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The Statistical and Numerical Study of the Longitudinally Asymmetric Distribution of Solar Proton Events Affecting the Earth Environment of 1996-2011

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Abstract: Large solar proton events (SPEs) affect the solar-terrestrial space environment and become a very important aspect in space weather research. In this work, we statistically investigate 78 solar proton events of 1996-2011 and find that there exists a longitudinally asymmetric distribution of flare sources of the solar proton events observed near 1 AU, namely, with the same longitude separation between magnetic field line footpoint of observer and flare sources, the number of the solar proton events originating from sources located at eastern side of the nominal magnetic footpoint of observer is much larger than that of the solar proton events originating from sources located at western side. A complete model calculation of solar energetic particle (SEP) propagation in the three-dimensional Parker interplanetary magnetic field is presented to give a numerical explanation for this longitudinally asymmetric distribution phenomenon. We find that the longitudinally asymmetric distribution of solar proton events results from the east-west azimuthal asymmetry in the topology of the Parker interplanetary magnetic field as well as the effects of perpendicular diffusion on the transport of SEPs in the heliosphere. Our results would be valuable in understanding the solar-terrestrial relations and useful in space weather forecasting.

Keywords: solar proton events (SPEs), longitudinally asymmetric distribution, interplanetary medium, magnetic turbulence, diffusion, flares, coronal mass ejections (CMEs), solar-terrestrial relations.

1 Introduction

Solar energetic particles (SEPs), which are charged energetic particles occasionally emitted by the Sun, risk the health of astronauts working in space and damage electronic components on satellites, so they have become a very important aspect in affecting solar-terrestrial space environment and space weather. Theoretically, SEPs observed in the interplanetary magnetic field provide fundamental information regarding acceleration mechanisms and transport processes of charged energetic particles. Therefore, the subject has become a focus of astrophysics, space physics, and plasma physics.

Through several decades of investigations in the community with spacecraft observations and theoretical modeling, significant progresses have been achieved toward a better understanding of the transport processes of SEPs. As a pioneering work, [1] provided a focused transport equation to investigate the modulation of galactic cosmic rays and the transport of SEPs. It is very difficult to analytically solve the multidimensional transport equation; consequently, numerical calculations are usually adopted (e.g., [2, 3]).

Recently, [3] investigated the effects of particle source characteristics on SEP observations at 1 AU and found that the perpendicular diffusion has a very important influence on the propagation of SEPs in the heliosphere, particularly when a spacecraft is not directly connected to the acceleration regions either on the Sun or near the CME-driven shocks by the interplanetary magnetic field lines; in such cases, the earliest arriving particles can be seen propagating toward the Sun, having scattered backward at large distances. [4, 5] presented a direct method to quickly and explicitly determine the spatially dependent parallel, ra-

dial, and perpendicular mean free paths of SEPs with adiabatic focusing. They reported that when the turbulence strength $\delta B/B$ is sufficiently large, e.g., $\delta B/B \geq 2.34$, the ratio $\lambda_\perp/\lambda_\parallel$ would approach or exceed unity.

In this work, we statistically investigate 78 solar proton events (SPEs) of 1996-2011 observed near 1 AU and find that with the same longitude separation between magnetic field line footpoint of observer and flare sources, the number of the solar proton events originating from sources located at eastern side of the nominal magnetic footpoint of observer is much larger than that of the solar proton events originating from sources located at western side. Our systematical simulations also confirm the longitudinally asymmetric distribution of the solar proton events observed in the interplanetary space including Earth's orbit. We find that the longitudinally asymmetric distribution of solar proton events results from the east-west azimuthal asymmetry in the geometry of the Parker interplanetary magnetic field as well as the effects of perpendicular diffusion on the transport processes of SEPs in the heliosphere. Our results would be valuable in understanding the solar-terrestrial relations and useful in space weather forecasting.

2 Data Set

We collect 78 solar proton events affecting the Earth environment observed near 1 AU in the time period 1996-2011 from Space Weather Prediction Center of NOAA at http://www.swpc.noaa.gov/ftpdir/indices/SPE.txt. The data set covers an uninterrupted time period of 16 years including the whole solar cycle 23 and the rising phase of solar cycle 24. The maximum proton flux of each particle event

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measured by GOES spacecraft at Geosynchronous orbit for energies > 10 MeV is greater than or equal to 10 particle flux units (pfu, 1 pfu=1 particles/($cm^2 - sr - s$)). Note that the 78 solar proton events are selected from the original listing by excluding the events without definite location on the solar surface, since the explicit data of the active regions are indispensable to the investigations. The solar wind speed used in this work is averaged from SOHO or ACE data measured within the time range $[t_{max} - 2hours, t_{max} + 2hours]$, where t_{max} is the maximum time of each SEP event.

3 Statistical Results

The heliospheric magnetic field is "frozen-into" the solar wind and travels along with it to form the Archimedes spirals. The well-known Parker spiral can be expressed as

$$\phi_s = \Omega r / V^{sw}, \quad (1)$$

where Ω is the angular rotation rate of the Sun, r is the heliocentric distance, and V^{sw} is the solar wind speed. For each solar proton event, by inputting the solar wind speed V^{sw} into Equation (1), we can derive the Parker spiral angle ϕ_s of the nominal magnetic field line connecting the observer at 1 AU with the Sun. That is to say, we can determine the heliographic longitude of the nominal magnetic footpoint of the spacecraft located at Earth's orbit during the SEP events. For convenience in the investigations, we mark the west and east heliographic longitudes ϕ of the flare sources on the solar disk as positive and negative values, respectively. Then for each solar proton event, we can obtain the relatively longitudinal distance ϕ_r between the heliographic longitudes of the flare location and the nominal magnetic footpoint of the spacecraft located at 1 AU during the particle event, through the relation

$$\phi_r = \phi - \phi_s = \phi - \Omega r / V^{sw}. \quad (2)$$

Figure 1 presents the spatial distribution on the solar surface of the flare sources of the 78 solar proton events observed near 1 AU in the time period 1996-2011. Similar to the heliographic longitude, the heliographic latitude is marked as a positive value when the flare source located at the northern side of the solar equator and a negative value when the flare source located at the southern side. From the upper panel of Figure 1, we can see that the majority of flare sources of the solar proton events are distributed in the heliographic latitude range $[S30°, N30°]$. The lower panel of Figure 1 shows the number percentage distribution of the solar events along the relatively longitudinal distance ϕ_r, which is divided into 18 bins. The event number percentage P_i ($i = 1, 2, \ldots, 18$) within each bin of ϕ_r is obtained as follows:

$$P_i = \frac{N_i}{N} = \frac{N_i}{78} \times 100\%, \quad (3)$$

where N_i ($i = 1, 2, \ldots, 18$) denotes the corresponding solar event number in each bin. The vertical dashed line in the middle of the lower panel in Figure 1 indicates the $0°$ relatively longitudinal distance, where the nominal magnetic footpoint of the observer and the flare source have the same heliographic longitude. At the left side of this line, the negative values indicate that the flare sources locate at the eastern side of the nominal magnetic footpoint of observer, whereas the positive values at the right side of the middle line indicate that the flare sources locate at the western side
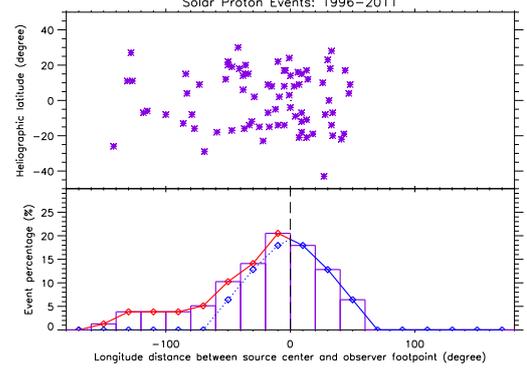
Figure 1: The spatial distribution on the solar surface of the flare sources of the 78 solar proton events observed near 1 AU in the time period 1996-2011. Upper panel: the latitudinal and longitudinal distribution of the solar sources of the proton events. Lower panel: the number percentage distribution of the solar events along the relatively longitudinal distance ϕ_r, which is divided into 18 bins. With the same longitude separation between the magnetic footpoint of observer and solar sources, the number of the solar proton events originating from sources located at eastern (left) side of the magnetic footpoint of observer is much larger than that of the solar proton events originating from sources located at western (right) side.
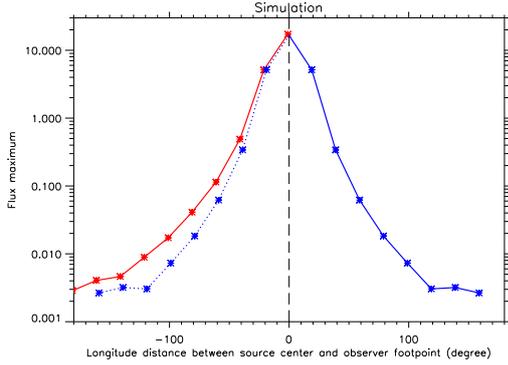
of the magnetic footpoint of observer. It can be seen that the event number percentage is maximum in the interval $[-20°, 0°]$ among all the 18 relatively longitudinal bins. Interestingly, we find that the event number percentage distribution is asymmetric about the vertical dashed line in the middle. We connect the event number percentages at the central value within each relatively longitudinal interval with red and blue lines on the left-hand and right-hand halves, respectively. We further mirror the event number percentages on the right-hand half to the left-hand half with a blue dotted line. Then we can clearly see that the event number percentage within each interval on the left-hand half is systematically larger than that in the symmetrical interval on the right-hand half. That is to say, with the same longitude separation between magnetic field line footpoint of observer and flare sources, the number of the solar proton events originating from sources located at eastern side of the nominal magnetic footpoint of observer is much larger than that of the solar proton events originating from sources located at western side.

4 Numerical Model and Results
4.1 Model
In our model, the five-dimensional focussed transport equation that governs the gyrophase-averaged distribution function $f(\mathbf{x}, \mu, p, t)$ of SEPs can be written as (e.g., [3])

$$\frac{\partial f}{\partial t} + \mu v \frac{\partial f}{\partial z} + \mathbf{V}^{sw} \cdot \nabla f + \frac{dp}{dt} \frac{\partial f}{\partial p} + \frac{d\mu}{dt} \frac{\partial f}{\partial \mu} - \frac{\partial}{\partial \mu} \left(D_{\mu\mu} \frac{\partial f}{\partial \mu} \right)$$

$$- \frac{\partial}{\partial x} \left(\kappa_{xx} \frac{\partial f}{\partial x} \right) - \frac{\partial}{\partial y} \left(\kappa_{yy} \frac{\partial f}{\partial y} \right) = Q(\mathbf{x}, p, t), \quad (4)$$

Figure 2: The flux maxima of the SEP events originating from 18 solar sources with different longitudinal locations relative to the magnetic footpoint of the observer at 1 AU, 90° colatitude. With the same longitude separations between the solar source centers and the magnetic footpoint of the observer, the flux maxima of the SEP events originating from solar sources located at eastern (left) side of the observer footpoint are systematically larger than those of the SEP events originating from sources located at western (right) side.

where **x** is particle's position, z is the coordinate along the magnetic field spiral, p is particle's momentum, μ is pitch-angle cosine, and Q is source term.

Under the diffusion approximation for a nearly isotropic pitch-angle distribution, the parallel mean free path $\lambda_\parallel$ could be written as ([6])

$$\lambda_\parallel = \frac{3v}{8} \int_{-1}^{+1} \frac{(1-\mu^2)^2}{D_{\mu\mu}} d\mu. \qquad (5)$$

In this work, we typically use radial mean free path $\lambda_r = 0.3$ AU (corresponding to parallel mean free path $\lambda_\parallel = 0.67$ AU at 1 AU) and perpendicular mean free paths $\lambda_x = \lambda_y = 0.006$ AU for 50 MeV protons. We utilize the time-backward Markov stochastic process method ([2]) to numerically solve the focused transport equation (4). In our simulations, the Parker interplanetary magnetic field **B** is set so that its magnitude at $1AU$ is $5nT$, and the solar wind speed is typically set as $V^{sw} = 400 \ km \ s^{-1}$. Typical sizes of SEP sources (flares or CMEs) are tens of degrees wide in heliographic latitude and longitude, so in the simulations, we set SEP sources with limited coverage of 30° in latitude and longitude. Generally, the unit of omnidirectional flux is used as $cm^{-2} - sr^{-1} - s^{-1} - MeV^{-1}$; in this work, however, we use an arbitrary unit for convenience in plotting figures.

4.2 Numerical Results

We simulate 18 cases to show the effect of solar source location on the SEP flux observed in the interplanetary space. All the solar particle sources have the same coverage, but their centers are located at various heliographic longitudes in the solar equator. Specifically, the longitude separations between the centers of 18 solar sources and the magnetic footpoint of the observer are set to be the following values: 0°, 20° west, 20° east, …, 160° west, 160° east, 180° east. All the other conditions and parameters are the same for each case. In these simulations, we typically investigate 50 MeV protons detected at 1 AU, 90° colatitude.

Figure 2 shows the flux maxima of the SEP events originating from the 18 solar sources with different longitudinal locations relative to the magnetic footpoint of the observer at 1 AU, 90° colatitude. The X-axis in Figure 2 is the relatively longitudinal distance ϕ_r between the solar source center and the magnetic footpoint of the observer, same as that in Figure 1. The vertical dashed line in the middle of Figure 2 denotes the 0° relatively longitudinal distance. As we can see, the maximum flux of SEPs in this case is the largest among all the 18 cases investigated. This means that when the observer in the interplanetary space is connected directly to the solar source by heliospheric magnetic field lines, the SEP flux is larger than that otherwise. We connect the flux maxima of SEPs in the simulated cases on the left-hand and right-hand halves with red and blue curves, respectively. It can be obviously seen from Figure 2 that, the farther the solar source center is away from the magnetic footpoint of the observer, the smaller is the maximum flux of SEPs observed (see also [3]). Similar to Figure 1, we further mirror the flux maxima of SEPs on the right-hand half to the left-hand half with a blue dotted curve. We can obviously observe that with the same longitude separations between the solar source centers and the magnetic footpoint of the observer, the flux maxima of SEP events originating from solar sources located at eastern side of the observer footpoint are systematically larger than those of the SEP events originating from sources located at western side.

5 Relationship between Simulations and Observations

Generally, a SEP event with a higher peak flux will reveal a larger intensity relative to other events through the entire evolution process including the rising phase and the decay phase (see the results, such as Figure 2 and Figure 3, in [3]). Generally, the probability of the SEP events being observed by spacecraft near Earth's orbit depends on the intensities of the particles in the events. An intense SEP event with high flux will experience relatively weak influences by the interplanetary structures (such as magnetic cloud, heliospheric current sheet, corotating interaction region, etc.) during the propagation process in the heliosphere. However, the not so intense SEP events with small fluxes will be significantly affected by the interplanetary structures and then to weaken or even dissipate before entering Earth's orbit. Consequently, the intense SEP events would have larger probability of reaching the Earth and being observed by spacecraft at 1 AU; whereas the relatively weak SEP events would have lower probability to arrive at the Earth and to be recorded by spacecraft.

As shown in Figure 2, the SEP events originating from solar sources located at eastern side of the magnetic footpoint of observer reveal larger flux maxima (corresponding to entire fluxes) than those originating from solar sources located at western side. Therefore, the SEP events originating from solar sources located at eastern relative longitudes would have higher probability to reach the Earth and to be observed by spacecraft near 1 AU. On the contrary, the SEP events from solar sources on the west side relative to the magnetic footpoint of observer will be more easily influenced by the interplanetary structures and then to weaken or even dissipate during their propagation processes. As a result, the spacecraft at 1 AU would have a larger probability to miss the SEP events originating from solar sources located at western relative longitudes. Accordingly, taking

into account a large data set with 78 solar proton events accumulated over a long time period, we can expect that with the same relatively longitudinal distance, the number of the solar proton events originating from solar sources located at eastern side of the magnetic footpoint of observer would be larger than that of the solar proton events originating from sources located at western side, just as shown in Figure 1. Therefore, our numerical simulations explain and confirm the observational results; and the combination of simulations and spacecraft observations demonstrates that there exists a longitudinally asymmetric distribution of solar sources of the proton events observed near 1 AU.

6   Summary and Discussion

In this work, we statistically investigate a large data set with 78 solar proton events accumulated over a long and uninterrupted time period 1996-2011. We find that with the same longitude separation between magnetic footpoint of observer and solar sources, the number of the proton events originating from the solar sources located at eastern side of the magnetic footpoint of observer is systematically larger than that of the proton events associated with the sources located at western side. Our simulation results show that with the same longitude separation between the solar sources and the magnetic footpoint of the observer, the flux of SEPs released from the solar source located east is systematically higher than that of SEPs originating from the source located west. Consequently, the SEP events originating from solar sources located at the eastern relative longitudes would be detected and recorded with somewhat higher probabilities by the observer near 1 AU. Therefore, our numerical simulations testify and confirm the statistical results of the solar proton events accumulated over 16 years.

Generally, as viewed from above the north pole of the Sun, the Parker spiral magnetic field lines originating from the solar surface would meander clockwise to somewhere with more eastern longitudes in the interplanetary space. The scenario can be seen in Figure 3. As we can see, there is an east-west azimuthal asymmetry in the topology of the Parker interplanetary magnetic field. As a result, with the same longitude separation between the magnetic footpoint of the observer and the solar sources, the virtual distance $\overline{OA}$ between the observer (O) in the interplanetary space and the solar source (A) on the left is shorter than that $\overline{OB}$ between the observer and the solar source (B) on the right. According to the theoretical and observational investigations (e.g., [5]), for physical conditions representative of the solar wind, the perpendicular diffusion coefficient would be a few percent of the parallel diffusion coefficient in magnitude. In general, SEPs would mainly transport along the average interplanetary magnetic field after they have been produced from the surface of the Sun or a CME-driven shock. Therefore, when the observer is connected directly to the solar source by the interplanetary magnetic field lines, the omnidirectional flux and peak flux of SEPs are larger than those in the cases where the observer is not connected directly to the solar sources. The farther the solar source center is away from the magnetic footpoint of the observer, the smaller are the omnidirectional flux and peak flux of SEPs observed. In addition to the parallel diffusion, the SEPs will experience perpendicular diffusion to cross the heliospheric magnetic field lines during their transport processes in the interplanetary space. This is why the SEP events can be observed by a spacecraft which is not directly connected to
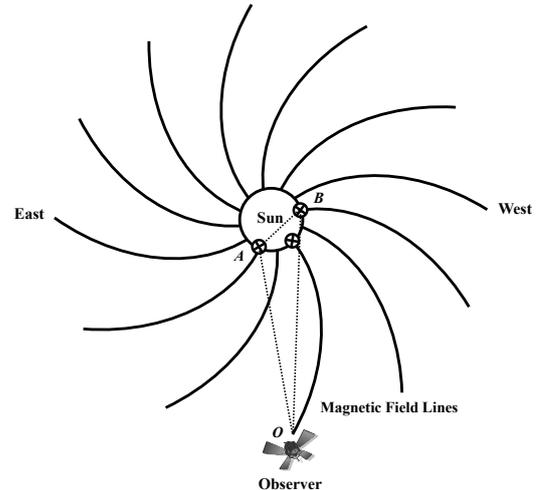
Figure 3: Sketch to show the east-west azimuthal asymmetry in the topology of the Parker interplanetary magnetic field. With the same longitudinal separation between the magnetic footpoint of the observer and the solar sources, the virtual distance $\overline{OA}$ between the observer (O) in the interplanetary space and the solar source (A) on the left is shorter than that $\overline{OB}$ between the observer and the solar source (B) on the right. On account of $\overline{OA} < \overline{OB}$, the SEPs originating from the solar sources on the east (left) side relative to the magnetic footpoint of the observer would have a lower probability to weaken or dissipate before arriving at the observer.

the acceleration regions. On account of the virtual distance relationship $\overline{OA} < \overline{OB}$, the SEPs originating from the solar sources located at eastern side of the magnetic footpoint of observer would have a lower probability to weaken or dissipate before arriving at the observer. Consequently, with the same longitudinal distances between the solar sources and the observer footpoint, the fluxes of the SEP events associated with solar sources located east are systematically larger than those of the SEP events associated with sources located west. Therefore, the longitudinally asymmetric distribution of solar proton events results from the east-west azimuthal asymmetry in the topology of the Parker interplanetary magnetic field as well as the effects of perpendicular diffusion on the transport processes of SEPs in the heliosphere.

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