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Three Modes of SEP Propagation in the Heliosphere

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Two decay constants observed during the decay phase of solar energetic particle (SEP) events might be taken as an indication of two fundamentally different processes of particle propagation (McKibben, 1972). Recent Ulysses and Cassini observations of SEP events from different locations in the heliosphere give a new insight into the problem. It looks like the first constant, comparable with propagation time along magnetic field lines to ~ 5 AU (10-20 hours), shows how fast the heliosphere is filled by SEP due to along-field diffusion; the second constant reflects the rate of particle release from the heliosphere. This rate should be rather small, so that the cross-field propagation could maintain a uniform flux within the inner heliosphere, independent of longitude, latitude, or radius (the "reservoir effect"). Particle convection from the heliosphere seems to be a natural explanation of the second decay constants observed.

1. Introduction

The diffusion and convection are arbitrary terms of the transport equation describing SEP propagation in the heliosphere. Recent observations of solar protons from different points in the heliosphere separated both by latitude and longitude indicate, at least for 38-125 MeV protons considered in this work, that dominant effects of the along and cross field diffusion and the convection are clearly separated in time during the SEP events [1-2]. Therefore we need to discuss three modes of SEP propagation operating consequently. These findings are closely associated with so called the “reservoir effect” firstly mentioned in [3].

The azimuthal propagation of solar protons in the energy range of 10-30 MeV was investigated in [3] by using observations on board the earth satellite IMP 4 and the deep-space probes Pioneer-6 and 7 widely separated at ~1 AU from the earth. It was found that during some events the decay phase was divisible into two phases. The first phase is characterized by strong azimuthal gradients of the proton intensity and exponential time decay constant in the range ~10-20 hours. During the second phase, azimuthal gradients are weak or nonexistent and time decay constants are generally in excess of 40 hours (the reservoir effect). Two distinct kinds of events, prompt and slow, observed by Ulysses in June 1991 were reported in [4]. The authors of [4] did not mention the clear similarity with the results of [3]. They discussed some interpretations, including effects of transport perpendicular to the average interplanetary magnetic field, which possibly should play a much more important role underlining that future studies of radial and/or azimuthal gradients should help to distinguish between them.

Reames et al. [5] have thought that the CME shock accelerating particles works as a magnetic barrier and is impeding their escape from the inner heliosphere. However, the reservoir effect at high heliospheric latitudes is reported in [6], where according to [7] the model of SEP acceleration by coronal mass ejections driven shocks does not account for the Ulysses observations. Comparing Cassini [8] and Ulysses [1, 6] observations in the ecliptic at ~6 AU and at polar latitudes for events of 2000-2001it is clear that the reservoir effect is really global and we have the same questions to be answer: what are the reservoir shape and position of its out boundary; how the reservoir is filling by SEP and what is the mechanism of particle leakage?

In this article we compare SEP events, which have had similar fluences near the earth, observed at far heliocentric distances and high heliospheric latitudes, and try to answer the above questions. Finally in terms of the proposed scenario we reanalyzed the Ulysses observations in June 1991.

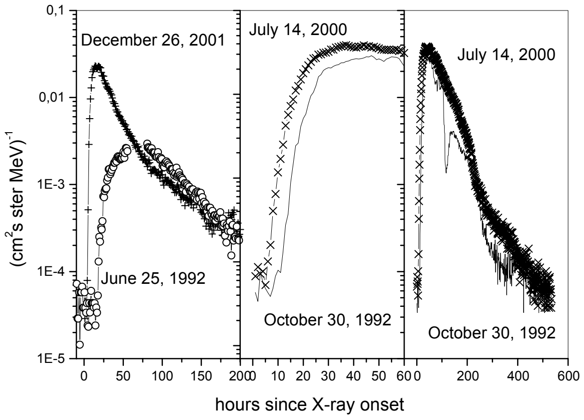

Figure 1. Comparison of polar and far distant SEP events observed by Ulysses after June 25, 1992(5.33 AU, S12.8E114), October 30, 1992 (5.17 AU, S19.5W120), July 14, 2000 (3.2 AU, S62E115) and December 26, 2001 (2.5 AU, N67W39). Proton intensity within 38-125 MeV energy range measured by KET/Ulysses

2. Observations

Below we discuss the experimental results from COSPIN/KET for 38-125 MeV protons (http://helio.estec.esa.nl/ulysses/ftp/data/cospin/ket/) and from the Energetic Particle Sensor (EPS) on board the GOES satellite (http://rsd.gsfc.nasa.gov/goes/text/goes.databook.html) for 40-80 MeV protons. Figure 1 compares time profiles of SEP events observed by Ulysses from different points in the heliosphere. The events of June 25, 1992(5.33 AU, S12.8E114) and December 2001(2.5 AU, N67W39) have comparable proton fluences near the earth [1-2].

It was noticed in [2] that the time profile of the June 25, 1992 event would coincide with time profiles of the larger event of October 30,1992 (5.17 AU, S19.5W120), during first 50 hours, if one normalizes the first to the maximum intensity and accounts that proton flux with less intensity would be below background longer. From another hand the events observed at high latitudes [1] as July 14, 2000 (3.2 AU, S62E115) and December 26, 2001 (2.5 AU, N67W39) have proton intensities within a factor of 3 during first thirty hours of the events. Therefore we may conclude that the same propagation mechanism with similar transport parameters operates during the initial phase of SEP events observed by Ulysses both at large heliocentric distances and high heliospheric latitudes, but observers in the ecliptic plane might be magnetically connected to a source with different source strength.

During the decay phase the Ulysses events are considerably different. A total number of SEP injected into the heliosphere becomes important during the decay phase as well as their cross-field diffusion, modulation and trapping by local solar wind structures. Events, which are larger near the Earth, show larger intensities and time scales in polar regions and close to the Jupiter orbit. However events with nearly equal fluences appear to be similar at large heliocentric distances and high heliospheric latitudes.

The exponential decay after 75-100 hours since the proton onset at Ulysses (the reservoir effect) has been observed in all events considered in [1-2] excepting two, which are very slow and have minimal fluences (November 6, 1997 and August 24, 2002). The last events were attributed in [2] for the cross-field diffusion. The determined exponential time decay constants are similar to those reported by McKibben (1972) for his second decay phase. Comparison of their values with solar wind velocities observed by Ulysses shows that they anticorrelate with each other.

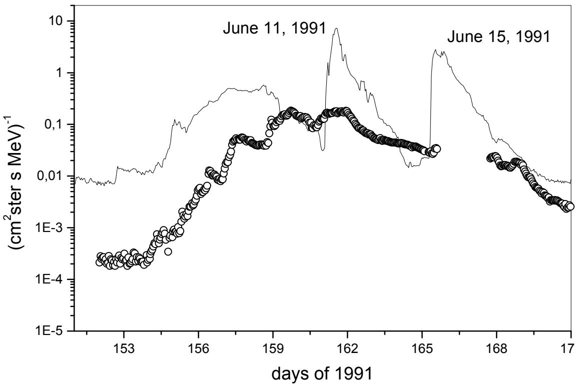

Figure 2. SEP events of June 1991, view from GOES (line) and Ulysses (circles, 3.2 AU in the ecliptic). Proton intensity are measured within 38-82 MeV and 38-125 MeV energy ranges respectively.

3. Discussion

Since the ratio of the cross and along field diffusion coefficients $D_{\perp} / D_{\|}$ is ~0.01, the SEP dominantly propagate along interplanetary magnetic field lines (IMF). Thus magnetic field lines connected to the source, which might be extended by more than 120^0 both in longitude and latitude [1,2], would bound the heliosperic region containing the largest amount of SEP.

It looks like the first decay constant [3], comparable with propagation time along magnetic field lines to ~ 5 AU (10-20 hours), shows how fast the heliosphere is filled by SEP due to along-field diffusion (see numerical modeling in [10]) creating large cross-field gradients. Later the cross-field diffusion operates reducing the spatial gradients and forming uniform distribution of SEP in the reservoir. The effective mean free path to fill the region of a linear dimension L during a time interval τ is $\lambda = L^2 / \tau V$, where V is the solar wind velocity [9]. The uniform distribution of SEP in the heliosphere is observed after about 75-100 hours within the radius of ~5 AU. Since fractal properties of the solar wind should be changed at heliocentric distances of 5-6 AU [10] due to nonlinear interaction between magnetic flux tubes. This should be a natural out boundary of the particle reservoir. The effective mean free path for protons is about 0.01 AU. This boundary possibly does not exist at polar latitudes, where open magnetic field lines provide a way for SEP escaping from the helioshere.

The SEP density at the beginning of the reservoir effect depends on a total number of SEP injected into the heliosphere and volume of the reservoir. The second constant reflects the rate of particle release from the heliosphere. The rate of particle release from the heliosphere should be rather small, so that the cross-field propagation could form and maintain a uniform flux within the reservoir independently on heliospheric longitude and latitude; and radius.

Let us look from this point of view on solar proton intensities measured in June 1991 (Fig. 2). The famous X-ray events of June 1 and 4, 1991 occurred on the east solar and possibly produced a large number of SEP particles, however, due to the bad magnetic connection neither Ulysses and GOES observed the prompt (along field) component. About one order difference between the proton intensities observed by GOES and Ulysses during the rising phase might be attributed to different heliocentric distances. Later the earth was better connected to the solar source, so GOES observed two distinct promt1 events of June 11 and 15, 1991.

The total number of particles released during the last two events was much less than during the first two, so their influence on the reservoir population was minor.

Particle convection from the heliosphere may explain the exponential time decay of particle intensity during the reservoir effect. For some region with uniform particle density n we have: $V \cdot dn/dt \sim -n \cdot U \cdot S$, where V- volume of the reservoir; S - effective area of the convection; U - the solar wind velocity.

The situation was much more complex in October-November 2003, when the largest decay constant and the reverse gradient of SEP were observed [2]. The interplanetary conditions observed by Ulysses in October-November 2003 were interpreted as a combination of CIR and shock waves. Solar cosmic rays in the region between the CIR and the shock wave were compressed by the moving shock creating the reverse gradient. Later the shock opened the trap destroying the out boundary.

4. Conclusions

Interplanetary magnetic field lines connected to the source of SEP form the reservoir with out boundary at ~ 5 AU. During about first 30-50 hours of the event SEP dominantly propagate along magnetic field lines, so large spatial gradients of exist in the reservoir due to different intensity of the source. Later the cross-field diffusion reduces the spatial gradients and forms the uniform distribution of SEP inside the reservoir.

The particle density at the beginning of the reservoir effect depends a total number of particles injected into the reservoir and its volume.. Thus the SEP events are different during the second decay phase, large events at 1 AU in the ecliptic plane have larger time scales and intensities in distant points of the heliosphere.

Particle convection from the heliosphere seems to be a natural explanation of exponential time decay of particle intensity during the reservoir effect.

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