GEOPHYSICAL RESEARCH LETTERS, VOL. 30, NO. 19, 8035, doi:10.1029/2003GL017139, 2003

Properties of high heliolatitude solar energetic particle events and constraints on models of acceleration and propagation

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Received 15 February 2003; revised 29 April 2003; accepted 15 May 2003; published 18 September 2003.

[1] We analyse 9 large solar energetic particle (SEP) events detected by the Ulysses spacecraft at high heliolatitudes during the recent solar maximum polar passes. Properties of time intensity profiles from the Ulysses/COSPIN instrument are compared with those measured by SOHO/COSTEP and Wind/3DP near Earth. We find that onset times and times to maximum at high latitude are delayed compared to in-ecliptic values. We show that the parameter which best orders these characteristics of time profiles is the difference in latitude between the associated flare and the spacecraft. We find that the presence of a shock is not necessary for the establishing of near equal intensities at Ulysses and in the ecliptic during the decay phase. The model of SEP acceleration by coronal mass ejection driven shocks does not appear to account for our observations, which would more easily be explained by particle diffusion across the interplanetary magnetic field. *INDEX TERMS:* 7514 Solar Physics, Astrophysics, and Astronomy: Energetic particles (2114); 2114 Interplanetary Physics: Energetic particles, heliospheric (7514); 7807 Space Plasma Physics: Charged particle motion and acceleration. **Citation:** Dalla, S., et al., Properties of high heliolatitude solar energetic particle events and constraints on models of acceleration and propagation, *Geophys. Res. Lett.*, *30*(19), 8035, doi:10.1029/2003GL017139, 2003.

1. Introduction

[2] The properties of time intensity profiles of solar energetic particles (SEPs) close to the ecliptic plane have been extensively studied for decades. For example, the dependence of time to peak intensity on flare location is well known for near-Earth data, with maximum intensities being reached later for eastern flares than for western ones.

[3] The recent passage of the Ulysses spacecraft over the solar poles at activity maximum, provided the opportunity to detect SEPs from a new viewpoint, i.e. at high heliographic latitudes. Our first aim in this paper is to measure properties of time intensity profiles for a set of 9 high latitude SEP events, and establish whether they are in any way systematically different from those of in-ecliptic events. Secondly we examine the physical interpretation given to each property by models of SEP acceleration and propagation and discuss whether it can be applied to high latitude SEP events.

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0094-8276/03/2003GL017139$05.00

2. Instrumentation and SEP Event Selection

[4] We consider energetic particle data from the COSPIN suite of instruments on board Ulysses, and from the SOHO/COSTEP and Wind/3DP instruments near Earth (references describing the instrumentation can be found in *Dalla et al.* [2003]). We focus on the time period between February 2000 and May 2002, during which Ulysses passed over the South solar Pole, performed a fast latitude scan that took it through the ecliptic plane, and went over the North Pole.

[5] Surprisingly, SEPs were detected at the highest heliographic latitudes reached by the spacecraft [*McKibben et al.*, 2003]. In this study we focus on the 9 high latitude SEP events with largest intensities at proton energies >38 MeV at Ulysses. Details of the events are given in Table 1.

3. Properties of Time Intensity Profiles

[6] Figure 1 shows a comparison between SEP fluxes measured at Ulysses at a latitude of 63°N and distance from the Sun of 1.63 AU and at SOHO in the ecliptic at 1 AU, for event 4 in Table 1. Some features of these profiles are common in all the events we examined: the peak intensity at high latitudes is typically smaller than in the ecliptic, and it is reached at a later time. The quasi exponential decay lasting more than 15 days, appears to have a similar decay time constant at the two locations. The time of onset at Ulysses is later than in the ecliptic. In Sections 3.1–3.4 below we present the results of a systematic analysis of the characteristics of the profiles. We measure all time delays with respect to the type III radio burst onset time, determined from Wind/WAVES data (see Table 1), minus the 8.2 minutes travel time of electromagnetic radiation to Earth.

3.1. Onset Times

[7] Particle onsets at Ulysses and near Earth were analysed by *Dalla et al.* [2003]. The times of onset in several energy ranges at Ulysses and near Earth were determined, and a linear fit to plots of onset times versus c/v was made, where c is the speed of light and v the particle speed. This yielded values of the apparent length travelled by the

Table 1. SEP Events at High Latitudes

n	year	date	doy	type III ons.	flare loc.	R_{Uly} (AU)	θ_{Uly}(°)	ϕ_{Uly}(°)	ϕ_{footpt}(°)	t^{ACE}_{shock}	t^{Uly}_{shock}
1	2000	14 Jul	196	10:20	N22W07	3.17	−62.1	−115.7	18.5	197.594	–
2	2000	12 Sep	256	11:45	S17W09	2.80	−70.9	−162.7	8.8	259.166	–
3	2000	8 Nov	313	22:53	N10W77	2.41	−79.3	−182.9	−28.0	316.167	–
4	2001	15 Aug	227	00:02	–	1.63	+63.1	34.4	88.5	229.428	–
5	2001	24 Sep	267	10:18	S16E23	1.90	+78.2	31.1	98.0	268.837	270.890
6	2001	4 Nov	308	16:13	N06W18	2.18	+77.6	63.3	138.0	310.055	312.287
7	2001	22 Nov	326	20:32/22:34[a]	S25W67/S15W34[a]	2.31	+73.7	60.1	132.0	328.240	330.629
8	2001	26 Dec	360	05:13	N08W54	2.54	+66.7	39.0	147.5	363.199	–
9	2002	21 Apr	111	01:20	S14W84	3.28	+47.9	−65.1	107.4	113.177	–

θ_{Uly} is Ulysses' latitude, ϕ_{Uly} its longitude and ϕ_{footpt} the nominal longitude of its footpoint calculated from a Parker spiral model using the measured solar wind speed. Within this model the latitude of the footpoint is the same as latitude of the spacecraft. Longitudes are with respect to the Earth-Sun line, with + = West and − = East.

[a]We used timing and location of first flare for onset time analysis and those of second flare for time to maximum analysis. If onsets at Ulysses were associated to the second flare this would shift the datapoint with largest delay in release in Figure 2 down by 122 minutes and to the left by 10°.

energetic particles before reaching the spacecraft, and of the time at which they appeared to be released from the Sun.

[8] Release times to high latitudes between 100 and 350 minutes later than in the ecliptic were found. Figure 2 shows the delay in release, plotted versus the separation in latitude $|\Delta\theta|$ between spacecraft magnetic footpoint and flare. The great circle angular separation $|\Delta\alpha|$ between location of the flare and of the footpoint was found not to order the measured delays as well as $|\Delta\theta|$ [*Dalla et al.*, 2003].

3.2. Time to Maximum

[9] We measured the time to maximum, defined as the difference between the time at which intensities peak and the type III burst onset time. In this measurement we neglected the intensity peak associated to the arrival at the spacecraft of the shock driven by the CME, and considered only the so-called prompt peak which usually precedes shock arrival. We considered high energy particles because at low energies it is often not possible to distinguish the two peaks. Measurements of the time to prompt peak in the ecliptic show its well-known east-west longitude dependence (e.g., see open circles in the mid-panel of Figure 8 in *Cane et al.* [1988]).

[10] We determined times to maximum near Earth using SOHO/COSTEP data for protons 25–53 MeV. For those events for which pile-up effects were present at COSTEP, we used GOES data for protons >30 MeV. Ulysses data points are from COSPIN/HET for protons in the range 26–38 MeV. For event 3, the time to maximum was not measured at Ulysses due to a flat profile for several days.

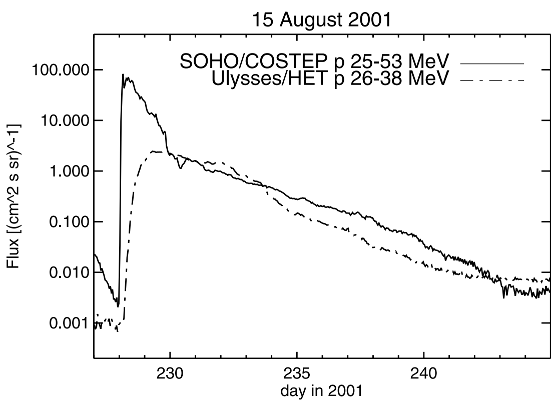

Figure 1. Flux profiles of energetic protons at Ulysses and SOHO, for event 4. Ulysses was at 63N and 1.63 AU.

[11] We found that at Ulysses the time to maximum is typically later than in the ecliptic, having values between 0.8 and 2 days. In Figure 3 we plot the time to maximum versus (a) the difference $|\Delta\theta|$ in latitude between flare and spacecraft, (b) the great circle angle $|\Delta\alpha|$ between flare and nominal location of the spacecraft footpoint (includes latitude and longitude), and (c) the radial distance of the spacecraft from the Sun, for Ulysses data points. We observe that the Ulysses data points are fairly well ordered by $|\Delta\theta|$, and not as well ordered by $|\Delta\alpha|$. The in-ecliptic data are less well ordered by $|\Delta\theta|$, showing that the longitudinal separation becomes important at low latitudes. We find no dependence on the radial distance between Ulysses and the Sun.

3.3. Correlation Between Onset Time and Time to Maximum

[12] The values of the release time plotted in Figure 2 were obtained by measuring the onset times in many energy channels and doing a linear fit to obtain the time at which particles appear to have left the Sun. The question arises of whether there is any correlation between the time of onset in a given energy channel and the time at which intensities peak in that channel. In Figure 4 we plot the onset time versus the time to maximum, for protons ~25–40 MeV. We find that there is a correlation between these two quantities,

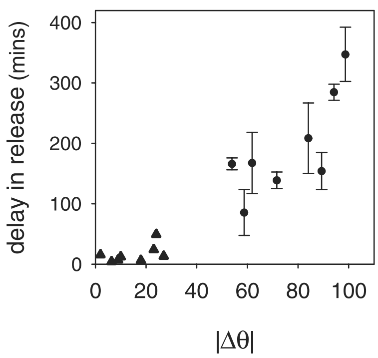

Figure 2. Release delay obtained from onset time analysis, versus $|\Delta\theta| = |\theta_{fl} - \theta_{footpt}|$, with θ_{fl} the latitude of the flare and θ_{footpt} the latitude of the footpoint. Delays are with respect to type III burst onset time minus 8.2 mins. Triangles: near Earth; circles: Ulysses. Linear correlation coefficient is 0.92.

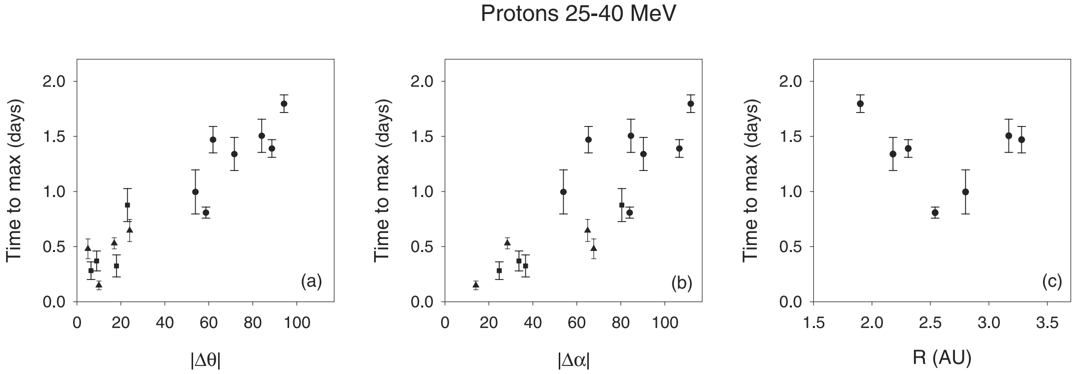

Figure 3. Time to maximum as a function of (a) the difference in latitude $|\Delta\theta|$ between footpoint and flare, (b) the great circle angle $|\Delta\alpha|$ between spacecraft footpoint and flare, and (c) the radial distance of Ulysses from the Sun. Circles: Ulysses; triangles SOHO/COSTEP; squares: GOES/EPS.

suggesting that the same process that causes the delay in onset is also what determines the time of peak intensity.

3.4. Decays

[13] We compared intensity profiles during the decay phase of the 9 events at Ulysses and in the ecliptic, using data from Ulysses/COSPIN and SOHO/COSTEP. We found that the decay phase is characterised by similar decay time constants at the two locations. This is so for all events but two, for which in-ecliptic profiles show an injection from a separate particle event taking place during the decay phase.

[14] Magnetic trapping by the shock driven by the CME associated to the particle event has been suggested as the cause of long duration decays [*Reames et al.*, 1997]. A fast CME was associated to each of the 9 events [*Dalla et al.*, 2003]. In the ecliptic, an interplanetary shock likely to have been driven by this CME could be found in all 9 events [Source: ACE shock list, www.bartol.udel.edu/~chuck/ace/ACElists/obs_list.html]. Such a shock could be found only in 3 out of 9 cases at Ulysses [R.J.Forsyth, private communication, 2003]. Shock arrival times are given in Table 1.

4. Discussion

[15] Within the current paradigm, the main source of particle acceleration in gradual SEP events is the shock driven by a CME through the corona and interplanetary space [*Reames*, 1999]. The properties of SEP profiles are explained in terms of direct magnetic connection between the shock and the detecting spacecraft, within the assumption that particle motion is mostly along the magnetic field direction, and that particles do not easily drift across the field. Particles are thought to experience low interplanetary scattering once they are released from the shock region [*Reames*, 1999].

[16] The features of SEP intensity profiles are accounted for by the CME acceleration model as follows. The time of onset corresponds to the time at which the shock intercepts the magnetic field lines to the spacecraft plus the particle travel time to the spacecraft. The time of maximum is thought to indicate the time at which the spacecraft is connected to the part of the shock which accelerates particles most efficiently. The nose of a shock is assumed to be a more efficient accelerator than its flanks. The ordering of time to maximum with flare heliolongitude observed near the ecliptic results from the curvature of the interplanetary field lines: for western solar events an Earth orbit spacecraft is connected to the shock nose early in an event, resulting in a small time to maximum. For eastern events, connection is to the flanks at the beginning of an event, and only later it is to the nose, resulting in a much longer time to maximum. Finally, the long duration quasi-exponential decay of large SEP events has been interpreted as due to magnetic trapping of particles behind the CME shock. This also explains why intensities observed at far away spacecraft during the decay phase are characterised by a similar decay time constant [*Reames et al.*, 1997].

[17] Can the characteristics of SEP profiles at high heliolatitudes be explained in terms of the CME acceleration model?

[18] The delayed onset at high latitudes would be interpreted as due to the time taken by the shock to intercept the magnetic field lines connecting to Ulysses. It would then be expected that a faster shock would result in a shorter delay in release. In *Dalla et al.* [2003] two proxies for CME shock speed were considered: the plane of the sky CME speed from coronograph observations, and the average transit speed calculated from the time of shock passage near Earth. Neither of these showed any correlation with the delay in release. The same is true also of the ratio of the flare-footpoint angular separation to the CME speed.

[19] As far as the time to maximum is concerned, at high latitudes we would expect Ulysses to have been connected

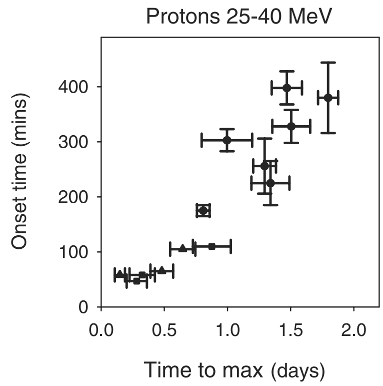

Figure 4. Onset time vs time to maximum. Triangles and squares: near Earth; circles: Ulysses.

to the flanks of a possible CME shock, given the fact that angular separations of the spacecraft footpoint from the flare site were always >50°, and most of the time very large. More importantly, if the spacecraft is connected to the flanks of a shock at the beginning of an event, we would expect this to remain the case as time goes on. In other words, the spacecraft would not connect to regions of the shock with markedly different acceleration efficiencies throughout an event, as might be the case in the ecliptic. No east-west effect would be expected at Ulysses because the magnetic field lines at high latitudes have almost no curvature. It therefore remains unexplained why intensities should peak at Ulysses between 1 and 2 days after the solar flare, and why a large variation in times to maximum is observed.

[20] An important observation is also that only in 3 out of 9 events the shock driven by the CME associated to the event reached Ulysses. In all cases the particle event lasted for more than 13 days at Ulysses, for proton energies ~25–40 MeV. Hence very long duration SEP events take place at high latitudes without a CME driven shock. Decay time constants at Ulysses are similar to in-ecliptic ones even when no shock is seen.

[21] In summary, the model of CME shock acceleration, developed to account for features of intensity profiles in the ecliptic, does not fit the high latitude experimental data very well. While it cannot be ruled out that the particles of the onset and rise phase of these events might be shock accelerated, in most events no shock can account for trapping of decay phase particles at high latitudes.

[22] Are other models of particle acceleration and propagation better suited to explain the Ulysses data? Evidence has been emerging recently that particle propagation across magnetic field lines might be more important than previously thought. Analysis of anisotropies detected at Ulysses during the Bastille event, showed considerable cross-field drift [*Zhang et al.*, 2003]. In a study of delays between the start of low frequency local radio emission and times of particle arrival at a spacecraft, *Cane and Erickson* [2003] suggested that particles must undergo lateral transport. The same conclusion was reached from the analysis of galactic cosmic ray and jovian electron data [*McKibben et al.*, 2003; *Heber et al.*, 2002]. *Dwyer et al.* [1997] found evidence of transport of energetic charged particles across the local average magnetic field in corotating interaction regions. If one allows cross-field diffusion, the possibility exists that so-called gradual SEPs might be accelerated in the flare rather than at the CME shock [*Cane and Erickson*, 2003]. Analysis of anisotropies at Ulysses for the event of 24 September 2001 shows that the first arriving particles have a small anisotropy directed along the magnetic field [*Sanderson et al.*, 2003]. However local motion preferentially along the field lines does not exclude that particles might have scattered across the field between the Sun and spacecraft.

[23] Our observation of increase in delay to onset and to maximum with the latitudinal separation $|\Delta\theta|$ between flare and spacecraft, is suggestive of particles being released close to the flare location and having to scatter across the interplanetary magnetic field to reach the high latitude magnetic field lines. The better correlation of the measured delays with $|\Delta\theta|$ than with the great circle angle between flare location and spacecraft footpoint also seems to indicate an easier transport across the field in longitude than in latitude.

[24] The cross field scattering interpretation can account for the near equal intensities of the decay phase as the result of particles having diffused throughout the inner heliosphere.

5. Conclusions

[25] Experimental observations at Ulysses show that the difference in latitude between a spacecraft and the associated flare orders both onset times and times to maximum well. Trapping by the shock driven by the CME associated to an SEP event is not the cause of long duration decays, nor of near equal intensities at far away spacecraft. Given the large separation between Ulysses and near-Earth spacecraft, it seems unlikely that a closed magnetic structure associated to prior solar events might have had the wide spatial extent needed to trap particles at both locations [*Reames*, 1999].

[26] Together with the lack of correlation of delay in onset with CME parameters, these findings point towards propagation across the magnetic field being the process by which particles reach high latitudes. It would appear that large SEP events result in a long duration enhancement of energetic particles at all locations in the inner heliosphere. Modelling of particle propagation in the whole heliosphere is required to reproduce this observation.

[27] **Acknowledgments.** We acknowledge use of the Ulysses Data System, and of GOES/EPS data made available through the SPIDR facility at NGDC/NOAA. S.D. acknowledges financial support from the UK Particle Physics and Astronomy Research Council through a Post-Doctoral Fellowship.

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