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The peculiar behavior of high-energy particles affected by an interplanetary shock wave

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Abstract: An energetic proton event was observed at a geosynchronous orbit nearly at the same time as an interplanetary shock wave reached the Earth's magnetosphere, which indicates that these two events interacted with each other during their passage to Earth. The behavior of the energetic protons is not explained by the shock acceleration mechanism since no enhancement of the proton flux occurred before the shock wave passage. Taking into account that a solar flare occurred at a well-connected position before the proton event, this flare is a candidate for the origin of the high-energy protons. However, the delay time for the propagation of the energetic particles was too long if those particles were ejected during that solar flare. In this paper, we show that the peculiar behavior of high-energy particles can be explained by the following scenario. The protons produced during a proton flare that occurred after the CME catch up with the CME, enter the turbulent region behind the shock wave, are scattered by an irregular magnetic field there, that is, the Fermi acceleration, and are captured in the turbulent region behind the shock wave. We estimate the increment of the momentum of the protons through the acceleration process and show that the acceleration mechanism considered explains these events. In our scenario, the proton arrival time may be delayed when a coronal mass ejection occurs before the energetic proton event.

1. Introduction

There is much evidence that suggests that energetic particles observed in large gradual solar energetic events are accelerated by the shock waves driven by coronal mass ejections (CMEs). Kahler *et al.* (1984) reported that large solar energetic particles (SEPs) and CMEs were very highly correlated (96%) and Reames *et al.* (1997) found the invariance of the energetic particles spectral shape at different energies (~0.03–6 MeV) and concluded that this invariance of the spectral shape indicated ion acceleration by the shock wave. Lario *et al.* (1998) modeled energetic proton events associated with interplanetary shocks to fit the observed flux, assuming that ions were injected into the interplanetary medium by the shock wave. They found that the efficiency of a shock wave as an injector of accelerated protons decreases sharply above 2–5 MeV. Mason *et al.* (1999) reported that observations of large SEP events pointed to different seed and acceleration mechanisms dominating at low and high energies. Thus, the evidence suggests that low-energy ions, probably up to 3–4 MeV, are accelerated by CME-driven shock waves, while the acceleration mechanism of high-energy ions has not been identified yet.

An enhancement greater than a 5-MeV energy proton flux was observed at a geosynchronous orbit nearly at the same time as an interplanetary shock passed the L1 point on 18 October 1998. This indicates that the interplanetary shock event contributed to an acceleration of the high energy protons. However, taking note of Mason *et al.*'s and Lario *et al.*'s studies, the shock diffusion acceleration of the protons over 5 MeV, in this event, may not have been efficient. Indeed, there was no typical behavior reaction to the shock acceleration for those high-energy protons. Furthermore, an increase of high-energy proton flux does not always occur when a CME-driven shock wave passes Earth. If the shock acceleration is responsible for the enhancement of the high-energy proton flux, that enhancement should be seen as frequently as shock passages, but the frequency of the enhancement of the high-energy proton flux is much smaller than that of the shock passage. Thus, we should seek other origin of those energetic particles. Several energetic solar flares were observed before the proton flux enhancement and could be candidates for the origin of the high-energy protons. It is well-known that the delay time for SEPs can be predicted because the propagation time correlates well with the longitude on the solar surface where a corresponding flare occurs. If the most energetic flare having occurred at west 52 on the solar surface, a so called "well-connected" longitude, was associated with the SEPs, the delay time was too long which is inconsistent with the empirical relations obtained in previous studies. Thus, it is difficult to explain how the high-energy protons interacted with the interplanetary shock, and determine the origin of these protons.

We guess that the energetic protons were accelerated by the Fermi acceleration in the irregular magnetic field behind the shock. This acceleration mechanism is the second order one, so an efficient acceleration of particles cannot be expected. We suppose that there are pre-existing "seed" high-energy particles and their origin is one of energetic flares that occurred before the proton flux enhancement and after a CME-driven interplanetary shock wave, which arrived at almost the same time as the energetic particles. If the high-energy protons were produced in conjunction with one of the energetic flares, these protons would have been ejected after the CME. The propagation of the protons was faster than that of the CME, so these protons caught up with the CME somewhere in interplanetary space. A CME-driven shock wave is thought to form in front of the CME and that there is a turbulent region behind the shock wave. The protons enter the turbulent region and are scattered and accelerated by the interplanetary magnetic field. This field is expected to be irregular because of the turbulence, and the field is strengthened by it. The irregular magnetic field actually plays the role of "a wall" for the Fermi acceleration mechanism. The high-energy protons are surrounded by a lot of "walls" and are accelerated to an extent during the propagation through interplanetary space. If the acceleration time is long enough, their energy can increase to the point where they can escape the turbulent region and the shock wave, since their Larmor radius gets so large that they do not "feel" the shock scale. However, the acceleration time is actually limited at most to the time it takes for the shock wave to reach Earth. Thus, if the acceleration time and energy are insufficient, the particles cannot escape from the CME and the shock wave, and they arrive at the Earth' magnetosphere with the turbulent region.

In this paper, we describe an estimation of the increase of proton momentum through the acceleration mechanism by using a number of assumptions and available observation data. We also investigate the feasibility of our scenario by comparing a mean free path with the Larmor radius. In the next section we report our observational results. In Section 3 we briefly describe the acceleration mechanism, estimate the accelerated momentum, and show that our scenario can explain the phenomena. Section 4 is devoted to discussion.

2. Observational results

On 18 October 1998 at about 2200 UT, the GOES satellite observed an increase in the high-energetic particle flux (> 5 MeV) from its geosynchronous orbit (Fig. 1). At that time the proton flux for channel I1 and the electron flux for channel E1 were affected by the geomagnetic field, thus making it difficult to observe SEPs in these channels. The Preliminary Report and Forecast (PRF) of Solar Geophysical Data published in the U.S. by the Space Environment Services Center (SEC)/National Oceanic and Atmospheric Administration (NOAA) reported an interplanetary shock passage at the L1 point at 1902 UT on 18 October 1998 observed by the Advanced Composition Explorer (ACE)

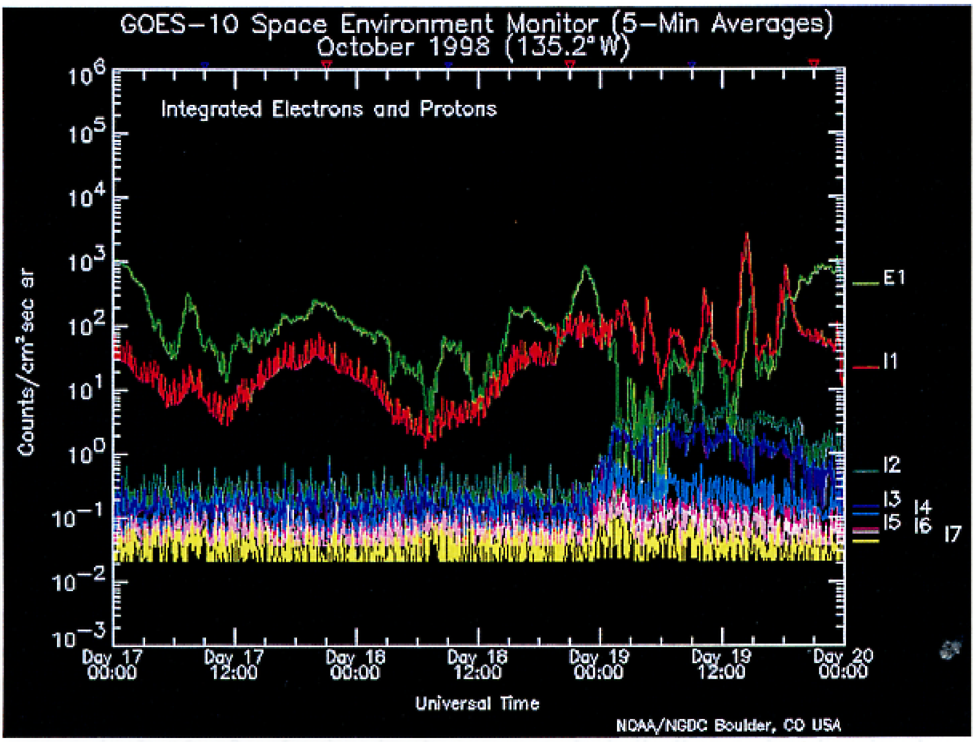

Fig. 1. Time sequence of the proton and electron flux observed by GOES-10 from 18 to 20 October. The proton flux has seven energy channels: I1>1 MeV, I2>5 MeV, I3>10 MeV, I4>30 MeV, I5>50 MeV, I6>60 MeV and I7>100 MeV. The electron flux has one channel, E1>2 MeV.

spacecraft. This shock was associated with the CME observed on 15 October (SWO PRF 1207 20 October 1998), and was driven by the ejecta from the CME. Taking into account the distance between the L1 point and a geosynchronous orbit, approximately 1.5 $\times 10^6$ km, the proton flux increase of over 5 MeV is probably related to the shock wave passage, as written in SWO PRF 1208 27 October 1998. Figure 1 shows that the particles arrived after the shock passage, not preceding it. Figure 2 is plots of the lower energy proton flux, ranging from 47 keV to 5.75 MeV, observed by the Electron, Proton, and Alpha Monitor (EPAM) onboard the ACE spacecraft. Each flux, especially the lower energy proton one, shows typical behavior indicating that the particles were accelerated by the shock wave, that is, an enhancement of the flux began in advance of the shock wave's passage. The particle flux ranging from 71 keV to 2074 keV observed by the WIND spacecraft also shows similar behavior (S. Krucker, private communication, 1999). Thus the over 5-MeV protons apparently were not accelerated by the shock wave. SWO PRF 1207 20 October 1998 also reported that several energetic events were observed in X-ray by the GOES satellite during the period from 1841 UT on 17 October to 0145 UT on 18 October (Fig. 3). The most energetic one was M2.4/1N which occurred in region 8358 (N16W52) at 0145 UT on 18 October. Because no active regions beyond the west limb produced such proton flares, one of these flares can be regarded as the possible origin of the high-energy protons. According to a statistical analysis done by Van Hollebeke *et al.* (1975), the delay time of 20–80 MeV proton

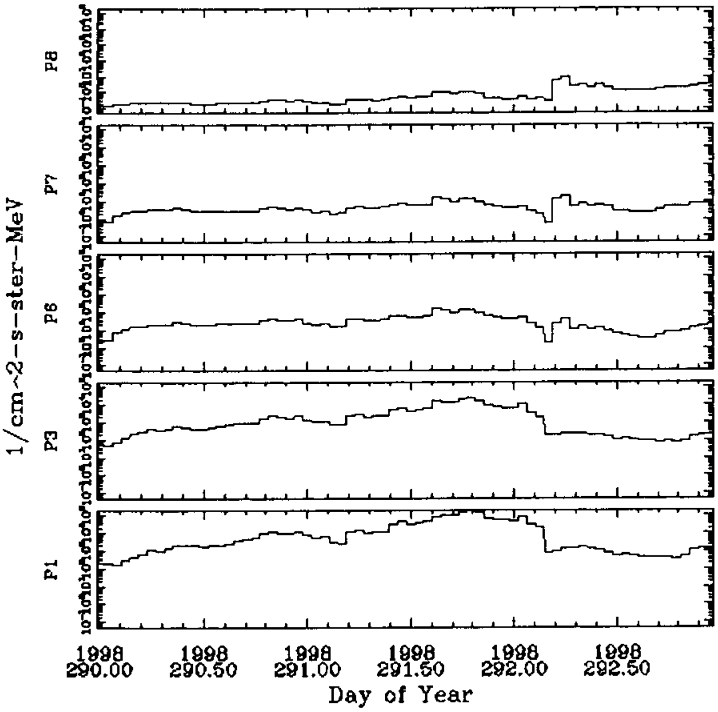

Fig. 2. The proton flux for low-energy channels observed by the EPAM onboard the ACE spacecraft from 17 to 19 October. The channels presented here consist of the five energy range; P1 (47–65 keV), P3 (112–187 keV), P6 (580–1060 keV), P7 (1.06–1.91 MeV), and P8 (1.91–4.75 MeV).

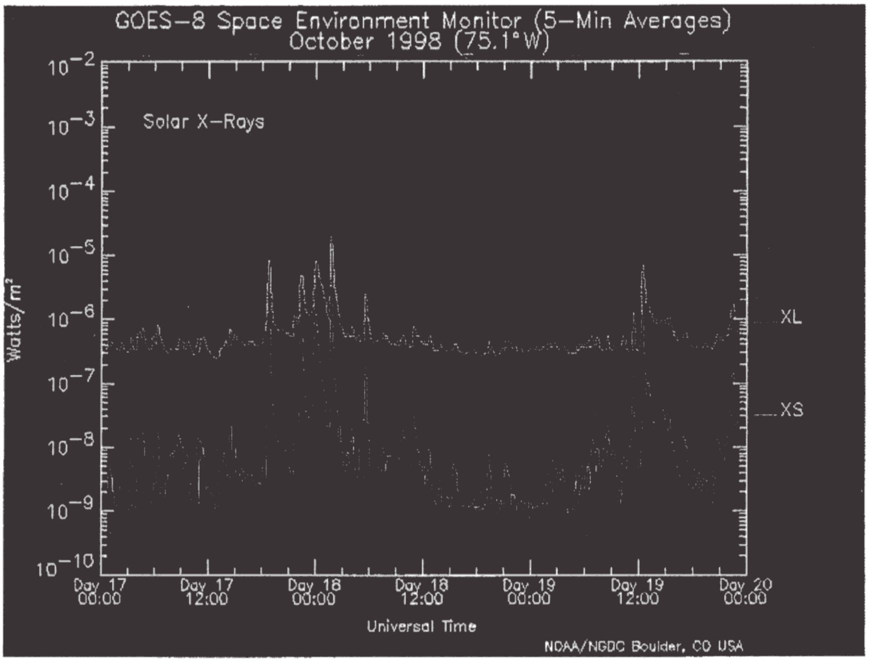

Fig. 3. Solar X-ray plot for three days corresponding to Fig. 1 observed at two wavelengths XL—1–8 angstroms and XS—0.5–4 angstroms by GOES-8.

ejected on west 50 solar longitude was about 1 to 6 hours, while the delay time for the energetic protons that arrived on 18 October, was about 20 hours. The protons ejected in this event took a very long time to propagate. This result is inconsistent with the relations obtained in previous studies

Thus, the source of the high energy protons observed on 18 October cannot be explained by the shock diffusion acceleration, while and the long delay time of these protons was not consistent with the simple relation based on the statistical analysis done in the previous studies if the origin of the protons was one of the energetic solar flares.

3. The acceleration mechanism

According to the Fermi theory of acceleration, the change of momentum P for one particle in unit time is given by

$$\frac{\mathrm{d}P}{\mathrm{d}t} = \frac{4mV_{\mathrm{B}}^2}{\lambda}, \tag{1}$$

(Fermi, 1954) where m, V_{B}, and λ are respectively the proton mass, the velocity of the irregular magnetic field in the frame moving with the shock, and the mean free path of the protons in the turbulent region (see Fig. 4). Equation (1) can be integrated if the λ and V_{B} are assumed to be constant, so the accelerated momentum here is

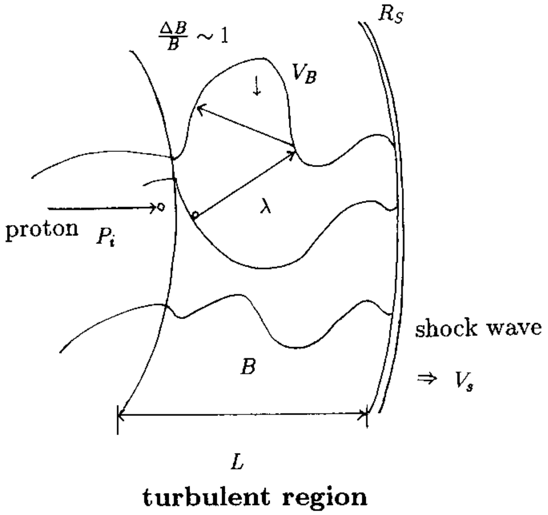

Fig. 4. Schematic drawing of a proton being scattered by the irregular magnetic field formed in the turbulent region behind the shock wave.

$$\begin{aligned} P(t) &= \frac{4mV_B^2}{\lambda}(t-t_i)+P_i \\ &= \Delta P + P_i, \end{aligned} \tag{2}$$

where P_i is the momentum of the protons before entering the turbulent region and t_i is the time when acceleration of the protons started. In this section, we estimate the momentum of the protons that is gained through the process of the acceleration for the events observed on 18 October. The time sequence is shown in Fig. 5: $t=0$ is defined as the time at which a proton flare occurred, $-t_s$ is the time when the shock wave was formed, t_{ent} is the time when the protons produced by the flare process enter the turbulent region, and t_E is the shock passage time at the L1 point. To estimate the maximum increase of momentum acceleration shown in eq. (2), we set $t_i = -t_s$, that is, the protons were accelerated at the same time the CME-driven shock was formed. If the seed protons were produced in one of the several energetic flares that occurred on 17 or 18 October as we assumed, assumption $t_i = -t_s$ is not correct and the acceleration time $t - t_i$ becomes smaller. However, the determination of t_{ent} requires more assumptions since the "initial" momentum, P_i, the distance of the front of the shock wave from the sun, and the width of the turbulent region, L, at t_{ent} should be given to obtain t_{ent}. Additionally, all these variables are time-dependent; they are not given by observations at the L1 point.

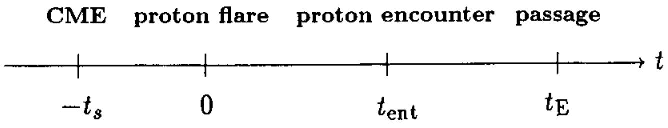

Fig. 5. Time sequence of formation of shock wave (t_s), proton flare (0), encounter of a proton with the turbulent region (t_{ent}), and shock wave passage near Earth (t_E).

We focused on the estimation of the increase of the momentum ΔP and will discuss the dependence of t_{cnt} later. Assuming that the shock wave formation and the CME occurred at the same time, $t - t_{\mathrm{i}} = t_{\mathrm{E}} + t_{\mathrm{s}} \sim 81$ [hour] $= 2.9 \times 10^5$ [s]. The values of V_{B} and λ are very important for determining ΔP. We define V_{B} as $\tilde{V}_{\mathrm{B}} \times 100$ [km/s] using the typical local magnetohydrodynamic speed, and $\tilde{V}_{\mathrm{B}}$ is expected to be O (1). As for λ, L should be obtained because λ must always be less than L. The total intensity of the interplanetary magnetic field (IMF) was observed in the ACE Magnetic Field Experiment (MAG) (Fig. 6a). The turbulent behavior of the irregular magnetic field occurred during the period 291.791667 DOY (the shock passage time) to 292.162419 DOY, about 8.9 hours. The shock wave speed can be obtained from the observational data provided by the ACE Solar Wind Electron, Proton, and Alpha Monitor (SWEPAM) (Fig. 6b) and $V_{\mathrm{s}}(t_{\mathrm{E}}) = 400$ [km/s]. Thus, the order of L at the L1 point is given by $V_{\mathrm{s}}(t_{\mathrm{E}}) \times 8.9$ [hour] $= 1.3 \times 10^7$ [km]. When λ is defined as $\tilde{\lambda} \times 10^7$ [km], $\tilde{\lambda}$ is required to be less than 1.0 for our scenario. With these variables, eq. (2) becomes

$$\Delta P(t_{\mathrm{E}}) = \frac{4m(\tilde{V}_{\mathrm{B}} \times 100\,[\mathrm{km/s}])^2}{(\tilde{\lambda} \times 10^7\,[\mathrm{km}])}(t_{\mathrm{E}} + t_{\mathrm{s}})$$

$$= \frac{\tilde{V}_{\mathrm{B}}^2}{\tilde{\lambda}} \times 2.0 \times 10^{-16}\,[\mathrm{erg/cm/s}]. \tag{3}$$

The increase of the energy is

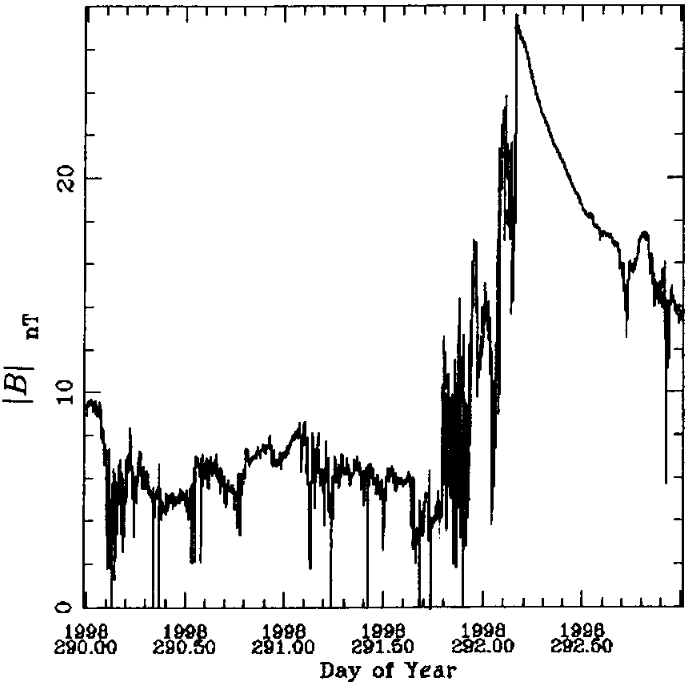

Fig. 6a. Plots of the 16-s averaged magnetic field intensity observed by the MAG onboard the ACE spacecraft for the same period as Fig. 2.

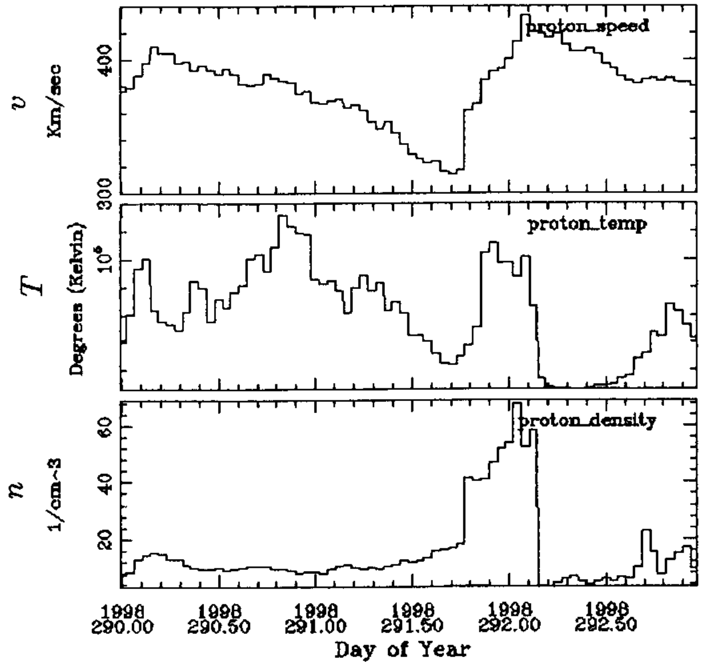

Fig. 6b. Plot of the 1-hour averaged solar wind density, speed, and temperature observed by the SWEPAM onboard the ACE spacecraft for the same period as Fig. 2.

$$\begin{aligned} \Delta E(t_{E}) &= E(t_{E}) - E(t_{i}) \\ &= \frac{P_{i}\Delta P(t_{E})}{m} + \frac{\Delta P(t_{E})^{2}}{2m}. \end{aligned} \tag{4}$$

We think that $\Delta P(t_E)$ is not much larger than P_i because the Fermi acceleration mechanism considered here is not effective, so the first term of the right hand side in eq. (4) cannot be neglected for the accurate estimation. However, an order of the first term is expected to be at most the same as that of the second term and the indeterminate factor of ΔE (t_E) can be absorbed in uncertainty of $\tilde{V}_B$ (see below). Furthermore, we limit λ by using observation data of the occurrence of the enhancement of the proton flux ranging 10 MeV to 100 MeV in the following, which indicates that a factor of each parameter is not important but its order is important in our estimation. Hence we neglect the first term of the right hand side in eq. (4) and define the increase of the energy as

$$\begin{aligned} \Delta E(t_{E}) &= \frac{\Delta P(t_{E})^{2}}{2m} \\ &= \left(\frac{\tilde{V}_{B}^{2}}{\tilde{\lambda}}\right)^{2} \frac{(2.0\times10^{-16})^{2}}{2\times1.7\times10^{-24}} \\ &= \left(\frac{\tilde{V}_{B}^{2}}{\tilde{\lambda}}\right)^{2} 0.7\times10^{4}[\mathrm{eV}]. \end{aligned} \tag{5}$$

The observational data obtained by the GOES satellite constrains $\Delta E(t_{\rm E})$ as

$$10\,[\mathrm{MeV}] \leq \Delta E(t_{\rm E}) \leq 100\,[\mathrm{MeV}]. \tag{6}$$

Substituting eq. (5) into eq. (6),

$$3.7 \times 10 \leq \frac{\tilde{V}_{\rm B}^2}{\tilde{\lambda}} \leq 1.2 \times 10^2.$$

As a factor of each parameter is not important in our estimation as mentioned above, we set $\tilde{V}_{\rm B} = 1.0$. Thus $\tilde{\lambda}$ is limited as

$$0.8 \times 10^{-2} \leq \tilde{\lambda} \leq 0.3 \times 10^{-1},$$

and a limitation for λ is given by

$$0.8 \times 10^5\,[\mathrm{km}] \leq \lambda \leq 3.0 \times 10^5\,[\mathrm{km}].$$

This range for λ is consistent with the condition $\lambda < L$. Accordingly, the momentum of the protons obtained through this acceleration can be shown to be on the order of 10 MeV, by using the appropriate assumptions and observational data. Particles can be scattered effectively if the Larmor radius for these particles and the mean free path are of the same order. We can check the consistency of the order of the mean free path by comparing it with the Larmor radius. Using the 16-s averaged magnetic field intensity, ~15 nT in the turbulent region provided by the ACE MAG data, and the velocity of the protons whose energy is 10 MeV, the Larmor radius $r_{\rm L}$ was 0.3×10^5 km. The order for the mean free path can be said to be same as that of the Larmor radius, thus the 10-MeV protons were scattered effectively by the irregular magnetic field behind the shock wave.

The "start acceleration" time, $t_{\rm i}$, should be $t_{\rm ent}$ for our scenario, but, it is difficult to determine $t_{\rm ent}$ correctly, as we described above. The protons ejected by the energetic proton flares that occurred around west 52 on the solar surface could have caught up with the CME within about 1.3 hours in direct propagation along the garden-hose field even if the CME had almost reached Earth. Thus we assume $t_{\rm ent} = 1.3$ [hour] and giving an acceleration time of $t_{\rm E} - t_{\rm i} = t_{\rm E} - t_{\rm ent} = 17.15 \sim 17$ [hour]. Compared with the former estimation $t_{\rm E} - t_{\rm i} = 81$ [hour], the acceleration time is about one fifth. This change affects the limitation of λ, and the changed limitation is given by 1.8×10^4 [km] $\leq \lambda \leq$ 5.6×10^5 [km]. The values in this range are not inconsistent with the Larmor radius. Thus, the particles in this energy range were scattered effectively in this scenario.

4. Discussion

We proposed a scenario to explain the time sequence of the enhancement of the high-energy proton flux and the shock wave passage. The energetic protons were scattered by the irregular magnetic field in the turbulent region behind the CME-driven shock wave. This is the second order Fermi acceleration; namely, it may not be very efficient for protons to be accelerated up to a high-energy such as 10 MeV. We supposed that there were pre-existing high-energy particles produced by one of the energetic flares observed by the GOES satellite, which occurred after the CME, and that they entered the turbulent region behind the shock wave. As the acceleration was not efficient, they could not attain sufficient energy to escape the turbulent region and thus arrived at Earth almost at the same time as the interplanetary shock, as observed by GOES and ACE. We estimated the momentum of the particles gained through the acceleration by making of a number of assumptions for the shock formation time and the time when the protons entered the turbulent region, and by using the available observation data for the width of the turbulent region and the magnetic field intensity. We limited the range of the mean free path using the observed proton energy range and concluded that our scenario was feasible since the obtained mean free path was consistent with the Larmor radius.

Both the mean free path, λ, and the speed of variation of the irregular magnetic field, V_B, play important roles in the acceleration mechanism, but it is difficult to determine those values precisely. The value λ is probably on the same order as the scale of the irregularity of the magnetic field. This scale may be the wavelength that has the most rapid growth rate in the instability causing the turbulence. Thus, to determine λ, the growth process of the instability should be investigated, but this is beyond the scope of our study. If the pitch angle diffusion coefficient, D_m, can be obtained, we can determine λ using the relation $\lambda = v/D_m$, where v is the particle velocity. This method can give λ directly and may be an effective method for checking our scenario. As for V_B, we simply set an order for this paper, and the theory of the instability causing the turbulence should be used to determine the exact value of V_B. The results obtained in this paper are correct within the scope of an order estimate. To perform a more precise estimate, we need to clarify the physical processes of the turbulence and the formation of the irregular magnetic field, as well as the scattering process of the energetic particles. We will address this in a future work and also try to obtain the pitch angle diffusion coefficient.

Questions may arise, such as how does the same acceleration mechanism act on the solar wind protons and how does the shock diffusion acceleration mechanism act on the high-energy particles studied here. For the former questions, the low-energy (≤ 1 MeV) solar wind particles may be hard to scatter in the turbulent region because their corresponding Larmor radii are smaller than the scale of the irregularity of the magnetic field. As seen in Fig. 2, the low-energy proton flux, ranging from 47 keV to 5.75 MeV, are accelerated by the shock wave efficiently. If they were accelerated by the irregular magnetic field to some extent, this effect may be negligible when compared with the shock diffusion acceleration, since the shock diffusion acceleration is of the first order Fermi acceleration. For the latter question, it is very difficult to find the answer, even though it is possible that high-energy particles escaped through diffusion process, because the Fermi process considered here is statistic. We guess that the irregular magnetic field takes the role of "a magnetic mirror", and there are a lot of "mirrors" in the turbulent region, so the probability for escape of the particles was small. From an observational viewpoint, we remark that if the shock diffusion acceleration acts on high-energy particles, there could be more events exhibiting typical behavior of the shock wave acceleration in the particle flux as seen in solar wind particles events. However, the number of high-energy particle enhancement events associated with an interplanetary shock wave is clearly much smaller than that of a shock wave passage, which indicates shock wave diffusion is not an efficient acceleration process for high-energy particles.

Finally, from viewpoint of space weather, the arrival time of solar energetic protons can be forecast if the region for a corresponding flare is observed. However, the arrival time may be delayed if a CME and the CME-driven shock are propagating at the same time that a proton flare occurs, unless the energy of the protons is sufficiently high, *e.g.*, about one GeV, so that the protons can escape from the turbulent region. Thus, we should note whether or not a CME occurrence precedes a solar proton flare.

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