Long-lived solar $\gamma$-ray emission during 2011 March 7 to 8 detected by Fermi-LAT

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Abstract: We present preliminary result on the Fermi-LAT detection of long-lived solar $\gamma$-ray emission following M3.7 flare on March 7, 2011. The $\gamma$-ray emission ($E > 100$ MeV) lasted for $\sim 12$ hours after the impulsive phase. The emission site seems to be located around the active region where the M3.7 flare emitted. The $\gamma$-ray spectrum accumulated for the flare duration is well represented by pion-decay model of energetic protons whose index is between $-4.0$ and $-5.0$. Possible acceleration mechanisms of protons up to above 300 MeV are qualitatively discussed.

Keywords: The Sun, gamma-rays

1 Introduction

It is widely accepted that a solar flare is caused by magnetic reconnection (e.g., [1]); Namely, the magnetic energy stored in the corona suddenly released and converted to thermal and kinetic energies of plasmas. During the solar flare, broad-band electromagnetic radiation from radio to $\gamma$-rays is observed by satellites and ground-based telescopes. Non-thermal emission by accelerated particles is commonly seen in radio, hard X-ray, and $\gamma$-ray bands (e.g., [2]). Hours-long $\gamma$-ray emission ($E > 50$ MeV) from the Sun was observed only three times in the past by EGRET on-board Compton Gamma-ray Observatory [3]. The $\gamma$-ray emission clearly lasted even after non-thermal emissions in hard X-ray and radio bands ended. Especially, $\gamma$-ray emission after the 1991 June 11 flare was peculiar because the emission lasted for about 7 hours [4]. The light curve showed clear exponential decay which is represented by two different decay times. The origin of the long-lived nature has been unclear for past decades, and hence further detections are awaited. In this paper, we present Fermi-LAT detection of long-lived solar $\gamma$-ray emission from the Sun during 2011 March 7 to 8.

2 Observation

Fermi-LAT significantly detected $\gamma$-rays from the Sun after the impulsive phase of M3.7 flare on 7 March, 2011. The Sun was out of the field of view of the LAT during the impulsive phase around 20:10 UT. After $\sim 6$ hours from the first detection, the $\gamma$-ray flux reached a peak, and then it decayed in a similar manner. We have collected multi-wavelength information from RHESSI, GOES, and Nobeyama polarimeter. No corresponding enhancements were seen in other wavelengths during the LAT detection. Remarkable features of the M3.7 flare are; (1) Fast coronal mass ejection (CME) was observed by SOHO following the M3.7 flare. The CME velocity is estimated to about 2200 km/s. This is the fastest since 2005 January. (2) During the impulsive phase, neither neutron capture line at 2.2 MeV nor $\gamma$-ray nuclear deexcitation lines at 4-7 MeV were detected by RHESSI.

A preliminary significance map (so-called TS map; TS is test statistics [5]) of MeV/GeV emission is produced by accumulating the data for the flare duration. To do this, the Sun-centered analysis method is utilized (see [6] for details of the method). We have found that the LAT emission is originated from the North-Western part of the Sun. The emission site grossly corresponds to a flare site of the M3.7 flare which occurred just before the LAT detection. A preliminary MeV/GeV spectrum obtained by Fermi-LAT for the data accumulated for the whole duration showed clear turnover at 100-200 MeV. Preliminary gtlike, rmfit,
and OSPEX analyses indicate that pion-decay model [7] of accelerated protons of index between $-4.0$ and $-5.0$ interacting with solar atmosphere combined with the quiet Sun solar-disk component [6] well represent the observed spectrum. Reasonable likelihood values were also obtained by using broken a power-law model. Hence, the leptonic origin cannot be excluded from spectral fitting alone.

3 Discussion

Here we consider two possible acceleration mechanisms. The pion-decay $\gamma$-rays are produced by the most energetic protons above $\sim$300 MeV, the important problem is how the energetic protons are accelerated. One possibility is that the high energy protons are accelerated by a shock in front of the fast CME (e.g., [8]). Indeed, fast CME was observed following the M3.7 flare. According to the Diffusive Shock Acceleration theory, the fast CME-driven shock can easily and immediately accelerate protons up to above 300 MeV on the basis of the The maximum attainable energy is calculated as follows.

$$E_{\text{max}} = \frac{3}{20} \frac{V_{\text{shock}}}{c} e B R \xi$$

$$\simeq 20 \left( \frac{V_{\text{shock}}}{2200 \text{ km/s}} \right) \left( \frac{B}{10 \text{ G}} \right) \left( \frac{R}{0.1 R_\odot} \right) \left( \frac{\xi}{1} \right) \text{ GeV},$$

where $V_{\text{shock}}$ is shock velocity, $B$ is magnetic field strength, $R$ is distance from the solar corona, and $\xi$ is the parameter of turbulence ($\xi \equiv B/\delta B$). Here coronal magnetic field strength of 10 Gauss at the base of the solar corona $R = 0.1 R_\odot$. It is clear that the fast shock can easily accelerate protons up to tens of GeV. In addition, acceleration time of 1 GeV protons is estimated as follows.

$$t_{\text{acc}} \simeq \frac{20 c}{3} \frac{1}{V_{\text{shock}}^2} \frac{1}{\xi}$$

$$\simeq 2 \left( \frac{2200 \text{ km/s}}{V_{\text{shock}}} \right)^2 \left( \frac{10 \text{ G}}{B} \right) \left( \frac{1}{\xi} \right) \text{ sec}.$$

Hence, the fast shock can immediately accelerate protons up to 1 GeV.

However, the main difficulty of this shock acceleration scenario is that extended emission region over the solar disk would be expected, which seems inconsistent with the observed compact emission region.

The other possibility is that protons are accelerated by turbulence within the loop (namely, second order Fermi acceleration, e.g., [9]). In this scenario, turbulence needs to be present for the flare duration of $\sim$12 hours. However, assuming a typical loop size of $10^5$ km and Alfvén velocity of 1000 km/s, the MHD turbulence is maintained only for $\sim$100 s, unless there is an energizing process in flaring loops. The big problem for this scenarios is how the MHD turbulence is maintained, so it seems difficult to explain the long-lived nature by turbulence acceleration. Nonetheless, we note that the compact emission region of the TS map is quite consistent with this scenario. Further quantitative discussion is now in progress.

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