2-3-5 Solar Proton Event and Proton Propagation in the Earth's Magnetosphere

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Solar proton event is the manifestation of the high-energy protons (Their energy ranges from MeV to GeV.) generated by the solar flare or interplanetary shocks. Researches on the solar protons have a long history, and they have been discussed in this journal several times[1]-[3]. In this paper, we review general topics about the solar proton event first. Then, we focus on the recent progress of the solar proton research, especially the propagation in the earth's magnetosphere.

Keywords
Solar proton event, Propagation, Cutoff latitude, Bow shock, MHD simulation

1 Outline

A solar proton event was originally considered caused by the acceleration of protons due to solar flares (explosions on the solar surface) occurring in solar active regions. After the discovery of coronal mass ejection (CME), however, the occurrence of a solar proton event has also been known to originate from the acceleration of protons due to interplanetary shock waves associated with CME (Fig. 1)[4]. Based on the different rates of

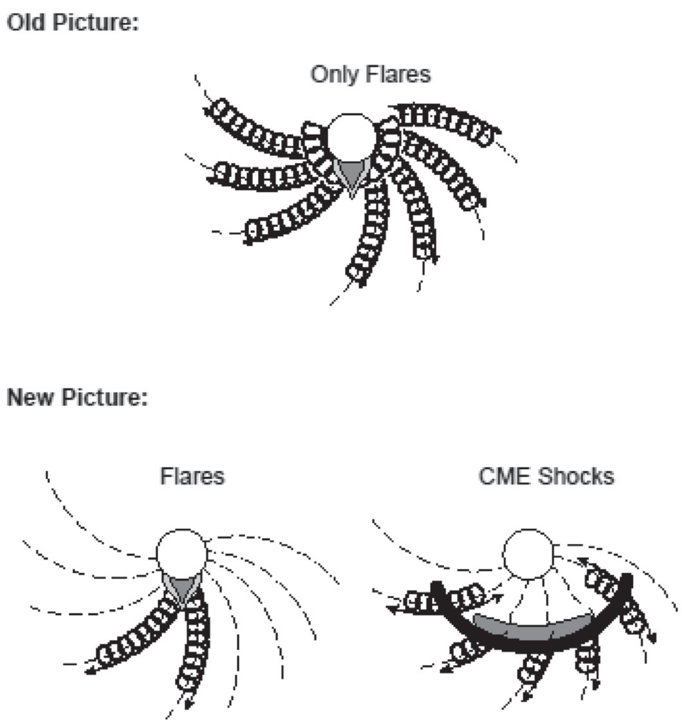

Fig. 1 *Pattern diagram of the acceleration source of solar protons (adapted from[4])*

increase in solar proton flux observed near the Earth, the solar proton event is divided into the gradual and impulsive events (Fig. 2), where proton acceleration originates from flares and shock waves associated with CME, respectively. The gradual event is characterized by a relatively gradual increase in flux, followed by the observation of particles trapped behind the shock waves. Such an event is believed to consist of protons (at 80 to 90%), α particles (10 to 20%), and heavy ions (1%). Compared with the gradual event, the impulsive event exhibits a drastic increase in flux and high percentages of the helium isotope ratio 3He/4He and heavy ions.

The propagation of protons from the Sun to the Earth depends on where a flare occurs on the solar surface and the interplanetary magnetic field. Figure 3 shows how solar proton fluxes are observed on the Earth, depending on the location where a flare occurs on the solar surface and its positional relation with the Earth. For example, a flare occurring on the west side of the Sun results in a drastic increase in flux, while one occurring on the east side entails a relatively gradual increase in flux. In addition, the impulsive event in particular tends to involve the propagation of protons generated by a flare occurring on the west side toward the Earth (Fig. 4). This is attributed to orientation of the interplanetary magnetic field in the direction of the Parker spiral, and the relatively small diffusion of protons in the vertical direction, as protons travel more easily parallel to the magnetic field.

A solar proton event also affects human business activities. High-energy protons generated by a solar flare reach the Earth in 30 minutes to several hours. Some penetrate the magnetosphere, thereby posing a most serious risk to astronauts due to radiation exposure. Moreover, some protons may reach geostationary satellite orbit on the equatorial plane, causing such anomalies as faults in the semiconductors of satellite instrumentation and the deterioration of solar cell panels. The solar proton events that frequently occurred in 1989 significantly deteriorated the solar cells on weather and broadcast satellites, where a single solar proton event caused a level of deterioration equivalent to that over a period of several years.

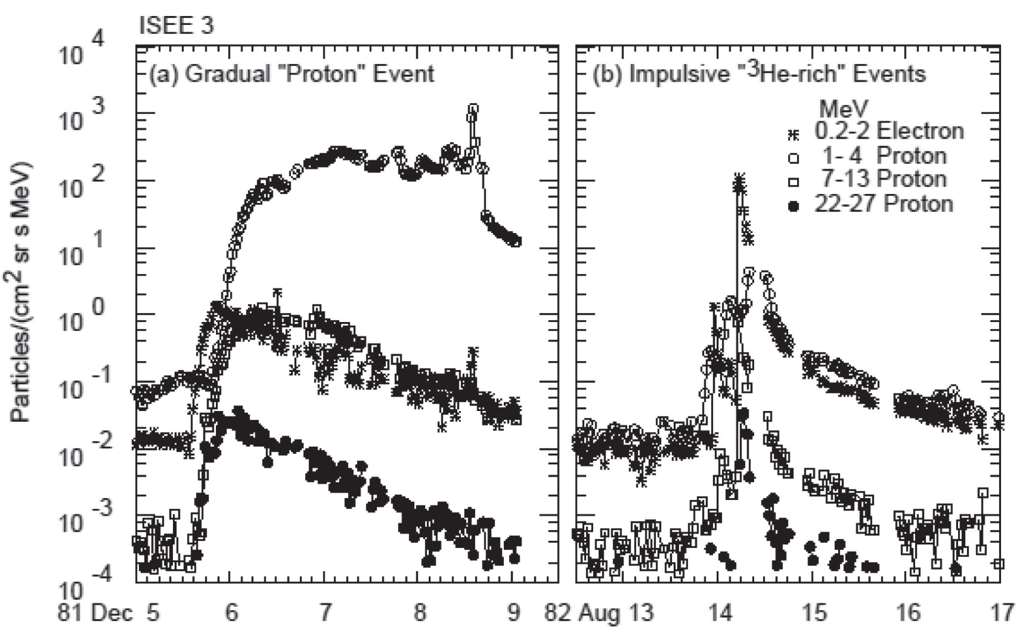

Fig.2 *Intensity-time profiles of (a) gradual event and (b) impulsive event (adapted from [4])*

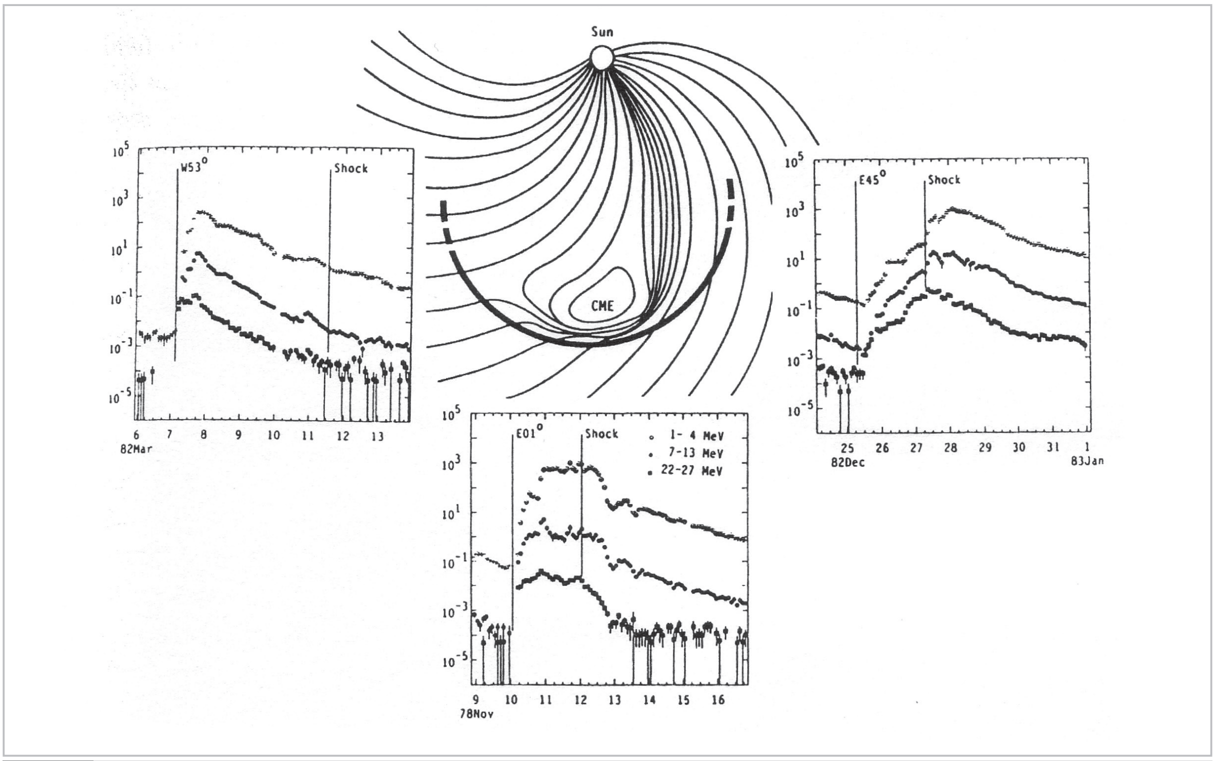

Fig.3 *Intensity-time profiles for typical three events regarding CME and interplanetary shock waves, as viewed from different longitudes of the Sun (adapted from*[4]*)*

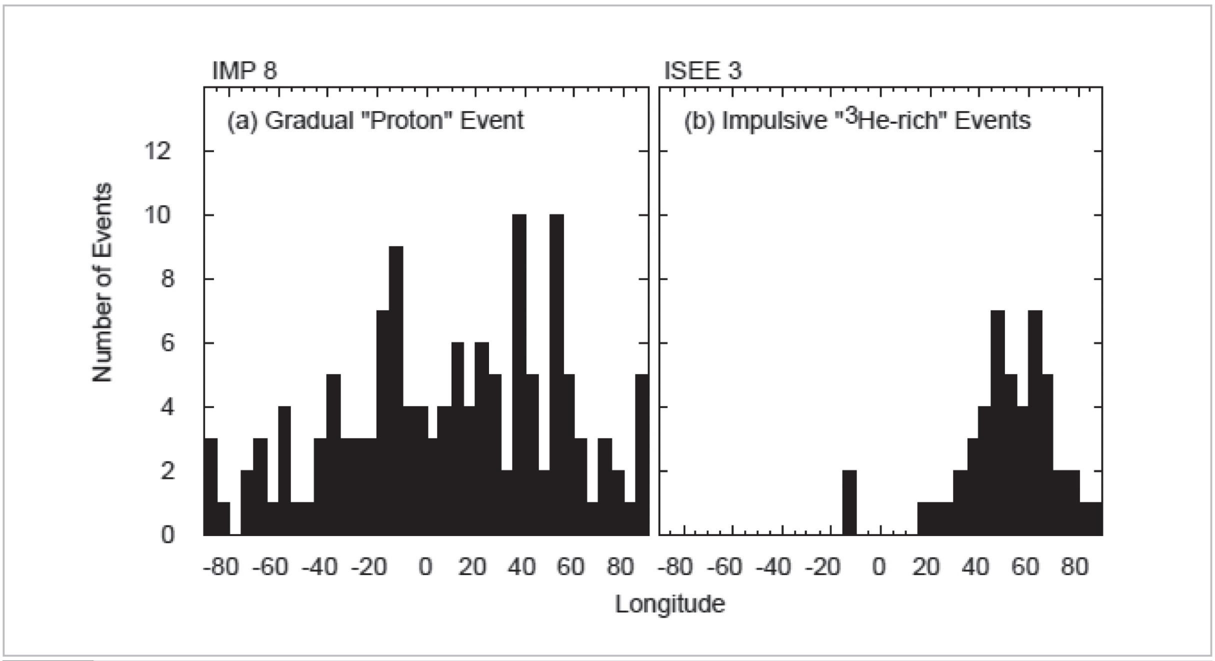

Fig.4 *Longitudinal distribution on the solar surface for the occurrence source of solar proton events; (a) gradual event and (b) impulsive event (adapted from*[4]*)*

Solar protons, on the other hand, cannot reach the mid-to-low latitudinal ionosphere, but can penetrate into the polar region ionosphere along the Earth's magnetic field lines. Consequently, these protons possibly affect satellites in polar orbits, and secondarily irradiated X-rays could also influence aircraft around the poles. Solar protons that reach the polar ionosphere intensely ionize the ionosphere and possibly cause polar cap absorption, thereby influencing short-wave communications that propagate through the polar regions. This significantly affects aircraft navigating over the polar regions, as short waves may be used for communications.

The latitude that solar protons may reach is referred to as the cutoff latitude. Studies on cutoff latitude commenced as early as when the theory of Störmer was developed, and the former Radio Research Laboratory conducted studies on variations in cutoff latitude during magnetic storms[5]. In recent years, a more precise model for cutoff latitude has been devised by using the instrumentation onboard space shuttles and other equipment[6].

2 Purpose of this study

Many studies have been conducted on the penetration of solar protons into the geomagnetosphere from both theoretical and observational viewpoints; however, the majority of past theoretical studies used static models for the magnetospheric electromagnetic field. Since a more realistic structure of the magnetospheric electromagnetic field has been reproduced by applying recent global MHD simulations, the use of simulation data must enable a study to accurately take into account the actual topology of the magnetosphere. Based on this viewpoint, solar proton propagation through the geomagnetosphere has been studied in recent years by using MHD simulation data[7]-[9].

The interaction between solar protons and the geomagnetosphere can be classified based on the cyclotron radius of a proton and the magnitude of the geomagnetospheric scale. First, given a cyclotron radius larger than the size of the magnetosphere, protons of approximately 50 MeV or more are hardly influenced by the magnetosphere. Secondly, protons of approximately 10 keV or less or the thermal particles of solar wind vary the magnetospheric magnetic field because they carry currents. Note that such protons and thermal particles typically do not lead to radiation exposure or instrumentation problems due to low energy. Next, protons ranging from 100 keV to 50 MeV or other than the above-mentioned ranges are influenced by the magnetospheric magnetic field. However, the small quantity of such protons results in hardly any magnetic field variation. Therefore, protons in this energy range can be tracked in a simulation as test particles by providing an electromagnetic field. In other words, protons in this energy range can be handled by providing an electromagnetic field in MHD simulation, and then simulating test particles. Handling protons this way allows practical space weather issues related to the problems of manned flights or onboard instrumentation to be addressed, while taking advantage of "real-time magnetospheric simulation," on which NICT has worked.

This study simulated solar protons penetrating the geomagnetosphere in the electromagnetic field as obtained from global MHD simulation. The orbits of protons ranging from 100 keV to 10 MeV were tracked upstream of the solar wind. The protons in this energy range are considered to hardly vary the magnetospheric electromagnetic field according to the above-mentioned typology; however, orbits are influenced by the magnetospheric electromagnetic field, as the cyclotron radius equals the magnetospheric scale or less.

3 Method

To track proton orbits, calculations were performed by using the electromagnetic data obtained from global MHD simulation[10]. Settings were made on the MHD model as follows: solar wind density of 10.0 cm^{-3} and velocity of 350 km/s; the interplanetary magnetic field configured by the components of $Bx = 0$, $By = -2.5$ nT, and $Bz = 4.2$ nT or -4.2 nT on the GSM coordinates. The grids were assumed as the number of $56 \times 58 \times 40$ on the modified spherical coordinates[10] and in north-south symmetry (excluding the dipole tilt).

Particle injection locations were assumed in the following domains surrounding the magnetosphere upstream of the solar wind: (1) $0 < x/Re < 30$, $0 < y/Re < 30$ and $28 < |z|/Re < 30$, (2) $0 < x/Re < 30$, $28 < |y|/Re < 30$ and $0 < z/Re < 30$, and (3) $28 < x/Re < 30$, $-30 < y/Re < 30$ and $-30 < z/Re < 30$, where Re is the Earth's radius. Assumptions were made for energies of protons to be monochromatic per run (at 0˚C temperature), for pitch angle distribution to be isotropic, and for particle injection to be constant during the period. The equation of motion including the relativistic effect was numerically solved in the domain from 4 to 70 Re and proton orbits were tracked.

4 Results

The use of MHD simulation data enables the handling of particle acceleration due to time variations of the electromagnetic field. This study focused on solar proton acceleration in case of the Earth's bow shock occurring with a drastic increase in solar wind density, although there has been little theoretical focus on whether solar protons are accelerated near the Earth[11]. A bow shock is a shock wave generated in supersonic solar wind reaching the Earth on the side facing the Sun.

The solar wind density was increased from 10.0 cm^{-3} to 30.0 cm^{-3} (from 2 nPa to 6 nPa in dynamic pressure). The sign of Bz was assumed as being positive. A proton event was assumed to first occur before an interplanetary shock wave reaches the Earth.

After a drastic increase in density, the following was observed: an increase in the flux of protons reaching the ionosphere and lowering in reaching latitude. As shown in Fig.5, protons with energy of 100 keV at injection were significantly accelerated, some reaching as high as 300 keV.

Figure 6 shows the orbit of a proton with energy of 100 keV as a white line. This proton was accelerated to 200 keV or more. Acceleration occurred while the proton moved roughly along the bow shock; analysis of the orbit and the electromagnetic field encountered by the proton revealed that the proton passed traversely across the bow shock many times. The bow shock in this event is a quasi-perpendicular shock and the proton is believed to undergo shock drift acceleration. After being accelerated in the bow shock domain, the proton was trapped by the geomagnetic field from the upper side of the cusp and drifted in the geomagnetosphere from the dawn side to the dusk side.

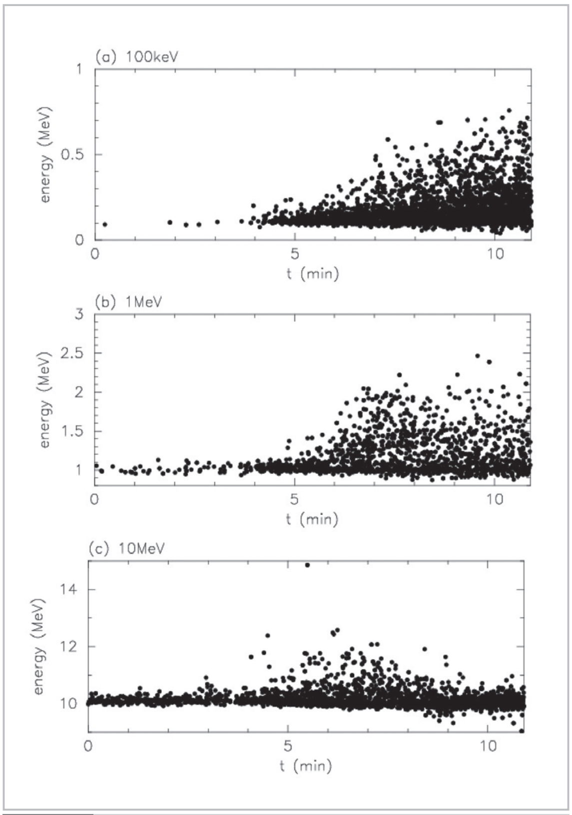

Fig.5 *Calculation result of the energy distribution of solar protons before and after reaching interplanetary shock waves (adapted from[11])*

The figure is for initial energy of (1) 100 keV, (b) 1 MeV and (c) 10 MeV. Interplanetary shock waves reached the geomagnetosphere around when the vertical axis indicates four minutes.

Shock drift acceleration occurs when the surface of a shock wave serves as a reflective surface for incident particles, since the magnetic field downstream is stronger than that upstream. Reflected particles are in the gradient-drift motion along the shock surface, thereby being accelerated by an electromag-

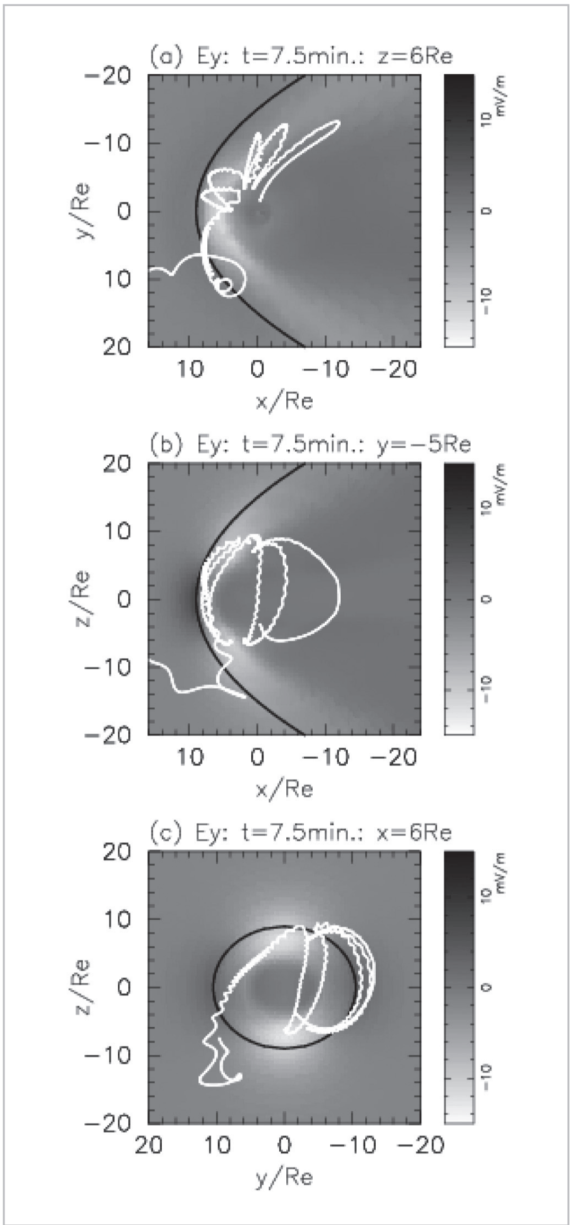

Fig.6 *Example of solar proton orbit (white line)*

The contrasting density in the background indicates the east-west component of the electric field. The black curved line indicates the position of bow shock. The three panels show a single event as viewed from three cross sections (adapted from [11]).

netic field viewed from the shock rest frame. If the cyclotron radius of reflected particles is larger than the curvature radius or structure of the shock waves, these particles can pass traversely across the shock wave surface many times during cyclotron motion, and thus undergo dramatic acceleration[12]-[16].

Regarding the pitch angle distribution of protons having energy of approximately 100 keV and reaching downstream of the shock wave, a peak was found at about 45 degrees, similar to a finding in a study on the shock drift acceleration of curved shock waves[15]. Therefore, this fact also supports the occurrence of shock drift acceleration.

The presence of protons shock-drift-accelerated by the bow shock of the Earth is also known according to observations using artificial satellites[17][18].The *IMP8* and *IMP7* satellites observed protons being accelerated near quasi-perpendicular shock waves. Our simulation demonstrated this event under conditions approximating those of observations for the first time ever.

Protons of 100 keV could not reach the inner boundary (4 Re) according to simulation results under a quiet condition. In case of a drastic increase in solar wind density, however, the protons in this energy range were found shock-drift-accelerated with highly increased levels of energy, thereby allowing the protons to reach near the Earth. The cutoff latitude was found to decrease due to the effects of both proton acceleration and compression of the magnetosphere in conjunction with a drastic increase in solar wind density.

We also calculated the north-south component of the interplanetary magnetic field to be changed from northward to southward. Disturbances in the geomagnetosphere are well known to occur generally in the southward interplanetary magnetic field. Calculations show a greater quantity of protons of approximately 1 MeV or less in the interplanetary magnetic field having the southward component, and such protons can penetrate into the lower latitudes (lower cutoff latitude). However, no significant variation (acceleration) in proton energy was found[19]. This is different from the case of a drastic increase in density.

5 Summary

This study simulated solar proton penetration into the geomagnetosphere in the electromagnetic field as obtained from global MHD simulation. Orbits of protons in the range from 100 keV to 10 MeV were tracked from upstream of the solar wind. After a drastic increase in solar wind density, the amount of protons reaching the geomagnetosphere increased and the cutoff latitude decreased.

Protons were found to be shock-drift-accelerated at the bow shock; such protons had energy of approximately 1 MeV or less due to the magnitude of the electromagnetic field downstream as viewed from the shock rest frame. In contrast, protons having energy of approximately 100 keV or more easily penetrated into the low altitudes of the Earth. Thus, in the energy range from 100 keV to 1 MeV, protons that reached the low altitudes of the Earth may have been shock-drift-accelerated by bow shock.

This study showed that the high-energy particle tracking method using MHD simulation results is very useful in understanding solar proton acceleration events. The method can significantly contribute to realizing the prediction of solar protons reaching the Earth, particularly since it can accurately track particle orbits by using the electromagnetic field approximating the actual magnetosphere.

Preparing a model for predicting the intensity or composition of a solar proton event is currently very difficult, although very important. In addition, a problem from a practical aspect concerns whether manned flights or onboard instrumentation may encounter a huge proton event (on a frequency scale of once per cycle or none at all). Studies in such a direction may be necessary in the future.

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