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ULYSSES COSPIN observations of the energy and charge dependence of the propagation of solar energetic particles to the Sun's south polar regions

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Abstract. We present a first report of energetic charged particle observations at latitudes above $70°$S from the COSPIN instruments on Ulysses during Ulysses' recently completed pass over the Sun's south polar regions. Solar energetic particles dominated the particle flux during most of the pass, and for > 30 MeV protons there was a close correspondence between intensity increases at IMP-8 near Earth and at Ulysses. Intensities in the equator and polar regions were often comparable, especially in the late phases of large events, despite the large radial, longitudinal and latitudinal separations of the spacecraft. Enhancements attributable to events originating near the solar equator were observed at Ulysses down to the lowest energies measured (˜0.3 MeV). The clear conclusion is that even at solar maximum, latitudinal propagation is far more efficient than had been expected before Ulysses. At high energies (>˜100 MeV) two Forbush decrease-like events were observed, the highest latitude such events ever seen.

1 Introduction

Ulysses has just completed its first pass over the South Pole of the Sun in solar maximum conditions, reaching a maximum heliographic latitude of $80.2°$S during Nov. 23-26, 2000 and remaining above $70°$S latitude from Sep. 6, 2000 to Jan. 17, 2001. During the previous pass over the Sun's south polar regions in 1994 solar activity was near minimum levels. The interplanetary medium had a simple structure, with a modestly tilted current sheet surrounded by a band of slow solar wind at low latitudes and nearly featureless fast solar wind from the polar coronal holes at latitudes above about $30°$. A stable configuration of CIRs at lower latitudes resulted from the tilt of the near-equatorial band of slow wind. The major discoveries from energetic particle observations were of the persistence of effects, both recurrent modulation of cosmic rays and 26-day periodic enhancements of low energy particle fluxes produced by the low latitude CIR shocks to the highest solar latitudes, leading to the conclusion that latitudinal propagation, even for very low energy particles, was much more efficient than had been expected. (See McKibben, 2001, and Lanzerotti and Sanderson, 2001, for summaries of the solar minimum observations).

During the recently completed south polar pass, conditions were completely different. Slow solar wind and mixed magnetic polarity were found at all latitudes, the interplanetary structure was highly dynamic, evolving in times short compared to the solar rotation period, and the energetic particle observations were dominated by particles produced in solar energetic particle (SEP) events.

In this paper we give a first report of observations of SEPs at latitudes $> 70°$S made with the Cosmic and Solar Particle Investigations (COSPIN) instruments on Ulysses, and compare them to similar observations from the University of Chicago cosmic ray intrument on IMP-8. The current paradigm for explaining the time-intensity profiles of SEP events relies on direct connection via interplanetary field lines to the acceleration region, believed to be the shock front pre-

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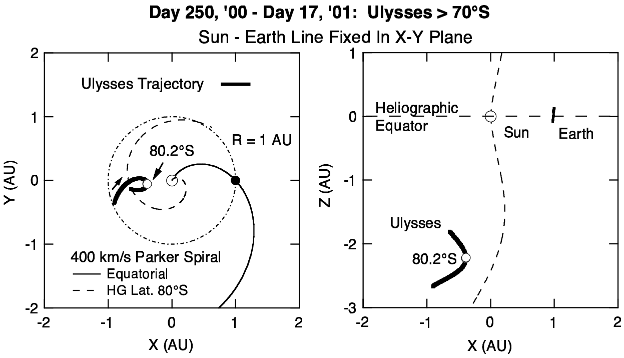

Fig. 1. Relative locations of Earth, Ulysses, and equatorial and $80°$S Parker spiral fields through the connection longitude of Earth during Ulysses' south polar pass.

ceding an expanding CME in the solar wind (e.g. Reames, 1996). Therefore the large separations between Ulysses and Earth would lead one to expect rather different responses to SEP events at the two spacecraft. Thus the polar pass provides a good opportunity to test the consistency of this current model with observations.

The COSPIN instrumentation has been described by Simpson et al. (1992), and the IMP-8 instrument has been described by Garcia-Munoz et al. (1987).

2 Ulysses Trajectory

As shown in Fig. 1, in a coordinate system with the Earth-Sun line fixed in the X-Y (solar equatorial) plane Ulysses kept a relatively constant position with respect to the Earth while it was at latitudes $> 70°$S. While coming inwards from ˜2.8 to ˜1.9 AU, it remained nearly on the opposite side of the Sun from Earth, making it unlikely that a single disturbance in the solar wind would impact both Earth and Ulysses. For particles propagating along the interplanetary Parker spiral fields, the longitudinal separations of the photospheric foot points of field lines through Earth and Ulysses were smaller. Assuming a 400 km/s solar wind velocity, the photospheric connection longitude of Ulysses ranged from ˜$85°$ east of Earth's at the start of the period, to ˜$135°$ east at the end of the period (see Fig. 2). Nevertheless, combining longitude and latitude, there was at all times a more than $90°$ angular separation between the foot points of field lines through Earth and Ulysses.

3 Observations

Figure 2 contains an overview of energetic particle observations from several of the instruments from the COSPIN consortium experiment on Ulysses, compared to comparable measurements, where available, made near Earth on the IMP-8 satellite. The energy ranges for protons extend from 0.3 MeV (HFT) through $>$100 MeV (HET), and the rigidity ranges from ˜3 MV for the KET electrons through $>$1GV for the highest energy protons.

Full discussion of the observations is not possible in this short paper, and full understanding will require continuing effort over the coming months. Here we can give only highlights and first impressions from the observations.

3.1 General Comments

Several conclusions are directly apparent from Fig. 2:

a) Over the entire energy range considered the observations at Ulysses and Earth are generally similar, and in some cases similar in detail, despite the large spatial separations between the spacecraft.

b) For all channels except the electron channel and the highest energy proton channel, SEPs dominate the energetic particle environment over the Sun's south pole, as well as at the equator throughout the south polar pass.

c) Following large SEP events, energetic protons (˜30 MeV and above) and electrons (˜3 MeV) have rapid access both to Earth and Ulysses. At lower energies, arrival, if discernible, may be significantly delayed, especially in the polar regions. While not shown in Fig. 2, strong anisotropies were frequently detected at Ulysses during onsets, indicating outward flow of particles from the Sun.

d) Even for the lowest energy particles there is little apparent correlation between intensity variations and variations in solar wind speed over the south pole.

e) For < 1 MeV protons (HFT channel) the range and rate of time variations is in general much smaller and slower over the pole than near Earth. Indeed there appears to be a division at about 1 MeV between event-dominated time-intensity profiles at higher energies, and more generalized variations in particle intensity at lower energies, where it is often to difficult to identify specific sources for particle increases. This may be because of the larger radius of Ulysses, where propagation effects may lead to integration and smoothing over of smaller events, distinct at 1 AU, into larger more gradual and long-lasting increases. Nevertheless, particularly for the events on day 256, 290, 303, and possibly others, there appear to be distinct onsets of low energy protons (AT and HFT channels) associated with events.

3.2 Comments on SEP Events

Table 1 contains identifications and other details for solar events associated with the SEP events observed at IMP-8. The information is derived primarily from the weekly NOAA Space Weather Highlights and, for additional CME information, the SOHO LASCO web-site.

Every SEP event for which LASCO observations are available was associated with a halo CME. Only two of the halo CMEs (events 10 and 11) were directed away from Earth (and thus toward Ulysses). Most of the others could be plausibly associated with a CME recorded at Earth, and thus presumably not directed towards Ulysses.

Of the 12 flare events, only 2 (events 1 and 5) were clearly

Table 1: Solar Events Giving Rise to SEP Events observed at Earth

Event No.	Day of 2000	Onset UT	Event Location	Event Type	CME Characteristics	>30 MeV Protons at Earth	Ulysses	Ulysses Rad. , Lat.
1	256 *(12 Sep)*	1213	S17 W09	M1/2N	Halo, Filament Eruption near CM Earth: 0300, D258	Yes	Yes	2.80, -70.9
2	283 *(9 Oct)*	2343	N01 W14	C6/1f	Halo Earth: 2145, D286	Yes	Yes	2.62, -75.2
3	290 *(16 Oct)*	0728	~N01 W110	M2	Halo Ulysses: D292?	Yes	Yes	2.57, -76.3
4	299 *(25 Oct)*	1125?	Behind W Limb	LD X-ray	Halo, Begin ~0826 Earth: 0900, D302	Yes	**No**	2.51, -77.6
5	303 *(29 Oct)*	0157	S25 E35	M2/2B	(no LASCO data) Earth: 1600, D305	Yes	Yes	2.48, -78.1
6	313 *(8 Nov)*	2328	N10 W77 (N20 W55)?	M7	Halo Earth: 0604, D315	Yes	Yes	2.41, -79.3
7	329 *(24 Nov)*	0502	N20 W05	X2/3B	Halo Earth: 0500, D331	Yes	Yes	2.30, -80.2
8	330 *(25 Nov)*	0100	N07 E50	M8/2N	Halo	Yes	Yes	2.29, -80.2
9	353 *(18 Dec)*	1111	N15 E01	C7/sf	Halo Earth: 1800, D357	Small	**No**	2.13, -78.0
10	363 *(28 Dec)*	mid- day	Back Side	??	Halo	Yes	Yes	2.06, -75.8
11	371 *(5 Jan)*	~1700	Back Side	??	Halo	Yes	Yes	2.00, -73.7
12	376 *(10 Jan)*	0103	N13 E36	C5/1N	Halo Earth: 0200, D379	Yes	Yes	1.97, -72.2

identified as southern hemisphere events. Nevertheless, 30 MeV protons were observed at Ulysses from all but 2 of the events (events 4 and 9).

Following large events (eg. events 1, 6, and 8) we see that, as reported previously for lower latitudes by McKibben et al (2001), within a few days proton fluxes at energies of 10's of MeV are approximately equal at both Ulysses and Earth, and remain so for the remainder of the decay phase, in each case here for more than 10 days. Roelof (private communication, 2001) has reported similar behavior for low energy (˜50 keV) electrons following the Bastille Day, 2000 event. Persistence of equal fluxes at widely separated observation points implies essentially null radial, latitudinal, and longitudinal gradients in the SEP intensities, which Roelof et al. (1992), based on earlier observations in the ecliptic, have termed a "reservoir effect". The south polar pass observations demonstrate that this "reservoir effect" is a truly 3-dimensional characteristic of SEP events in the inner heliosphere. It is difficult to see how such uniform reservoirs could develop without the existence of significant cross-field transport in the inner heliosphere.

Event 1 (day 256), associated with an event near central meridian, about midway between the connection points of Ulysses and Earth, is particularly striking for the near-exact similarity of time-intensity profiles for 30 MeV protons at Ulysses and Earth from onset through return to background. For 0.3 MeV protons, the arrival at Ulysses appears significantly delayed with respect to arrival at Earth, suggesting a diffusive process for propagation of these particles.

From the relative connection longitudes of Ulysses and Earth (see Fig. 2, top), we might expect that, if particles are propagating along the field lines from an acceleration site near the Sun, Ulysses would see larger and more prompt SEP fluxes than Earth from events originating toward the East limb, and smaller and more delayed fluxes from events originating on the far west limb. The observations do not clearly support this in all cases. For example, event 8 (day 330), associated with an M8/2N event at E50 on the sun, is more delayed at Ulysses than at IMP. This, however, may be the result of Ulysses' larger radial distance from the sun.

Event 3 on day 290 is interesting as the single example where the observations seem to be clearly in accord with the model of Reames et al. (1996), which suggests that uniform fluxes may be achieved in the region behind the CME front that produces the particle acceleration. The event originates behind the west limb and is clearly very poorly connected to Ulysses. Arrival of particles at Earth is reasonably prompt, but is very gradual at Ulysses until, after an abrupt, if small, increase late on day 294, the Ulysses fluxes become and remain approximately equal to IMP fluxes, consistent with disappearance of spatial gradients. On day 292 examination of SWICS iron charge state data suggests that a CME may have passed Ulysses, and the interplanetary magnetic field at Ulysses displayed a relatively smooth rotating behavior until

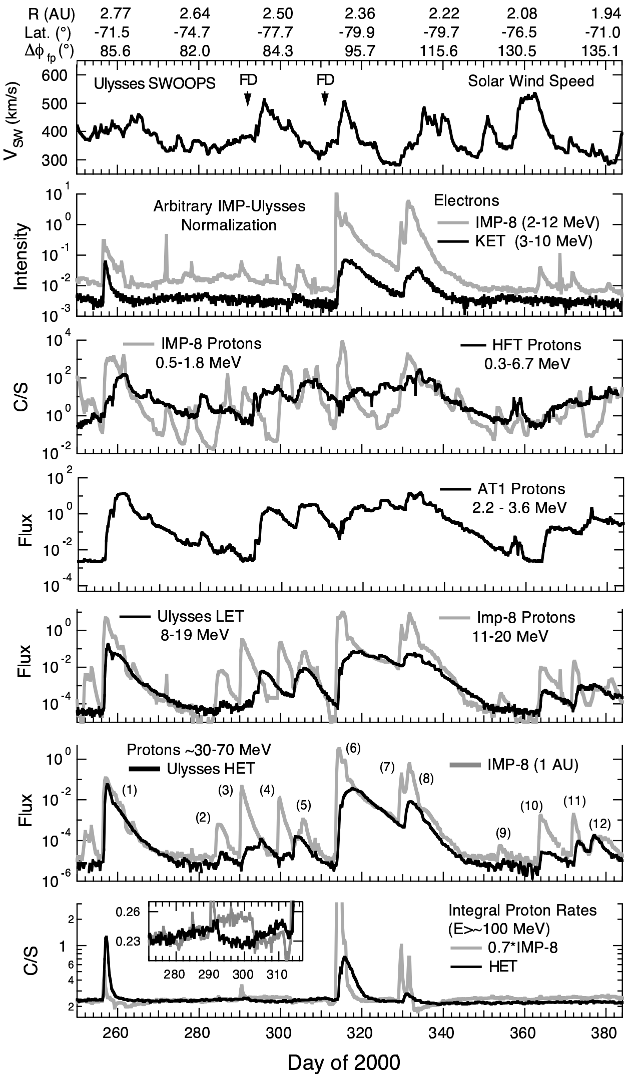

Fig. 2. Six hour averages from the COSPIN instruments (black traces) and IMP-8 (light traces) during Ulysses' south polar pass. Numbered events (2^{nd} from bottom panel) correspond to events in Table 1. normalization of IMP and Ulysses is uncertain. Ulysses position and connection longitude relative to that of Earth (positive east from Earth) are at the top.

late on day 294. If a CME did indeed pass Ulysses, a reasonable interpretation would be that for this event the uniform particle reservoir existed only behind the CME.

3.3 Modulation Events

While at energies below ˜100 MeV SEPs dominate the particle fluxes observed at Earth and Ulysses during the South Polar pass, at higher energies the galactic cosmic ray flux was the dominant contributor to the particle flux except during the largest events. Two significant modulation events were observed at high latitudes during the south polar pass, and are illustrated in the inset in the bottom panel of Fig. 2 where the vertical scale of the integral proton rates has been enhanced. The first event appears to be associated with the probable CME that passed Ulysses on days 292-294, and looks like a classic Forbush decrease, the first observed at polar latitudes. Interestingly no corresponding decrease was observed at Earth until approximately 10 days later when an abrupt decrease restored the near-equality of the normalized IMP and Ulysses intensities.

The second event was a near-simultaneous decrease in the intensities observed at IMP and Ulysses beginning on day 310. What may be a solar wind stream interaction region passed Ulysses at about the same time, but we can offer no interpretation of the near simultaneity of the decrease at IMP and Ulysses at this time. Following recovery, the intensity at Ulysses remained approximately 10% lower than it had been before the event for the remainder of the polar pass, whereas the intensity at IMP recovered fully. Again, no interpretation is clear at this time.

4 Final Remarks

Observations of energetic charged particle during Ulysses 2000-2001 south polar pass offer a rich field for investigation and testing of models of charged particle propagation in the inner heliosphere. We have only begun to scratch the surface, and we hope that this compilation and overview of observations is useful to stimulate discussion. Even with only a first look it is already clear that even at solar maximum, with its chaotic and turbulent interplanetary solar wind and magnetic structure, propagation of energetic particles across the mean magnetic field in the latitudinal direction is surprisingly easy. This was also true at solar minimum. Affecting both modulation and SEP propagation, this is one of the fundamental conclusions from the Ulysses mission to date.

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