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Anomalous cosmic rays in the distant heliosphere and the reversal of the Sun's magnetic polarity in Cycle 23

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[1] Beginning in early June 2001 and extending over a ~3 month period the Cosmic Ray Subsystem (CRS) experiment on Voyager 1 (80.3 AU, 34°N) observed a rapid transition in the energy of the peak intensity of anomalous cosmic ray (ACR) He from ~11 MeV/n to ~25 MeV/n. One month later there began a similar spectral shift at Voyager 2 (64.7 AU, 24°S). When these ACR transition times are extrapolated back from the estimated location of the heliospheric termination shock (TS) to the Sun (~1 year) there is reasonable agreement with the range of times obtained for the polarity reversal of the interplanetary magnetic field (IPB) in the northern hemisphere near the Sun and the later reversal in the south. We interpret these changes in the ACR spectra as giving a global view of the interplanetary field reversal at the TS and confirmation of the important role of the TS in controlling the ACRs. **Citation:** McDonald, F. B., E. C. Stone, A. C. Cummings, W. R. Webber, B. C. Heikkila, and N. Lal (2007), Anomalous cosmic rays in the distant heliosphere and the reversal of the Sun's magnetic polarity in Cycle 23, *Geophys. Res. Lett.*, *34*, L05105, doi:10.1029/2006GL028932.

1. Introduction

[2] Galactic and anomalous cosmic rays (GCRs and ACRs) probe the large-scale structure and dynamics of our heliosphere. In this study we use the Voyager observations of these energetic particles in the distant heliosphere to study the times of the reversal of the Sun's magnetic polarity as reflected in the changes in the IPB field at the heliospheric TS over the recent solar maximum period of cycle 23 (2000–2001).

[3] Below some 50 MeV/n, ACRs are the dominant energetic particle population in the outer heliosphere [*Cummings et al.*, 2002]. These predominantly singly-charged particles [*Klecker et al.*, 1995, *Mewaldt et al.*, 1996] have their origin as interstellar neutral atoms which have been ionized either by solar ultraviolet photons or through charge exchange with solar wind ions. These singly-charged pick-up ions are then convected out to the distant heliosphere by the outward flowing solar wind where, by the still generally accepted paradigm, they are accelerated at the TS [*Fisk et al.*, 1974; *Pesses et al.*, 1981]. Their relative charge composition of H, He, N, O, Ne and A along with a small C abundance - when corrected for ionization rates, filtration effects and acceleration efficiency - is very similar to the abundance of neutral atoms in the local interstellar medium and their energy spectra are consistent with that expected from shock acceleration at the TS [*Cummings et al.*, 2002]. The heliospheric TS, which was crossed by Voyager 1 (V1) on 16 Dec. 2004 at 94 AU, represents an abrupt transition in the solar wind flow when the ram pressure of the expanding solar wind reaches approximately that of the local interstellar medium.

[4] Near solar minimum the IPB field reflects the major dipole component of the Sun's magnetic field and consists of hemispheres separated by a near-equatorial, thin heliospheric current sheet (HCS) with the field being oppositely directed on either side of the sheet. When the open field lines in the northern hemisphere are outward directed from the solar surface (positive polarity, $A > 0$), ACRs drift and are accelerated along the TS away from the equatorial region and toward the Northern and Southern polar regions. They then drift from these polar regions down through the heliosphere along with positively charged GCR ions. With increasing solar activity the inclination of the HCS increases, reaching 90° near solar maximum. In $A < 0$ epochs this drift pattern is reversed. In this note we study the effects of the cycle 23 reversal of the solar magnetic polarity on ACR helium.

2. Observations

[5] The V1 and V2 time histories of GCR He and ACR He^+ (Figure 1) from 1996.0–2006.25 show the small variation of GCR He from solar minimum to solar maximum in the distant heliosphere and the larger temporal variation of the ACRs. There are no obvious features in these time histories that would be ascribed to the polar magnetic field reversals from $A > 0$ to $A < 0$ over the solar maximum period of cycle 23.

[6] However a V1 regression plot of the intensity of 15.5 MeV/n He^+ versus that of 43 MeV/n He^+ (Figure 2a) reveals a straight line fit from 1997.0–2001.35 followed by a 95 ± 12 day transition to a new regression line (from 2001.64 ± .03 to 2004.21 ± .04). This line is well defined until ~2004.21 when there is increased dispersion perhaps due to the passage of strong interplanetary transients. There is also a significant change in the relative behavior of the two ACR components some 6 months after V1 entered the heliosheath. The V2 ACR He^+ follow a similar pattern except the transition occurs a month later over a 128 day

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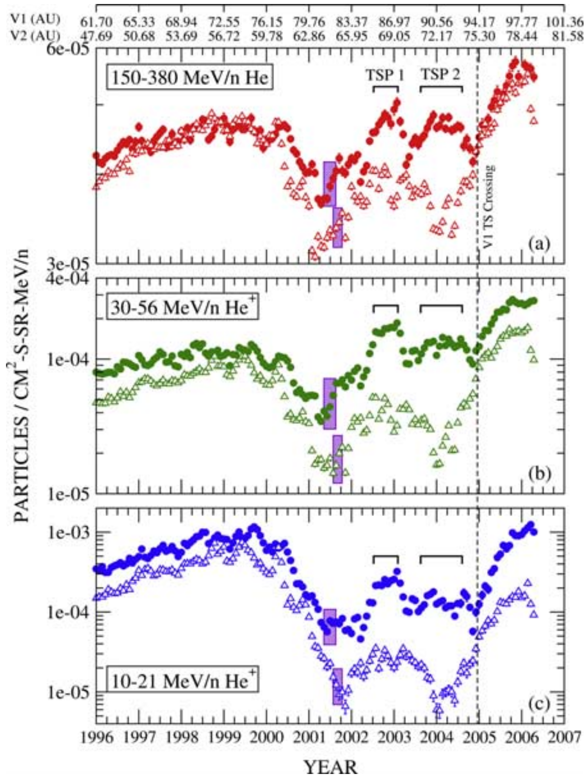

Figure 1. Voyager-1 (solid circles) and Voyager-2 (open triangles) 26 day average time history of GCR and ACR He. The 30–56 and 10–21 MeV/n He^+ have been corrected for GCR He but not for the lower energy termination shock particles. The top brackets in each panel mark the time of termination shock particle events at V1 [*McDonald et al.*, 2005]. The shaded rectangles mark the observed transition from positive to negative polarity at V1 and V2 while the vertical dashed line shows the time V1 crossed the termination shock. All of the particle data in this paper are from the Voyager CRS experiment [E.C. Stone, P.I.]

period (Figure 2b). Similar transition times were obtained for 8 MeV/n He^+ versus 43 MeV/n He^+. A regression plot of the intensity of higher rigidity GCRs versus that of 30–56 MeV/n He^+ (Figure 2c) gives a straight line fit from 1997.0–2006.21 and yields the same transition times as the lower energy He^+ components.

[7] From the V1 and V2 energy spectra just before and after the transition (Figures 3a and 3b) it can be seen that the main effect of the polarity reversal is a suppression of the particles below the spectral peak and at V1 a modest increase in the particle intensity above the peak region. This difference between the spectral changes at V1 and V2 leads to different trajectories in the hysteresis plots over the transition period (Figures 2a and 2b). At both spacecraft the spectral peak shifts from ~6.5 MeV/n at solar minimum to 11 MeV/n at solar maximum to 25 MeV/n immediately after the transition (Figures 3c and 3d). It remains at this higher energy at V1 but over time it gradually merges with the lower energy termination shock particle population [*Cummings et al.*, 2006; *Hill et al.*, 2006]. At V2 there is no shift in the spectral peak from 2001.85 to 2006.21 despite the x25 increase in 15.5 MeV/n He^+.

3. Analysis

[8] We interpret these ACR spectral transitions as marking the time of the reversal of the magnetic field at the TS near the nose region of the heliosphere. The next step is to relate the transition times at the TS back to the Sun. Due to the effects of pick-up ions there is deceleration with increasing heliocentric distance which *Wang and Richardson* [2003] have shown to be on the order of 1.1 km/s/AU between 1 and 60 AU and in their model this deceleration remains constant out to the TS. The measured V2 daily averages of the solar wind speed are used to find the time when the solar wind associated with a given transition at the TS passed V2 (Table 1, column C). This V2 time is then extrapolated back to the Sun (Table 1, column F).

[9] There is good agreement between the V2 observed values of the solar wind speed, *V*, and the inferred speed at V1, using the transit time of MeV solar energetic particle events [*Richardson et al.*, 2005, *McDonald et al.*, 2005]. The location of the TS over this period has been estimated by *Richardson et al.* [2006] and *Webber* [2005] using the plasma pressure measured by V2 and in the case of *Richardson et al.* [2006], normalizing to the crossing of the TS at 94 AU on 16 Dec. 2004. The values of *V* used in

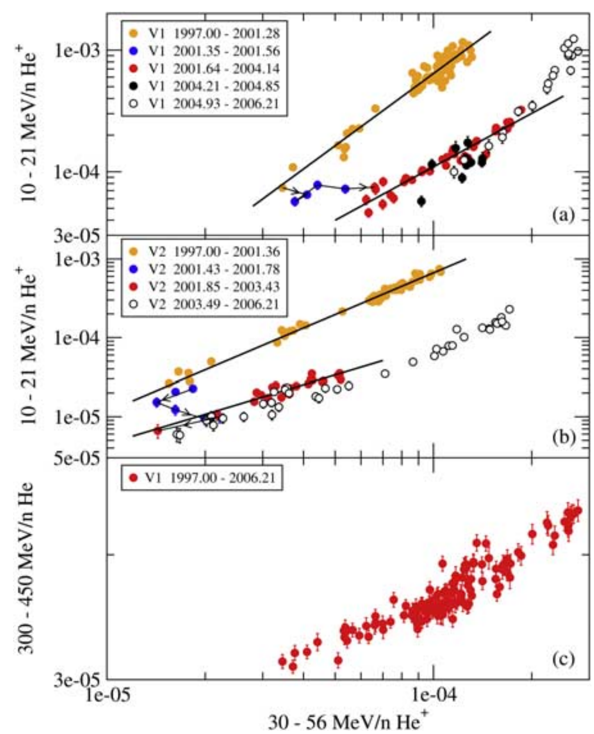

Figure 2. Regression plot of 10–21 MeV/n He^+ (V1, V2) and 300–450 MeV/n GCR He (V1) versus 30–56 MeV/n He^+ for the periods shown in Figure 1. The top solid lines are least square fits to the data from solar minimum to solar maximum. After the transition a shorter time interval is selected. In the data the times shown are the beginning of each 26 day interval.

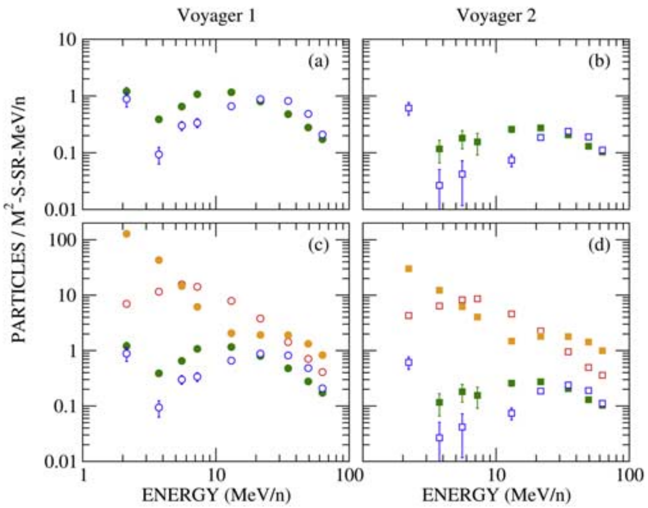

Figure 3. V1, V2 combined ACR and TSP He^+ spectra for (a, b) time periods just prior to the transition time [V1 filled green circle 03/20–04/15/2001(80.7 AU), V2 filled green square 04/15–05/11/2001 (63.9 AU)] and just after the transition time [V1 open blue circle 08/23–09/18/2001(82.2 AU), V2 open blue square 12/05–12/31/2001 (65.8 AU)]. (c, d) Time periods prior to the cycle 23 solar maximum [V1 open red circle 01/01–03/20/1998 (69.3 AU), V2 open red square 01/01–03/20/1998 54.0 AU)] and subsequent solar minimum with V1 in the heliosheath [V1 filled orange circle 02/22–03/20/2005(94.7 AU), V2 filled orange square 01/27–02/22/2006(78.8 AU)]. The spectra from Figures 3a and 3b are included in Figures 3c and 3d.

this analysis, the transit times and the estimated transition times at the Sun are given in Table 1.

[10] The V2 solar wind velocity that would reach the TS at the time of the V1 transition was ~425 km/s which gives a transit time between the Sun and the TS of 0.9 years and therefore a reversal of the polarity of the Northern interplanetary magnetic field near the Sun starting in early June 2000 and completing in early August 2000. The transition times at the Sun in the southern hemisphere extend from mid June 2000 to early October 2000.

[11] *Opher et al.* [2006] and references therein, have shown that an interstellar magnetic field parallel to the plane defined by the deflection of interstellar H atoms can produce a north-south asymmetry in the TS. In their model this distortion depends on the angle between the interstellar wind velocity and the magnetic field and the magnitude of the interstellar magnetic field. They find relative displacements of 8–11 AU for interstellar fields of 1.8–2.5 μG and a median angle of 45°. The effect of an 8 AU displacement is to slightly delay the V2 transition interval at the Sun to 2000.51 (early July)–2000.81 (Late October).

4. Discussion

[12] A comparison of the Voyager derived reversal times with a representative set of times obtained by solar observers is given in Table 2. *Wang et al.* [2002] used a potential-field source surface analysis of a photospheric magnetic field map to obtain the open flux of the IP magnetic field at a source surface of 2.5 solar radii and determine the time of the polarity reversal. The Voyager transition times extrapolated back to the Sun are in reasonable agreement with the Wang et al. observation (Table 2).

[13] The reversal of the photospheric magnetic field (Table 2) occurs at a later time than that of the IPB field over solar maximum. *Wang et al.* [2002] find that most of the open field lines originate in active region latitudes from small coronal holes with strong footprint fields and pre-

Table 1. Extrapolation of T.S.B. Field Reversal Back to the Sun

	Time[a]	TS Location,[b] AU	V2[c]	V(V2)[d], km/s	$\overline{V}(V_2 \rightarrow Sun)$,[e] km/s	Time at Sun[f]
			Voyager 1 (λ = 34°N)			
Onset of Reversal	2001.35 ± .04	87	2001.09/63.16AU	429	463	2000.44 (early June)
Completion of Reversal	2001.61 ± .04	88	2001.31/63.8AU	394	429.6	2000.60 (early August)
			Voyager 2 (λ = 26°S)			
Onset of Reversal	2001.43 ± .04	87.5	2001.13/63.2AU	411	445	2000.45 (mid June)
Completion of Reversal	2001.78 ± .04	86.5	2001.52/64.47AU	373	407	2000.75 (early October)

[a]Transition times observed at V1 and V2 which are assumed to be the time the field reversal reached the TS.
[b]Predicted location of TS at time from previous column [*Richardson et al.*, 2006].
[c]The time the IPB transition is predicted to have passed V2 and location of V2 at that time.
[d]Solar wind speed from Sun to V2 at time given in column c.
[e]Predicted avg. solar wind speed from Sun to V2 at time given.
[f]Time the field transition at the TS (a) occurred back at the Sun.

Table 2. Comparison of Observed Reversal of the Solar Magnetic Polarity

	Heliospheric Termination Shock	Interplanetary Magnetic Field	Photospheric Magnetic Field			
	Voyager Observation (This Work)	*Wang et al.* [2002]	*Durant and Wilson* [2003]	*Harvey and Recely* [2002]	*Bilenko* [2002]	*Gopalswamy et al.* [2003]
		Northern Hemisphere				
Onset of Reversal	2000.44 (early June)	January 2000	6 May 2001	March 2001	February 2001	November 2000
Completion of Reversal	2000.60 (early August)	April 2000	2 June 2001			
		Southern Hemisphere				
Onset of Reversal	2000.45 (mid June)	June 2000	19 Sept. 2001			
Completion of Reversal	2000.77 (early October)	November 2000	17 Oct. 2001	May 2001	April 2001	May 2002

dominantly slow solar wind. In this model the IPB field reflects what is happening at latitudes below the polar region. *Smith et al.* [2003] reached a similar conclusion based on the constant value of B with latitude during the Ulysses fast latitude scan (Nov. 2000–Oct. 2001).

[14] *Fisk and Schwadron* [2001] have proposed that the open field lines reconnect with closed loops at the Sun producing the rotation of an essentially intact current sheet. The polarity reversal is produced by the rotation of the current sheet over the solar poles. Both models appear consistent with the high latitude Ulysses current sheet observations near solar maximum [*Smith et al. 2003*].

5. Conclusion

[15] The changes in ACR He produced by the reversal of the magnetic polarity in the polar region at the TS reflect a global sampling and confirms that the reversal of the IPB field is completed well before that of the photospheric polar fields.

[16] In the distant heliosphere large increases in the radial intensity gradients of ACRs and GCRs were observed starting around 2001.37 [*McDonald et al.*, 2005]. The absence of any significant change in these gradients over the period from solar minimum to solar maximum and the temporal association with the IPB reversal in the distant heliosphere argues this is also a drift effect that becomes important immediately after the reversal of the interplanetary magnetic field.

[17] The V1 ACR transition time associated with the polarity reversal of the IPB field is 0.26 ± 0.06 years (Figure 2a) and is due to an increasing intensity of 30–56 MeV/n He^+. This may not require a rapid acceleration rate since it could reflect the drift of previously accelerated ions from the polar regions. The V2 transition time is controlled by the decrease of ACR He^+ below ~25 MeV/n so the acceleration time is not involved.

[18] Previously *Jokipii* [1986] carried out a numerical study of the diffusive acceleration of charged particles at the termination shock assuming that the particles were preferentially injected in the polar region during a period near solar minimum, when the inclination of the heliospheric current sheet was small. This work was extended by *Steenberg* [1998] and *Florinski et al.* [2004] using more complete simulations but without preferential injection in the polar regions. In these studies there was a pronounced increase in higher energy ACRs relative to lower energies at solar minimum for $q < 0$ epochs consistent with the Voyager observations. Over the ensuing 4.4 years after the IPB reversal in the southern hemisphere, the V2 spectral peak has remained at ~25 MeV/n as the current sheet inclination and GCRs have steadily evolved toward solar minimum conditions. Clearly the TS plays a vital role in the acceleration and transport of anomalous cosmic rays.

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