AN INTERPRETATION OF GLE71 CONCURRENT CME-DRIVEN SHOCK WAVE

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ABSTRACT

Particle accelerations in solar flares and CME-driven shocks can sometimes result in very high-energy particle events (≥1 GeV) that are known as ground level enhancements (GLEs). Recent studies on the first GLE event (GLE71 2012 May 17 01:50 UT) of solar cycle 24 suggested that CME-driven shock played a leading role in causing the event. To verify this claim, we have made an effort to interpret the GLE71 concurrent shock wave. For this, we have deduced the possible speed and height of the shock wave in terms of the frequency (MHz) of the solar radio type II burst and its drift rate (MHz min−1), and studied the temporal evolution of the particle intensity profiles at different heights of the solar corona. For a better perception of the particle acceleration in the shock, we have studied the solar radio type II burst with concurrent solar radio and electron fluxes. When the particle intensity profiles are necessarily shifted in time at ~1 AU, it is found that the growth phases of the electron and cosmic ray intensity fluxes are strongly correlated (>0.91; >0.87) with the frequency drift rate of the type II burst, which is also consistent with the intensive particle accelerations at upper coronal heights (~0.80 R_s < 1.10 R_s). Thus, we conclude that the CME-driven shock was possibly capable of producing the high-energy particle event. However, since the peaks of some flare components are found to be strongly associated with the fundamental phase of the type II burst, the preceding flare is supposed to contribute to the shock acceleration process.

Key words: Sun: corona – Sun: coronal mass ejections (CMEs) – Sun: evolution – Sun: flares – Sun: heliosphere – Sun: particle emission

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1. INTRODUCTION

Ground level enhancements (GLEs) are the highest-energy relativistic solar particle events (≥1 GeV) that conspicuously appear as sudden, sharp, and short-lived increases in the cosmic ray intensity. They contain the most high-energy solar particle spectra that represent the strongest acceleration episodes on the Sun. Many years earlier, only solar flares were considered as the particle acceleration process in the Sun, and hence the source of GLE production was ascribed to flares. However, after the confirmation of the occurrence of coronal mass ejection (CME) in 1971 December, scientists (e.g., Tousey 1973; MacQueen et al. 1974; Howard et al. 1982) curiously studied this issue, and over the last ~30 yr a consensus has formed that the shock waves driven by CMEs are also the particle acceleration processes in the Sun (e.g., Chen et al. 1997; Gopalswamy et al. 1998; Cliver et al. 1999), and that the energy released from the CME-driven shock wave might be able to produce high-energy particles. Depending on the concept, many studies have been carried out on GLE events with concurrent solar flares and CMEs (e.g., Cliver et al. 1982; Belov et al. 1985; Shea et al. 1987; Stoker & Makgamathe 1990; Perez-Peraza et al. 1991; Vashenyuk et al. 1993; Kahler 1994; Cramp et al. 1995, 1997; Lovell et al. 1998; Duldig & Humble 1999; Ryan et al. 2000; Duldig 2001; Deely et al. 2002; Bieber et al. 2004; Struminsky 2005; Simnett 2007; McCracken et al. 2008; Fluckiger & Büttiker 2009; Kurt et al. 2010; Firoz et al. 2010, 2011a; Perez-Peraza et al. 2011; Moraal & McCracken 2012; Miroshnichenko et al. 2013).

To identify whether high-energy particle events might be caused by solar flares or CME-driven shocks, several researchers (e.g., Gomez-Herrero et al. 2000; Kocharov & Torsti 2002; Vashenyuk et al. 2006) categorized relativistic solar energetic proton (SEP) events as “prompt events” with strong anisotropic phases and “delayed/extended events” with mild anisotropic phases. On this concept, several other researchers (e.g., Reames 2009; Aschwanden 2012) suggested that the prompt events originate from a narrow range of solar longitudes and the delayed events from a broad range of heliolongitudes. Taking this suggestion into account, Firoz et al. (2012) demonstrated that the prompt event may result from the particle acceleration at relatively low altitudes in the solar corona, whereas the delayed or extended/hybrid events may result from the particle acceleration at higher altitude of the corona. The finding has been generalized by means of some criteria with respect to a possible time line defined in terms of the hardest spectrum of the particle fluxes. Adopting those criteria, Firoz et al. (2013, 2014a) carried out studies over the first ground level enhancement (GLE71) of solar cycle 24 that took place on 2012 May 17 along with an M5.1 solar flare and a high-speed halo CME. They suggested that GLE71 might have resulted from the particle acceleration in CME-driven shock, which had been boosted...
by the energy emanating from the preceding flare components. However, those studies did not have observational evidence for the shock wave to justify the claim, so an interpretation of the GLE71 concurrent shock wave is pending.

In this paper, we interpret the GLE71 concurrent CME-driven shock wave to perceive its possible capability of producing high-energy particles. For this purpose, we use the frequency of an observed radio type II burst and its drift rate to deduce the possible speed and height of the shock. Then, the frequency drift rate is studied with concurrent solar radio flux density and electron flux measurements. The hard X-rays and soft X-rays are also surveyed with the frequency drift rate in order to contemplate any connection between the flare and the shock wave. Finally, the status of the particle acceleration is investigated at different heights of the solar corona.

2. DATA TREATMENT AND ANALYSIS

We have processed the data of the cosmic ray intensity of GLE71 registered by Neutron Monitors (NMs) of the South Pole (SOP) and South Pole Bare (SOPB) situated at an altitude of 2.82 km above sea level in the geographical coordinates of $-90.0^\circ$S (latitude) and 0.0$^\circ$E (longitude). SOP contains lead-shielded detectors (standard 3NM64) with rigidities of 0.10 GV that can detect particles with energies of $\sim$1.44 GeV, whereas SOPB contains unshielded detectors (12 bare counters) with rigidities of 0.10 GV that can detect particles with energies of $\sim$1.35 GeV (Abbasi et al. 2012; Bieber et al. 2013). The data have been collected from the Neutron monitor database (NMDB)$^8$ center (e.g., Mavromichalaki et al. 2011). (More details on the data analysis of GLE71 are given in Firoz et al. 2014a.)

To hypothesize the cause of the GLE, the most important concept is to visualize the mechanism of particle acceleration processes that can be comprehended by studying the temporal evolution of electron particle fluxes and concurrent solar radio bursts. With this aim, the data of electron fluxes of several energy bands ($\sim$27 keV, $\sim$40 keV, $\sim$66 keV, $\sim$108 keV, $\sim$182 keV, $\sim$310 keV, and $\sim$517 keV) recorded by the “Three-Dimensional Plasma and Energetic Particles experiment (3DP)” instrument on board the Wind$^9$ spacecraft (e.g., Lin et al. 1995) are analyzed with radio bursts recorded by Wind-WAVES$^{10}$ (e.g., Bougeret et al. 1995). The WAVES radio instrument on board the Wind spacecraft has three radio receivers (RAD1, RAD2, and TNR) that cover the frequency range from 4.0876 kHz to 13.825 MHz. We have employed the data of the first Radio Receiver Band (RAD1) and the second Radio Receiver Band (RAD2). RAD1 has a frequency range of $\sim$0.02 to $\sim$1.040 MHz with 256 channels, a 3 kHz bandwidth, and 7 nV/(Hz)$^{1/2}$ sensitivity. RAD2 has a frequency range of 1.075–13.825 MHz with 256 channels, a 20 kHz bandwidth, and 7 nV/(Hz)$^{1/2}$ sensitivity.

To better understand the solar radio bursts with the particle acceleration processes (flare & CME-driven shock), we have compared the low-/high-frequency (MHz) solar radio flux density (SFU) with the solar flare components (SXR and HXR) and the CME-driven shock. We retrieved the X-ray fluxes from RHESSI$^{11}$ (e.g., Lin et al. 2002) for five different energy channels (12–25 keV, 25–50 keV, 50–100 keV, 300–800 keV, and 800–7000 keV) and SXR fluxes from GOES/NOAA$^{12}$ (e.g., Aschwanden & Freeland 2012), while the data of the solar radio flux densities (245 MHz, 410 MHz, 610 MHz, 1000 MHz, 2695 MHz, 4000 MHz, 8800 MHz, 9000 MHz, and 17000 MHz) were obtained from NRO$^{13}$ (e.g., Nakajima et al. 1985) and from RSTN$^{14}$ (e.g., Yue et al. 2013).

The radio observations in composite dynamic spectrum together with solar radio flux density (SFU), high- (hard X-rays), and low-energy (soft X-rays) flare components are compiled with the concurrent cosmic ray and electron particle fluxes (see Figure 1). (An artificial offset is attributed to the electron times.) Since the particles travel a path much longer ($>1.1$ AU) than the path (1 AU) traveled by the radio and X-ray emissions, from a pragmatic viewpoint, it is important to shift the temporal profiles of particle fluxes at $\sim$1 AU. To shift the particle profiles, it is necessary to determine the possible velocity of particles in each energy band, and for this we have exploited the relativistic equations employed by Firoz et al. (2011b, 2014a). After shifting the cosmic ray proton and electron particle fluxes by the difference in travel times to the Earth, the resultant data have been interpolated. To view all of the data together at $\sim$1 AU, the interpolated particle fluxes are composed once again with the hard X-rays, soft X-rays, radio flux, and radio emission burst (see Figure 2).

To visualize the structure of the coronal mass ejection (CME), we have inspected images of the GLE71 concurrent CME observed by the Large Angle Spectrometric Coronagraph (LASCO) C2 on board the Solar and Heliospheric Observatory. The LASCO instrument consists of a set of three coronagraphs (C1, C2, and C3). C2 is a traditional white-light coronagraph that we have used to envisage the possible connection with the shock wave (e.g., Chen 2009). Details can be found in the catalog of the Coordinated Data Analysis Workshop$^{15}$ (Yashiro et al. 2004). The evolution of CME has been visualized by using LASCO image data obtained from the Virtual Solar Observatory (VSO)$^{16}$ (Hill et al. 2009). In this regard, two of the running difference images are displayed in Figure 3.

3. DETERMINATION OF THE POSSIBLE SPEED OF THE SHOCK WAVE

Shock waves are generally simplified in terms of a slow drift toward decreasing frequencies in solar radio type II bursts. The frequency of the type II burst and its drift rate can be used to deduce the kinematics of the shock (e.g., Robinson & Stewart 1985; Mann et al. 1999, 2003; Vršnak 2001; Nindos et al. 2011). Accordingly, the frequency drift of the type II burst observed in Figure 1(f) has been exploited to determine the possible shock speed as follows:

$$V_{sh} = \frac{Df}{\beta(f)} ,$$

where $\beta(f) = \left( \frac{df}{dN_e} / \frac{dN_e}{dr} \right)$ and $D_f = \frac{df}{dt}$.

Here, $N_e$ is the electron density in the solar radio type II burst, $r$ is the distance from the Sun (heliocentric distance), $f$ is the frequency in the radio type II burst, and $V_{sh}$ is the shock speed assumed radial. The frequency drift rate ($D_f$) at any given
Figure 1. During the GLE71 event (2012 May 17 01:50 UT). (a) Increase rate (Ir%) of the cosmic ray intensity (CRI) registered by the Neutron Monitors of the South Pole (SOPO) and South Pole Bare (SOPB). (b) Left y-axis: hard X-ray (HXR) flare components of several energy bands (12–25 keV, 25–50 keV, 50–100 keV, 300–800 keV, 800–7000 keV). Right y-axis: soft X-ray (SXR) flare components. SXRL (1–8 Å) is the SXR of the longer wavelength and SXRS (0.5–4 Å) is the SXR of the shorter wavelength. (c) Solar radio flux density (SFU) from NRO13 for the frequency of 1000 MHz, 2000 MHz, 4000 MHz, 9000 MHz, and 17,000 MHz. (d) Solar radio flux density (SFU) from RSTN15 for the frequency of 245 MHz, 410 MHz, 610 MHz, 2695 MHz, and 8800 MHz. (e) Solar radio bursts (1.075–13.825 MHz) registered by the second Radio Receiver Band (RAD2) of WIND-WAVES. Its type II burst is synthesized over a tiny stripe at lower frequency marked by “II,” while the type III burst is not clear enough to be identified. (f) Solar radio burst (∼0.02 to ∼1.040 MHz) registered by the first Radio Receiver Band (RAD1) of WIND-WAVES. The lane between the two vertical lines is the apparent duration of the type III burst while the lane between the two curved lines is the apparent duration of the prominent phase of type II bursts. The fundamental (F) and harmonic (H) lanes are ignited with downstream and upstream electron perturbations, respectively. (g) Electron fluxes of seven energy bands (∼27 keV, ∼40 keV, ∼66 keV, ∼108 keV, ∼182 keV, ∼310 keV, and ∼517 keV). An artificial offset is attributed to the electron times. The dotted line (parallel to the y-axis) is drawn with respect to the lowest value of the spectral indices determined by employing those electron fluxes following the power-law spectrum (Firoz et al. 2012, 2014a). (In Figure 1, we displayed the raw data in which cosmic ray proton/electron particles traveled ∼1.51 AU along the spiral magnetic field lines from the Sun to the Earth (Firoz et al. 2014a), whereas electromagnetic radiation components (X-rays, radio flux, radio burst) traveled 1.0 AU straight from the Sun to the Earth at the speed of light. 1 AU ≈ 1.5 × 10¹⁴ km.)
Figure 2. All of the data of Figure 1 are rearranged at ~1 AU in Figure 2. The data of the cosmic ray and electron particle fluxes are shifted at ~1 AU and interpolated. The interpolated particle fluxes are then composed with the data of the electromagnetic radiation components (hard X-rays, soft X-rays, radio flux, and radio emission burst). (The procedure of how to shift particle fluxes at ~1 AU has been explained in the data analysis; Section 2.)

(A color version of this figure is available in the online journal.)
time is directly proportional to the instantaneous speed of the propagating shock wave. (Details of the mathematical solution and analysis procedure are given in the Appendix.)

4. OBSERVATION AND DISCUSSION

4.1. Propagation Nature of Solar Particles and Electromagnetic Radiations

In general, the temporal profiles of GLE particles are associated with short-lived (minutes to hours) X-ray and solar radio flux increases (e.g., McCracken et al. 2012). However, in essence, there is a distinction in the propagation nature of particles and solar radio flux/X-rays that should be taken into account for better precision. For instance, both X-rays and radio emissions are electromagnetic radiation that travel at the speed of light in a straight line directly from the source to the observer unaffected by magnetic field lines, so they take about 8.3 minutes to travel the path length of 1 AU from the source above the solar photosphere to the detectors in Earth’s orbit for X-rays and on Earth’s surface for the radio signals. On the other hand, the GLE particles travel at much less than the speed of light and follow the magnetic field lines along the Parker spiral and hence take a much longer time to reach the detectors on Earth. Accordingly, the temporal profiles displayed in Figure 1 are the raw data in which cosmic ray proton and electron fluxes are supposed to have traveled a path length of \( \sim 1.5 \times 10^8 \) km.

Because of the difference in path length, there occurs a significant time delay between the electromagnetic radiation components (hard/soft X-rays, solar radio flux, radio burst) and concurrent cosmic ray proton/electron particle fluxes. This is clearly visible in Figure 1. So, the comparison of the electromagnetic radiation components with particle fluxes shows the near simultaneity of the temporal evolution of the particle and radio fluxes. This is shown in Figure 2. The temporal evolution of particle fluxes displayed in the figures (Figures 1 and 2) can be distinguished by the onset time variation as well as by the spectral indices (e.g., Firoz et al. 2012). More importantly, the particle fluxes at \( \sim 1 \) AU can be scrutinized with the radio type II burst to assess the possibility of the high-energy particle production in the CME-driven shock acceleration. In such case, it is useful to apply a polynomial fitting procedure (e.g., Mavromichalaki et al. 2013) ideally when the growth (ascending) phases of the particle intensity profiles match the course of increasing frequency drift rate of the radio type II burst (Firoz et al. 2014b).

4.2. Trends of the Temporal Evolution of Solar Particles

The temporal evolution of the cosmic ray particles exposes both anisotropy and isotropy trends (Figures 1(a) and 2(a)). The beginning phase is anisotropic when the particles are believed to move directly toward the magnetic field lines without undergoing any scattering, whereas, near maximum phase, the evolution becomes practically isotropic when the particles suffer scatterings due to resonant interactions with magnetic field turbulence in the interplanetary medium (e.g., Sáiz et al. 2005, 2008; Dorman 2006, 2008; Firoz et al. 2014a). Hence, we have taken into account the particle propagation that varies depending on the energy level. Accordingly, since the probable energies of the particles detected by NMs at SOPO and SOPB are 1.44 GeV and 1.35 GeV, respectively (Abbasi et al. 2012; Bieber et al. 2013), there would have been a small difference in propagation times along the interplanetary magnetic field lines leading to a fractional time difference in the onsets of the time profiles of cosmic ray particles at SOPO and SOPB (Figures 1(a) and 2(a)).

In contrast, the temporal evolution of the electron particles of different energy bands exposes different onset times with relatively weak anisotropic phases (see Figures 1(g) and 2(g)). The amplitudes of keV electron fluxes are smaller than those of the GLE GeV proton fluxes. This is likely because the particles of keV energy traditionally undergo less scattering than the GeV particles. Those electrons of different energies (\( \sim 27 \) keV, \( \sim 40 \) keV, \( \sim 66 \) keV, \( \sim 108 \) keV, \( \sim 182 \) keV, \( \sim 310 \) keV, \( \sim 517 \) keV) are assumed to originate from the same source, but delayed in the interplanetary medium because of the different velocities (e.g., Cane et al. 2002). As the propagation of particles varies depending on the energy, velocity dispersion for different...
energy bands occurred, and thus the growth phase (including the peak) of each energy band differs.

4.3. Possible Relation between the Solar Flare and Concurrent Solar Radio Flux

Solar radio emissions arise from bremsstrahlung when energetic electrons are accelerated in the chromosphere. The same accelerated electrons precipitated into the chromosphere are responsible for the generation of the bremsstrahlung hard X-rays. Hence, the temporal evolution of solar-radio-emitting electrons and hard-X-ray-emitting electrons can show similar trends (e.g., Raulin et al. 1999; Ning et al. 2009; White et al. 2011; Huang & Li 2011; Firoz et al. 2012). Thus, the relationship between hard X-ray and radio flux can be used to investigate the flare electron acceleration.

As observed (Figure 2(f)), the type III radio emission generated by the propagation of nonthermal keV electrons from lower corona toward the upper corona shows a rapid frequency drift of $\sim$1.2 MHz in $\sim$5 minutes, and is concurrent with the peak of the solar radio flux components. In this regard, we have checked the low- and high-frequency solar radio fluxes with the low- and high-energy solar flare components (Figures 2(b)–(d)) and found that the peak (01:39 UT) of the high-energy (>300 keV) flare components are $\sim$3 minutes earlier than the peak (01:36 UT) of the high-frequency (>800 MHz) solar radio fluxes. In contrast, the peak (01:40–01:41 UT) of the lower-energy (<300 keV) flare components are $\sim$1–2 minutes earlier than those (01:42 UT) of the lower-frequency (<800 MHz) solar radio flux. Thus, we have recognized that the peak of the high-frequency solar radio flux component is earlier than that of the low-frequency solar radio flux, and similarly, the flash phase of the high-energy flare component is earlier than that of the low-energy flare component. The flash phase of the high-energy flare component corresponds closely in time with the peak phase of the high-frequency radio flux, thereby suggesting a common origin.

4.4. CME and Shock Wave During the Event

Coronal mass ejection (CME) is the spurt of magnetized gas produced during a massive burst of solar wind in the solar corona. It is the most energetic large-scale manifestation that can drive a shock wave outward and provide energy continuously throughout the propagation of the wave (e.g., Liu et al. 2009). Therefore, it is essential to survey the coronal mass turbulence in order to visualize the CME-driven shock wave.

It is observed (Figure 3) that the GLE71 concurrent CME was a very fast ($\sim$1582 km s$^{-1}$) halo CME that erupted with a bright front in the northwest (N13°W83°) from the center of the solar disk. The CME first appeared in LASCO C2 at 01:48:05 UT as a spectacular ring of dense plasma with a leading edge that expanded outward and apparently exceeded the local magnetosonic fast mode velocity, indicating that a shock wave could have formed (e.g., Hundhausen et al. 1987; Reiner et al. 2000; Liu et al. 2008). An insight into the animation of the coronal plasma turbulence, we have witnessed that the nascent stage of the CME was at $\sim$01:31 UT, while the shock (as shown by the type II burst) began at $\sim$01:38 UT and lasted for a longer duration until at least $\sim$04:00 UT, stating a wide heliolongitude ($\sim$41°) with a prominent phase at $\sim$01:40–02:20 UT (see Figure 2(f)).

The solar radio type II bursts appear in two frequency bands drifting from higher to lower frequencies which evolve over time while most emission is synthesized in the form of plasma as a consequence of the shock wave (e.g., Shanmugaraju et al. 2009; White et al. 2011). Likewise, the emission mechanism of type II bursts (Figure 2(f)) demonstrates that the narrowband radio emissions drifted downward in frequency, thereby showing that the plasma density decreased with increasing heliocentric distance. Thus, it is observed that the prominent phase of the type II burst showed a frequency drift of $\sim$0.6 MHz through 0.2 MHz with increasing temperature toward the upper corona. (Note that some light areas seen in the type II burst have occurred presumably due to solar ultraviolet emission; e.g., Reiner et al. 2007.)

For a comprehensive outlook, we have verified the consistency of the composites of type II bursts with the leading edge of the CME (Figure 3), which was in extreme plight with expanding dimmings, and associated with the type II burst, implying that the shock wave was driven by the concurrent CME. In this respect, the frequency (MHz) of the type II burst has been deduced for those two lanes of the type II burst (Figure 2(f)) by utilizing Equation (1) and examined with the sequent evolution of the CME. It is observed that the fundamental phase of type II bursts lies within $\sim$01:38 to 01:44 UT, while the harmonic phase lies within $\sim$01:45–02:00 UT. The prolonged type V burst conjugated the fundamental phase of a type II burst. The frequency drift for the fundamental type II burst started at $\sim$01:38 UT and began for the harmonic type II burst at $\sim$01:45 UT. Data obtained over these two phases by means of a curve fitting procedure are displayed in Figures 4(a1-b1). The harmonic phase of this type II burst seems to have split into more than one trace. However, we have exploited the first harmonic phase (curved line marked by “H”) for this study. (The second harmonic phase seems to have undergone suppression through fragmentation with complex split bands; hence, it was too ambiguous to analyze for the study.)

4.5. Possible Relation Between the Shock Wave and the Concurrent Solar Radio Flux

It is found that most of the peaks of solar radio flux density components are more or less in coincidence with the high-energy flare peaks and the prominent phase of the type III burst, whereas the descending phases exist over the type II burst (see Figure 2). For this reason, we have checked for correlations between the frequency of the type II burst and simultaneous solar radio flux (SFU) components in order to determine if any flare component had any possible scope of contributing to the shock acceleration (see Figure 5). (A few spikes seen in the solar radio flux density components before and after the actual peaks have occurred presumably because of flare energy fragmentation; e.g., Fleishman & Melnikov 1998.)

The fundamental phase of a type II burst is typically a lower frequency phenomenon than a type III burst. As the fundamental phase of the type II burst appeared as a continuous succession of the type III burst (Figure 2(f)), the peaks of some solar radio flux components can be related to the fundamental type II burst. This is compatible with the results (Figure 5) that (except 2000 MHz) all of the growth phases (including peaks) of the solar radio flux components have strong correlations (0.858–0.939) with the simultaneous frequency of the fundamental type II burst, hinting that the principal drifting phase of the type II burst is associated with the flare. In contrast, the harmonic type II burst has mostly strong correlations (0.851–0.939) with the concurrent phases (peaks plus some parts of the descending phases) of the solar radio flux components, even though spikes of a few components
occur during the harmonic phase. Therefore, it is reasonable to argue that a contribution of the energy emanated from the preceding flare to the shock is not an unexpected occurrence (e.g., Firoz et al. 2014a).

Furthermore, the peak (01:47 UT) of the low-energy flare component (SXRL) of the longer wavelength is about 6–8 minutes later than the high-/higher-energy (HXR) flare components. The association of the fundamental phase of the type II burst with the flare implies that the preceding flare contributed to the shock wave. In fact, the low-energy flare seems to have made contributions to the shock process, as the frequency drift rate of the type II burst maintained strong correlations with
Figure 5. Linear correlations between GLE71 concurrent solar radio flux density (SFU) components and frequency (MHz) of the radio type II burst are exhibited. (The frequency (MHz) data along the x-axis are the same data exhibited in Figure 4(a1)-(b1).) Here, the data of the frequency (MHz) of the type II and simultaneous SFU (MHz) components over a time span of 90 minutes are chosen for the linear correlation: (a) The frequency (MHz) of the radio type II burst starting at 01:38 UT over the fundamental phase and simultaneous SFU (MHz) components. (b) The frequency (MHz) of the radio type II burst starting at 01:45 UT over the harmonic phase and simultaneous SFU (MHz) components.
simultaneous SXR emission. (For the fundamental type II, the polynomial correlations between the frequency drift rate and simultaneous SXRL and SXRS are 0.957 and 0.993, respectively. For the harmonic type II, the correlations are 0.975 and 0.992, respectively.) Thus, we point out that when the flare flash phase is considered in relation to the peaks of the SXR components, the type II is well correlated with the solar flare. (NOAA12 considers the flare flash phase in relation to the SXRL peak; e.g., Aschwanden & Freeland 2012). However, if the flare flash phase is considered in relation to the peaks of the HXR components, then the type II burst is not strongly related to the flare.

4.6. Possible Relation between the Shock Wave and Electron Fluxes

Electrons originating from the shock acceleration process can be characterized from the solar radio type II burst. Generally, a propagating shock creates electron beams and excites Langmuir waves (plasma oscillations), which, in turn, convert into radio waves at the fundamental and harmonic of the local plasma frequency as observed in type II radio bursts (e.g., McTiernan et al. 1993; Mancuso & Abbo 2004; Shanmugaraju et al. 2006). So, the correlation between the frequency drift rate of the type II burst and concurrent electron flux measurements should be surveyed for a better perception of the particle acceleration in the shock wave.

The drift behavior in the type II burst satisfies the density model (Equation (A3) in the Appendix) that the electron density \( n_e \) varies with respect to the altitude in the solar corona, implying that the density decreases as the coronal height increases. Thus, the drift from higher to lower frequencies signifies that, at the time of upward propagating beams, the plasma frequency at lower altitude is stronger than at the higher altitude of the corona. This is further evident in the observational data analysis (Figures 2, 4, and 6) that the frequency of the type II follows the course of decreasing electron fluxes, while the frequency drift rate matches the course of increasing electron fluxes. To clarify the evidence, the polynomial fit has been applied over a suitable time window \( (n = 35) \) covering growth phases of both electron fluxes and drift rate, started from 01:38 UT for the fundamental type II burst and from 01:45 UT for the harmonic type II burst. The fundamental type II that existed over a relatively short time \( (<10 \text{ minutes}) \) refers to the most prominent phase, while the harmonic type II that existed for a long time \( (>30 \text{ minutes}) \) refers to the phase when the upstream of the shock wave is supposed to occur at the time of its propagation from the corona to the interplanetary space.

In practice, the electron fluxes are strongly correlated with both the fundamental and the harmonic of the type II burst. Since the time for the harmonic phase mostly covers the growth phase, including some data points at the beginning of the descending phase, the polynomial best-fit line did not agree with all the data points of the temporal evolution, so the correlations \( 0.916–0.978 \) are weaker than those \( 0.956–0.991 \) over the fundamental phase (often associated with peaks of some flare components and type V burst), which is the precursor phase that initiated the development for the harmonic phase (see Figure 6). Above all, the strong correlations between type II bursts and concurrent electrons suggest that the energetic particles could be generated in the shock process.

The growth phases of keV electron fluxes are intimately related to particle acceleration in the solar corona. Thus, the evolution of the intense phases of electron fluxes at different heights of the solar corona may show the status of the acceleration. As observed (Figure 7), the electron particle acceleration started at an altitude of \( \sim0.80 \text{ Rs} \) and underwent intensive evolution at an altitude of \( \sim0.90 \) to \( \sim1.10 \text{ Rs} \). The descents of the electron (keV) fluxes are found after \( \sim1.10 \text{ Rs} \) when the particles are supposed to have started traveling toward the interplanetary space.

4.7. Possible Relation between the Cosmic Ray Intensity and Shock

As reported in earlier sections (4.4–4.6), the source of the GLE71 concurrent type II bursts is the CME-driven shock in which high-energy particles are produced. In principle, the shock wave extends over a wide range of heliolongitude, and hence the particle acceleration in the shock process can plausibly persist for longer durations. As the shock is simplified in terms of the frequency (MHz) of radio type II bursts, we have checked the frequency drift rate (MHz min\(^{-1}\)) with the concurrent cosmic ray intensity at \( \sim1 \text{ AU} \). This is because the frequency drift rate matches the course of the temporal evolution of the growth phase of the cosmic ray intensity. Furthermore, it is observed that the intensive frequency drift rates of the fundamental and harmonic phases of the type II burst lie within the growth phase of the cosmic ray intensity. This extends the idea of looking into the polynomial correlation between the frequency drift rate and the cosmic ray intensity at \( \sim1 \text{ AU} \) (see Figure 8).

It is found (Figure 8) that the correlations between the cosmic ray intensity and frequency drift rate over a fundamental phase vary within 0.918–0.961, while over the harmonic phase they vary within 0.866–0.935. (The strong correlations of GLE71 with the frequency drift rate of type II bursts indicate that the shock might be capable of producing high-energy particles). Although both phases maintained strong correlations, on average, the fundamental phase was a little better. This is likely because of the synergy that the fundamental phase conjugated the prolonged prominent phase of type V bursts, whereas the harmonic phase did not (e.g., Hamidi et al. 2012). This can be better understood when particle acceleration is investigated at different heights of the solar corona (see Figure 9).

As found (Figure 9), the ascending/growth phase of the cosmic ray particle was strongly associated with the particle acceleration in the corona at an altitude of \( \sim0.80 \) to 1.05 \( \text{Rs} \), while it started to descend after \( \sim1.05 \text{ Rs} \). Thus, the propagation of the particles started to decrease as soon as they entered the interplanetary medium and interacted with the spiral magnetic field lines. Since the shock driven by the CME commenced at \( \sim01:38 \text{ UT} \) (Section 4.4), it is conceivable that the beginning of the growth phases of electrons and protons (Figures 7 and 9) are nearly concomitant with the onset \( \sim01:38 \text{ UT} \) of the shock (see also Figure 2). (Note that the Newkirk density model (Newkirk 1961) does not satisfy the particle acceleration analysis precisely beyond the heights of \( \sim1.4 \text{ Rs} \) in the solar corona. However, we have found the growth phases of cosmic ray proton/electron fluxes existing before 1.10 \( \text{Rs} \), so the investigation on the evolution of GLE71 concomitant particle acceleration in the corona is evidently reliable.)

5. SUMMARY

We have illustrated the GLE71 concurrent CME-driven shock, which seems to have played a principal role in causing the event. To carry out the investigation, we have processed...
Figure 6. Polynomial correlations of the frequency drift rate (MHz min$^{-1}$) of the type II burst with concurrent electron (keV) fluxes: (a) over the fundamental phase of the type II burst starting at 01:38 UT, and (b) over the harmonic phase of the type II burst starting at 01:45 UT. (The data of the electron (keV) fluxes at ∼1 AU shown in Figure 2 and the data of frequency drift rate (MHz min$^{-1}$) shown in Figure 4 (a2)-(b2) are processed here for the time windows from 01:38 to 02:13 UT and 01:45 to 02:20 UT.)
the solar radio type II burst and deduced the frequency (MHz) and frequency drift rate (MHz min$^{-1}$) as functions of time and related them to the possible speed and height of the shock wave. To clarify the particle acceleration in the shock, we have studied the frequency (MHz) and frequency drift rate (MHz min$^{-1}$) of the type II burst as functions of the time with simultaneous solar radio flux and proton/electron flux components. Thus, we have proposed an approach to verify the possibility of energetic particle production in the CME-driven shock. The key results of this study are summarized as follows.

Figure 7. Temporal evolution of electron particles at different heights of the GLE71 concurrent CME-driven shock: (a) the fundamental phase of the type II burst starting at 01:38 UT, and (b) the harmonic phase of the type II burst starting at 01:45 UT. (The data of the electron (keV) fluxes at $\sim$1 AU shown in Figure 2 and the shock height ($R_s$) shown in Figure 4(a4)-(b4) are processed here over time windows from 01:38 to 02:13 UT and 01:45 to 02:20 UT. $R_s \approx 6.955 \times 10^5$ km.)
1. Intensive particle accelerations evidently took place in the upper corona \( (\sim \geq 0.80 R_S < 1.10 R_S) \), whence the CME \( (\sim 1582 \text{ km s}^{-1}) \) erupted and subsequently energized the shock wave.

2. The time evolution of the frequency drift rate of the solar radio type II burst matches the course of growth phases (including peaks) of the cosmic ray particle fluxes corrected to their point of origin. This concept helps to evaluate the possibility of producing energetic particles by the shock acceleration.

3. Strong correlations \( (>0.91) \) between the frequency drift rate \( (\text{MHz min}^{-1}) \) of the radio type II burst and the concurrent electron (keV) fluxes measured at \( \sim 1 \) AU are suggestive of the possibility of energetic particle production in the shock acceleration process.

4. Growth phases (including peaks) of some flare components maintained very strong correlations \( (>0.95) \) with the fundamental of the type II burst, indicating that the flare flash phase was associated with the start of the shock acceleration. The fact is otherwise conceivable that the principal drifting bands of the type II burst overlapped with the earlier type III burst.

5. The peaks of several solar radio flux density (SFU) components coincide with the onset of the type II burst, and most of the growth phases (including peaks) of the SFU components maintained strong correlations \( (>0.95) \) with the fundamental phase of the type II burst, thus inferring that the preceding flare might have the scope to contribute any fractional amount of energy to the CME-driven shock wave.

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Figure 9. Temporal evolution of cosmic ray particles at different heights of the GLE71 concurrent CME-driven shock: status of the Cosmic Ray Intensity (CRI) registered by the Neutron Monitors at SOPO and SOPB over (a) the fundamental phase (starting at 01:38 UT) of type II burst, (b) the harmonic phase (starting at 01:45 UT). (The data of the CRI at ∼1 AU shown in Figure 2 and the shock height (Rs) at 1 AU shown in Figure 4(a4)-(b4) are processed here over time windows from 01:38 to 02:08 UT and 01:45 to 02:15 UT. 1 Rs ≈ 6.955 × 10^5 km.)

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APPENDIX

Shock Speed: The time derivative of the frequency (f) of the type II burst is the frequency drift rate (df/dt), which is simplified as follows.

\[
D_f = \frac{df}{dt} = \left( \frac{dN_e}{dr} \right) \left( \frac{dr}{dt} \right) = \left( \frac{df}{dN_e} \right) \left( \frac{dN_e}{dr} \right) \cdot V_{sh} \tag{A1}
\]

Type II emissions appear at the fundamental plasma frequency (f), which is directly proportional to the square root of the electron plasma density (N_e), i.e.,

\[
f = \sqrt{\frac{e^2 N_e}{\pi m_e}} \quad \text{(e.g., Smerd et al. 1962)}.
\]

Hence, \( N_e = \frac{f^2 \pi m_e}{e^2} \) and

\[
\frac{df}{dN_e} = 1 \frac{2N_e}{dN_e} \sqrt{\frac{e^2 N_e}{\pi m_e}} = \frac{1}{2} \times \frac{f}{N_e}, \tag{A2}
\]

where \( m_e \) is the electron mass and \( e \) is the elementary charge.
From Newkirk (1961), $N_e = N_0 \times 10^{4.32R_s/r}$, where $R_s$ is the radius of the Sun and $r$ is the shock height.

So, $\frac{4.32R_s}{r} = \log_{10}\left(\frac{N_e}{N_0}\right)$ and $\frac{dN_e}{dr} = -\frac{4.32R_s}{r^2} \times N_e \log_{10} e$ (A3)

Putting Equations (A2) and (A3) into the Equation (A1), the frequency drift rate is as follows:

$$D_f = -\left(\frac{f}{\log_{10} e \times 8.64R_s}\right) \left[\log_{10}\left(\frac{f^2 \pi m_e}{N_0 e^2}\right)^2\right] V_{sh}.$$ (A4)

So, the shock speed is $V_{sh} = \left(\frac{D_f}{\beta(f)}\right)$.

Where $\beta(f) = -\left(\frac{f}{\log_{10} e \times 8.64R_s}\right) \left[\log_{10}\left(\frac{f^2 \pi m_e}{N_0 e^2}\right)^2\right].$

Shock Height: Using Equations (A2) and (A3), we can determine possible shock height as follows.

$$r = \frac{4.32R_s}{\log_{10}\left(\frac{f^2 \pi m_e}{\pi N_e}\right)}$$

By applying curve fitting on the spectral profile of the radio frequency in the type II burst (Figure 2(f)), we have obtained the data of frequency $(f)$ for the fundamental phase. It is noteworthy that the harmonic plasma frequency is supposed to be twice the fundamental plasma frequency (e.g., Reiner et al. 2000), and, accordingly, possible speed and height of the shock wave has been computed for both the fundamental and harmonic phases.

For constant parameters, the well-known values have been exploited for the computation $[N_0 = 4.2 \times 10^6 (\text{cm}^{-3}); R_s \approx 6.955 \times 10^{10} (\text{cm}); m_e \approx 9.109 \times 10^{-28} (\text{g}); e \approx 4.803 \times 10^{-10} (\text{e.s.u.})].$

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