Monitoring solar flares with *Fermi*-LAT

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***Abstract*. *Fermi*-LAT is performing an all-sky gamma-ray survey from 20 MeV to > 300 GeV with unprecedented sensitivity and angular resolution. *Fermi* is the only mission able to detect high energy (> 20 MeV) emission from the Sun during the new solar cycle 24. *Fermi* was launched on June 2008, since then high energy emission from the Sun was continuously monitored searching for flare events. Upper limits were derived for all the solar flares detected by other missions and experiments (RHESSI, *Fermi*-GBM, GOES). We present the analysis techniques used for this study and the preliminary results obtained so far.**

***Keywords*: Solar flares, Sun, Gamma-rays**

I. Introduction

Fermi was successfully launched from Cape Canaveral on 2008 June 11. It is currently in an almost circular orbit around the Earth at an altitude of 565 km having an inclination of 25.6° and an orbital period of 96 minutes. After an initial period of engineering data taking and on-orbit calibration[1], the observatory was put into a sky-survey mode in August 2008. The observatory has two instruments onboard, the Large Area Telescope (LAT)[2], a pair-conversion gamma-ray detector and tracker (energy range 20 MeV - > 300 GeV) and a Gamma Ray Burst Monitor (GBM), dedicated to the detection of gamma-ray bursts (energy range 8 keV - 40 MeV). The instruments on *Fermi* provide coverage over the energy range measurements from few keV to several hundreds of GeV.

Here we report results of the monitor of solar flares seen by other missions searching for flares seen by *Fermi*-LAT. Solar flares are the most energetic phenomena that occur within our Solar System. A flare is characterized by the impulsive release of a huge amount of energy, previously stored in the magnetic fields of active regions. During a flare plasma of the solar corona and chromosphere is accelerated and electromagnetic radiation covering the entire spectrum is emitted. The production of γ-rays involves flare-accelerated charged-particle (electrons, protons and heavier nuclei) interactions with the ambient solar atmosphere. Electrons accelerated by the flare, or from the decay of $\pi^{\pm}$ secondaries produced by nuclear interactions, yield X and γ-ray bremsstrahlung radiation with a spectrum that extends to the energies of the primary particles. Proton and heavy ion interactions also produce γ-rays through π^0 decay, resulting in a spectrum that has a maximum at 68 MeV[3].

Intensity and frequency of solar flares depend on the Sun activity, according to the 11 year solar cycle. Most intense flares occur during the maximum, but intense flares can occur also in the rising and decreasing phases of the cycle. The new solar activity cycle 24 has started at the beginning of year 2008, the maximum is predicted in year 2012. *Fermi* has been launched during the minimum of the solar cycle, so frequency and intensity of solar flares will increase throughout most of the mission. If the goal of a 10-year mission life is achieved, *Fermi* will operate for nearly the entire duration of solar cycle 24. During this time, *Fermi* will be the only high-energy observatory to complement several solar missions at lower energies: RHESSI, GOES, SoHO.

II. Previous observations

The 2005 January 20 solar flare produced one of the most intense, fastest rising, and hardest solar energetic particle events ever observed in space or on the ground. γ-ray measurements of the flare[4][5] revealed what appear to be two separate components of particle acceleration at the Sun: i) an impulsive release lasting $\sim$ 10 min with a power-law index of $\sim$ 3 observed in a compact region on the Sun and, ii) an associated release of much higher energy particles having a spectral index $\leq$ 2.3 interacting at the Sun for about two hours. Pion-decay γ-rays appear to dominate the latter component. Such long-duration high-energy events have been observed before, most notably on 1991 June 11 when the EGRET instrument on CGRO observed > 50 MeV emission for over 8 hours[6]. It is possible that these high-energy components are directly related to the particle events observed in space and on Earth.

Fermi will improve our understanding of the mechanisms of the γ-ray emission by solar flares thanks to its large effective area, sensitivity and high spatial and temporal resolution.

III. Monitor of solar cycle 24

The solar cycle 24 has started at the beginning of 2008, but actually we are in an extended period of minimal solar activity. We are seeing an interesting

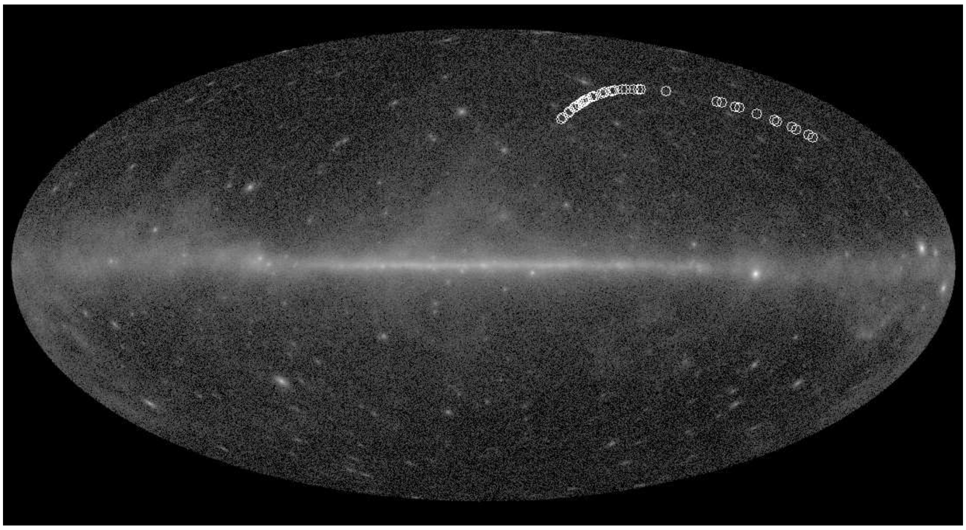

Fig. 1: Location of solar flares detected by RHESSI superimposed on a count map of the first three months (August - October 2008) of LAT data ($E > 200$ MeV). There is no evidence of correlation between flare positions and excesses of the LAT events.

diminished level of activity. There are some discussion ongoing if sunspots and flares ever return and how unusual is this behavior[7]. A closer look at the daily values of three indices: F10.7 (10 cm radio flux from the Sun), the total solar irradiance TSI, and the classical sunspot number gives a clear appearance of a little up-turn. Probably F10.7 is giving us an early warning about the sudden increase of cycle 24 spots. These should appear within the next few weeks or months.

In the modern era there is no precedent for such a protracted activity minimum, but there are historical records from a century ago of a similar pattern (transition between cycles 13 and 14, 107 year ago). We do expect activity to pick up fairly suddenly soon. In the meanwhile is a good opportunity to use the excellent data available from many satellites to improve LAT analysis of solar flare and practise in flare monitoring and analysis, to be ready when the first intense flare of cycle 24 will arrive.

IV. Data selection

Since August 2008 we monitor continuously the flares detected by RHESSI and GOES, analysing LAT data for flare events potentially detectable by the LAT and computing upper limits on the solar high energy emission. We searched for solar flares in the LAT data from August 2008 to the end of May 2009. We analysed LAT data in the time intervals of flares detected by GBM, RHESSI and GOES. We have applied a zenith cut of 105° to eliminate photons from the Earth's albedo. For this analysis we adopted the "Diffuse" class[2] selection, corresponding to the events with the highest photon classification probability, using the IRFs (Instrumental Response Functions) version P6_V3.

V. Analysis method

We monitor constantly at a daily basis the list of flares detected by RHESSI[8] and the *Solar Monitor* web site[9]. We select the flares seen by RHESSI and GOES with more than 10^5 counts (detected by RHESSI). For each of these flares we compute start and end time of the event in *Fermi* MET (Mission Elapsed Time), the position of the Sun during the flare and the angle of the Sun direction with the LAT boresight.

For flares within the LAT field of view (angle with the LAT boresight $< 80^\circ$) we search for excess of events in the LAT data. Although the Sun is a moving source in the sky, covering about 1° per day, in this analysis we consider the Sun as a fixed source, due to the short duration of the flare events ($<$ 1 h). As analysis method we use a likelihood fitting technique performed with a model that includes the Sun as a point source and fixed galactic and extragalactic diffuse emission.

VI. Results

At 20:14:42.77 UT on 02 November 2008, *Fermi*-GBM triggered and located a very soft and bright event[10]. The event location was RA = 217.6 deg, Dec = -15.7 deg (± 1.1 deg), in excellent agreement with the Sun location. The time of the event coincides with the solar activity reported in the GOES solar reports (event 9790: onset at 20:12 UT, max at 20:15 UT, end at 20:17, B5.7 flare). This is the first GBM detection of a solar flare. The GBM light curve (fig. 2) shows a multiple peak event lasting approximately 177 s (8-30 keV). The event fluence (8-30 keV) in this time interval is $(1.54 \pm 0.03) \cdot 10^{-4}$ erg cm^{-2}.

We selected LAT data in the energy range 100 MeV - 300 GeV between Nov 02 12:00 to 21:00 UT, according

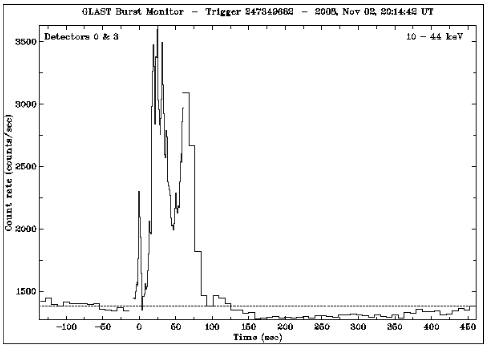

Fig. 2: GBM light curve of the 2008 November 02 solar flare. Courtesy of V. Connaughton (UAH).

to the solar activity detected by GOES and RHESSI. No high energy emission has been detected by the LAT. From August 2008 to all May 2009 RHESSI has detected 150 flares with $> 10^5$ counts. The highest energy band in which most of these flare have been observed by RHESSI is 3-6 keV. Few flares (< 20) have been observed in the energy band 6-12 or 12-25 keV. We discarded flares outside the LAT field of view and the ones that occurred while the LAT was transiting in the SAA. As a result we analysed LAT data of about 90 flares computing upper limits on the high energy (> 100 MeV) emission.

VII. Conclusions

We have searched for solar flare events in the first 10 months of LAT data (August 2008 - May 2009). Up till now we have no evidence of high energy emission from solar flares detected by the LAT, while the quiet Sun emission has been detected[11][12][13]. However, the Sun is at the minimum of its activity cycle and no intense flare has occurred. The solar activity is expected to rise in the next months, reaching the maximum in 2012. We will continue to monitor the active regions of the Sun and to improve our analysis techniques, waiting for an intense flare detectable by the LAT.

VIII. Acknowledgements

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