Evidence for perpendicular transport of solar energetic particles in interplanetary magnetic fields

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***Abstract*. The September 12, 2000 solar flare and its subsequent fast halo CME event produces a large dose of solar energetic particles (SEP) in the inner heliosphere. The event is centered around 20° S and 5° W. Although, Ulysses is farther away at 2.78 AU, 70° S heliographic latitude and 163° E longitude, Ulysses sees flux time profiles in several high-energy channels almost exactly the same as those seen by spacecraft in Earth orbit. Three-dimensional model of particle propagation suggests that the SEP source of this event has to have a significant variation in strength as a function of distance from the center of the CME and Ulysses happens to be connected to the major source better than Earth so that Ulysses can see higher particle flux in the early phase of the event when particle transport occurs mainly along the field lines. Later in the event, the fluxes at both locations decay at the same rate and same level which lasted over 12 days. This event provides a clear evidence that the source of SEP on the sun cannot be assumed uniform even in large CME-related gradual events. The formation of uniform reservoir of solar energetic particles in the inner heliosphere in this and many other events requires an efficient particle transport across magnetic field lines.**

***Keywords*: Solar energetic particles, Interplanetary propagation, Coronal mass ejection**

I. INTRODUCTION

Solar energetic particles (SEP) are high-energy charged particles produced in explosive solar events, such as the solar flare or coronal mass ejection (CME) shock. In the solar flare, the site of SEP production is fairly small. Even though CME can drive a shock that covers substantial range of solar latitude and longitude, the SEP source region is still limited. Conventional idea requires that one has to have a direct magnetic connection to SEP source in order to see these particles. This is based on a typical assumption that particle transport across magnetic field lines is much slower than the parallel transport by several orders of magnitude. There is an indication that this assumption may not be true for SEP. First, results from analysis of cosmic ray modulation often requires that the diffusion coefficient of cosmic rays perpendicular to the magnetic field is not that small compared to the parallel one. Numerical simulation of cosmic ray modulation find that it requires a perpendicular-to-parallel diffusion coefficient ratio in the order of 10% to fit measurements of cosmic ray radial and latitudinal gradients [1]. Similar large perpendicular diffusion is also required for the Jovian electrons observed interplanetary space [2].Since the propagation of SEP shares the same interplanetary magnetic medium as cosmic rays or Jovian electrons, we need to consider the role of cross-field transport for SEP too. That means SEPs may come from unconnected solar particle sources. Second, simultaneous multiple spacecraft observations have established that SEPs can often reach a nearly uniform flux in the entire inner heliosphere in just maximum of a few days after the onset of any large solar event. This phenomenon is call SEP reservoir [3,4]. It has been confirmed by spacecraft located at various radial distances, latitudes and longitudes. This observation indicates that SEP must have an efficient cross-field transport or a uniform solar source. According to our recent numerical simulation of SEP transport [5], either of two conditions can result a SEP reservoir.

In this paper, we use the September 12, 2000 SEP event to demonstrate that SEP source in the corona cannot be uniform. The event reached a nearly uniform reservoir in the inner heliosphere up to 2.78 AU and high latitude of 70° S. It is most like to be achieved through particle transport across magnetic field lines.

II. OBSERVATION

The September 12, 2000 solar event starts with a M-1 solar flare at around 1140 UT. The flare is roughly located at 20° S latitude and 5° W Earth meridian longitude. A bright ribbon seen in Hα emission erupts from the flare site, triggering a massive CME. The CME is a fast halo CME as observed by SOHO of speeds from 1550 km/s to 1839 k/m. and drives a strong shock in front of it [6]. The event produces a quite large dose of SEP up to >100 MeV into interplanetary space. Because of the limitation of SOHO observation, the latitudinal and longitudinal size of the CME is not known. Figure 1 shows the location of the flare on a Carrington map along with the solar surface magnetic field calculated from Wilcox solar magnetic field measurements [7]. We use observations by Ulysses, which is located at 2.78 AU from the sun, 70° S latitude and 163° E Earth meridian longitude, and compare similar measurements by spacecraft IMP-8 and ACE at Earth which is at 7° N heliographic latitude. The latitude and longitude locations of Ulysses and Earth are shown in Figure 1. The footpoints of magnetic field lines connected to Ulysses and Earth on the solar surface are calculated with 400 km/s solar wind speed. The longitude of

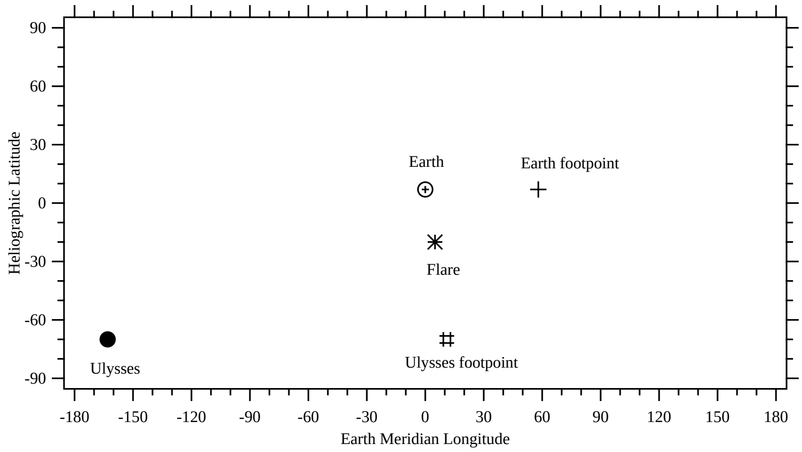

Fig. 1: Locations of the September 12, 2000 solar flare, Ulysses, Earth and their footpoints of magnetic field line on the solar surface. On the background the the isocontour of solar magnetic field obtained by Wilcox Observatory.

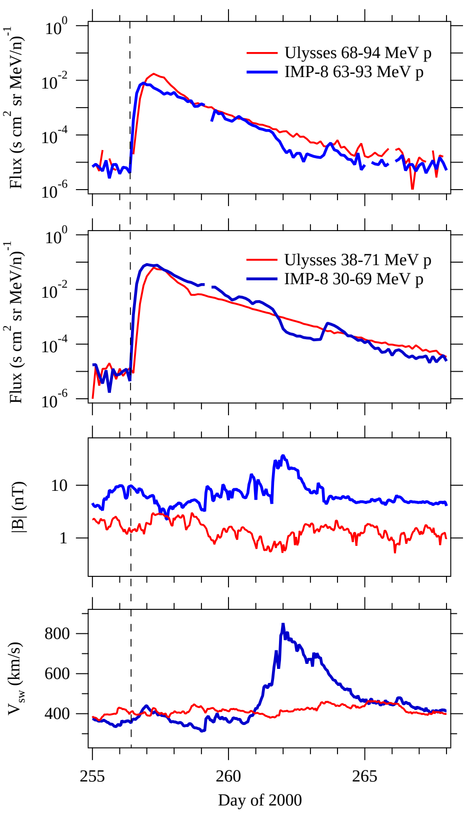

Fig. 2: From top to bottom show comparison of ∼70-90 MeV proton flux, ∼ 40-70 MeV proton flux, interplanetary magnetic field strength and solar wind speed measured by Ulysses and by spacecraft at Earth. All the data are 3-hour averages. Blue thick lines are for measurements at Earth while the red thin lines are for measurement by Ulysses. The vertical dashed line indicate the time of solar flare.

Ulysses is quite away from the solar event, but the magnetic field line to Ulysses is very close to the flare or CME.

Figure 2 show the 3-hour resolution measurements of ∼70-90 MeV and ∼40-70 MeV proton fluxes by Ulysses and IMP-8. Energetic particle measurements on Ulysses are from the COSPIN/HET experiment and energetic particle measurements at Earth are from the University of Chicago CRNC telescope on IMP-8. For details of the instrumentation and data processing, see [8] and [9]. The fluxes have been calibrated with uncertainties no more than ∼20%. The SEP fluxes at Earth (blue lines) rise almost immediately after the eruption of solar event, the onsets of the fluxes at Ulysses delay ∼2.5 hours relative to the onset of SEP at Earth. The SEP fluxes at both locations gradually increase and reach their maxima approximately half a day to a day later. What is surprising here, the maximum fluxes seen at Earth are comparable to even lower than those seen at Ulysses, despite the fact Ulysses is about 3 times distance away. Then the fluxes decay at the same level with in a factor of 2 or 3 and at the same rate at both locations, and this lasts over 10 days, which resembles a typical SEP reservoir phenomenon. There is a period on days 261-262 when the SEP fluxes at IMP-8 is much lower due to the arrival of the CME at the Earth location as it is shown by the solar wind and magnetic field measurements in the two lower panels.

The interplanetary solar wind and magnetic field conditions at both Ulysses and Earth are mostly undisturbed except the brief period of CME arrival at Earth. The solar wind speed is roughly 400 km/s throughout the entire SEP event at Ulysses, indicating that the CME did not reach the longitude or latitude of Ulysses or the CME had a limited size. The magnetic field at Ulysses is lower than that at Earth, which is just the radial distance

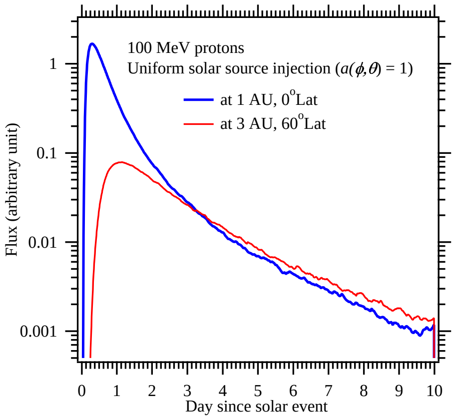

Fig. 3: Model calculation of omni-direction flux time profiles at two different locations in the heliosphere as produced by a uniform SEP source on the sun.

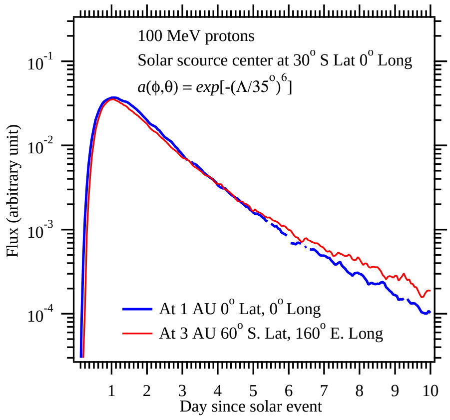

Fig. 4: Model calculation of omni-direction flux time profiles at two different locations in the heliosphere as produced by a SEP source of approximately 35° in radius and centered at a flare site in between the footpoints of the magnetic field lines to the observers.

effect.

III. Analysis

The major interesting point of the above observation is that the SEP fluxes at Ulysses are almost identical to those seen at Earth throughout the entire event. Since the field line to Ulysses is almost 3 times the distance to Earth, we will expect that the maximum SEP flux at Earth should be much higher than that at Ulysses, as it has been seen in many other SEP events, such as the July 14, 2000 event [10]. By just using scaling law of geometric factor of radial profile, one will get a maximum flux at Earth should be almost 9 times the flux at Ulysses. But this is not what is observed. In fact, the maximum flux at Ulysses in the $\sim$ 70-90 MeV channel is even a little higher than at Earth.

To understand this observation, we turn to our model for SEP propagation in 3-d heliospheric magnetic field. Our model simulation solves the Fokker-Planck diffusion equation for the particle distribution function $f(\mathbf{x}, \mu, p, t)$ as a function of spatial location $\mathbf{x}$, particle momentum p, pitch angle cosine μ and time t:

$$\frac{\partial f}{\partial t} = \nabla \cdot \boldsymbol{\kappa}_\perp \cdot \nabla f - (v\mu\hat{\mathbf{b}} + \mathbf{V}_{sw}) \cdot \nabla f + \frac{\partial}{\partial \mu} D_{\mu\mu} \frac{\partial f}{\partial \mu} - \frac{d\mu}{dt}\frac{\partial f}{\partial \mu} - \frac{dp}{dt}\frac{\partial f}{\partial p} \qquad (1)$$

with

$$\frac{d\mu}{dt} = \mu(1-\mu^2)(\nabla \cdot \mathbf{V}_{sw} - 3\hat{\mathbf{b}}\hat{\mathbf{b}} : \nabla \mathbf{V}_{sw})/2 - (1-\mu^2)v/2L_B$$

$$\frac{dp}{dt} = -[\,1-\mu^2(\nabla \cdot \mathbf{V}_{sw} - \hat{\mathbf{b}}\hat{\mathbf{b}} : \nabla \mathbf{V}_{sw})/2 + \mu^2 \hat{\mathbf{b}}\hat{\mathbf{b}} : \nabla \mathbf{V}_{sw}\,]\,p$$

It contains essentially all the major particle transport mechanisms: cross-field spatial diffusion $\boldsymbol{\kappa}_\perp$ tensor, streaming along the ambient magnetic field direction $\hat{\mathbf{b}}$ with particle speed v and pitch angle cosine μ, convection with the solar wind $\mathbf{V}_{sw}$, pitch angle diffusion $D_{\mu\mu}$, magnetic focusing with focal length $L_B = (\hat{\mathbf{b}} \cdot \nabla \ln B)^{-1}$ in the non-uniform ambient interplanetary magnetic field B, pitch angle change due to anisotropic adiabatic cooling by the solar wind, and momentum change through adiabatic cooling. The source of SEP is assumed to be injected near the sun, which is particularly true for high-energy SEP because only the conditions near the sun can allow acceleration of particles to high energies. The injection of the SEP is specified as the following boundary condition at the interface between the solar corona and interplanetary medium, which we assume to be at 0.05 AU or $\sim$10 solar radii:

$$f_b(\mathbf{x}, \mu, p, t) = a(\phi, \theta) p^{-\gamma} \frac{1}{t} \exp\left(-\frac{T_c}{t} - \frac{t}{T_l}\right), \qquad (2)$$

where γ the spectral index of source particles, T_c and T_l time constants controlling the time profile of particle release from the solar corona, and $a(\phi, \theta)$ a function specifying the longitudinal and latitudinal dependence of SEP source strength. The time constants T_c and T_l are 2 hours and 6 hours, presenting the period when the CME shock is propagating in the upper corona producing most does of source SEP. The power-law form of source particle spectrum is intended to be consistent with diffusive shock acceleration. In our model, we take $\gamma = 6$. We use the Parker model for the interplanetary magnetic field and solar wind. The parallel mean free path determined by pitch-angle diffusion is spatially varying in such a way the particle mean free path in the radial direction is a constant of 0.05 AU for 100 MeV protons. The parallel mean free path is also chosen to be proportional to $p^{2/3}$. The perpendicular diffusion coefficient is assumed to be isotropic $\kappa_\perp = 2 \times 10^{20} (v/c) p^{2/3} B_e/B$ where B_e is the strength of magnetic field B at Earth orbit. We solve the above equation with simulation of stochastic processes [5,11].

Figures 3 and 4 show the time profiles of 100 MeV SEP proton omni-directional flux as would seen at 1

AU in the Equator and 3 AU 60° S latitude which approximately simulates the condition of Ulysses on September 12, 2000. A few scenarios of SEP source distribution are tested. If we assume that the source injection on the sun is uniform, the time profiles of SEP flux at Ulysses and Earth will behave as those shown in Figure 3. The maximum flux seen at Earth will be at least an order of magnitude higher than that see at Ulysses. The higher flux at Earth is due partially to the geometry factor and partially to few scattering over shorter distance. This property of much higher maximum flux at Earth persists even in a model that has a SEP source of limited size as long as Earth is connected to the source directly in the early part of the event where maximum flux occurs. Later in the event the fluxes at the two locations reach an approximately same level, indicating the formation of nearly uniform reservoir of SEP in the inner heliosphere.

In order to lower the maximum flux seen at Earth, we have to disconnect the major SEP source location from the footpoint of magnetic field line to Earth. This has to be done in the early phase the SEP event because the particle transport is mainly through propagation along the magnetic field line. We found that we cannot just lower the value of particle parallel mean free path on the line to Earth to reduce the maximum flux, because if we drastically reduce the parallel mean free path the onset of SEP will be delayed too much to be consistent with the actually observation.

The most likely scenario for the September 12, 2000 event is that Ulysses has a better magnetic connection to the major part of SEP source on the sun. Figure 4 show the flux time profiles seen at the two locations from a SEP source that approximately covers a circle of angular distance 35° in radius. The center of the circle is set at 30° S latitude (middle between the latitudes of Earth and Ulysses) 0° Earth meridian longitude, which approximately simulates the solar flare on September 12, 2000. The SEP source strength falls off as $exp[-(\Lambda/35^o)^6]$, where Λ is the angular distance from the center of the solar flare. The flux time profiles at the two locations are almost identical. The same flux in the early part of the event is just accidental due to the assumption that Earth less well connected to the SEP source. In the later part of the event, the same flux level seen at the two locations is the result of reservoir phenomenon. If there is no perpendicular transport of particles, the flux at Earth will be much lower because the field lines to Earth are less populated with source particles.

It should be noted that the identical flux time profile at the two locations shown in Figure 4 is achieved with one set of parameters. There are other possibilities of SEP source distribution and transport coefficients that may produce time profiles of SEP flux at the two locations that resemble the above observations. No matter how, we have to make the major source of SEP disconnect from the magnetic field line to Earth in the early phase of the event. This suggests that even for a large halo CME, the SEP source on the sun still has a limited coverage of latitude and longitude. In order to achieve a uniform SEP reservoir in the inner heliosphere, particles have to transport across magnetic field lines in interplanetary space.

IV. CONCLUSION

The September 12, 2000 solar event is a large flare-CME event that produces a large dose of high-energy particles in the inner heliosphere. Although Ulysses is at much larger radial distance and high heliographic latitude, it observes a flux time profile that is almost identical to that observed at Earth for the entire SEP event of over 12 days long. Our analysis with model calculation show that Earth must be less well connected to the major SEP source on the sun than Ulysses in the early part of the event and particles reach a nearly uniform reservoir in the inner heliosphere a few days later through transport across magnetic field lines in interplanetary space.

V. ACKNOWLEDGMENT

I would thank Mr. Ismael Diaz for discussion on the possibility of making model runs specifically for the September 12, 2000 event. The work was supported in part by NASA grant NNX08AP91G and by JPL contract 1240373.

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