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Solar Energetic Particle Event of 2005 January 20: Release Times and Possible Sources *

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Abstract Based on cosmic ray data obtained by neutron monitors at the Earth's surface, and data on near-relativistic electrons measured by the WIND satellite, as well as on solar X-ray and radio burst data, the solar energetic particle (SEP) event of 2005 January 20 is studied. The results show that this event is a mixed event where the flare is dominant in the acceleration of the SEPs, the interplanetary shock accelerates mainly solar protons with energies below 130 MeV, while the relativistic protons are only accelerated by the solar flare. The interplanetary shock had an obvious acceleration effect on relativistic electrons with energies greater than 2 MeV. It was found that the solar release time for the relativistic protons was about 06:41 UT, while that for the near-relativistic electrons was about 06:39 UT. The latter turned out to be about 2 min later than the onset time of the interplanetary type III burst.

Key words: Sun: flare – Sun: particle acceleration – shock acceleration – interplanetary propagation

1 INTRODUCTION

Solar energetic particles (SEPs), or solar cosmic rays (SCRs), as known, are particles accelerated at/near the Sun to the energies from $\geq$10 keV SEP events to $\geq$10 GeV Ground Level Enhancements (or GLE events) (e.g., Reames 1999; Miroshnichenko 2001). There are pieces of evidence that a coronal mass ejection-driven (CME-driven) shock can accelerate particles to energies above 100 MeV (e.g., Reames 1999; Le & Han 2005; Le 2006). As regards particles in GeV range, there are still different points of view on the acceleration mechanism. Cliver et al. (1982) have analyzed 32 GLEs, and the conclusion was that flares but not shocks are responsible for the acceleration of the GeV particles. Their proof was that the solar release time (SRT) for the particles with GeV energy at the Sun was near the peak time of the first significant microwave burst (FSMB).

Kahler (1994) also studied the relationship between the solar release times of GeV particles and the height of the CME. He found that the SRT for particles with energy from 470 MeV to 4 GeV was not earlier than the peak time of the flare impulsive phases, while the peaks of the 470 MeV to 4 GeV injection profiles occurred when the associated CMEs reached the heights of 5–15 solar radii. It should be noted that Kahler (1994) took into account the transit time; however, the transport distance for particles travelling along the interplanetary magnetic field (IMF) line from the Sun to the Earth was simply set to 1.3 AU.

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Bieber et al. (1995, 2002–2005) calculated the release time of particles of ∼GeV energy using a focused transport equation with an injection function. One important result in their research is that the path length of a particle travelling from the Sun to the Earth is much longer than 1.3 AU. Also, Cohen (2003) pointed out that many studies have demonstrated that the real length for Sun-Earth magnetic connection line is much longer than 1.3 AU. For example, in the event of 2003 October 28 the path length of relativistic solar protons (RSPs) was estimated to be 2.2 AU (Miroshnichenko et al. 2005a). Recently, Sáiz et al. (2005) discussed the SEP injection timing, and their conclusion was that the estimated path length can deviate greatly from the actual path length for particles passing along magnetic field lines between the Sun and the Earth. Their point of view is basically in favor of that the real path length travelled by charged particles from the Sun to the Earth is larger than the length of the nominal Parker field line.

The study of travelling time (or path length) and solar release time for SEPs is very important for understanding the acceleration mechanism of the SEPs. Whether a flare plays an important role in a large SEP event is still in debate (Reames 2002; Kallenrode 2003; Cane & von Rosenvinge 2003; Mewaldt et al. 2003; Simnett 2006; Cane et al. 2006). Until now, using the time method (Bieber et al. 2002, 2004; Tylka et al. 2003; Gopalswamy et al. 2005), no evidence has been found that flares can produce relativistic particles. Based on the results obtained for the GLE of 2000 July 14 (the Bastille Day Event, BDE), Tylka et al. (2002, 2005, 2006) insisted on that it is CME-driven shock that accelerates relativistic solar protons (RSPs).

Different from this conclusion, Tang & Dai (2003) argued that the BDE is a large gradual event with a prompt impulsive component. Recently, Li & Tang et al. (2006) studied magnetic reconnection in this event, and estimated a maximum induced electric field of E ∼13.0 Vcm $^{-1}$. The amplitude evolution of this field correlated in time with the evolution of hard X-ray and γ-ray emission, indicating that induced electric field may play an important role in the acceleration of non-thermal particles. Given the maximum E ∼13.0 Vcm^{-1}, an acceleration length $\sim 7.0 \times 10^7$ cm is needed to accelerate the protons to ∼ GeV energies in the reconnection current sheet by the DC electric field. The ratio of the acceleration length to the whole filament length in this event is 10^{-2}. Therefore, the reconnection electric field probably makes a crucial contribution to the acceleration of relativistic particles and the impulsive component of the large gradual SEP events. In the case of GLE of 28 October 2003, Tylka et al. (2005) and Gopalswamy et al. (2005) again insisted that the CME-driven shock accelerated solar protons to relativistic energies; meanwhile Miroshnichenko et al. (2005a) concluded that the flare was responsible for the acceleration of the RSPs.

On 2005 January 20 the NOAA active region 10720 produced an X7.1/2B flare (N12, W58); the associated CME was observed by LASCO C2 (Gopalswamy et al. 2005). A very strong GLE was registered at the Earth's surface soon after the flare. This GLE has now been extensively investigated by many researchers (Belov et al. 2005; Kuznetsov et al. 2005; Labrador et al. 2005; Mewaldt et al. 2005; Gopalswamy et al. 2005; Simnett 2006). In particular, Gopalswamy et al. (2005) studied the relationship between the CMEs and GLEs for 14 GLEs of the solar cycle 23 (1996–2005), and their general conclusion is that CME-driven shocks are responsible for the acceleration of relativistic protons in all those GLEs, including the event of 2005 January 20. This conclusion is just based on the CME onset time and on the coronal shock having been formed before the solar release time of the RSPs. Their main reasons, in the particular case of the 2005 January 20 event, are that 1) the CME highest sky-plane speed exceeded 3000 km s $^{-1}$, and 2) the metric type II radio burst, which is a signature of coronal shock, had already formed before the GLE onset. However, there are two questions that have not been answered.

The first one is: How quickly were the SEPs accelerated to relativistic energies? And the second question is: Why CME-driven shock stopped to produce relativistic particles after a few minutes in the event under consideration? This dilemma was also pointed out by Simnett (2006). By using the data of hard X-rays, gamma-rays, radio bursts and SEPs, Simnett (2006) analyzed the spectral index of the electrons in GLE event of 2005 January 20, and his conclusion was that the relativistic particles had been produced by the flare.

The main goals of the present study are to determine the solar release times (SRTs) for the SEPs produced in the event of 2005 January 20 and to estimate the acceleration effect of the interplanetary (IP) shock on the solar energetic protons and electrons. Section 2 comprises the observational data obtained by several neutron monitors (NMs) and two near-Earth satellites (GOES 10 and WIND) that are used in the present study. In Section 3 we describe the method of analysis and present the results of our determination of the SRT of the relativistic protons. The results of a similar analysis are given in Section 4 for near-relativistic electrons measured by the satellite WIND. Section 5 is devoted to a possible acceleration effect of the IP shock on the solar protons with energies up to 700 MeV and on the solar electrons with energies greater than 2 MeV. Our results and conclusions are summarized in Section 6.

2 OBSERVATIONAL DATA

On 2005 January 20 the NOAA region 10720 located at (N12, W58) produced an X7.1/2B-class flare. It started at 06:36 UT and peaked at 07:01 UT (Fig. 1). After several minutes, the worldwide network of neutron monitors (NMs) at the Earth' surface registered a very large GLE (Figs. 2–3). Also, two satellites, GOES-10 and GOES-11 measured intensive fluxes of SEPs in the energy range 9–700 MeV (Fig. 4). Intensity-time profiles observed by several neutron monitors are shown in Figures 3–4. Solar electron flux in the energy range of 127–225 keV was measured, in particular, on board the WIND satellite (Fig. 5). It is important to note that all these data show a strong impulsive phase. Figure 6 shows solar energetic electron fluxes measured by GOES 10 at relativistic energies > 2 MeV on January 20–21.

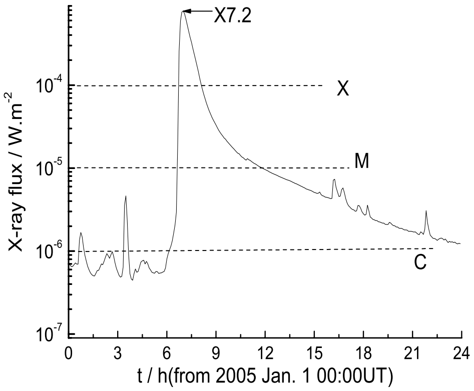

Fig. 1 Solar flare of X7.1 importance observed on 2005 January 20 by GOES 10.

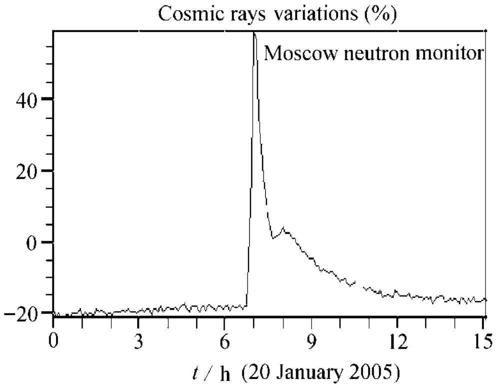

Fig. 2 Variation of cosmic ray intensity observed at the Moscow neutron monitor (IZMIRAN).

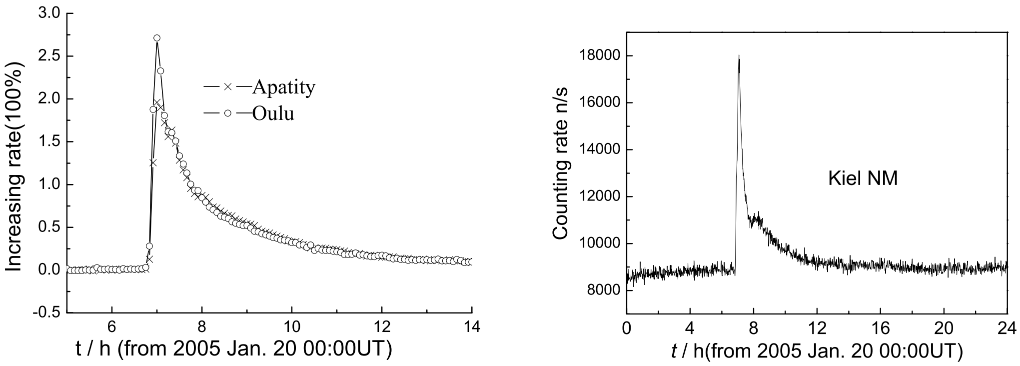

Fig. 3 Variations of cosmic ray intensity observed at three neutron monitors (Apatity, Oulu and Kiel stations).

As noted by Kahler (1994), the interplanetary magnetic field (IMF) has a minimal effect on particles with energies greater than 500 MeV. So, the data obtained by neutron monitors are often used to study the solar release time of relativistic particles. To estimate the onset time of first arriving particles, we use a standard deviation σ given by the formula

$$\sigma = \sqrt{\sum_{i=1}^{N} (x_i - \bar{x})^2 / N}, \tag{1}$$

where x_i and $\bar{x}$ are the current and background values of measured quantity, respectively, and N is the number of measurements (experimental records). The estimation is based on the particle intensity greater than $\bar{x} + 2\sigma$ (e.g., Tylka et al. 2003; Mewaldt et al. 2003; Miroshnichenko et al. 2005b). By using this method we can obtain the onset times of the relativistic protons from the data observed by the several neutron monitors (Figs. 2–3), as well as the onset time of the near-relativistic electrons (127–225 keV) from the data observed by the satellite WIND (Fig. 5).

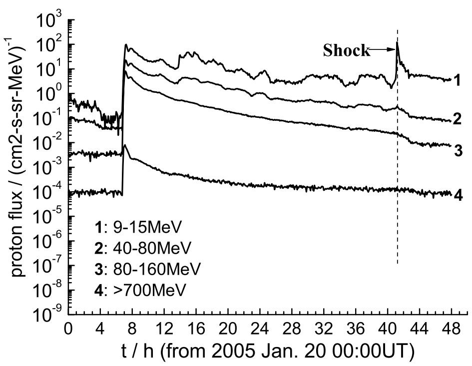

Fig. 4 Solar energetic proton fluxes observed by the GOES 10 on 2005 January 20.

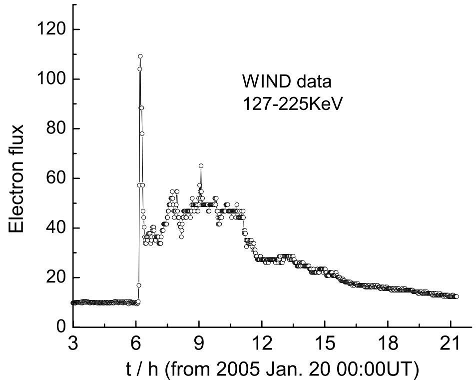

Fig. 5 Electron flux in the energy range of 127–225 keV observed by the WIND satellite on 2005 January 20.

The solar wind speed for the previous day (January 19) was typically between 600 km s $^{-1}$ to 800 km s^{-1} (ACE data archive), so Simnett (2006) estimated the nominal length of the IMF line to be 1.1 AU. Assuming the relativistic particles traveled 1.1 AU along the spiral field line with no scattering from the Sun to the Earth, we obtain their release time,

$$t_{\rm sonset} = t_{\rm gonset} - 1.1\,{\rm AU}/v\,, \tag{2}$$

where v is the particle velocity, $t_{\rm sonset}$ and $t_{\rm gonset}$ are, respectively, the solar release time (SRT) and onset time of these relativistic particles at the Earth's orbit. The values of $t_{\rm gonset}$ and v being known, one can estimate the solar release time $t_{\rm sonset}$.

3 NEUTRON MONITOR DATA ANALYSIS

Besides the energy units E (eV, MeV or GeV), for cosmic ray particles, units of rigidity R (V, MV or GV) defined as follows are commonly used

$$R = pc/Ze\,, \tag{3}$$

where c is the speed of light, p and Z are the particle momentum and charge number, respectively, and e is the electron charge. The relationship between the total energy $(E_k + E_0)$ and particle rigidity R is (e.g., Miroshnichenko 2001),

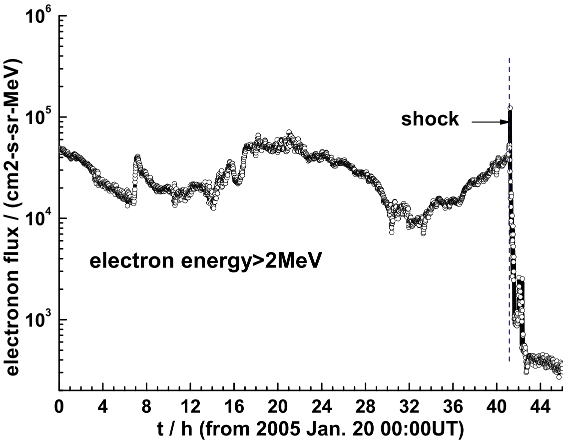

Fig. 6 Solar energetic electron flux ($> 2\,\mathrm{MeV}$) observed by GOES 10 on 2002 January 20–21.

$$E_0 + E_k = \left[(m_0c^2)^2 + p^2c^2\right]^{1/2} = \left[E_0^2 + (ZeR)^2\right]^{1/2}, \tag{4}$$

where E_k and E_0 are the kinetic energy and particle rest energy, respectively, and m_0 is the particle rest mass. It is timely to write here two other useful working expressions

$$E_k = \frac{-2E_0 + \sqrt{4E_0^2 + 4(ZeR)^2}}{2}, \quad v = \frac{\sqrt{E_k^2c^2 + 2E_km_0c^4}}{E_k + E_0}. \tag{5}$$

We can obtain the particle velocity and the time needed for particle to travel from the Sun to the Earth based on the particle rigidity or energy (Eqs. (3)–(5)) and the length of the Sun-Earth magnetic filed line. Also, from the onset time and travelling time of a particle from the Sun to the Earth, one can estimate the solar release time of the particle.

The onset time and peak time of relativistic protons recorded by Apatity NM on 2005 January 20 were 06:53 UT and 07:04 UT, respectively. The corresponding times at Oulu and Kiel stations were, 06:51 UT and 07:00 UT, and 06:51 UT and 07:04 UT, respectively. Note that Moscow NM has the highest cutoff rigidity ($R_c = 2.43$ GV) among the four NMs, so we analyze below only the solar release time of relativistic protons registered by this station (IZMIRAN).

According to Equation (5), the lowest energy of a relativistic proton which can reach Moscow NM is no lower than 1666.8 MeV. The onset time of the relativistic protons observed by Moscow NM was 06:51 UT. The time needed for the RSPs travelling from the Sun to the Earth is at least 9.8 min for the 1.1 AU path length. So, the solar release time (SRT) for the relativistic particles was about 06:41 UT on January 20, which was before the peak time (06:53 UT) of the X7.1 flare (Fig. 1).

4 ANALYSIS OF ELECTRON DATA

Near-relativistic electrons (127–225 keV) were detected on January 20 (Fig. 5) by the satellite WIND located on a small "halo" orbit, about the sunward Sun-Earth gravitational equilibrium point (L1), varying from 235 to 265 Earth radii (*http://cdaweb.gsfc.nasa.gov/cgi-bin/eval2.cgi*). The location of the satellite was about 256.4 Earth radii from the earth (G. C. Ho 2006, private communication) during the solar flare X7.2 . The satellite was obviously outside the magnetosphere during the GLE event. The onset time of those electrons occurs at about 06:54 UT, and their SRT was about 06:39 UT assuming that the nominal path length was 1.1 AU. The time information for the GLE of 2005 January 20 is summarized in Table 1. Also given parameters of the hard X-rays (HXR), CME, interplanetary (IP) type III radio emission at the

Table 1 Characteristic Times of the GLE of 2005 January 20

Solar or IP emission	Energy	Onset time (UT) at 1 AU	Travelling time min	Solar release time (UT)
NM (2.43 GV)	1666.8 MeV	06:51	9.8	∼06:41
NM (2 GeV)	2.000 MeV	06:49	9.6	06:39
Electrons	127–225 keV	06:54	15.27	<06:39
Electrons	∼ 250keV	06:57	12.2	06:45
Soft XR (1–8Å)	∼ 12.5–1.5 keV	06:36	8.3	06:28
Hard XR	40 keV	06:38	8.3	06:30
Gamma Rays	4–7 MeV	06:44	8.3	06:36
CME		>06:40		06:32
14 MHz (IP)		06:45		06:37

frequency of 14 MHz (IP), gamma-rays in the energy range of 4–7 MeV, and SRT values were estimated by Simnett (2006).

Our results differ considerably from that of Simnett (2006). Note, however, that Simnett (2006) analyzed the data on near-relativistic electrons (∼175–300 keV) detected at around 06:57 UT by the EPAM instrument on the ACE spacecraft, that was ∼8 min after the proton onset. As is known, ACE orbits the L1 libration point which is about 1.5 million km from the Earth and 148.5 million km from the Sun. According to our estimate, the SRT of near-relativistic electrons (127–225 keV) by the satellite WIND data was no later than 06:39 UT, which is about 6 min earlier than that obtained by Simnett (2006) (06:45 UT) for the electrons of ∼250 keV.

Based on the NM data (mainly on the data of the South Pole NM), Simnett (2006) also gave the onset and solar release times (06:49 and 06:39 UT, respectively) for the relativistic protons of 2 GeV. Because the nominal cutoff rigidity of South Pole (R_c = 0.09 GV) is much lower than that of Moscow (R_c = 2.43 GV), the lowest energy of a proton, which can reach the South Pole NM, must be lower than 2 GeV. So, the SRT of relativistic protons obtained by Simnett (2006) might be questioned.

Note also that Simnett (2006) used a nominal path length of 1.1 AU. In fact, due to atmospheric cutoff in the polar regions (e.g., Miroshnichenko 2001), effective energy of primary protons registered by the South Pole NM is not less than 500 MeV ($R \geq 1$ GV).

5 EFFECT OF INTERPLANETARY SHOCK

The CME-driven shock associated with the X7.1/2B flare of 2005 January 20 reached the magnetosphere and caused an intensive magnetic storm with the lowest value of D_{st} index of -121 nT at 07:00 UT on January 21 (WDC-2 Kyoto D_{st}Service Center, http://swdcdb.kugi.kyoto-u.ac.jp/dstdir/). According to the geomagnetic storm report from Beijing Geomagnetic Observatory, the sudden commencement of the severe geomagnetic storm (K_p = 8) was at January 21, 17:11 UT. Based on the GOES-10 data (Figs. 4 and 6), it is of interest to analyze here the SEP acceleration by interplanetary (IP) shock. The dotted vertical lines in Figures 2 and 4 show the moment when the IP shock driven by the CME was passing through the magnetosphere.

From Figure 4 it is clearly seen that a sudden and obvious enhancement occurred in solar proton intensity in the channel 9–15 MeV, and then the proton intensity decreased when the IP shock passed though the magnetosphere. Also, we can note that the change in the solar proton intensity was negligible in the energy range 80–160 MeV. There were almost no variations in the energy channel of $>$ 700 MeV. This may be considered as clear evidence that the IP shock had certain acceleration effect on the solar protons with energies 9–15 MeV and very small effect in the energy range of 80–165 MeV (average 130 MeV). Moreover, in this particular case the IP shock had almost no acceleration effect on the solar protons with energies greater than 700 MeV. From the GOES-10 data (Figure 6), it is also clearly seen that a sudden and obvious enhancement occurred in the solar electron intensity for energies greater than 2 MeV, and then the electron intensity decreased sharply with time when the IP shock passed though the magnetosphere.

6 SUMMARY AND DISCUSSION

As a summary of our results, we note that the solar release time for relativistic protons on 2005 January 20 was about 06:41 UT, and the SRT for near-relativistic electrons (127–225 keV) was no later than 06:39 UT. This was about 2 min later than the onset time of the 14 MHz type III burst and slightly earlier than SRT of relativistic protons. According to our analysis, the SEP event under discussion was a mixed one, with IP shock accelerating mainly solar protons with energies below 130 MeV. The IP shock had an obvious effect of acceleration on relativistic solar electrons with energies greater than 2 MeV.

As is known (e.g., Lin 1985), impulsive electron events are often flare-related. From Figure 5 it is seen that the electron flux of 127–225 keV had a very sharp impulsive phase. The intensity-time profiles of RSPs registered by many NMs also have a similar spike structure. This structure may be strong evidence that the RSPs were accelerated by the solar flare of 2005 January 20. By analyzing the spectral indexes of the electrons in the energy range of $\sim$175–300 keV by the ACE spacecraft data, Simnett (2006) came to the conclusion that both near-relativistic electrons and RSPs had been accelerated by the flare.

Why did Simnett (2006) obtain that the protons were injected about 8 min before the electrons? As it was already noted in Section 3, one of the reasons might be that the slowest relativistic protons which can reach the South Pole NM are not effective at energies $\sim$2 GeV, but at considerably lower energies. In fact, all the high-latitude NMs (those with geomagnetic cutoff rigidities below 1 GV) have an essentially identical cutoff (about 1 GV), which is determined by the atmosphere absorption only (e.g., Miroshnichenko 2001; Bieber et al. 2002). The other reason is that the SRT for the near-relativistic electrons (127–225 keV) was no later than 06:39 UT (as it was obtained by us), which is about 6 min earlier than the 06:45 UT given in the paper by Simnett (2006). The locations of the satellites WIND and ACE were about 256.4R_e and 235.4 R_e, respectively, away from the Earth along the Sun-Earth connective line. So, both satellites should detect solar electrons almost at the same time.

If a flare starts to accelerate protons and electrons from the same time instant by direct electric field, then, because of their large mass difference, the electrons should reach 127 keV earlier than the protons reach 1.67 GeV. Therefore, our finding of near-relativistic electrons having been released from the Sun about 2 min earlier than relativistic protons, may reveal that the particle acceleration in the flare is due to direct electric field. Because the real path traveled by the RSPs is generally longer than the length of the nominal Parker spiral field line (e.g., Cohen 2003), the SRT of near-relativistic electrons may be earlier. Assuming that the SRT of near-relativistic electrons can not be earlier than the onset time of IP type III burst, the earliest of the SRT of accelerated electrons can not be earlier than 06:37 UT, which corresponds to a path length of 1.23 AU. This also implies that the SRT of the RSPs can not be earlier than 06:40 UT, which is still later than the peak time of the hard X-rays and the peak time of gamma-ray burst.

So, the solar release time of relativistic protons, which was around 06:41 UT (i.e., about 3 min later than the peak time of the hard X-ray burst and 2 min later than the peak time of the gamma-ray burst), may imply that the earliest solar protons could not be injected into interplanetary space immediately after they obtained their relativistic energies. Mewaldt et al. (2005) pointed out that the timing and energy spectrum of the 2005 January 20 event are consistent with the data (Kuznetsov et al. 2005) on solar gamma rays produced by the particles accelerated in the flare of X7.1 importance. Just based on that the onset time of metric type II burst is earlier than the SRT of relativistic particles only, we cannot deduce that the CME-driven shock is responsible for the acceleration of the relativistic particles. Much more study is needed to understand the acceleration mechanism of relativistic particles.

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