Gamma-ray Emission from the Quiet Sun as Observed with *Fermi* Observatory

The *Fermi* LAT Collaboration
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ABSTRACT

We report the detection of high-energy gamma rays from the quiet Sun with the Large Area Telescope (LAT), on board the *Fermi Gamma-Ray Space Telescope*, during the first eleven months of the mission. The observed solar emission is produced by interactions of cosmic- ray hadrons with the solar atmosphere and photosphere via pion decay, and by inverse-Compton scattering of cosmic-ray electrons with solar photons in the heliosphere. *Fermi* observed a total flux of ? $\times\ 10^{-6}$cm^{-2}sec^{-1} above 100 MeV, with the extended emission accounting for about ??'s of the emission. The EGRET instrument on the *Compton Gamma-Ray Observatory* first observed these two components with a total flux of 0.45 $\times\ 10^{-6}$cm^{-2}sec^{-1} at only a 2 σ significance above 100 MeV. The significantly larger flux observed by *Fermi* probably reflects the current low level of solar modulation during this extended period of minimum solar activity.

Observations with *Fermi* will provide a probe of the extreme conditions near the solar surface, and monitor the modulation of cosmic rays over the inner heliosphere, impossible by any other means.

V3

Subject headings: Gamma rays, Cosmic rays, Sun ; Fermi Gamma-ray Space Telescope

1. Introduction

The Sun is an extremely bright source of high-energy (> 10 MeV) gamma-rays during solar flares when flare-accelerated electrons and ions interact with the solar atmosphere. The *Solar Maximum Mission* gamma-ray spectrometer was the first to observe this flare emission with a measured peak flux ...(I couldn't find the exact reference of Forest with the flux, as suggested by Gerry) (**?**). In contrast, quiescent solar gamma-ray emission from hadronic cosmic-ray (CR) interactions with the solar atmosphere and photosphere (the disk component), first suggested by **?** to be detectable by the EGRET experiment, is only expected to have a flux of $\sim 5 \times 10^{-7}$cm^{-2}sec^{-1} above 100 MeV (**?**). **?** reported a 95% confidence upper limit on the flux in the disk component of about 2.0×10^{-7} photons cm^{-2}s^{-1} at E>100 MeV. This work did not take into account a second extended solar component produced by Inverse-Compton (IC) scattering of CR elec-

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trons with solar photons producing a halo around the Sun that complicated the analysis (?) (?). A recent analysis of the EGRET data that revealed both disk and Inverse Compton contributions yielded a total flux of $(4.44 \pm 2.03)\times10^{-7}$ cm^{-2}s^{-1} for E>100 MeV, with the disk component estimated to be about 1/4 of the total flux (?). Solar activity was mostly near its peak in Cycle 22 during the period when the EGRET data used for this analysis were accumulated. There was large solar modulation of the cosmic radiation during this time period resulting in low quiescent solar gamma-radiation.

In contrast to the EGRET observation, solar activity has been extremely low during the first year of the *Fermi* Mission corresponding to a maximum in the cosmic-ray flux. Hence, we expect the quiescent solar gamma-ray emission to be at its maximum in the period analyzed in this paper.

2. Data selection and background determination

Fermi was successfully launched on June 11, 2008 into a low Earth circular orbit at an altitude of 565 Km, an inclination of 28.5^o and an orbital period of 96 minutes. The observatory consists of the Large Area Telescope (LAT) and the Gamma-ray Burst Monitor (GBM). The LAT (?) is a pair-production telescope with a large effective area and field of view (2.4 sr), sensitive to gamma rays between 30 MeV and 300 GeV. After a commissioning phase devoted to the instrument fine tuning and calibrations, the LAT began its normal science operations on 11 August 2008. The Mission was designed with a five-year lifetime and a goal of at least ten years of operations. The point spread function (PSF) of the photon arrival directions is energy dependent as described in (?), ranging from about 5° for E>100 MeV to 0.1 ° for energies above a few GeV. During the first year of operations, *Fermi* has been working in survey mode, observing the whole sky in about 3 hours (or 2 orbits) with an almost uniform exposure in 1 day.

The LAT data sample used in this analysis of the quiescent solar emission was collected from 4 August 2008 to the end of June 2009. We have applied a zenith cut of 105° to eliminate photons from the limb of the Earth's atmosphere. We also use the "Diffuse" class of automatic data screening (?), corresponding to events with the highest probability of being photons. Special software was developed for sources moving in celestial coordinates in order to permit analysis of data in a Sun-centred system.

In order to reduce celestial background, we exclude the data when the Sun is within 30° (right?) of the galactic plane and we remove the brightest objects within 5° from the Sun. (is this right?; please also define 'brightest'). To further minimize the effects of background in the solar-coordinate system, we use what we call the "fake source method". This method entails creating a background data set identical to the solar data set (e.g. the same data cuts described above), but centred on a fake-Sun that is assumed to be shifted along the ecliptic by 30° from the real position of the Sun. This background subtraction method accounts for the anisotropic background component including diffuse Galactic and extragalactic emissions, residual instrumental background, and sources below the brightness level excluded from the data (how bright?). The 'fake Sun' method assumes that the background exposure is constant over a 30 minute interval, which is clearly not the case, but we do not believe that this effect will be significantly affect our results. With this method we approximately correct for the anisotropy of the background along the Sun's path in the ecliptic.

Figure ?? shows the Gaussian-smoothed

(0.5 deg)) > 100 MeV count map centered on the solar position accumulated over 11-months from August 2008 to the end of June 2009 and the count map of the background obtained with the method of the fake-Sun. The map centred on the Sun represents an update of the count maps already published in **?**, **?** and **?** with reduced data accumulations.

3. Model template

In order to take into account the inverse-Compton scattering as extended emission, a model template to be fitted with the likelihood technique has been produced. The modulation of the electron spectrum close to the Sun is not known. Hence we decided to have a simplified model for the IC emission. In fact we checked that the detection and the flux estimation does not depend significantly on the different model of the solar modulation to be fitted. Hence, referring to **?**, **?** and **?**, the extended emission is obtained with the isotropic formulation (which distribution differ for a factor of less that 15% close to the Sun (**?**)) and for solar modulation of 500 MV, corresponding to the solar minimum. The interstellar electron spectrum obtained by *Fermi* **?** with a spectral index of -3.04 is used and modulated 500 MV using the force field approximation. For this model, within 1 AU, where the modulation of cosmic-ray electrons is unknown, the assumption is that the cosmic-ray flux towards the Sun equals the flux at Earth (for more details see **?**). For this analysis the comparison with different models of solar modulation and electron spectra close to the Sun is not an issue. For future work and comparison with models of electron modulation a more accurate modelling will be performed. The point source was assumed to have a spectral index of -2. Since this is not well known, the analysis has been performed also for values ranging from -1 to -3. This gives an idea on the uncertainties on the determination of the resulted fitted fluxes. Models of the disc and inverse-Compton components have been convolved with the response function of the instrument (P6_V3_DIFFUSE for STv9r15), using the science tools. Only fluxes will be reported. Spectra of the 2 components and comparison with models of solar modulation will be obtained in future.

4. Method of analysis

We perform the separation of the two quiescent solar components using a maximum likelihood analysis technique on the two-dimension count map shown in Figure **??**. This fitting code was developed distinct from the standard *Fermi* Science Tools to fit simultaneously contributions from background ('fake Sun') and the disk and halo components.

The analysis has been performed for two energy bands: > 100 MeV and > 1 GeV. Although the statistics are more limited > 1 GeV, this is in part compensated for by the improved point spread function of the instrument and the reduced amount of solar modulation of cosmic rays that needs to be modelled. We performed the fit over a region contained within 20 degrees of the Sun, hence the flux of the inverse Compton emission is integrated over that area. For the cases analysed, we obtained the logarithm of the likelihood ratio, where -2 log(L/L_0) is distributed as χ^2_n with L_0 the global maximum, and L the alternative hypothesis; n is the number of degrees of freedom (**?**).

5. Results

All the fits are made leaving the 3 parameter free, normalization of disc and inverse Compton flux and the background counts. Since the interesting parameters are solar disc and extended fluxes, the likelihood is maximised over the the background flux. Values of the likelihood for each pair of disk and extended fluxes are obtained by allow the background component to vary to maximise the likelihood. Figures **??** and **??** show the $\mathrm{Log}(L/L_0)$ as a function of the disc flux and the extended flux for the 2 energy ranges analysed; 1, 2 and 3 sigma confidence contours for 2 degrees of freedom are shown, supposing a χ^2_2 distribution. For illustration we report here only the plots obtained using the value -2 for the spectral index of the source.

The analysis reveals detection of the two different component of the solar emission, disc and extended, with high statistical significance, for each components and both energy ranges. Values of the best-fit fluxes and 1 sigma errors for the joint probability of the two parameters are reported in Table **??**. Counts of the components and TS are also tabled. No systematic errors are included. The computed errors include only the stastical uncertainties; the estimation of the overall systematical error is of about 20% (right?). The table reports the values obtained using different values of the spectral index of the disc emission, as initial assumption, ranging from -1 to -3, since this is not well known. However from the data we can obtain more information on spectral index using the best fitted value for the disc flux, as discussed in the next section.

In order to have a visible confirmation of the different component of the solar emission, in Figure **??** (TO BE ADDED) the event density profiles of the count map with respect to the Sun, and the fitted components, background, disc and inverse Compton emission are plotted. The figures show the evidence of a solar emission component extended above 15 deg from the centre of the Sun with a density increasing at high energies. The simulated data for the disc has been obtained using a simple pointlike source with spectral index of -2.1 and total flux of 3×10^{-7} $\mathrm{cm}^{-2}\mathrm{s}^{-1}$ for E>100 MeV. For the inverse-Compton emission the model described in the previous section has been used.

6. Discussion

This analysis has revealed the detection of the two components of the solar emission with high confidence level. Referring to Table **??**, the spectral index of the disc emission calculated from the best fit fluxes are: -? assuming a priori spectral index of -1 for the fit; -2 assuming a priori spectral index of -2; -2.25 assuming a priori spectral index of -2.5; -2.37 assuming a priori spectral index of -3. Hence, we can affirm that the expected spectral index rages between -? and -2.3. To be conservative the fluxes of the solar components will be reported taking into account this uncertainty on the spectral index. Hence, we give the fluxes obtained fitting the model for the source with a spectral index between -? and -2.5, values that give the upper and lower limit on the fluxes. The difference is of the order of 20% on the iC flux(?) and a factor of 2 in the disc flux (?). In general, the higher the spectral index, the higher the disc flux and the lower the IC flux. The resulted disc and inverse-Compton fluxes above 100 MeV and 1 GeV are reported in Table **??** (TO BE ADDED with the fitted values). This table contains also the expected inverse-Compton fluxes (**?** and **?**) calculated for a region of 6 degrees radius from the Sun. Moreover also the measured fluxes obtained with the analysing of the EGRET data above 100 MeV by **?** are given for both extended and disc emission. The extended fluxes are scaled in order to directly compare the results of different region size. **?** and **?** estimated a flux of (2-5) $\times$ $10^{-7}\mathrm{cm}^{-2}\mathrm{sec}^{-1}$ within 6 degrees, depending on the solar conditions. These values are in agreement with what we obtained from the analysis of the LAT data. On the other hand, on a first sight, the fluxes obtained with the *Fermi* data seem to overpre-

Table 1: Maximum likelihood fitting results for two energy ranges above 100 MeV and above 1 GeV. Fluxes are given in $cm^{-2}sec^{-1}$

Energy	>100 MeV	>1GeV
IC flux	1.33e-6 +0.1-0.06	1.14e-7/+0.11-0.09
Disc flux	7.4e-7 +0.5-0.6	3.7e-8/+-0.1
Bkg fit scaling factor	0.99	0.99
IC counts sun	10132.6	1976.82
source	2823.16	416.18
background	79576.4	10955
Total TS	4922	2325.4

dict the values obtained with previous analysis of the EGRET data (**?**), who determined a total flux of $(4.44\pm2.03)\ \times10^{-7}cm^{-2}sec^{-1}$ within 10° radius. However we have to take into account that, in the first year of the *Fermi* mission, there was an anomalous condition of solar minimum, while the EGRET data covered mostly the period of solar maximum, when the cosmic-ray flux and hence the gamma-ray solar emission is lower. The same consideration has to be done for the disc flux found with Fermi, that is much higher that what previously found by EGRET data analysis (**?**). However, within big uncertainties in the model of the disc emission, the flux found in this analysis is in agreement with the theoretical value for pion decay obtained by**?**.

In the future work we expect to obtain the spectra of the two solar components and gain information on the solar modulation of cosmic rays even close to the Sun. In fact, observations with Fermi-LAT of the inverse Compton scattered solar photons will allow for continuous monitoring of the cosmic-ray electron spectrum even in the close proximity of the solar surface for the entire Solar Cycle 24.

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Table 2: Fluxes obtained with the Fermi-data analysis compared with expectations and previous analysis of EGRET data. Fluxes are given in $cm^{-2}sec^{-1}$

Component	Fluxes	Radius of integration (°)
IC (LAT)	(1.3-1.6) e-6	20
IC (LAT)	(0.8-1.0) e-6	10
IC (EGRET)	(2+-6)e-7	10
IC (LAT)	(4-4.8) e-7	6
IC (ESTIMATES)	(2-4.5) e-7	6
Disc (LAT)	(2-5)e-7	-
Disc (EGRET)	(2-8.5)e-8	-

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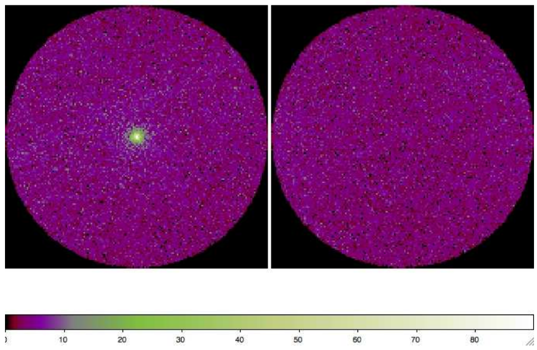

Fig. 1.— Count maps above 100 MeV of the data between August 2008 and the end of May 2009 centred on the Sun (left) and centred on the fake-Sun (right) that represents the background. The region is 20 degree-radius and the pixel side is of 0.25 degrees. Colorbar shows the number of counts per pixel.

This 2-column preprint was prepared with the AAS LaTeX macros v5.2.

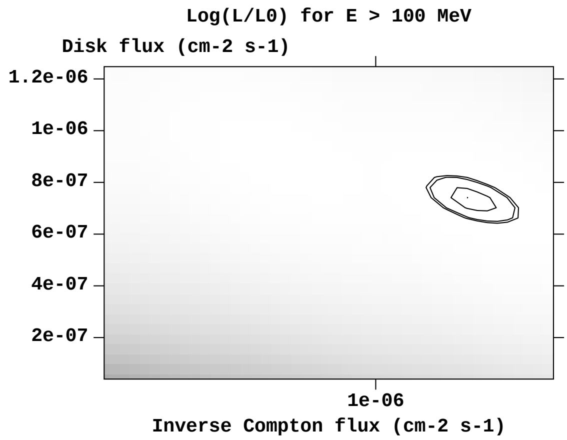

Fig. 2.— Log(L/L0) as a function of the disc flux (y axis) and the extended flux (x axis) for E>100 MeV. 1, 2 and 3 sigma confidence contours for 3 degrees of freedom are shown, supposing a χ^2_3 distribution.

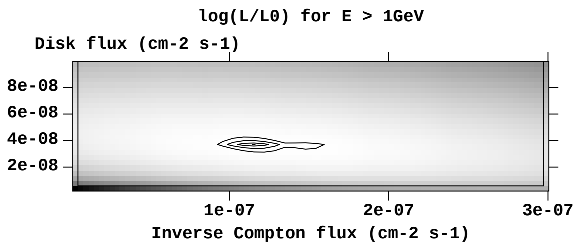

Fig. 3.— Log(L/L0) as a function of the disc flux (y axis) and the extended flux (x axis) for E>1 GeV. 1, 2 and 3 sigma confidence contours for 3 degrees of freedom are shown, supposing a χ^2_3 distribution.