragalactic background [9].

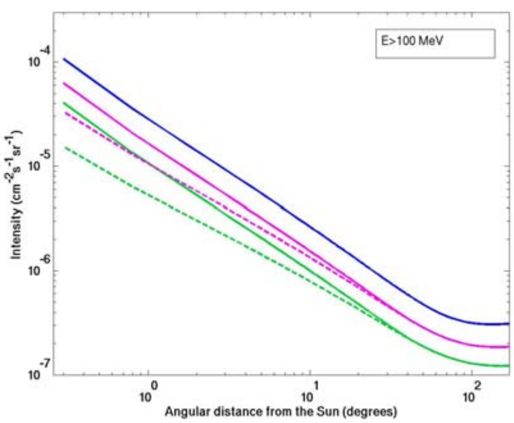

Figure 2: Profile of the emission as a function of the angular distance from the Sun above 100 MeV. Blue lines: no modulation; pink lines: 500 MV (solar minimum); green lines: 1000 MV (solar maximum); solid lines: naïve model; dashed lines: nominal model.

Moreover, since the emission depends on the electron spectrum and its modulation in the heliosphere, observations in different directions from the Sun can be used to constrain the electron spectrum at different positions, even very close to the Sun.

Analysis of the EGRET data

As reported in [3], we have analyzed the EGRET data using the code developed for the moving target Earth [10] and adding necessary features (solar and lunar ephemerides, occultation, background point source trace calculations). The diffuse galactic background was reduced by excluding the Galactic plane. Otherwise all available exposure within mission phases 1-3 was used. When the Sun passed by other gamma-ray sources (moon, 3C279 and several other quasars), these sources were included in the analysis. We fitted the data in the Sun-centred system using a multi-parameter likelihood fitting technique, leaving as free parameters the solar extended inverse-Compton flux from the model, the solar disk flux from pion decay [11], a uniform background, and the flux of 3C279 (the dominant background point source). The moon flux was determined from moon-centred fits and the 3EG source fluxes were fixed at their catalogue values. All components were convolved with the energy-dependent EGRET PSF. The region used for fitting was a circle of radius 10º centred on the Sun. Since the interesting parameters are solar disk source and extended emission, the likelihood is maximized over the other components. In order to verify our method, we checked that the fluxes of the Crab Nebula, 3C 279, and in particular the moon [12] were reproduced.

Results

The log-likelihood ratio for E >100 MeV is displayed in Fig 3 as a function of solar disk flux and extended flux, compared with the model prediction of solar inverse-Compton flux for modulation parameter 500 MV at 1 AU. The TOTAL solar emission is detected with 5.3σ significance. There is evidence for extension of the emission at a level of 2.7σ; the extended component has a flux compatible with the IC model. The total flux from the Sun is more than expected for the disk source [12], so this is clear evidence for the IC emission, even without the proof of extension.

Figure 4 shows the fitted model EGRET counts of the main components and the total including uniform background. More details and the spectral analysis will be given in [13].

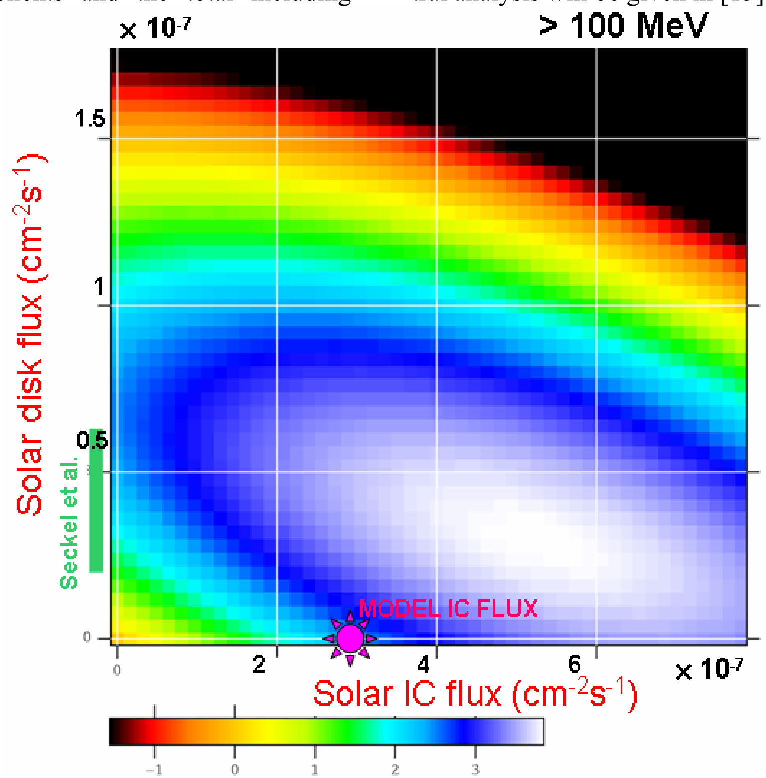

Figure 3: Log Likelihood above 100 MeV as function of the solar disk flux and extended solar flux, relative to point at (0,0). The level of our predicted IC model flux and the predicted disk flux [12] are shown.

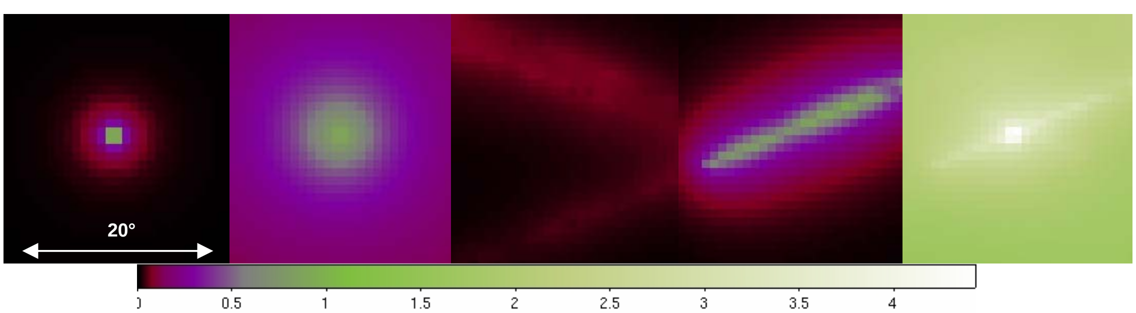

Figure 4: Fitted model EGRET counts of the main components centered on the Sun. From left to right: Sun disk, Sun IC, moon, 3C 279, and the total predicted counts including uniform background. The colors show the counts/pixel, for 0.5°× 0.5° pixels.

Conclusion

We have studied the Sun as an extended source of gamma-ray emission, produced by inverse-Compton scattering of cosmic-ray electrons with the solar radiation. Analyzing the EGRET database, we find clear evidence for the emission from the Sun and its vicinity, compatible with our predictions. More details, the study of other energy ranges and the spectrum of the emission, and the sensitivity to the solar modulation, will be given in [13]. Future missions such as GLAST will allow more detailed studies.

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