EXTENDED $^3\text{He}$-RICH PERIODS OF SOLAR ENERGETIC PARTICLES IN STRUCTURED SOLAR WIND

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ABSTRACT

We have surveyed helium isotope abundance data (1997–2005) measured with the UltraLow-Energy Isotope Spectrometer (ULEIS) on the Advanced Composition Explorer (ACE) and have found multiday periods of $^3\text{He}$-rich solar energetic particles (SEPs) in the energy range of $\sim$0.4–10 MeV nucleon$^{-1}$ with $^3\text{He}/^4\text{He}\sim 0.1–1$. We analyzed 17 periods where there were good counting statistics, also using in situ measurements of solar wind at ACE and Solar and Heliospheric Observatory (SOHO) along with solar observations by SOHO telescopes, to study coronal and interplanetary magnetic field (IMF) structures associated with multiday periods of $^3\text{He}$-rich SEPs. The analysis indicates that all events are associated with slow solar wind and most of them with significant compressions in solar wind at 1 AU. About half of the events are associated with a deep well in solar wind speed that is followed by a fast rise of the wind speed, typically by about 200 km s$^{-1}$. The corresponding coronal structure consists of an active region, leading coronal hole and trailing coronal hole situated not far from the solar equator. We have employed a simplified model of corotating compression in the solar wind to estimate the possible effect of the rising speed wind on confinement of $^3\text{He}$-rich SEPs in IMF structures. Numerical modeling indicates that

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a fast increase of the wind speed by 200 km s\(^{-1}\) can significantly affect the SEP time-intensity profiles at 1 AU and results in higher SEP intensities than would be expected based on a standard model of solar wind.

Subject headings: Sun: particle emission — acceleration of particles — solar wind

1. Introduction

A classic \(^3\text{He}\)-rich event may be defined as a small solar energetic particle (SEP) event that is strongly enhanced in the isotope \(^3\text{He}\), \(^3\text{He}/^4\text{He} \gtrsim 0.1\), in association with an impulsive flaring in the western hemisphere of the Sun (see reviews by Kocharov and Kocharov 1984; Reames, Meyer, & von Rosenvinge 1994; Mason 2007). Theoretical investigations have shown that the most promising mechanism to explain the \(^3\text{He}\) enrichment was plasma resonance (pre)acceleration in the flaring region (Fisk 1978; Reames 1999; Mason 2007, and references in two later papers). Impulsive injection of energetic \(^3\text{He}\) from the Sun is controlled by magnetic structures of solar corona and followed by interplanetary propagation, to produce an impulsive SEP event at 1 AU. A new feature of \(^3\text{He}\)-rich SEPs recently discovered on the Advanced Composition Explorer (ACE) spacecraft has been the existence of multiday periods of energetic \(^3\text{He}\) enhancement (Wiedenbeck et al. 2002; Mason 2007).

The interplanetary transport of solar energetic particles depends on the state of ambient solar wind. However, the solar wind state is highly variable and depends on coronal structures at the wind’s base. Zwickl et al. (1978) focused attention on the relation of impulsive SEPs with the low-speed solar wind that precedes the onset of fast wind streams. Slivka, Kocharov, & Dvoryanchikov (1984) performed a statistical study of solar wind profiles associated with \(^3\text{He}\)-rich SEP events and found a minimum in the wind speed at the site of the \(^3\text{He}\)-rich flare (see also §4.5 of Kocharov and Kocharov 1984). Recent progress in space instrumentation has allowed a new insight into solar origins of \(^3\text{He}\)-rich SEPs. Wang, Pick, and Mason (2006) concluded that the SEPs originated at the interface between active regions and small coronal holes. Accurate source identification of regions of \(^3\text{He}\) emission have been achieved using energetic ions and electrons, imaging radio, EUV, and hard and soft X-rays, revealing an association with EUV and white light jets previously identified as sites of magnetic reconnection from newly emerging flux (Pick et al. 2006). The SEPs escape into the interplanetary medium along open magnetic field lines, some of which were connected to the spacecraft orbiting the Sun in the ecliptic plane. However, possible effects of associated solar wind structures on transport of \(^3\text{He}\)-rich SEPs in the interplanetary medium have not been investigated. It is noteworthy that the interface between active regions and growing low-latitude coronal holes was previously regarded also as the origin of coronal mass ejec-
tions (CMEs) (Gonzales et al. 1996) and that some impulsive SEP events were found to be associated with narrow CMEs (Kahler, Reames, and Sheeley 2001).

Energetic particles traveling in the interplanetary medium undergo scattering at the short-scale inhomogeneities in the IMF along with focusing by the long-scale component of the field (in application to $^3$He-rich events see, e.g., Tsurutani et al. 2002). They suffer adiabatic deceleration, which has been incorporated into different numerical techniques. However, most of the models assume a uniform radial expansion of solar wind, which results in an Archimedes spiral IMF. The classic model of solar wind does not include dynamical processes such as overtaking high-speed streams. For instance, corotating high-speed streams can interact with the upstream low-speed wind, leading to magnetic field compressions (e.g., Pizzo 1985; Tsurutani et al. 1995). The magnetic compressions, in turn, can affect the propagation of solar energetic particles. In application to energetic particles associated with corotating interaction regions (CIRs), Giacalone, Jokipii, and Kóta (2002) modeled particle transport in a steady-state longitude-dependent solar wind. They considered the CIR particles, which are accelerated in the interplanetary medium. Then Kocharov et al. (2003) applied a similar model of the corotating transition region to Monte Carlo simulations of SEP propagation from the Sun to near-Earth spacecraft. We will use the later code for the quantitative estimates of our present paper.

The present study is focused on multiday periods of $^3$He-rich SEPs observed onboard ACE. We analyze solar wind and coronal structures associated with the $^3$He-rich periods. In Appendix we present results of stochastic simulations of SEP transport in a structured solar wind to estimate its significance for the $^3$He intensity-time profiles observed at 1 AU.

2. Observations

Energetic $^3$He observations of the present study were made using the UltraLow-Energy Isotope Spectrometer (ULEIS) on ACE. ULEIS is a time-of-flight mass spectrometer with high resolution and sensitivity, covering the energy range of $\sim$0.02–10 MeV nucleon$^{-1}$, depending on species (Mason et al. 1998). A qualitatively new feature of $^3$He-rich SEPs discovered on ACE has been the existence of multiday periods of continuous presence of energetic $^3$He at 1 AU. We surveyed the ACE data from 1997 through the end of 2005 and found approximately 50 periods of continuous $^3$He presence. Table 1 lists the 17 highest quality periods, where there were good counting statistics and minimal contributions from other activity. The selection criteria are the following: (i) $^3$He clear signature in the 0.4–10 MeV nucleon$^{-1}$ range; (ii) $^3$He intensity in excess of $\sim 0.5 \times 10^{-2}$ particles (s cm$^2$ sr MeV nucl$^{-1}$)$^{-1}$; (iii) Significant enhancement in the iron-to-oxygen ratio, Fe/O$\sim 1$; and (iv) the SEP event lasts for
2 days or more. The latter distinguishes the multiday $^3$He-rich periods studied here from the classic $^3$He-rich events described more than twenty years ago.

We used $ACE$ Magnetometer (MAG) (Smith et al. 1998) and Solar Wind Electron Proton Alpha Monitor (SWEPAM) (McComas et al. 1998) observations to identify large-scale magnetic field structures present in space during the $^3$He-rich periods observed with ULEIS. The hourly averaged solar wind parameters in the RTN coordinate system include two components of solar wind velocity — the radial component, $V_R$, and the tangential component in the ecliptic plane, $V_T$; the proton number density, $N_p$; the magnetic field magnitude, $B$; and the magnetic-field azimuthal angle measured from the radial direction anticlockwise as seen from the northern hemisphere, $\lambda_B$. The magnetic field direction in the solar wind depends on the magnetic field structures in the underlying solar corona. We used solar images collected by the Extreme-Ultraviolet Telescope (EIT) on the Solar and Heliospheric Observatory (SOHO) to study coronal magnetic structures associated with periods of energetic $^3$He. The EIT provides wide-field images of the solar corona, from the transition region and up to 1.5 $R_\odot$ (Delaboudinière et al. 1995). Polarities of the coronal magnetic field were determined using data from the Michelson Doppler Imager (MDI) also onboard $SOHO$ (Scherrer et al. 1995).

Most of the prolonged $^3$He enhancements in our survey are spatial, i.e., they start simultaneously at all energies when the spacecraft enters a magnetic flux tube that was previously filled with $^3$He-rich SEPs. Such events comprise almost 90% of all $^3$He-rich periods listed in Table 1, and we focus on them. All $^3$He-rich periods were observed, completely or partly, in slow solar wind. Based on the solar wind speed profile during the period, they can be divided into three categories. Events of the first category are observed during a declining phase of solar wind speed that is followed by an increase near the end of the period. The second category consists of events with a flat speed profile followed by an increase of solar wind speed near the end of the $^3$He-rich period. In events of the third category the solar wind speed reaches a maximum value inside the period. Note, that at this stage we do not mix SEP events with velocity dispersion and the spatial SEP events. Thus, we keep two temporal events, #8 and #17, as a separate group.

Almost half of the events fall into category 1, events ## 1–3, 9, 11–13, and 16 (8 of total 17 events; Table 1). A typical category 1 event, event #1, is shown in Fig. 1. All events of this type are shown in Fig. 2. It is seen from upper panel of Fig. 1 that the $^3$He-rich period is situated in the region of minimal solar wind speed and south magnetic field polarity (magnetic field vector pointing away from the Sun). The end of the $^3$He-rich period coincides with an interplanetary magnetic sector boundary and an increase of solar wind speed. At that time the solar wind velocity vector deviates from the radial direction, so that a S-shaped feature appears in the time profile of the tangential component, $V_T$. An increase
in magnetic field intensity, $B$, along with a coincident increase in solar wind proton density, $N_p$, indicates a transverse compression formed at the transition from the slow wind to a faster wind stream. This compression and the deviation of the solar-wind velocity direction are signatures of interaction between the preceding slow solar wind and the following higher-speed stream. The lower panel of Fig. 1 shows the global structure of solar corona at the base of the solar wind. Two coronal holes are shown with blue color, the leading hole of south (+) polarity and the trailing hole of north polarity (−). Three meridian lines, 37.4°W, 9.6°W, and 23°E, indicate the nominal longitudes of the IMF footprints at three selected instants of time, respectively $M_1$, $M_2$ and $M_3$. The selected time points are shown on the solar wind profile of Fig. 1. For this estimate we have assumed that solar wind expands radially with a constant speed while the Sun rotates with the period $T_S = 655$ hr. The source of $^3$He-rich SEPs and source of slow solar wind are situated in active regions between the longitudes $M_1(37.4°W)$ and $M_2(9.6°W)$ and overlayed by the IMF of the same polarity as in the leading coronal hole. The trailing coronal hole (−) is a source of the higher speed wind, which interacts with the slow speed wind to produce the $B$-$N_p$ compression at 1 AU. Note that two events with SEP velocity dispersion in the beginning of the period, #8 and #17, are also observed during the declining phase of solar wind speed and shown in Fig. 3.

Category 2 has 4 events: ##6, 10, 14, and 15. A typical event of this category, event #10, is shown in Fig. 4, and all events of this category are shown in Fig. 5. In events of category 2 the solar wind speed profile is flat during the $^3$He-rich period but rises at the end of the SEP event. The magnetic field polarity (magnetic sector) changes in all events except event #14. For instance, at the end of period #10 the magnetic field polarity changes from the north (−) polarity to the south (+) polarity. The latter may be associated with the trailing coronal hole seen near the longitude $M_3$, 48.1°E (Fig. 4). In contrast to event #1 discussed above, the major coronal holes of period #10 are far from the ecliptic. A solar wind compression near the Earth’s orbit is seen as simultaneous enhancement of the magnetic field intensity, $B$, and proton number density, $N_p$, at the transition from the low speed to higher speed wind, near the end of period #10 (Fig. 4). Note that event #14 may be exceptional, because the solar wind compression in that event was identified with an interplanetary shock (SOHO/CELIAS observation).

Category 3 periods (##4, 5, and 7) reveal the most complicated behavior of solar wind parameters. Coronal structures also look more complicated than in category 1. A typical category 3 event, #7, is shown in Fig. 6, and all three events of this category are shown in Fig. 7. One can see from Fig. 6 that during and after the period #7 the IMF polarity is identical to the north polarity observed in the equatorial coronal holes. Some of the coronal holes are seen also between the longitudes 10.8°E and 58.4°W, where the $^3$He-rich SEPs and the solar wind come from. Several density enhancements are seen in the $N_p$ profiles of Fig. 6,
but only one of them coincides with an enhancement in the magnetic intensity, $B$. There are clear deviations of the wind velocity from the radial direction ('oscillations' in $V_T$).

Figures 8 and 9 show solar wind profiles on a longer time scale, covering 4 solar synodic periods, $4T_S$. These figures make it possible to identify co-rotating structures in the solar wind and in energetic particles. Panel $a$ of Fig. 8 shows an event-average profile, which is the average of ten intervals centered on those periods in the survey that showed during declining of solar wind speed: eight events from category 1 and two events with velocity dispersion of the SEP onset. The average profile of panel $a$ can be compared with panel $b$ showing the solar wind speed around the period #1. Significant co-rotating features are clearly seen in both profiles, namely a minimum at the time of $^3$He-rich event following a high speed stream. Trailing enhancement of the wind speed changes markedly from one rotation to another. Panel $c$ shows the 3.3–6.4 MeV proton profile registered from the ERNE instrument onboard SOHO (Torsti et al. 1995). There is a maximum in energetic particles corresponding to the leading high-speed solar wind (CIR event). Thus, co-rotating structures are present also in energetic particles but not in the lower energy $^3$He/$^4$He. The $^3$He/$^4$He enhancement follows the CIR event and lasts less than one solar rotation. Fig. 9 is an additional illustration of co-rotating structures for representative events of each category. In that figure we have plotted on the same time interval a current solar rotation profile, $V_R$, and the previous and following rotation profiles, respectively $V_R(-T_S)$ and $V_R(+T_S)$, and similarly for magnetic field direction and magnitude. Repetitive features can be easily seen, as well as their changes from one rotation to another.

3. Discussion

Classical $^3$He-rich events can be observed on near-Earth spacecraft when the parent flare occurs in a limited range of heliolongitudes, typically $\sim 40^\circ$W–$80^\circ$W (e.g., Figure 31 by Kocharov and Kocharov 1984). The $\sim 40^\circ$-wide SEP-injection sector at Sun corresponds to $\sim 3$ days of solar rotation (Fig. 10). If at the time of a $^3$He-rich flare the spacecraft was within the range of well-connected longitudes, it would observed the entire $^3$He-rich event or at least its velocity-dependent onset. Only such SEP events could be associated with flaring at the Sun making it possible to locate the coordinates of the parent flare. However, it is also possible for a spacecraft to enter the source-connected longitude region well after the flare, when SEPs have filled up the connected magnetic tubes out to 1 AU. In such a case, only the late phase of the event will be observed, with simultaneous rise of particle intensities in all energy channels. This can be referred to as a dispersionless onset, or spatial onset, or a connection to an old event. Prolonged $^3$He-rich periods without velocity dispersion of the
SEP onset are in the focus of our present study.

The probability of detecting an old SEP-event depends on the rate of SEP transport in the IMF. In particular slowing down the SEP transport makes their detection more likely. Dynamic processes in solar wind can change the magnetic field and affect the propagation of solar energetic particles. Even in a steady state, the solar wind speed is a function of heliographic longitude. As the Sun rotates, flows of different speeds become radially aligned in an inertial frame of reference. Faster wind runs into slower wind ahead while simultaneously outrunning slower trailing wind. Since these radially aligned parcels of plasma originate from different positions on the Sun at different times, they are threaded by different magnetic field lines and are thus prevented from interpenetration. As a result, a corotating compression region forms (e.g., Giacalone, Jokipii, and Kóta, 2002, and references therein). Zwickl et al. (1978) studied SEP events enhanced in $Z > 3$ ions and focused attention on association of $Z$-rich events with the low-speed wind that precedes the onset of fast solar wind streams. According to Slivka, Kocharov, & Dvoryanchikov (1984), typical $^3$He-rich flares occur at the origin of slow solar wind, 300–400 km s$^{-1}$, followed in 1–2 days time, as the Sun rotates, by a faster solar wind, 500–700 km s$^{-1}$ (see Figures 28 and 30 of Kocharov and Kocharov, 1984). Thus, corotating compressions are part of magnetic environment for SEP transport in a typical impulsive SEP event.

Our analysis of solar wind profiles of multiday $^3$He-rich periods indicates that all events are associated with slow solar wind of changing speed, and most of the events are associated with significant compressions in solar wind at 1 AU. The solar wind profiles can be divided into three major categories. About half of the events (events of category 1) are associated with a deep well in solar wind speed that is terminated at the trailing (east) end by a fast rise of the wind speed, typically by about 200 km s$^{-1}$. The corresponding coronal structure consists of an active region, a leading coronal hole and a trailing coronal hole, not far from the solar equator. If the leading high-speed stream is missing, an event falls into category 2. Category 3 events have revealed a more complicated behavior.

An impact of corotating compression in solar wind on the SEP profiles observed at 1 AU can be estimated using the analytical model of a corotating interaction region by Giacalone, Jokipii, and Kóta (2002). The model does not include a leading coronal hole and thus is most relevant to the events of category 2. In the Appendix we describe our Monte Carlo simulations of SEP transport in that model. The stochastic simulation results indicate that a realistic compression in solar wind can significantly confine $^3$He and other species from impulsive solar events, and therefore enhance the probability of detection of a prolonged $^3$He-rich period at a near-Earth spacecraft.

The presence of the imprint of active regions in the solar wind near the Earth’s orbit is
a well established, implying that active regions are a source of slow solar wind (e.g., Liewer, Neugebauer, and Zurbuchen 2004; Woo and Habbal 2005). A recent model of the slow solar wind origin suggests the solar wind acceleration to be a result of the reconnection of open magnetic flux with coronal loops (Fisk 2003). Reconnection of open magnetic flux with closed magnetic loops will distribute a small fraction of the open flux into a uniform, radial component in active regions that do not underlie the overexpansion of the magnetic field from coronal holes. This component of open flux will facilitate the escape of energetic particles from flares and also the escape of plasma to the slow solar wind (Fisk and Zurbuchen 2006). The Helium-3 rich periods in our present study are observed in slow solar wind that originates from active regions observed with SOHO/EIT. Those active regions could be overlayed by the open magnetic flux that has diffused from the nearby coronal holes. However, we note a marked West-East asymmetry of the solar wind profiles, that is the leading (western) slope of the well in the wind speed profile is less steep and more prolonged than the trailing (eastern) slope (Figures 1, 2). If the reconnection of open field lines with coronal loops results in a diffusive transport of open field lines into the \(^{3}\text{He}\)-source area, there should be an additional term in the diffusion equation to drive open magnetic field lines preferentially from West to East, in the solar corotating frame.

Impulsive solar energetic particle events are typically associated with a special structure of solar wind, that is the SEPs are produced in a vicinity of interface between a very slow solar wind and a 100–200 km s\(^{-1}\) faster solar wind stream (Zwickl et al. 1978; Kocharov and Kocharov 1984, see Figs. 28 and 30 in the later paper). Recent observations indicate that the source of the impulsive SEPs lies next to a coronal hole containing Earth-directed open field lines (Pick et al. 2006; Wang, Pick, and Mason 2006). In the classic, short-duration SEP events with velocity dispersion at the event onset, the particle injection time can be estimated and then compared with broadband solar observation. That allowed Wang, Pick, and Mason (2006) to find an association of \(^{3}\text{He}\)-rich SEP source with a jet-like ejection aligned with the open field lines. The jets show a tendency to recur. A straightforward interpretation is that the jets are signatures of magnetic reconnection between closed and open field lines, and energetic \(^{3}\text{He}\) ions originate from those reconnection sites. In the prolonged, multiday \(^{3}\text{He}\)-rich events of our present study, the velocity dispersion is not typically observed, and history of \(^{3}\text{He}\) production could not be learned. However, we speculate that \(^{3}\text{He}\) ions of the multiday events initially come from the same coronal processes as in classical impulsive events, perhaps from a series of impulsive events, which could produce the highest amount of \(^{3}\text{He}\) SEPs, making it more likely that “old” SEP events would be seen at 1 AU.

Most of prolonged \(^{3}\text{He}\)-rich events considered in the present paper have a spatial onset, indicating that first particles were accelerated at the Sun and have propagated to 1 AU before the spacecraft enters the well-connected magnetic flux tube. The dominance of spatial events
(15 out of 17 events) can be caused either by a sufficiently long confinement of SEPs in solar wind structures or by the long-lasting production of SEPs. We have employed a simple model of corotating compression in the solar wind to estimate possible effect of changing solar wind speed on confinement of $^3$He-rich SEPs in solar wind structures (see Appendix). Figure 10 shows an interplanetary compression region that could originate from the 200 km s$^{-1}$ rise in the solar wind speed typically observed at the end of a $^3$He-rich period. We assume that the orbit segment A–B is in the well-connected region of a previous $^3$He-rich flare. Then we calculated how the $^3$He fluence collected onboard a near-Earth spacecraft over the segment A–B depends on the delay of the spacecraft’s entering the well-connected region with respect to the time of the previous $^3$He-rich flare. Figure 12 indicates that the fluence is significantly enhanced when the corotating structure is present. The enhancement is caused by temporal confinement of SEPs in a magnetic trap of the corotating region and by partial canceling of adiabatic deceleration of SEPs by their re-acceleration in the converging solar wind flow inside the compression (Kocharov et al. 2003).

The large-scale magnetic trap is one of significant factors of prolonged $^3$He-rich events. Another factor could be the occurrence of a series of previous $^3$He-rich flares, which could provide a sufficient amount of $^3$He to be confined in the trap and to remain observable above actual background for a few days. However, in the absence of the particle anisotropy data a continuous production of $^3$He-rich SEPs could not be ruled out either. In any case a role of interplanetary confinement is to enhance the SEP density in space and thus to increase a probability that the long lasting SEPs will be observed. It is also important that a $^3$He-rich period can be observed only at a very low ‘background’ level of ions with a ‘normal’ composition, $^3$He/$^4$He< 0.01. Thus, a combination of factors could be responsible for the occurrence of multiday $^3$He-rich periods at 1 AU.

The large-scale magnetic structures in solar wind can be caused by a longitude dependence of solar wind speed originating from coronal structures that are static, or nearly static, in a fixed frame corotating with Sun (corotating IMF structures). However, transient solar phenomena, like coronal mass ejections, can also cause magnetic compressions and rarefactions at 1 AU (transient IMF structures). In order to reveal corotating structures, we have compared solar wind profiles observed during 3–4 rotation periods (Figures 8 and 9). It turns out that, while corotating structures are present, the solar wind profiles originating from the source region of $^3$He are still not exactly one and the same before and after the $^3$He injection. This may indicate some reconfiguration of solar corona during the $^3$He production at the Sun. Note that a minor fraction of the low-energy $^3$He-rich periods may be associated with traveling shocks.
4. Conclusions

We have studied solar wind profiles and coronal structures associated with multiday $^{3}$He-rich periods observed onboard ACE and conclude the following:

- Multiday $^{3}$He-rich periods are associated with solar wind of changing speed, interaction of different solar wind streams and magnetic compressions at 1 AU.

- Numerical modeling of SEP transport in a corotating compression of solar wind indicates that a fast increase of the wind speed by 200 km s$^{-1}$, which is typical for the $^{3}$He-rich periods, can significantly affect SEP time-intensity profiles at 1 AU and results in higher SEP intensities than would be expected based on a standard solar wind model.

- Temporal confinement of $^{3}$He-rich SEPs in the structured solar wind is an essential factor of occurrence of multiday $^{3}$He-rich periods in interplanetary space, while both the $^{3}$He-rich SEPs and the solar wind structures confining them originate from the coronal magnetic structure containing magnetic loops of active region and open lines of nearby coronal holes.

The structured solar wind simultaneously is a signature of the SEP-producing region at the Sun and a significant factor of the $^{3}$He confinement in the inner heliosphere. Solar wind structures typically associated with impulsive SEP events can significantly affect the SEP transport in the interplanetary medium and should be taken into account in fitting of SEP events and other applications.

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A. Modeling

Giacalone, Jokipii, and Kóta (2002) constructed an analytical model of a corotating interaction region, applicable for heliocentric distances $\lesssim$2 AU, where the forward and reverse shocks have not yet been formed. This is perhaps the simplest model describing an interplanetary corotating structure formed when a fast-speed stream is embedded into the
ambient slow wind. In the adopted solar wind model, the plasma flow at each point is radial in a non-rotating heliocentric frame, with a speed $u$, and in steady state in the solar corotating frame, with a speed $u_c$. The spherical coordinates, $r$, $\phi$, and $\theta$, are defined in the frame that corotates with the Sun. The azimuthal angle is measured anti-clockwise, if observed from the North pole of the Sun. The radial flow speed is assumed to be a function of the radial distance, $r$, and the azimuth angle, $\phi$:

$$u(r, \phi) = u_s + \frac{1}{2}(u_f - u_s) \tanh \left( \frac{\phi_c - \Omega \frac{r}{W} - \phi}{\Delta \phi_c} \right) - \frac{1}{2}(u_f - u_s) \tanh \left( \frac{\phi_{rf} - \Omega \frac{r}{W} - \phi}{\Delta \phi_{rf}} \right),$$

(A1)

where $u_s$ and $u_f$ are the slow and fast solar wind speeds; the angular parameters $\phi_{c(rf)}$ and $\Delta \phi_{c(rf)}$ respectively control a position and an azimuthal width of the compression (rarefaction) region of solar wind; the model parameter $W$ is a speed at which the disturbance moves radially outward in the non-rotating frame of reference. Thus, $u$ varies as a function of $\phi$ from $u_s$ to $u_f$ and back to $u_s$, but with different widths over which the variation takes place. The model can reproduce either “reverse” or “forward” compressions of different strength, depending on the value of the parameter $W$. If the disturbance speed, $W$, is faster than the fast solar wind speed, $u_f$, then the disturbance will be a “forward” compression.

A magnetic field vector is introduced to be parallel to the plasma velocity in corotating frame: $B \propto u_c$. For simplicity, consider only magnetic field lines situated in the equatorial plane, $\theta = 90^\circ$. In this case, magnetic field is of the following form (Giacalone, Jokipii, and Kóta 2002):

$$B_r(r, \phi) = \frac{\Psi_i}{u(r, \phi) - W} \left( \frac{r_\odot}{r} \right)^2 u(r, \phi),$$

$$B_\phi(r, \phi) = -\frac{\Psi_i}{u(r, \phi) - W} \left( \frac{r_\odot}{r} \right)^2 \Omega_\odot r,$$

(A2)

where the function $u(r, \phi)$ is given by equation (A1), and few constants are grouped together as $\Psi_i$. The normalization factor $\Psi_i$ is defined for a magnetic line ‘i’ as a constant that maintains at the line footpoint $(r_\odot, \phi_i)$ the magnetic field strength equal to a boundary value $B(r_\odot, \phi_i)$. Near the Sun the magnetic field is almost radial, $B_r(r_\odot, \phi) \approx B(r_\odot, \phi_i)$, and hence the first equation (A2) connects $\Psi_i$ to the physical parameters at the Sun:

$$\Psi_i \approx \left( u(r_\odot, \phi_i) - W \right) \frac{B(r_\odot, \phi_i)}{u(r_\odot, \phi_i)}.$$

(A3)

We model IMF based on equations (A1–A3) for the uniform boundary field $B(r_\odot, \phi_i) = 1$ G. In what follows we use the ‘anchored’ longitude of the magnetic line footpoint, $\Phi_i$, that is
measured with respect to the compression longitude $\phi_c$: $\Phi_i = \phi_i - \phi_c$. The reference magnetic line, whose footpoint is at $\phi_c = \phi_i$ ($\Phi_i = 0$), is shown with a long-dash-dot curve in Figure 10. In Figure 10 we have mapped magnetic field lines of the adopted model on ecliptic plane, while Figure 11 shows corresponding solar wind profiles observed on an imaginary near-Earth spacecraft, which orbits the Sun in corotating frame over a 27 days period.

Using the numerical code of Kocharov et al. (2003), we have simulated an SEP event in the sector A–B that is connected to the SEP source on the Sun (Fig. 10). The $^3\text{He}$-rich SEPs were impulsively injected at the Sun when the 1 AU spacecraft was out of the sector A–B and are observed after the spacecraft has penetrated this sector. Corresponding SEP-observation period is shown with a horizontal bar in Figure 11. We assume the energy spectrum injected at the Sun to be of the exponential form:

$$N(E) = A_o \exp \left( -aE^{1/4} \right),$$  \hspace{1cm} (A4)

where $E$ is kinetic energy per nucleon and $a=12$ (MeV/n)$^{-1/4}$, which corresponds to the local slope $E^{-3}$ at 1 MeV nucleon$^{-1}$. For Monte Carlo simulations of SEP transport, we adopt the mean free path to be independent of spatial coordinate and proportional to a power of the ion’s speed: $\lambda = \lambda_o (v/v_o)^\alpha$, where $\lambda_o$ and $v_o$ respectively are the mean free path and the speed of 1 MeV nucleon$^{-1}$ ion; $\alpha = \frac{1}{3}$, which corresponds to the Kolmogorov turbulence spectrum.

We inject SEPs at the footpoints of a set of magnetic field lines of the sector A–B and trace particles along their trajectories for a 7 day travel period. We collect particles at 1 AU along the sector A–B as it would be done with a detector onboard a near-Earth spacecraft. The model results for the injection spectrum (A4) are presented in Figure 12, which shows the $^3\text{He}$ fluence that would be collected inside the sector connected to the source of $^3\text{He}$-rich SEPs. The fluence depends on the difference between the observation start time (spacecraft’s entrance time of the sector A–B) and the $^3\text{He}$ flare time, $t_A - t_0$. It is seen that the fluence collected in the corotating structure is significantly enhanced. A strong difference between the cases of standard solar wind and compressed solar wind exits late in the event, when the fluence observed inside the corotating structure is up to one order of magnitude higher than would be expected based on the standard model of solar wind.

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Table 1. Multiday $^3$He-rich periods observed with ACE/ULEIS.

<table>
<thead>
<tr>
<th>Year</th>
<th>DOY start</th>
<th>hr start</th>
<th>DOY end</th>
<th>hr end</th>
<th>$^3$He/$^4$He $\times 100$</th>
<th>Onset dispersion?</th>
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<tr>
<td>1</td>
<td>2000</td>
<td>33</td>
<td>12</td>
<td>36</td>
<td>12</td>
<td>52 ± 4</td>
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<td>2</td>
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<td>124</td>
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<td>3</td>
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<tr>
<td>4</td>
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<td>339</td>
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<tr>
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<td>6</td>
<td>359</td>
<td>18</td>
<td>19 ± 1</td>
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<tr>
<td>6</td>
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<td>56</td>
<td>18</td>
<td>63</td>
<td>12</td>
<td>30 ± 1</td>
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<tr>
<td>7</td>
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<td>156</td>
<td>12</td>
<td>162</td>
<td>6</td>
<td>12 ± 1</td>
</tr>
<tr>
<td>8</td>
<td>2002</td>
<td>232</td>
<td>9</td>
<td>236</td>
<td>0</td>
<td>1.7 ± 0.1</td>
</tr>
<tr>
<td>9</td>
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<tr>
<td>10</td>
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<td>14</td>
<td>6</td>
<td>18</td>
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<tr>
<td>11</td>
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<tr>
<td>16</td>
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<td>231</td>
<td>0</td>
<td>234</td>
<td>6</td>
<td>27 ± 2</td>
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<tr>
<td>17</td>
<td>2005</td>
<td>285</td>
<td>0</td>
<td>289</td>
<td>12</td>
<td>32 ± 1</td>
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</table>

Note. — Onset times are extrapolated to injection at the Sun if onset dispersion is present; otherwise are start of $^3$He-rich interval at ULEIS energies.
Fig. 1.— Solar wind parameters (upper panel) and coronal structures (lower panel) associated with $^3$He-rich period #1, which is typical of category 1. In situ solar wind data – radial component of solar wind velocity $V_R$, tangential velocity $V_T$, magnetic field magnitude $B$, azimuthal angle of magnetic field $\lambda_B$, and plasma proton number density $N_p$ – are observed by ACE. The azimuthal angle is shown on the circle $50^\circ \leq \lambda_B < 410^\circ$; the nominal north polarity, $\lambda_B = 135^\circ$, is shown with blue dotted line; the red line $\lambda_B = 315^\circ$ is for nominal south polarity. Lower panel is the SOHO/EIT 195Å image taken on Feb 1, 2000, at 14:48 UT, with brightness converted into a color scale, from blue (dark) to yellow (bright), and with superimposed meridians of points (from left to right) $M_3$, $M_2$, and $M_1$. 

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Fig. 2.— Solar wind profiles for $^3$He-rich periods of category 1 (similar to upper panel of Fig. 1).
Fig. 3.— Solar wind profiles for $^3$He-rich periods with velocity dispersion in beginning of SEP event.
Fig. 4.— Same as in Fig. 1 but for period #10, which is prototype of category 2. Plasma number density is from SOHO/CELIAS (Hovestadt et al. 1995). Other solar wind parameters are from ACE. The EIT image was taken on Jan 12, 2003, at 22:36 UT.
Fig. 5.— Solar wind profiles for $^3$He-rich periods of category 2 (similar to upper panel of Fig. 4).
Fig. 6.— Same as in Fig. 1 but for period #7, which is typical of category 3. The plasma number density is from SOHO/CELIAS. Other solar wind parameters are from ACE. The azimuthal angle is shown on the circle $0^\circ \leq \lambda_B < 360^\circ$. The EIT image was taken on Jun 5, 2002, at 17:00 UT.
Fig. 7.— Solar wind profiles for $^3$He-rich periods of category 3 (similar to upper panel of Fig. 6).
Fig. 8.— Solar wind speed and energetic proton profiles over four solar rotation periods, centered to the center of a $^3$He-rich period (dashed lines are separated by one solar rotation period $T_S$). (a) Solar wind speed averaged over the events ##1–3, 8, 9, 11–13, 16, and 17. (b) Solar wind speed around event #1 (the $^3$He-rich period is shown with a pair of vertical dotted lines). (c) Energetic proton intensity profile observed with SOHO/ERNE around period #1.
Fig. 9.— Long-term solar wind profiles for prototype events of categories 1–3, respectively events #1, #10, and #7. We plot on the same interval (i) a solar wind profile of the solar rotation that includes a $^3$He-rich period (e.g., the solar wind speed $V_R$), (ii) a solar wind profile of the previous solar rotation (e.g., $V_R(-T_S)$), and (iii) a solar wind profile of the next rotation (e.g., $V_R(+T_S)$), so that corotating features and their changes could be easily seen.
Fig. 10.— A model IMF structure shown in the fixed frame that rotates with Sun (our equation (A2); Giacalone, Jokipii, and Kóta 2002). In the corotating frame the structure is static, while a near-Earth spacecraft orbits the Sun at 1 AU with a 27 days period. Letters A and B label the segment of the spacecraft’s orbit corresponding to the 60-hour-long $^3$He-rich period of the next figure. Model parameters: the fast and slow solar wind speeds, $u_f$ and $u_s$, respectively are 600 km s$^{-1}$ and 400 km s$^{-1}$; the disturbance speed, $W$, is 700 km s$^{-1}$; angular parameters are $\Delta \phi_c = 2^\circ$, $\Delta \phi_{rf} = 30^\circ$, and $\phi_c - \phi_{rf} = 50^\circ$. Footpoints of two neighboring magnetic field lines are separated by 15$^\circ$ in the longitude $\Phi_i$. The reference footpoint longitude, $\Phi_i = 0$, corresponds to the long-dash-dot line (the structure’s center). A pair of heavy solid lines in the right part of the figure ($\Phi_i = 30^\circ$ and $45^\circ$) illustrates the interplanetary magnetic trap formed by the compression. Model variables $r$, $z$, $\psi$, $u$, and $u_c$ are shown at one of magnetic field lines in the left part of the figure.
Fig. 11.— Passage of the model corotating compression as observed on a near-Earth spacecraft. The model parameters are adjusted to make the model profile comparable to observed one, with values the same as in Fig. 10. The $^3$He-rich interval is shown with bar A–B that corresponds to the sector A–B of Fig. 10. The reference time is the time of the spacecraft’s entering of the longitude sector filled with energetic $^3$He: $t_A = 0$. The lower panel shows the corotating longitude $\Phi_i$ of the solar footpoint of a current IMF line.
Fig. 12.— Simulated fluence of 0.4–10 MeV/nuc $^3$He at a spacecraft during the period A–B (Figures 10 and 11) versus the offset time $t_A - t_0$ from the spacecraft’s entrance of the well-connected sector A–B. The $^3$He-rich flare time is $t_0$. The solid line shows the fluence in the corotating structure. The dashed line shows the fluence that would be observed in a standard model without the compression. The solar injection spectrum corresponds to the total number of $>1$ MeV/n ions $N_{\text{inj}}(>1\text{MeV/n}) = 7 \times 10^{26}$ per steradian of heliocentric solid angle at the base of solar wind. Mean free path length is $\lambda_0=0.4$ AU.