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Study on 2012 March 7 Solar Particle Event and Forbush decrease with the PAMELA experiment

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Abstract: The PAMELA (Payload for Antimatter Matter Exploration and Light-nuclei Astro-physics) space-borne experiment was launched on 15 June 2006 and has been continuously collecting data since then. The apparatus measures electrons, positrons, protons, anti-protons and heavier nuclei from about 100 MeV to several hundreds of GeV. The on-board instrumentation is built around a permanent magnet with a silicon microstrip tracker, providing charge and track detection information. During solar maximum conditions of solar cycle 24, PAMELA has been providing key information about solar energetic particles (SEPs) and their influence at Earth. We discuss here the recent 2012 March 7 SEP event with a brief comment on the subsequent Forbush decrease, registered by PAMELA. This event was also observed by Fermi/LAT exhibiting unprecedented time-extended γ-ray emission ($>$ 100 MeV) lasting nearly 20 hours. We compare the derived accelerated ion population at the Sun with the ion population measured in space by PAMELA and discuss the implications for particle acceleration.

Keywords: PAMELA, Fermi, SEPs, protons.

1 Introduction

Solar energetic particles (SEPs) are thought to originate at the Sun either through Coronal Mass Ejection (CME-driven) shocks, or stressed, current-carrying (non-potential) magnetic fields present during magnetic reconnection, or perhaps a combination of such processes [1]. Understanding how particles are accelerated is one of the major goals

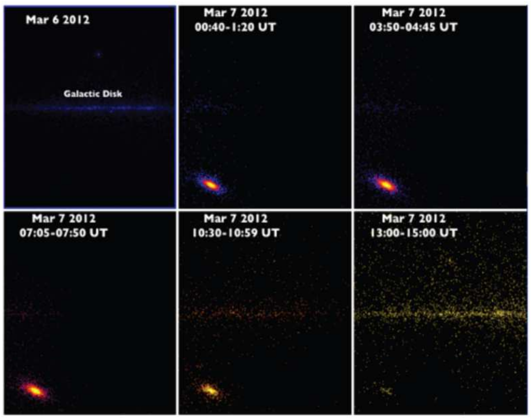

Fig. 1: Intensity of high-energy γ-rays plotted in galactic coordinates on March 6-7. This represents 20 hrs of extended emission from the Sun. The background was determined $\pm$ 30 orbits from the period of interest.

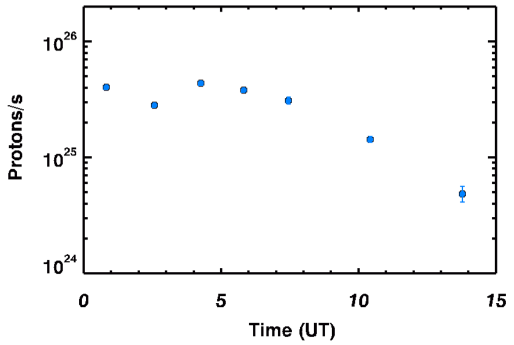

Fig. 2: Derived accelerated proton fluence above 500 MeV based on pion decay templates from a standard γ-ray production model (priv. comm. Ryan Murphy).

of solar physics, but disentangling acceleration from the subsequent transport is difficult. One can constrain the possible SEP origins by comparing the characteristics of SEPs with those of the accelerated ion population at the Sun deduced from γ-ray observations. Evidence for particle acceleration can be found in the X-ray and γ-ray emission resulting from interactions of accelerated particles in the dense chromosphere. Essentially three processes dominate high-energy flare emission: bremsstrahlung emission from energetic electrons (with typical power law spectra), γ-ray emission (0.5-8 MeV) from the excited states of or formation of nuclei, and high energy γ-ray emission from the decay of neutral and charged pions. The γ-ray emission between 1-10 MeV is dominated by accelerated ions with energies $<$ 50 MeV and the emission above 50 MeV is attributed to proton interactions ($>$ 500 MeV) producing neutral and charge pions. Several studies have shown that the accelerated ion population at the Sun does not correlate well with the characteristics derived for the SEP population [2][3]. Whether the poor correlation suggests that CME-driven shocks play a large role in SEP acceleration, as indicated by Cliver et al, is not clear. Furthermore flare-accelerated particles may play a significant role in a seed particle population required for further processing in some CME-driven shock models [4].

Typically, comparisons between SEPs and the ions interacting at the Sun to produce γ-ray emission have been restricted to the low-energy SEPs (from spacecraft) or the high-energy SEPs (in the form of ground level enhancements). How the low-energy population of SEPs ($\leq$ 100 MeV) is related to the high-energy population ($\geq$ 500 MeV) is unclear. This stems, in part, from the lack of instrumentation that can measure SEPs in an energy range between the low- and high-energy populations. Ideally, one would like to measure the composition, spectral shape, spectral evolution, and time-dependent behavior of the high-energy solar ions interacting at the Sun and those registered at 1 AU.

We present, for the first time, a direct comparison between PAMELA measurements of high-energy SEPs with the accelerated ion population at the flare derived from Fermi/LAT γ-ray observations. PAMELA closely examines the composition of a wide range of SEP species from protons, carbon, the isotopes of helium, neutrons, and possibly positrons from $\sim$ 100 MeV to several GeV $-$ bridging the gap in current SEP measurements by ACE, STEREO, and GOES, and ground-based neutron/muon monitors. Fermi/LAT γ-ray observations of the Sun have already changed our picture of high-energy γ-ray flares with recent observations of 19 flares with emission $>$ 100 MeV, many of which exhibit time-extended emission. The ions producing the emission observed with Fermi/LAT are in the same energy range as those observed with PAMELA, presenting a unique opportunity for a proper comparison of these two particle populations [5].

2 Instrumentation and Data Selection

The PAMELA apparatus was designed to perform very high-precision spectral measurements of charged particles in cosmic radiation of galactic, heliospheric and trapped origin over a large energy range. At high latitudes, the low geomagnetic cutoff permits particles down to about 50 MeV to be detected. The instrumentation comprises a number of high performance detectors, capable of identifying particles through the measurement of rigidity, energy, and charge. For a more detailed description of PAMELA instrument, see [6, 7].

The highly inclined orbit of PAMELA allows particles of different origin and nature to be studied. To separate the solar and galactic component of cosmic rays from the reentrant albedo one, the local geomagnetic cutoff must be evaluated with precision. Particles requiring a value of rigidity greater than 1.3 times the cutoff [1] were selected to remove any effect due to directionality in the instrument.

3 Data Analysis

In this study, we present the results of the analysis of the 7 March 2012 SEP event detected by PAMELA with SEP energies extending up to $\sim$ 800 MeV. The 2012 March 7 event was unique in that it was also registered by Fermi/LAT with emission $>$ 100 MeV lasting at least five successive orbits ($\sim$ 20 hours), as shown in Figure 1. The impulsive

1. Through different periodic measurements it is possible to estimate many of the coefficients to reproduce with a certain accuracy the geomagnetic field. The coefficients set used for PAMELA data analysis is the International Geomagnetic Reference Field (IGRF) computed by the International Association of Geomagnetism and Aeronomy.

X-Ray Flare	Class	Location	CME Km/s	Fermi > 200 MeV	Fermi > 500 MeV	PAMELA > 200 MeV	PAMELA > 500 MeV	Ratio @ 500 MeV
7 March 2012	X5.4/X1.3	N18E31	1785	2.6×10^{31}	1.5×10^{30}	7.2×10^{29}	8.0×10^{28}	15

Table 1: Comparison between PAMELA data and Fermi data.

phase of the X5.4 flare started at 00:02 UT, but for the first orbit, the LAT ACD suffered pile-up from hard X-rays. A second X1.3 flare, occurring about an hour after the X5 flare, exhibited emission at 2.2 and 4-8 MeV, implying ion acceleration. A fast CME was observed by LASCO with a CME speed of 2684 km/s.

The 7 March event provides the longest extended γ-ray emission of the so-called Long-Duration Gamma-Ray Flares (LDGRFs) observed to date. LDGRFs, identified with Compton Gamma Ray Observatory (CGRO), Solar Maximum Mission (SMM) and now Fermi, radiate (in at least one case up to 20 hours) almost entirely in γ-rays with energies above $\sim$ 30 MeV. This extended emission emanates from pion decay, produced by ions above $\sim$ 300 MeV [8]. To sustain hours of high-energy emission, particle trapping and/or continuous acceleration must take place within large coronal loops. CMEs may also play a role, through backward precipitation from a CME-driven shock, although several hours of extended emission would place the CME far from the solar surface. In seemingly all cases, LDGRFs are accompanied by SEPs. Whether these SEPs are accelerated by the same processes that produce ions responsible for the the high-energy emission or from subsequent CME-driven shocks is still not understood. Given that LDGRFs are prolific producers of high-energy ions, we would like to know what role they play, if any, in *similar* energy SEPs.

Above 100 MeV, we determined the spectral shape of the parent ion population for the next several orbits. The proton fluence is shown in Figure 2. We used the γ-ray production model [9] with an accelerated proton population with power law index between -2.5 and -7.5. This assumes normal solar system abundances, a potential source of uncertainty. However, preliminary observations of the PAMELA p/He ratio suggest an enrichment in helium, that may help to clarify these assumptions, if the two populations are related. The March 7 event shows spectral softening of the accelerated ions during the extended phase from $\sim$ 02:20 UT, consistent with the results of [10] and with similar measurements of spectral softening over several hours for the 1991 June 9 and 11 solar flares [8]. The average spectral index weighted by the intensity in each period of observations is $\sim$ 3.9. The total number of accelerated protons during the impulsive phase of the flare has been found to be a factor of 4 lower than the extended emission [10]. This represents a lower limit to the number of protons contributing to the impulsive phase since Fermi/LAT missed the first 25 minutes of the X5.4 flare. Assuming no primary electron component, the total number of protons at the Sun > 200 MeV (and > 500 MeV) is 2.6×10^{31} (and 1.5×10^{30}). It is important to note that above 500 MeV, the estimated number of protons is less sensitive to the assumed spectral index.

These numbers can be compared to equivalent ones in space. Because this was an eastern event with ample time for the particles to diffuse throughout the heliosphere, we constructed an instantaneous particle density at PAMELA at the time of maximum, see Figure 3. The model was that pro-

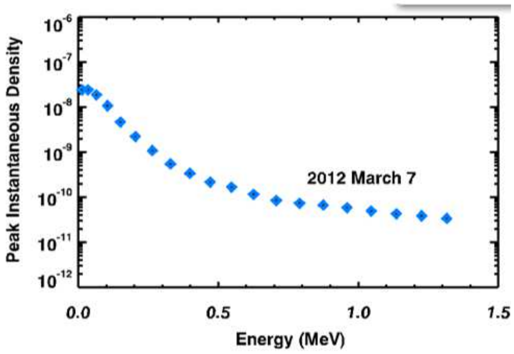

Fig. 3: Instantaneous density (particles/cm^3) at the peak of the event: flux/velocity = 7.15×10^{-10} particles/cm^3.

tons detected by PAMELA were injected impulsively from the flare and then diffused throughout much of the inner heliosphere. We estimated the filling factor of the volume occupied by SEPs by using the multi-point observations of GOES and STEREO > 10 MeV. A lower bound can be set by looking at the longitudinal spread of GLEs, producing proton numbers reduced by a factor of $\sim 1.6^2$. Considering the volume of an infinitesimal cone $dV = 1/3r^3 d\Sigma$, with a gaussian weighting factor we can obtain the differential number of particle as $dN \propto ne^{-\Theta/2\Theta_0}$. Converting the differential particle intensity to a volume-integrated density, we obtained $N_p \sim 7 \times 10^{29}$ and 8×10^{28} for energies above 200 and 500 MeV, respectively. These numbers are 18 $\times$ smaller than the ion population at the Sun (> 500 MeV). Because the March 7 event was not well-connected, we may have underestimated the total number of protons in space and can draw no conclusion on the timing of particle injection. A more straightforward comparison can be obtained with SEP events that are well connected and we are currently examining such events. The results, together with the results of the deduced number of accelerated ions at the Sun, are summarized in Table I.

The spectral index of the 7 March SEP event can be compared to that of the derived accelerated ion population at the Sun ($\sim$3.9). For the event-integrated case, the spectral shape may give some indications of acceleration mechanisms at play. Figure 4 shows the PAMELA flux determined during the polar orbits and integrated over a total period of $\sim$3 days (from 7 March to 10 March). The background, predominantly the GCR component, was determined from a quiet period of February 2012, and has been subtracted. The proton spectrum was fitted using two different functional forms [11]:

These two functions are showed in Figure 4, where Φ_p is the proton flux intensity, E is the kinetic energy (expressed in GeV), R is the magnetic rigidity and K_2 is a second-order modified Bessel function, with αT as a single

2. Allan Tylka priv. comm.

free parameter (α represents an acceleration rate and T is the escape time from the acceleration region). The first is typically associated with shock acceleration, where the actual acceleration occurs when particles cross a shock or any region of converging flow. The latter, instead, represents second order stochastic acceleration. The best fit to the data is with the first one with a $\chi^2/NDF \sim 2.6$ an index $\gamma \sim 3.8$ and $E_0 \sim 0.17$ GeV.

Another interesting effect linked to the March solar event is the solar modulation effect that lowers the number of protons below $\sim$ 10 GV after the passage of a CME: a Forbush decrease. The recovery time (the time before the particle flux reaches the quiet sun conditions) depends on the duration of the event and the CME characteristics. This can be seen in Figure 5 bottom panel for an arbitrary energy range.

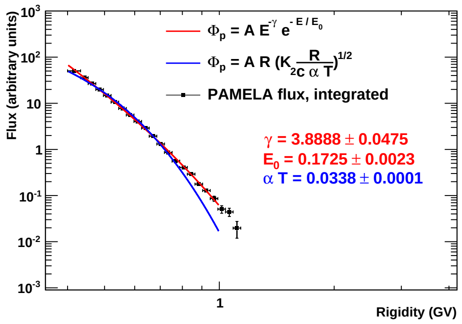

Fig. 4: Fit of integrated PAMELA flux with Bessel function (blue curve) and a power law function truncated with an exponential (red curve).

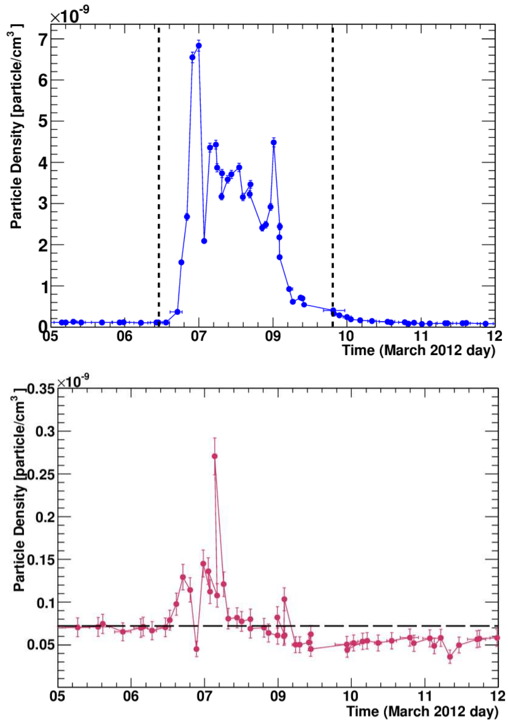

Fig. 5: (Top) Particle density measured by PAMELA during the March 7 event. Black dashed lines show the time interval in which differential flux in Figure 4 has been integrated. (Bottom) Particle density taken at a higher energy range to show Forbush decrease.

4 Conclusions

The total number of protons (energy $>$ 500 MeV) necessary to produce the time-extended emission for the 7 March solar flare is 18$\times$ greater than the protons measured in space. Whether the two populations are related is still unclear. One obvious possibility is that the ions at the Sun are accelerated by stochastic acceleration at the Sun and do not escape. The protons measured in space may be accelerated by a separate mechanism, such as the CME shock. It is possible that the extended emission is caused by back-precipitation from the CME-related shock. Such a scenario would have to be highly efficient in precipitating particles back to the Sun given that fewer are observed in space and that the CME is at 0.3 an AU after only 10 hours of emission. Finally, the two populations may be related as manifestations of continuous acceleration in large coronal loops that undergo some interchange reconnection with open magnetic field lines, releasing $\sim$5% of the particles into space.

To unambiguously determine whether there is a relationship between the accelerated ion population at the Sun and that in space or whether the two populations are accelerated through independent processes, we need more observations, particularly of magnetically well-connected events. In the case of magnetically well-connected events, we can compare the injection time scales, the composition, and the spectral evolution. Together, these observations will place important constraints, not possible with past instrumentation, on the different scenarios for particle acceleration. PAMELA offers for the first time a unique opportunity to observe high-energy SEPs with ion energies that are known to produce the high-energy γ-ray emission observed by Fermi/LAT, enabling the possibility to determine a connection, if any, between the particles at the Sun and those in space.

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