ELECTRON AND PROTON ACCELERATION DURING THE FIRST GROUND LEVEL ENHANCEMENT EVENT OF SOLAR CYCLE 24

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ABSTRACT

High-energy particles were recorded by near-Earth spacecraft and ground-based neutron monitors (NMs) on 2012 May 17. This event was the first ground level enhancement (GLE) of solar cycle 24. In this study, we try to identify the acceleration source(s) of solar energetic particles by combining in situ particle measurements from the WIND/3DP, GOES 13, and solar cosmic rays registered by several NMs, as well as remote-sensing solar observations from SDO/AIA, SOHO/LASCO, and RHESSI. We derive the interplanetary magnetic field (IMF) path length (1.25 ± 0.05 AU) and solar particle release time (01:29 ± 00:01 UT) of the first arriving electrons by using their velocity dispersion and taking into account contamination effects. We found that the electron impulsive injection phase, indicated by the dramatic change in the spectral index, is consistent with flare non-thermal emission and type III radio bursts. Based on the potential field source surface concept, modeling of the open-field lines rooted in the active region has been performed to provide escape channels for flare-accelerated electrons. Meanwhile, relativistic protons are found to be released ~10 minutes later than the electrons, assuming their scatter-free travel along the same IMF path length. Combining multi-wavelength imaging data of the prominence eruption and coronal mass ejection (CME), we obtain evidence that GLE protons, with an estimated kinetic energy of ~1.12 GeV, are probably accelerated by the CME-driven shock when it travels to ~3.07 solar radii. The time-of-maximum spectrum of protons is typical for shock wave acceleration.

Key words: acceleration of particles – magnetic fields – Sun: coronal mass ejections (CMEs) – Sun: flares

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1. INTRODUCTION

Large solar energetic particle (SEP) events draw more and more research enthusiasm, not only because of theoretical interest in high-energy solar phenomena, but also because of their perspectives into space weather forecasting. The relativistic extension of some large SEP events can produce sufficient secondary particles registered by ground-based neutron monitors (NMs). As a result, we observe the so-called ground level enhancement (GLE) of solar cosmic rays. Understanding where and how solar particles are accelerated to high energies in large SEP events is one of the main topics of space physics. This issue, however, still remains controversial (Miroshnichenko & Perez-Peraza 2008; Reames 2009).

Historically, it was thought that flares were the main sources of GLEs (e.g., Miroshnichenko 2001). The modern paradigm (Kahler 1994, 2001; Reames 1999, 2002, 2009; Cliver 2006; Gopalswamy et al. 2012) suggests that in large SEP events, especially in GLE events, particle acceleration mainly takes place at the shocks driven by coronal mass ejections (CMEs) rather than in flare active regions (ARs). However, large SEP events are always associated with flares and CMEs concomitantly (without exception in GLE events), and both of them are different manifestations of the same process of magnetic energy release (Harrison 1995; Zhang et al. 2001; Wang et al. 2003). Theoretically, the flares (e.g., Somov & Oreshina 2011) and CME-driven shocks (e.g., Zank et al. 2000; Berezhko & Tanev 2003) are both capable of accelerating charged particles to high energies. Observationally, we also have evidence that particle acceleration that occurs directly in flare sites cannot be ruled out (Cane et al. 2002, 2006, 2010). The question arises: what dominates SEP injection?

According to recent observations and modeling of the GLEs, the answer is mostly consistent with a flare-associated prompt component and a CME-associated delayed component (DC; e.g., Li et al. 2007a, 2007b, 2009; Vashenyuk et al. 2011; Aschwanden 2012). Assuming the existence of open-field lines that originated in ARs, a direct flare contribution should exist in large SEP events. Using the potential field source surface (PFSS) model, Schrijver & DeRosa (2003) found that a significant fraction of the interplanetary magnetic field (IMF) lines are directly connected to the magnetic plage of ARs. These lines may provide escape channels for particles accelerated at low coronal sites. By applying the same model, a statistical link between the coronal magnetic topologies and dynamics of in situ electrons was recently established (Li et al. 2010). For an individual SEP event, a more practical and accurate method for constructing coronal magnetic fields is absolutely necessary (Li et al. 2011).

The timing of SEPs with respect to flare emission (e.g., hard X-ray (HXR) production, type III radio bursts) and CME signatures (e.g., type II radio bursts) is generally a tool for identification of the particle acceleration source. One of the first statistical studies of the solar particle release (SPR) times was performed by Cliver et al. (1982), who found that ~100 keV electrons were released at least 5 minutes earlier than ~2 GeV protons, followed by ~MeV electrons at least 5 minutes later. Kahler et al. (2003) studied the first 10 GLE events of solar cycle
23 and found that in half of the event numbers, an injection of near-relativistic electrons was preceded by the GeV protons. More recently, Simnett (2006) carried out a comprehensive study of particle timing for the GLE of 2005 January 20. It was found that the injection of near-relativistic electrons is delayed by \( \sim 6 \) minutes from that of the GeV protons. The author suggested that the protons were directly related to the \( \sim 23 \) had produced five GLEs in the first 4.5 years. During the event, high-energy solar particles were recorded by both near-Earth spacecraft and some ground-based NMs, along with a medium-strength solar flare (1F\(_{\text{M5.1}}\)) and a high-speed CME (1582 km s\(^{-1}\)). It enables us to carry out a cross-disciplinary investigation by combining in situ particle measurements and NM data, as well as the results of remote-sensing solar observations. The main goal of this study is to extend our understanding of particle acceleration in large SEP events.

First, we describe in detail particle measurements and methods of data analysis (Section 2) to investigate the release of electrons and protons at the Sun. Section 3 presents available solar observations, including the data of the SEP-associated flare and concomitant CME. Section 4 is devoted to a discussion on possible solar source(s) of the two species by systematically analyzing event timing, particle energy spectrum, etc. A summary and discussion are given in Section 5.

2. PARTICLE MEASUREMENTS

2.1. Release of Electrons

The spacecraft WIND is currently an orbiting satellite in the Sun–Earth L1 libration point that registers non-thermal electrons with energies from a few keV up to a near-relativistic energy range. The three-dimensional Plasma and Energetic Particle Instrument (3DP; Lin et al. 1995) on board WIND observes electrons with solid-state telescopes (SSTs) from 27 to 517 keV with a time resolution of \( \sim 12 \) s. For SSTs, laboratory calibration shows that a proportion of incident electrons will scatter back out of each detector before fully depositing their original energy and produce secondary particles that contaminate lower energy channels. This leads to erroneous results when studying electron release from the Sun if contamination is not taken into account. Wang (2009) empirically corrected the count contamination by assuming that \(~10\%–25\%\) of incident electrons will be scattered out of each energy channel and be evenly distributed over the lower energy channels.

To correct the count contamination, here we apply the correction matrix, \( C \), that can be deduced, in principle, from the response function \( g^k(E_i) \) (Haggerty & Roelof 2003) as

\[
C_{k,n} = \int_{E_n}^{E_k^u} g^k(E_i) dE_i, \tag{1}
\]

where \( E_n^d \) (\( E_k^u \)) is the upper (lower) limit of the energy channel \( n \). The corrected flux, \( I \), is deduced from multiplication of the observed flux \( i \) by the correction matrix as

\[
I = C \otimes i, \tag{2}
\]

In the practical implementation, however, the coefficients of the correction matrix empirically vary from 0.05 to 0.3 for different energy channels. The corrected flux can then be validated by comparing its velocity dispersion (onset times are later for lower energies) with an expected one (see Sun 2012).

Figure 1 shows the electron intensity profiles observed by WIND/3DP/SSTs in seven channels before (black lines) and after (colored lines) the correction on 2012 May 17. It is found that lower energy channels suffer heavier contaminations due to more scattered particles from higher energy channels. Another fact is that the correction is more effective at the particle injection phase, resulting in an expected clear velocity dispersion.

A linear fit of the velocity dispersion has been commonly used to study the SPR times of beam-like SEP events (Lin et al. 1981; Reames et al. 1985; Krucker et al. 1999). Recently, Reames (2009) successfully applied this method to investigate the SPR times for protons and ions of He, O, and Fe during the 16 GLE events that occurred from 1994 to 2007 in solar cycle 23. Note that the author did not take electron data into consideration. Assuming that the first arriving particles are traveling along the IMF path length without scattering, the SPR time of electrons with energy \( E_n \) can be expressed as

\[
T_{\text{SPR}}(E_n) = T_{\text{onset}}(E_n) - L/v(E_n), \tag{3}
\]

where \( T_{\text{onset}}(E_n) \) is the onset time of the electron flux increase at 1 AU for each energy channel (\( n = 1, 2, \ldots, 7 \)), \( L \) is the IMF path length from the electron release site on the Sun to the spacecraft, and \( v(E_n) \) is the velocity of electrons. Note that \( T_{\text{onset}}(E_n) \) is determined for the first time when a background-subtracted flux exceeds the level of \( 3\sigma \) (standard deviation), and the error bars are determined by times of \( \pm 3\sigma \) excess around \( T_{\text{onset}}(E_n) \).

We apply Equation (3) to the WIND/3DP/SST-corrected electron data (the colored lines in Figure 1). Plotting onset times versus \( v^{-1} \) yields a line with the initial SPR time as the intercept and a slope that corresponds to the IMF path length, which is shown in Figure 2. The electron SPR time in these terms is 01:29 ± 00:01 UT, and the IMF path length is 1.25 ± 0.05 AU. Note that the SPR time of protons (see Section 2.2) is also marked by a triangle on the time axis.

To further confirm this evaluation, assuming that charged particles travel along the spiral IMF lines, the path length can be calculated by the solution of the IMF equation deduced from the solar wind model (Parker 1958). In a polar coordinate system, the IMF equation is expressed as

\[
\psi = \frac{\omega}{u} (r_0 - r), \tag{4}
\]

where \( \psi \) is the azimuth angle of the IMF footpoint on the solar surface, \( \omega \) is the angular speed of the solar rotation, \( u \) is the solar wind speed, and \( r \) is the radial distance from the Sun center,
Figure 1. Electron intensity profiles detected by WIND/3DP/SSTs in seven channels on 2012 May 17. The black lines indicate the original fluxes, and the colored lines show fluxes after correction for scatter-out electrons.

(A color version of this figure is available in the online journal.)

\( r_0 = 1 \text{ AU}, \text{ at the near-Earth space. Therefore, combining Equation (4), a formula for estimating the nominal length} \ L \ \text{of the IMF line, may be given as} \)

\[
dL = \sqrt{(dr)^2 + (r d\phi)^2} = \sqrt{1 + \left(\frac{\omega u}{r}\right)^2} dr. \tag{5}
\]

Integrating Equation (5) by \( r \) from the solar radius \( R_s \) to Earth’s orbit \( r_0 \), adapting the angular speed of the solar rotation \( \sim 1.7 \times 10^{-4} \text{ deg s}^{-1} \), and taking into account the solar wind speed \( \sim 360 \text{ km s}^{-1} \) before this event, we calculate that the value of \( L \) is \( \sim 1.21 \text{ AU} \). Then taking \( v(E_f) \) to be approximately \( 0.9c \) (where \( c \) is the velocity of light), which corresponds to
the highest energy channel \( E_7 = 517 \text{ keV} \), the electron SPR time derived from Equation (3) is \( \sim 01:30 \text{ UT} \). Therefore, this estimate is quite consistent with the previous one.

### 2.2. Release of Protons

To study the SPR time of protons, we analyze proton data obtained on board the *Geostationary Operational Environment Satellite* (GOES) 13 in the energy range of \( \sim 31–433 \text{ MeV} \) and with a time resolution of 1 minute (top panel of Figure 3). The averaged 1 minute intensities of SCRs observed at 4 NMs (bottom panel of Figure 3) were also taken from the Neutron Monitor Database (NMDB; http://www.nmdb.eu), which collects data from many NMs that operate permanently at different sites around the globe (the worldwide network of cosmic-ray stations). In total, for the GLE71 event there are records of 17 NMs from about 50 stations (Klein & Büntikofer 2012).

The GLE events only characterize a relativistic part of the entire energy spectrum of SCRs (kinetic energy \( E_p \gtrsim 433 \text{ MeV nucleon}^{-1} \) or magnetic rigidity \( R \gtrsim 1 \text{ GV} \)). If the energy of primary protons is \( E_p < 100 \text{ MeV} (R < 0.44 \text{ GV}) \), NMs do not respond to them due to the atmospheric absorption of neutrons (the so-called atmospheric cutoff, \( R_C \)). The maximum NM response is within 1–5 GV. This means that all high-latitude (polar) NM stations start to efficiently record secondary neutrons from the same rigidity as the primary protons at about 1 GV (433 MeV), irrespective of the NM nominal “geomagnetic cutoff rigidity,” \( R_C \). As it fortunately happened, rigidity \( R \sim 1.0 \text{ GV} (E_p \sim 433 \text{ MeV}) \) is approximately midway between the low rigidity and ultra-relativistic rigidity range, and it turned out to be a convenient reference point as a characteristic rigidity cutoff at the polar NM stations (Smart & Shea 1996).

As seen from the top panel of Figure 3, *GOES* 13 recorded a fast rise in the flux of non-relativistic solar protons followed by a slower decay, which was still ongoing on 2012 May 18. Note that several non-relativistic proton events stronger than the 2012 May 17 event were detected by *GOES* in 2012 January and March. But the 2012 May 17 event obviously extended into a much higher energy range than the other ones, even though it was considerably weaker at lower energies. Through our research (see Section 4.3), we try to understand the reason for these differences. Relativistic SCR increases have been mostly recorded by NMs at high (polar) latitudes at geomagnetic cutoff rigidities \( R_C < 1 \text{ GV} \). The bottom panel of Figure 3 presents the four most intensive increases of GLE71 recorded at SOPB (South Pole Bare, \( R_C = 0.1 \text{ GV} \)), SOPO (South Pole, 0.1 GV), APTY (Apatity, 0.65 GV), and OULU (Oulu, 0.8 GV).

The data of the four NMs showed that the first relativistic solar protons started to arrive at the Earth at nearly the same time, \( \sim 01:51 \text{ UT} \), in spite of the fact that two of the NMs are located in the Southern hemisphere and two others in the Northern hemisphere. One of the possibilities is that it may be evidence of isotropic flux in SCRs. On the other hand, according to Klein & Büntikofer (2012), some SCR increases have also been recorded by five other NMs (Kerguelen, Yakutsk, Newkirk, Magadan, and Kiel) with \( R_C > 1 \text{ GV} \) (1.14, 1.65, 2.10, 2.10, and 2.36 GV, respectively). The authors also believe that no signal was observed at the \( >3 \text{ GV} \) cutoff. In all of the surface observations, there are 5 minutes of data for 17 NMs. However, the signals of most of them are at the level of statistical fluctuations; therefore, there was, in practice, no possibility to build up a latitude effect curve in the cosmic-ray intensity. In fact, no latitude effect has been registered by NMs at Earth’s surface that turned out to be a simple consequence of a rather soft spectrum of accelerated protons (but not the result of SCR anisotropy). This may suggest that the SEPs on 2012 May 17 in general and the GLE71 event indeed had a rather soft energy spectrum (see Section 4.3).
Based on Figure 3, we can estimate the SPR time of protons by applying Equation (3) with the assumption that the first arriving protons traveled along the same IMF path length, $1.25 \pm 0.05$ AU, as the electrons did. If we take $v$ to be approximately 0.7$c$ corresponding to the highest energy channel of 433 MeV for GOES non-relativistic protons, then the evaluated SPR time is 01:40 ± 00:03 UT. For GLE relativistic protons with an energy of $\geq$GeV, we take $v$ to be approximately 0.9$c$, then the evaluated SPR time is 01:39 ± 00:02 UT (see also Figure 2). Considering the systematic errors, we believe that the GLE protons belong to the same population and form the relativistic extension of the first arriving GOES protons.

From the above analysis, it also follows that the SPR time of GLE protons is $\sim$10 minutes later than the near-relativistic electrons (01:29 ± 00:01 UT). Assuming scatter-free propagation in interplanetary space, we suggest that the most probable reason for this discrepancy may rise from a different acceleration source(s) of the two particle species.

3. SOLAR OBSERVATIONS

3.1. Flare Active Region

To identify the acceleration source(s) of SEPs, we first study the coronal morphology and magnetic topology of AR 11476. The left panel of Figure 4 shows the magnetic field lines derived from the PFSS model (Schrijver & DeRosa 2003) overlaid onto the magnetogram obtained from the Helioseismic and Magnetic Imager (Schou et al. 2012). The right panel of Figure 4 presents the two-ribbon flare structure obtained from the Atmospheric Imaging Assembly (AIA; Lemen et al. 2011) on board the Solar Dynamic Observatory (SDO) contoured with the RHESSI HXR sources.

One can see that the closed field lines straddle the two flare ribbons (the 1600 Å image in the right panel of Figure 4) and show loop-like structures (the 171 Å images in the left column of Figure 5). The open-field lines rooted in the AR with negative polarity can provide escape channels for flare-accelerated particles. The 12–25 keV thermal bremsstrahlung source shows a loop-top structure, whereas the 50–100 keV non-thermal sources are only located at the ribbons, or in other words, in the footpoints of the loop. This is consistent with the classical model of solar eruption, which introduces a loop-top HXR source and two sources at the footpoints on the ribbons.

According to the classical picture of a two-ribbon flare/three-component CME model, when a flux rope (filament on the solar surface or prominence on the solar limb) loses equilibrium and travels upward, an extensive reconnection current sheet (RCS) forms below the flux rope. As a result, a great number of particles can be accelerated to extremely high energies inside the RCS region. The upward motion drives the expansion of coronal loops above the flux rope to form the front of a CME, whereas the flux rope itself forms the core of the CME.

To display these consequences, we present the temporal evolution of the AR observed in the SDO/AIA 171 Å and 304 Å images shown in Figure 5. At $\sim$01:25 UT, a system of coronal loops is identified in 171 Å, beneath which a prominence is clearly seen in 304 Å. In fact, the prominence started to form much earlier, at $\sim$00:55 UT. At $\sim$01:34 UT, the prominence erupted and the coronal loops are stretched to “open” out of the field of view (FOV). In reality, the prominence started to erupt as early as $\sim$01:32 UT. It should be noted that the time of the prominence eruption is very close to the peak time of flare non-thermal emission and electron SPR time. At $\sim$01:55 UT, a thin line structure is identified at both wavelengths, which indicates the trajectory of the prominence eruption. This structure may be a candidate of the RCS.

Based on the observations and modeling shown in Figures 4 and 5, we propose a sketch of the coronal magnetic topology (see Figure 6) associated with the two-ribbon flare and prominence eruption. Particles accelerated in the RCS travel downward along closed field lines to produce HXR emission via bremsstrahlung and flare ribbons via collision with the chromosphere. A portion of high-energy particles can be scattered...
Figure 5. Temporal evolution of AR 11476 in SDO/AIA 171 Å and 304 Å. The labels “LP” and “PR” indicate the loop system and prominence, respectively. (A color version of this figure is available in the online journal.)
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Figure 6. Sketch of the magnetic topology associated with the two-ribbon flare and prominence eruption based on Figures 4 and 5.
(A color version of this figure is available in the online journal.)

or transported by diffusion perpendicularly to the nearby open-field lines and escape to interplanetary space.

On the other hand, particles can be selectively accelerated in the RCS; for instance, electrons are much more easily accelerated than protons in the RCS (Cane et al. 1986; Miller et al. 1997). It explains why the electron release at the Sun is consistent with the flare emission and type III radio bursts (see Section 4.1), while this is not valid for the proton release.

3.2. CME and the Associated Shock

Out of the FOV of SDO/AIA, the Large Angle and Spectroscopic Coronagraph (LASCO; Brueckner et al. 1995) on board Solar and Heliospheric Observatory (SOHO) provides white-light observations of the high-speed CME. Figure 7 shows the LASCO C2 running difference image at ~01:48 UT with a previous image subtracted. The three components of CME are identified as core (CO), cavity (CA), and leading front (LF). Combining Figures 4 and 5, we can see that the trajectory of the prominence eruption is along the direction of the CME core, and the expansion of coronal loops forms the LF of the CME. A diffusive structure or a signature of the wave propagating ahead of the CME LF is also found, which is probably the CME-driven shock (Vourlidas et al. 2003).

If one refers to the CME catalog (http://cdaw.gsfc.nasa.gov/CME_list/index.html), then the CME sky-plane velocity from linear extrapolation in this case is ~1582 km s⁻¹, which has a minor projection effect since it originated on the solar limb. The liftoff time of the CME is extrapolated onto the solar surface at ~01:32 UT, which coincides with the onset time of the prominence eruption, as was already mentioned before.

We can then evaluate the CME height with respect to the proton release. At the SPR time of GLE protons (01:39 UT + 8.3 minutes = 01:47.3 UT, 8.3 minutes is a light travel time of 1 AU), the CME reaches ~3.07 Rs. This is consistent with the conclusion by Gopalswamy et al. (2012), who studied the GLE events of solar cycle 23 and found that the release of protons occurs when the CMEs reach an average height of ~3.09 Rs for well-connected events with the source helio-longitudes in the range of W20–W90. It is timely to note that this result does not contradict the theoretical radius estimate of ~2.0–3.0 Rs for effective particle acceleration by the spherical shock wave (Berezhko & Taneev 2003).

4. RELATIONS TO THE ACCELERATION SOURCE

4.1. Event Timing

The particle injection phase with respect to solar multiwavelength emission is generally considered as a key for understanding SEP acceleration. Here, we demonstrate that the electron injection phase can be displayed in the form of spectral evolution by applying a power-law spectrum $f(E_e) \propto E_e^{-\gamma_e}$. The most dramatic change of spectral index $\gamma$ obviously corresponds to the moment of the impulsive injection phase. To do this, we use the electron SPR time (01:29 UT + 8.3 minutes = 01:37.3 UT) as a reference time with respect to solar multiwavelength emission. The onset time obtained from the intensity profile of every energy channel (see Figure 1) is shifted to the reference time. By fitting it to the power-law spectrum, the evolution of an electron spectral index is derived and shown in Figure 8 (top panel). The time range between the two vertical lines indicates the proposed most impulsive phase of electrons injection, which is compared with solar multiwavelength emission.

As shown in Figure 8, the 1F/M5.1 flare recorded in the soft X-ray (SXR) range of 1–8 Å started at 01:25 UT, peaked at 01:47 UT, and is followed by a ~2 hr decay phase. At that time, AR 11476 was situated at the position of N13W83 at the Sun, i.e., near the West limb of the Sun. This position is roughly well connected by IMF lines linking the Sun to near-Earth space. The time derivative of the SXR flux (the dashed line in positive values) is generally considered as a good approximation of the HXR flux according to the Neupert effect (Neupert 1968). It shows a similar profile to the microwave emission in 15.4 GHz, suggesting that the flare-accelerated...
electrons are traveling downward to generate HXR emission via bremsstrahlung or are becoming trapped in magnetic loops to generate microwave emission via synchrotron. Whereas, the microwave emission in 2.7 GHz shows a few pulses in the decay phase, which are not clearly manifested at 15.4 GHz.

On the other hand, the flare-accelerated electrons are traveling upward along open-field lines to generate type III radio bursts, which was demonstrated by the radio dynamic spectra in the frequency range 20 kHz to 14 MHz (Figure 8, two bottom panels). The type III radio bursts started at $\sim$01:33 UT with a group of intensive emission lasting until $\sim$01:44 UT. We found that the electron impulsive injection phase started at the peak time of HXR and microwave emission, at the most intensive emission of type III radio bursts, and lasted until the decay phase of HXR and microwave emission.

Type II radio bursts, which represent local electron acceleration at a shock wave moving out through a corona, were reported to have an onset time of $\sim$01:32 UT (Gopalswamy et al. 2013). This is consistent with the prominence eruption and CME liftoff. Note that the proton SPR time is $\sim$15 minutes later than the onset time of type II radio bursts, suggesting that proton injections occurred at a higher corona site ($\sim$3.07 $R_s$) when the CME-driven shock developed to be an effective accelerator.

### 4.2. Energy of GLE Protons

Another way to clarify the problem of solar sources for GLE events is to check whether a flare or CME is capable of producing relativistic protons. Theoretically, the answer is “Yes” (see Section 1) for both proposed mechanisms of SEP acceleration (flare magnetic reconnection and CME-driven shock). Observationally, for an individual GLE event, it is necessary to evaluate proton energy $E_p$ from its estimated time of travel to the Earth along the IMF path length under the assumption of scatter-free propagation. Firoz et al. (2011a, 2011b) proposed an empirical method to determine the possible relativistic energies of GLE69 and GLE70 that we promoted recently for the interpretation of possible acceleration mechanisms for the same two events (Firoz et al. 2012). By deducing from observations the time lag $\Delta t$ of
the GLE onset with respect to the related flare or CME, we can obtain the velocity of GLE protons \( v_p = L/(\Delta + 8.3\) minutes), where \( L \) is the IMF path length of protons from the release site on the Sun to Earth’s orbit (\( \sim 1.25\) AU for this event). Then the energy of GLE protons may be roughly estimated from the classic relativistic expression,

\[
E_p = (\gamma - 1)m_p c^2 = \left( \frac{1}{\sqrt{1 - (v_p/c)^2}} - 1 \right)m_p c^2, \quad (6)
\]

where \( m_p c^2 \) is the proton rest energy of 938.27 MeV.

Let us first assume that GLE protons are accelerated at the flare site. The time lag \( \Delta \) of the GLE onset (\( \sim 01:51\) UT) with respect to the peak time of flare non-thermal emission (\( \sim 01:36\) UT) is \( \sim 15\) minutes. Based on Equation (6), the energy from the protons is evaluated to be \( \sim 0.11\) GeV (\( R \sim 0.45\) GV), much less than the typical relativistic energy (\( \sim\)GeV) of the GLE protons and even less than the geomagnetic cutoff energy at polar NMs (\( \sim 433\) MeV or \( R \sim 1\) GV). Therefore, the GLE protons are not likely caused by flare acceleration. Let us then assume that GLE protons are accelerated at the CME-driven shock when it reaches \( \sim 3.07 R_s \), where the shock developed to be an efficient accelerator. The time lag \( \Delta \) is \( \sim 4\) minutes, leading the energy of the protons to be \( \sim 1.12\) GeV (\( R \sim 1.83\) GV), which is sufficient to cause a GLE event.

In this context, it should be noted that according to a theoretical model by Zank et al. (2000), rather high energies may be reached at the early stages of shock evolution. In particular, energies of the order of 1 GeV are possible for young shock waves. On the other hand, as was convincingly shown by Berezhko & Taneev (2003), with heliocentric distance \( r \), the efficiency of acceleration by the spherical shock wave decreases rather rapidly, and it causes the effective SCR acceleration to terminate when the shock reaches a distance of \( r \sim 2-3 R_s \). As a result, SCR particles intensively escape from the vicinities of the shock.

4.3. Time-of-maximum Spectrum for Protons

As noted above (Section 2.2, Figure 3), the GLE71 turned out to be rather small, and its latitude effect, unfortunately, was not manifested in due magnitude. In reality, no latitude effect was registered by NMs at Earth’s surface. Therefore, a standard method of energy spectrum evaluation (Vashenyuk et al. 2011) is not applicable in this case. Moreover, there were some suggestions that in fact, the first GLE of the current solar cycle had already been registered on 2012 January 27–28. To make this point clearer, we apply the method of the so-called time-of-maximum (TOM) spectrum (see, e.g., Miroshnichenko 1996; Miroshnichenko & Perez-Peraza 2008). As was noted by those authors, the TOM spectrum of SEPs is a rough proxy of their source spectrum, at least for well-connected events (Miroshnichenko et al. 1973; Forman et al. 1986).

The spectrum of the January event is estimated by the GOES 13 data obtained at energy thresholds of \( E_p > 10, 50, \) and \( > 100\) MeV. According to our estimates by three intensity points, an integral TOM spectrum of protons may be given in the form of \( I(\sim E_p) \propto E_p^{-\alpha} \), where the power-law index of the spectrum is \( \alpha \sim 2.0 \) (the index for a differential spectrum is \( \gamma = \alpha + 1 \)). Another significant SEP event occurred on 2012 March 7. In the range of non-relativistic energies, it may be considered as the largest one in the current solar cycle 24. Indeed, by GOES 13 measurements, the maximum proton intensity above 10 MeV reached about 6530 pfu. From the same data, we estimate integral intensities of 305 and 70.5 pfu for the protons \( > 10, 50 \) and \( > 100\) MeV, respectively. Again, we get an integral TOM spectrum with the index \( \alpha \sim 2.0 \) (\( \gamma \sim 3.0 \)).

Keeping this in mind, we also apply the TOM method to the event of 2012 May 17 to derive the integral spectrum of non-relativistic protons by using five energy channels (\( E_p > 10, 30, 50, 60, \) and \( > 100\) MeV) of the GOES 13 data as shown in Figure 9 (left panel). Hence, we get \( \alpha \sim 2.2 \) (for a differential spectrum this value corresponds to \( \gamma \sim 3.2 \)). One can see from Figure 9 (right panel) that the power-law spectrum is broken.
This method was elaborated for one hour of NM data. Averaging the data in Figure 3 (bottom panel), we get that a one hour increase of amplitude at the Apatity station was about 10%. Hence, we get the value of proton intensities for GLE24 were 433 MeV) should be taken from our previous publications (Miroshnichenko 1996; Miroshnichenko & Perez-Peraza 2008). Corresponding values of proton intensities for GLE24 were taken from our previous publications (Miroshnichenko 1996; Miroshnichenko & Perez-Peraza 2008). From Table 1, it may be concluded that SEP events of 2012 January 27 and March 7, most likely, had no extension into a relativistic range. On the other hand, between 2011 January and 2012 May the PAMELA spectrometer registered several solar events with >100 MeV protons. The most powerful event was on 2012 March 7 (Bazilevskaya et al. 2013). There are also some preliminary data on the effect of this SEP event registered by a special huge muon telescope (Makhmutov et al. 2013) in El Leoncito (CASLEO, Argentina). Obviously, in light of such observational indications, all NMDB data should undergo a thorough additional analysis. We believe that in the course of this analysis, the tendency of SEP spectra to steepen with increased energy (Miroshnichenko & Perez-Peraza 2008) should be taken into account. Anyway, those simple estimates of solar proton spectra for several recent SEP events give serious evidence that the event of 2012 May 17 was really the first GLE of solar cycle 24.

The value of $\alpha$ (or $\gamma$) obtained above seems to be typical for shock wave acceleration (e.g., Ellison & Ramaty 1985; Zank et al. 2000). However, as noted by Berezhko & Taneev (2003), in both of the above-mentioned papers, the authors considered a plane wave approximation case that does not allow us to take into account the finite size of the shock wave and its temporal dependence. Such an approximation is applicable to a bulk of accelerated particles in the vicinity of the shock, but it is broken in the range of ultimate energies where the spectrum undergoes an exponential cutoff (see the left panel of Figure 9). In fact, this approach results in the significant softening of the particle spectrum and a decrease in their maximum energy.

On the other hand, Kuwabara et al. (2012) recently derived the spectrum of relativistic solar protons for the GLE71 based on the data from a large Antarctic installation called IceTop Cherenkov detectors. They found that the differential spectral index varies from $\alpha \sim 4.3$ (pulse phase) to $\alpha \sim 4.9$ (broad enhancement phase). This is consistent with the estimates of Vashenyuk et al. (2011) who found that the values of differential spectral index for a DC of different GLEs are distributed from 4 up to 6. These authors attributed it to the stochastic acceleration in turbulence plasma, which may be connected to an expanding CME.

### Table 1

| Event       | $I_{>100\text{MeV}}$ (pfu) | $I_{>500\text{MeV}}$ (pfu) | $I_{>1000\text{MeV}}$ (pfu) | $I_{>433\text{MeV}}$ (pfu) | Spectral Index ($\alpha$) |
|-------------|----------------------------|-----------------------------|-----------------------------|-----------------------------|--------------------------|
| 1972 Aug 4  | $1.0 \times 10^6$          | $2.0 \times 10^6$           | $1.0 \times 10^6$           | 0.1                        | 3.0 \times 10^6          |
| 2012 Jan 27 | 796                        | 32                          | 8                           | 2.0                        | n/a                      |
| 2012 Mar 7  | 6530                       | 305                         | 70.5                        | 2.0                        | n/a                      |
| 2012 May 17 | 222                        | 62                          | 23                          | 2.2                        | 7.1 \times 10^{-4}       |

**Notes.** $I$ is the integral intensity of solar protons by the GOES 13 data. $I^{*}$ is derived by real NM data. n/a indicates no NM data available.

5. SUMMARY AND DISCUSSION

In this study, we combine a wide range of data sets, specifically in situ particle measurements, ground-based detections of SCRs, and remote-sensing solar observations, to identify the acceleration source(s) for electrons and protons during the first GLE event of solar cycle 24. The SPR times of the two species are derived and compared with the associated flare and CME phenomena. Detailed data on the solar eruptions are investigated and related to the possible particle acceleration source(s) by analyzing event timing, particle energy spectrum, etc.

Data analysis leads to the following results and main conclusions: (1) the SPR time of near-relativistic electrons is derived to be 01:29 ± 0:00:01 UT and the IMF path length is 1.25 ± 0.05 AU. (2) The impulsive injection phase of electrons, as indicated by the dramatic change of the spectral index, is consistent with the flare non-thermal emission and the type III radio bursts. (3) The PFSS-modeled open-field lines rooted in the AR provide escape channels for the flare-accelerated electrons. (4) Whereas, the GLE proton injection takes place at 01:39 ± 00:02 UT, which is ∼10 minutes later than the electrons injection. (5) The GLE proton injection time is in accordance with a type II radio burst and prominence eruption, which drives a high speed CME. (6) The GLE protons, with an estimated kinetic energy of ∼1.12 GeV, are probably accelerated by the CME-driven shock when it travels to ∼3.07 $R_{\odot}$.

Those preliminary results imply that, in general, our findings still cannot give a certain self-consistent scenario for GLE71. In particular, more accurate estimates of spectral properties of SEPs are needed, taking into account the interplanetary propagation of accelerated particles. Also, it would be timely to note that up to now the present solar cycle develops rather limply. Faint proton emissivity of the Sun in the first years of the cycle 24 may be evidence of the specific nature of this cycle, which, most likely, is a turning point in the course of solar activity of the current cycle. This is consistent with the estimates of Vashenyuk et al. (2011) who found that the values of differential spectral index for a DC of different GLEs are distributed from 4 up to 6. These authors attributed it to the stochastic acceleration in turbulence plasma, which may be connected to an expanding CME.

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