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Extremely high speed solar wind: 29–30 October 2003

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[1] On 29–30 October 2003 the Solar Wind Electron Proton Alpha Monitor (SWEPAM) instrument on the Advanced Composition Explorer (ACE) spacecraft measured solar wind speeds in excess of 1850 km/s, some of the highest speeds ever directly measured in the solar wind. These speeds were observed following two large coronal mass ejection (CME) driven shocks. Surprisingly, despite the unusually high speeds, many of the other solar wind parameters were not particularly unusual in comparison with other large transient events. The magnetic field reached −68 nT, a large but not unprecedented value. The proton temperatures were significantly higher than typical for a CME in the solar wind at 1 AU (>10^7 K), but the proton densities were moderate, leading to low to moderate proton beta. The solar wind dynamic pressure was not unusual for large events but, when coupled with the large negative B_z, was sufficient to cause intense geomagnetic disturbances. *INDEX TERMS:* 2111 Interplanetary Physics: Ejecta, driver gases, and magnetic clouds; 2164 Interplanetary Physics: Solar wind plasma; 2134 Interplanetary Physics: Interplanetary magnetic fields; 2139 Interplanetary Physics: Interplanetary shocks; *KEYWORDS:* high-speed solar wind, extreme solar wind, coronal mass ejections, interplanetary shocks, solar wind plasma, interplanetary magnetic field

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1. Introduction

[2] In two coronal mass ejection (CME) events observed on 29 October and 30 October 2003, the SWEPAM instrument on the ACE spacecraft measured solar wind speeds of >1850 km/s and 1700 km/s, respectively. These observations, part of a series of interplanetary shocks and CMEs in the solar wind during October and November 2003, represent some of the highest solar wind speeds ever measured in space.

[3] Extremely fast solar wind, with speeds >1500 km/s, has been directly measured near 1 AU on only one previous occasion, 4–5 August 1972, when the Prognoz 2 and HEOS 2 spacecraft measured speeds of 1700–1800 km/s, with speeds >2000 km/s inferred from the plasma measurements [e.g., *Vaisberg and Zastenker*, 1976; *d'Uston et al.*, 1977; *Cliver et al.*, 1990]. Similarly high speeds have been inferred for a number of other events based on time delays between flare observation and geomagnetic storm onset. Since high-speed solar wind near the Sun is typically slowed down through interactions as it travels to 1 AU, this method provides only an average solar wind speed over the time interval, not a 1 AU speed measurement. In addition, correlation of a flare and storm can be a difficult task, leading to uncertainties in the timing analysis of events, particularly at active times when multiple flares may be present. Nevertheless, it seems clear that transit times of less than a day have been observed on a number of occasions, and we briefly discuss such events as context for the present observations.

[4] Previous high-speed events include the 1 September 1859 event, the first solar flare ever observed, with a transit time of 17.5 hours [*Carrington*, 1859; *Hodgson*, 1859]. Early events were tabulated by *Newton* [1943], who examined solar flares and magnetic storms from 1859–1942 and noted several events with transit times of less than 25 hours (corresponding to average speeds greater than ~1650 km/s). More recent events were reviewed by *Cliver et al.* [1990], who studied geomagnetic storms from 1938 to 1989 that were preceded by major proton flares in an attempt to estimate the maximum speed of the solar wind. *Cliver et al.* [1990] identified several additional extremely fast events, the fastest being the 4 August 1972 event with a 14.6 hour transit time. *Cliver et al.* [1990] concluded that ~2000 km/s solar wind can reasonably be considered to occur within the high-speed tail of the distribution of solar wind speeds in large events.

[5] In this paper we present solar wind plasma and magnetic field observations from October and November 2003, including identification of shocks and CMEs. Our purpose is to document the physical nature of these extreme solar wind disturbances which have generated much interest

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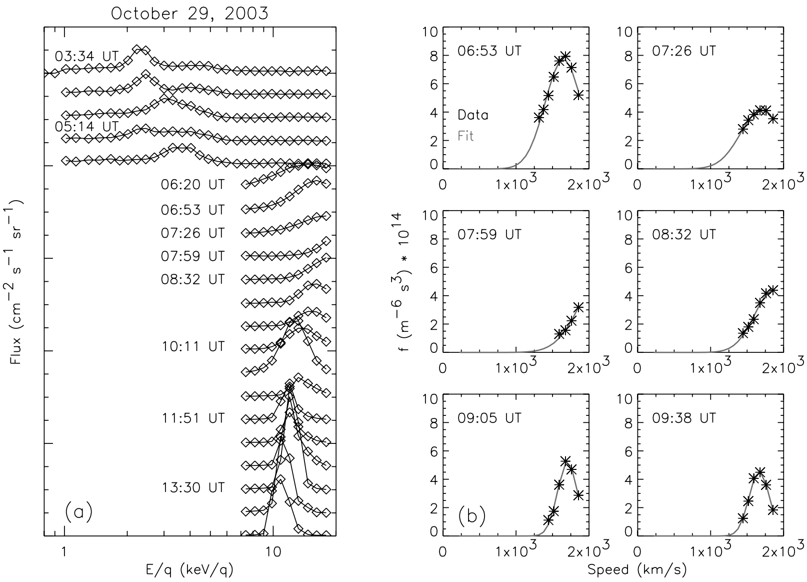

Figure 1. (a) One-dimensional (1-D) flux spectra from the SWEPAM search mode on 29 October 2003. Data have been summed over all angles to give flux (cm^{-2} s^{-1} sr^{-1}) as a function of E/q. A 64-s data point is obtained approximately every 33 min. (b) One-dimensional distribution function f (m^{-6} s^3) spectra for several of the highest-speed points on 29 October together with 1-D Maxwellian fits to the data.

in the space physics community. We compare the present observations with solar wind measurements in the August 1972 extremely high speed event and with other large transient events in the solar wind.

2. Instrumentation and Data Processing

[6] The Advanced Composition Explorer (ACE) spacecraft was launched in August 1997 and is in a halo orbit about the L1 Lagrangian point. In this paper we present plasma measurements from the Solar Wind Electron Proton Alpha Monitor (SWEPAM) [*McComas et al.*, 1998a] and magnetic field observations from the Magnetic Fields Experiment (MAG) [*Smith et al.*, 1998] on ACE.

[7] Solar wind conditions during these events pushed the measurement capabilities of the SWEPAM instrument. To understand the data that are available in this interval, we first discuss the SWEPAM operation. SWEPAM consists of two spherical section electrostatic analyzers, one measuring ions from 250–35,700 eV/q and the other measuring 2–1370 eV electrons. Ion and electron velocity distribution functions, f, are derived from the measured counts as a function of energy and look direction, and values of density, velocity, and temperature are obtained from moment integrals of f. Electron pitch angle distributions are obtained by combining the SWEPAM velocity distributions with magnetic field directions from the MAG instrument.

[8] The SWEPAM ion instrument collects data in two modes, each of which requires 64 s for a full measurement. In the normal (“track”) mode, solar wind ions are measured with 5% energy resolution at 40 energies actively chosen from the 250–35,700 eV/q range to cover the solar wind beam. These energies are selected based on the energy of the solar wind beam in the previous measurement. In addition, once every 31 cycles (approximately every 33 min) data are collected in “search” mode, in which ions are measured at a fixed set of energies from 260–17,900 eV/q with 10–12% energy resolution.

[9] Two issues affected the SWEPAM data during the October and November 2003 events. First, penetrating radiation from the intense solar energetic particle event led to high instrument background levels, which at times caused the solar wind tracking algorithm to fail. At these times (from 1241 UT on 28 October through 0051 UT on 31 October and again from 0225 to 1956 UT on 3 November), track mode data were collected at the lowest possible energies, from approximately 250–1870 eV/q, which did not cover the solar wind beam during these high-speed events. Therefore only search mode data, at energies up to 17.9 keV with ~33 min time resolution, are available during these periods.

[10] The penetrating radiation background was high enough to affect the calculated moments only from 1421 UT on 28 October through 1224 UT on 29 October. At these times, background counts were subtracted before the moments were calculated. Although this is a significant correction, we note that the background never dominated the measurement. The peak counts were at least an order of magnitude above the background level at all times. Since it is difficult to subtract the background perfectly, it is possible that the density and/or temperature were slightly overestimated at the times the background was the highest, just prior to the highest-speed flows on 29 October.

[11] Second, for several of the highest-speed points on 29–30 October 2003, the high-energy part of the solar wind beam exceeded the search mode energy range. Figures 1a and 2a show flux spectra from SWEPAM on 29 and 30 October, respectively. Figures 1b and 2b show the distribution function f as a function of speed for several of

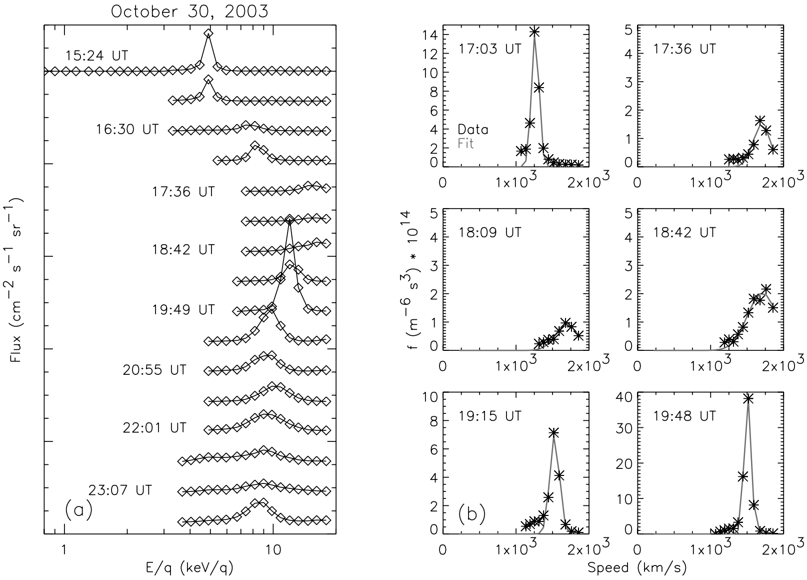

Figure 2. One-dimensional flux and *f* spectra from the SWEPAM search mode on 30 October 2003 in the same format as Figure 1.

the highest-speed spectra on each day. Although several of the flux spectra in Figure 1a peak above the highest measured energy, the E^2 factor used to convert from flux to *f* means that for all of the spectra except one (at 0759 UT), the peak in *f* was within the measured energy range. At the highest-speed times, estimates of the proton speed, density, and temperature were obtained from Maxwellian fits to the velocity distribution function *f* rather than from moment integrals. Both one-dimensional (1-D) Maxwellian fits (to *f* as a function of speed, shown in Figures 1b and 2b) and three-dimensional (3-D) Maxwellian fits (to *f* as a function of velocity) were performed. At lower-speed times, when both fits and integrals were possible, the methods show good agreement, suggesting that the data are reasonably well described by a Maxwellian distribution. In addition, the 3-D and 1-D fits are generally in good agreement. In the figures which follow, fitted data are used on 29 October from 0620 to 1150 UT (11 data points) and on 30 October from 1740 to 1840 UT (three data points).

[12] For the highest-speed time (0759 UT), measured data above the background level are available at only three energies (14.7, 16.1, and 17.9 keV), with the peak of the distribution clearly above 17.9 keV. A 1-D Maxwellian fit to these three data points gives a solar wind speed of 2240 km/s. A 3-D Maxwellian fit to the full 3-D measurement gives an even higher speed, 2400 km/s. In this paper we use the 1-D results for this time, since they are more consistent with adjacent measurements. However, the only definitive statement we can make is that the solar wind speed at this time exceeded the SWEPAM measurement limit of 1850 km/s.

[13] Under typical solar wind conditions, uncertainties in the calculated moments are of the order of 1.5% for speed, 15% for density, and 20% for temperature, based on comparison with moments from the SWE instrument on the Wind spacecraft [*McComas et al.*, 1998b]. Uncertainties are higher for the search mode measurements because of the reduced energy resolution. However, speed and temperature calculations are less dependent on the details of the distribution, and we thus expect the uncertainties in these parameters to no more than double for the events presented here. Comparable uncertainties are expected for the fitted points, although it is difficult to estimate an error for the highest-speed times, when the beam is not resolved. The densities have significantly larger uncertainties, as discussed in the next paragraphs.

[14] An additional issue is that the densities calculated using SWEPAM data appear to be too low for a portion of this interval. In particular, from 0600 UT on 29 October to 0400 UT on 30 October the proton densities obtained from SWEPAM are a factor of 2–5 lower than the electron densities obtained by the Plasma Wave Instrument (PWI) on the Geotail spacecraft (T. Terasawa, personal communication, 2004). Geotail entered the magnetosphere at 0400 UT on 30 October; when it returned to the solar wind, at 1100 UT on 31 October, the SWEPAM and PWI densities were in good agreement.

[15] We have considered a number of reasons for the underestimation of the proton density by SWEPAM but have been unable to come up with a definitive answer. The difference between electron and proton densities provides a ~10–30% correction. We also note that the ACE and Geotail spacecraft were separated by ~200 R_E, although we do not expect that to lead to a significant density difference for this large event. The unusually high energies measured in this event suggest a possible energy dependence of the SWEPAM detector efficiency. However, this effect is small (~15%) and acts to decrease the density further (H. Funsten, personal communication, 2004). A more probable explanation is that the density underestimation is caused by high count rates, either high background levels or high signal rates. The count rates in October 2003 were among the highest observed by SWEPAM, and thus the calculated densities are quite sensitive to the dead time correction applied to the data. Of the approximately 80 intervals in the entire SWEPAM data set with comparable count rates,

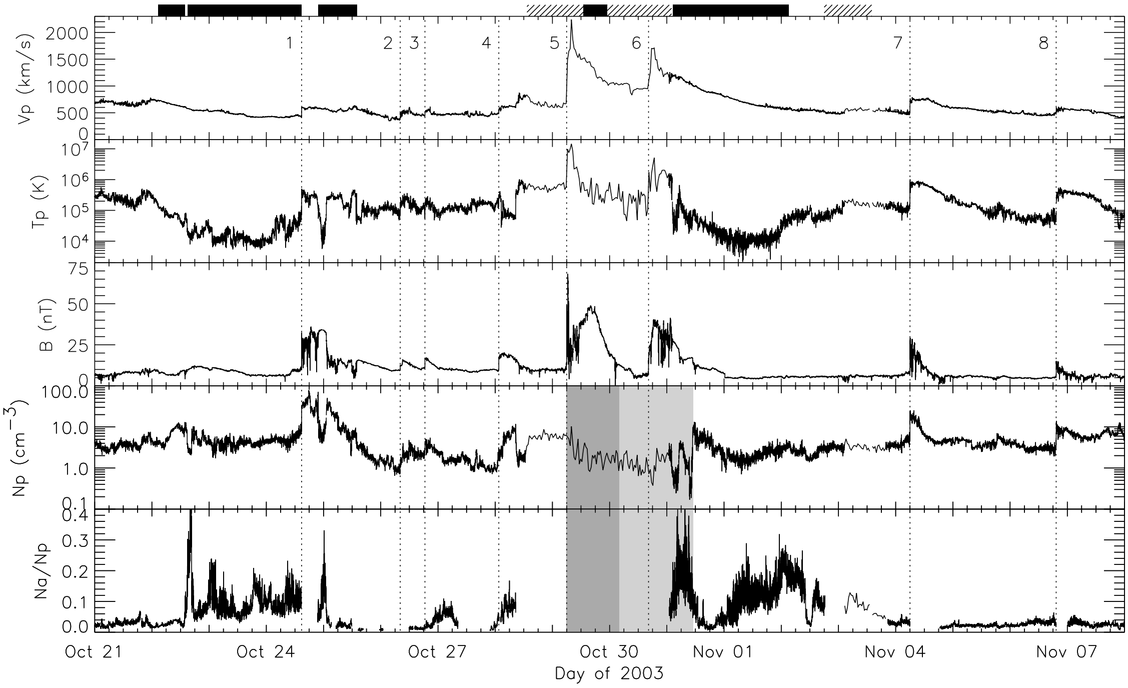

Figure 3. Plasma and magnetic field parameters for 21 October to 11 November 2003. From top to bottom, panels show proton speed, density, and temperature, He^{++}/H^{+} density ratio, and magnetic field. Solid bars at the top of the figure indicate the presence of counterstreaming suprathermal electrons (∼70–1370 eV), and striped bars indicate periods with no valid electron measurements. Shocks are indicated by vertical dotted lines. Gray shaded regions in the bottom panels indicate times when the density values are uncertain.

approximately one third show some evidence of density underestimation. However, underestimated densities in October 2003 occurred both at high count rate and low count rate times, so dead time considerations do not provide a complete explanation. Another possibility is that high count rates at times led to instrument saturation and thus that some of the times when the transmitted counts were low actually represent higher count rate intervals. In this case we would expect to see evidence of saturation in the form of "holes" in the measured distribution as a function of energy and angle (i.e., as in the case considered by *Skoug et al.* [1999]), but such artifacts were not observed in the present case, leading us to believe that saturation is not an issue. We thus do not completely understand the reasons for the low SWEPAM densities on 29–30 October 2003. Nevertheless, we find the PWI data compelling and so want to note the probable issue with the densities shown in this paper.

[16] The SWEPAM electron monitor was also affected by penetrating radiation during these events, with instrument saturation leading to a lack of valid data during several intervals, from 28 October, 1200 UT to 29 October, 1300 UT; from 29 October, 2300 UT to 31 October, 0030 UT; and from 2 November, 1800 UT to 4 November, 0700 UT.

3. Observations

[17] The unusually high solar wind speeds on 29–30 October 2003 were part of a series of events observed in the solar wind during October and November 2003. Figure 3 shows an overview of plasma and magnetic field measurements from 21 October to 7 November 2003 and provides context for the high-speed events. Gray shading in the bottom panels indicates times when the density values are uncertain, as discussed above. Dark gray indicates the period when SWEPAM densities disagree with the PWI results, and light gray indicates the interval with no PWI data available for comparison. The most unusual features in Figure 3 are the two high-speed intervals on 29 and 30 October. However, many solar wind disturbances were observed in this period. We have identified eight shocks in the 18-day period (marked with vertical dotted lines and listed in Table 1), using a combination of plasma and magnetic field observations, with times based on the higher time resolution field data. Shock normal angles, Mach numbers, and magnetic compression ratios (ratio of downstream to upstream magnetic field) from Rankine-Hugoniot fitting are given in Table 1 for shocks 1, 3, 7, and 8. Because of the low time resolution of the plasma data

Table 1. Shocks From 21 October to 6 November 2003[a]

Number	Date	Time	θ_{Bn}	M_A	R_B
1	24 Oct	1448	57	3.1	2.1
2	26 Oct	0809	–	–	–
3	26 Oct	1832	100	1.3	1.4
4	28 Oct	0131	68	–	–
5	29 Oct	0558	14	–	–
6	30 Oct	1619	54	–	–
7	4 Nov	0559	43	4.4	2.4
8	6 Nov	1919	114	3.0	2.2

[a]Columns give the shock time, shock normal angle θ_{Bn} in degrees, Mach number M_A, and magnetic field compression ratio R_B.

Table 2. CMEs From 21 October to 6 November 2003 With Identifying Characteristics

Start Time	End Time	CME Signatures
22 Oct, 0200 UT	24 Oct, 1445 UT	E[a], T_p[b], He^{++}[c], B[d]
24 Oct, 2200 UT	25 Oct, 1400 UT	E, brief T_p and He^{++}
28 Oct, 0230 UT	28 Oct, 0830 UT	T_p, He^{++}
29 Oct, 0800 UT	30 Oct, 1600 UT	B, E[e]
31 Oct, 0200 UT	2 Nov, 1800 UT	E, T_p, He^{++}, B

[a]E: counterstreaming electrons.
[b]T_p: low proton temperature.
[c]He^{++}: enhanced He^{++}/H^+ density ratio.
[d]B: magnetic field rotation.
[e]Exact timing difficult due to low time resolution data.

during the highest speed events, detailed shock analysis is difficult, and only shock normals from magnetic coplanarity analysis are included for shocks 4, 5, and 6. CMEs, listed in Table 2, were identified driving shocks 1, 4, 5, and 6, with an additional CME prior to the first shock. Shocks 2, 3, 7, and 8 may have been caused by CMEs which were not observed at ACE or may have been unrelated to CMEs. CME identification was based on measurements of counterstreaming suprathermal electrons, low proton temperatures, enhanced He^{++}/H^+ density ratios, and smooth rotations of the magnetic field [e.g., *Gosling*, 1990]. Note that neither He^{++} nor electrons were measured by SWEPAM for most of 28–30 October, making CME identification and timing difficult.

[18] Proton densities were generally low to moderate throughout this interval, with large enhancements only at shocks 1 and 7. Unusually high proton temperatures, up to 10^7 K, were observed when the speed was highest, particularly downstream from shocks 5 and 6, with very low temperatures, $<10^4$ K, observed in some of the CMEs, particularly on 23 October, 24 October, and 31 October to 2 November. Because of the high solar wind speeds and temperatures, He^{++} densities could be determined for only part of this period, but the He^{++}/H^+ density ratio was enhanced in several of the CMEs, reaching values of 20–40% on 22–24 October and 1–2 November. Comprehensive He^{++} densities for this interval are given by *Zurbuchen et al.* [2004] using data from the ACE Solar Wind Ion Composition Spectrometer (SWICS). The magnetic field increased at each shock, reaching values >25 nT at shocks 1, 5, 6, and 7, with typical values of ~5 nT between events.

[19] To examine the highest-speed events more closely, Figures 4 and 5 show plasma and magnetic field parameters from 28–31 October 2003. Figure 4 shows proton velocity and temperature together with magnetic field values, parameters which we do not expect to be affected by the uncertainties in the proton density.

[20] The solar wind speed exceeded 1500 km/s during two intervals, following the shocks on 29 October and 30 October, with the highest speeds observed ~2 hours following each shock. On 29 October a top solar wind speed of >1850 km/s, with a best-fit value of 2240 km/s (as discussed above), was calculated for one measurement time, with a speed of 1850 km/s at a second time. The solar wind speed exceeded 1500 km/s for a 6-hour period and exceeded

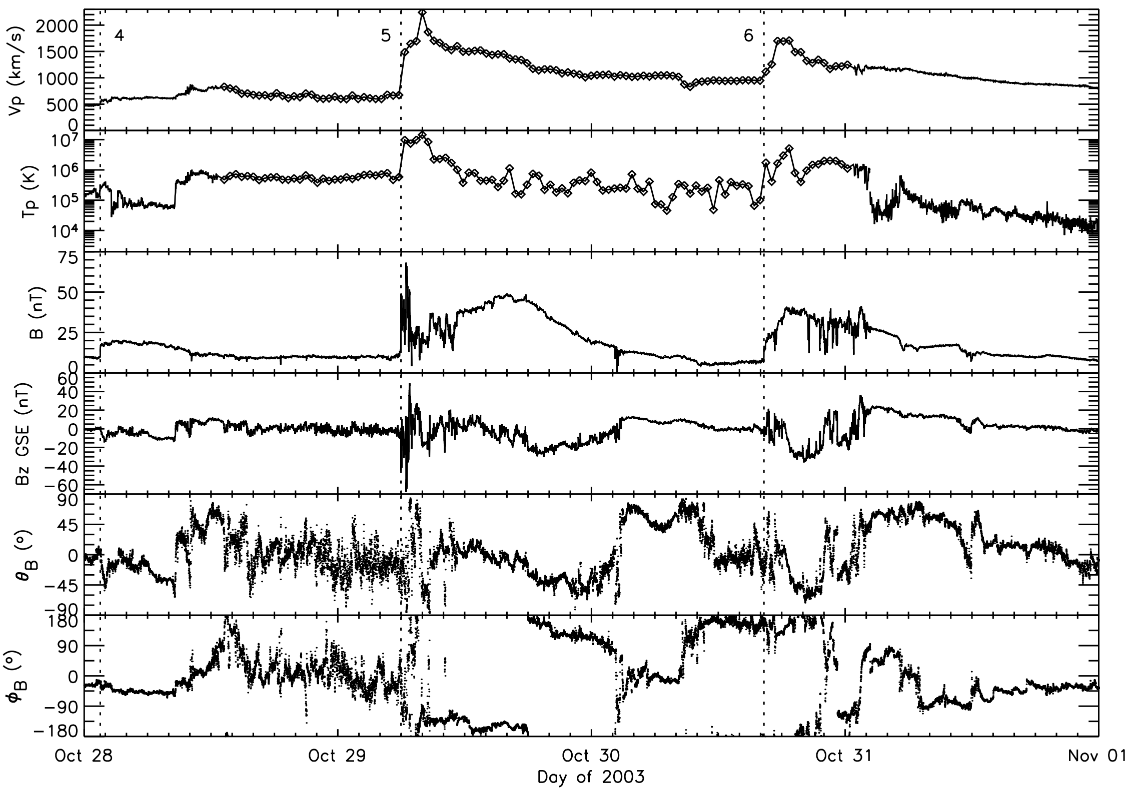

Figure 4. Plasma and magnetic field measurements for 28–31 October 2003. From top to bottom, panels show proton speed and temperature, magnetic field magnitude, the GSE Z component of the magnetic field, and the magnetic field polar and azimuthal angles in GSE coordinates. Shocks are indicated by vertical dotted lines.

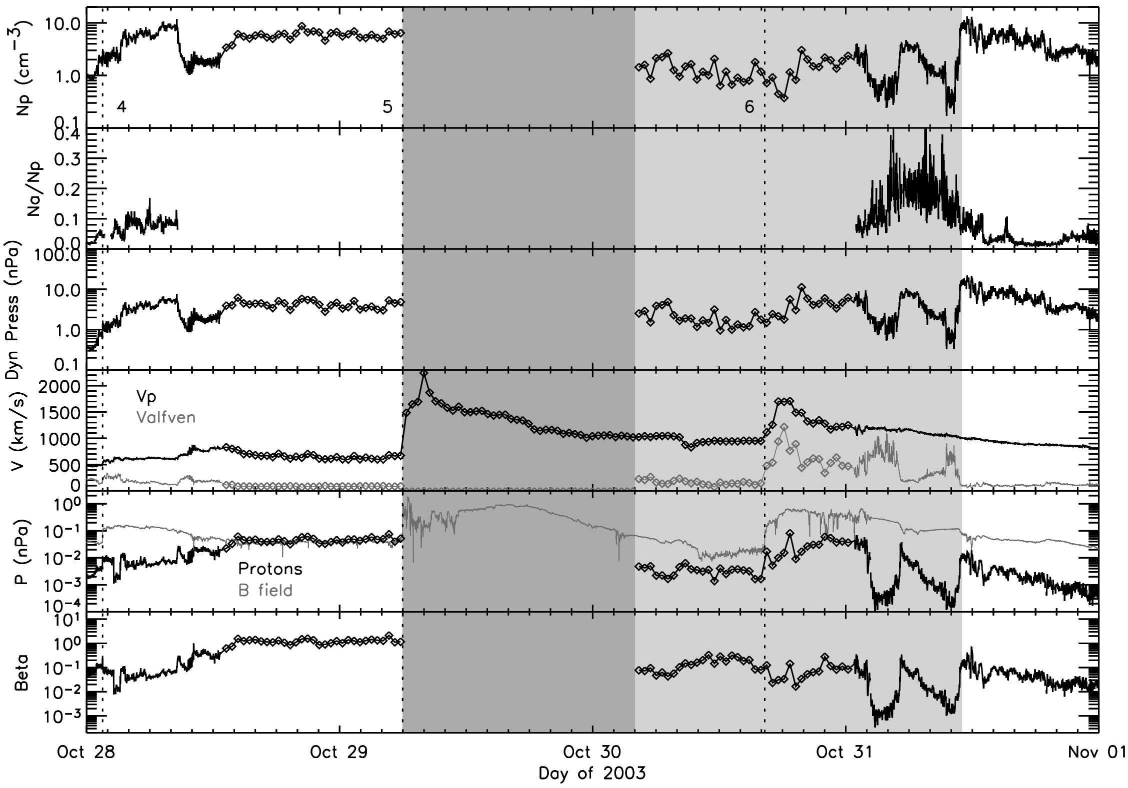

Figure 5. Plasma and magnetic field measurements for 28–31 October 2003 in the same format as Figure 4. From top to bottom, panels show proton density, He^{++}/H^{+} density ratio, solar wind dynamic pressure, Alfven speed, proton thermal and magnetic field pressures, and proton beta. Gray shaded regions indicate times when the density values are uncertain.

1000 km/s for 26 hours. The maximum solar wind speed on 30 October was lower, 1710 km/s, with the speed exceeding 1500 (1000) km/s for 1 (17.5) hours. It is of course possible that the speed exceeded these values during any of the ~1/2 hour gaps between SWEPAM data points.

[21] Proton temperatures were also unusually high, exceeding 10^7 K following the 29 October shock and reaching 5×10^6 K following the 30 October shock, roughly an order of magnitude higher than the highest temperatures previous recorded by SWEPAM. These temperatures also far exceed those predicted from empirical models of the correlation between temperature and speed [e.g., *Lopez and Freeman*, 1986], perhaps not a surprise since these models were derived using solar wind with speeds <800 km/s. The unusually high temperatures may be due to enhanced shock heating, as expected for such fast events.

[22] The magnetic field *B* increased at each of the shocks and was particularly enhanced following the 29 October shock, briefly reaching 68 nT. The B_z component briefly reached −68 nT at the same time but generally was only moderately southward or even northward during this interval. Following the 30 October shock, *B* reached values of 40 nT, with minimum B_z of −35 nT, and southward B_z for only a few hours. Smooth rotations of the magnetic field direction with reduced fluctuation levels were observed on 29 October and 31 October.

[23] Figure 5 shows parameters which are functions of proton density and are therefore less reliable during portions of this interval. Gray shading is as described for Figure 3. Density-related parameters are not shown in the dark gray interval because of the uncertainties in the data. Values in the light gray interval represent our best values for this period, although no corroborating observations are available. The density shown is presumably incorrect at the beginning of this interval, but the agreement between the SWEPAM and PWI densities after 1100 UT on 31 October implies that the SWEPAM density underestimation was corrected at some point during the light gray interval. There is some evidence to suggest the densities may be correct for portions of this interval. The SWEPAM density unexpectedly showed a drop at the 30 October shock. A similar drop was observed in the He^{++} density by ACE/SWICS [*Zurbuchen et al.*, 2004], suggesting the SWEPAM densities may be accurate at this time. In addition, two periods of unusually low density, ranging from 0.2 to 1 cm^{-3}, were observed on 31 October. Nearly identical densities were observed by the Solar Wind Experiment (SWE) instrument on the Wind spacecraft, located in the distant magnetosheath (J. Kasper, personal communication, 2004), suggesting that the SWEPAM densities were accurate at these times also.

[24] The He^{++}/H^{+} density ratio, dynamic pressure, thermal pressure, Alfven speed, and proton beta are strongly affected by errors in the calculated density. Figure 5 shows values of these parameters derived using the SWEPAM densities. Underestimation of the density means that the

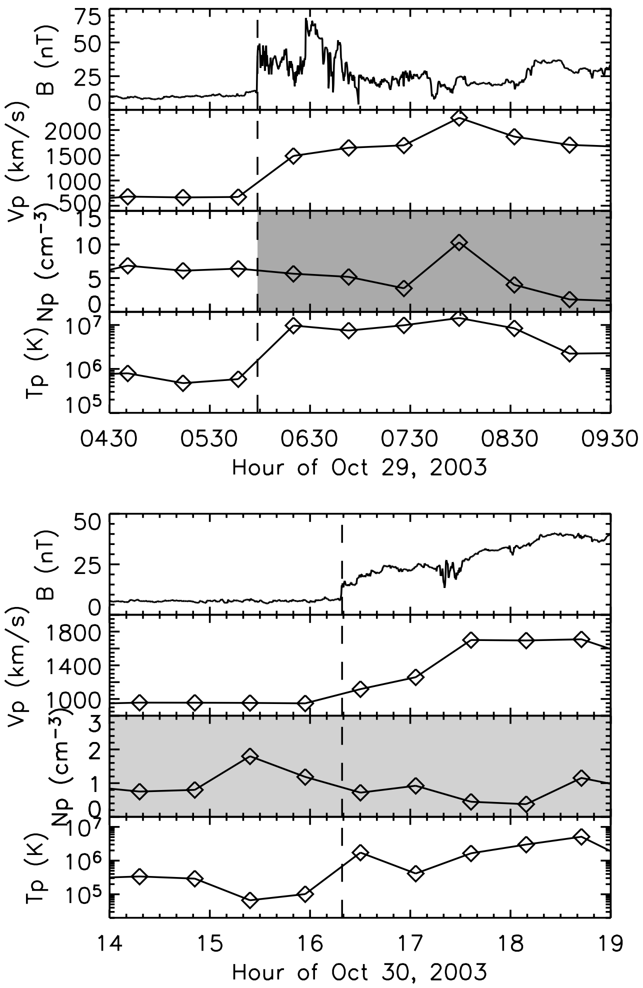

Figure 6. Plasma and magnetic field measurements for 5 hours surrounding the 29 October and 30 October 2003 shocks. From top to bottom, panels show solar wind magnetic field, speed, density, and temperature. Shocks are marked with vertical dashed lines. Gray shaded regions indicate times when the density values are uncertain.

dynamic and thermal pressures and beta values obtained are lower bounds to the actual values, while Alfven speeds and He^{++}/H^{+} density ratios are upper bounds.

[25] Note that the both the dynamic and thermal pressures shown here include only the protons. The He^{++} contribution to dynamic pressure was also significant, at times (e.g., during the 31 October to 2 November CME) comparable to the proton pressure. He^{++} and electrons of course also contribute to the total plasma thermal pressure, with contributions that can equal or exceed the proton pressure. Because of the gaps in the measurement of these particles during the high-speed events, their exact contribution is difficult to quantify.

4. Discussion

[26] The Alfven speed obtained from SWEPAM was very high during portions of these events (upper bound of >1000 km/s following the 30 October shock). In fast coronal hole flows, the He^{++} speed often exceeds the proton speed by up to the Alfven speed; such differential streaming has also been observed in CME flows [*Neugebauer et al.*, 1996]. It is thus possible that the He^{++} and proton speeds were quite different during portions of the October and November 2003 events. However, we note that when both protons and He^{++} were observable, for example, 31 October to 2 November, the proton and He^{++} speeds were nearly identical, even when the Alfven speed was high. It thus seems most likely that the physical processes which produce alpha-proton differential streaming were not acting in these extreme CMEs.

[27] Two unusual aspects of Figure 3 are the apparent constant proton density across the 29 October shock and drop in density at the 30 October shock. To examine these features more closely, Figure 6 shows the plasma and field parameters for 5 hours surrounding each of these shocks. Gray shading in the density panels is as in Figures 3 and 5. It is clear that the shocks were not well-resolved by the SWEPAM measurements. However, the density profiles are still surprising. We would expect that very fast solar wind would compress material ahead of it, leading to a density increase at each shock. The drop at the 29 October shock is presumably the result of an error in the SWEPAM density calculation, as discussed above, although the shock occurred at a time when the SWEPAM count rate was relatively low, and so the reasons for the low density determination are not well understood. As noted above, the density drop on 30 October was also measured by ACE/SWICS [*Zurbuchen et al.*, 2004], suggesting this is likely a real decrease.

[28] It is possible that the half hour time resolution of the SWEPAM data points prevented measurement of the compressed material swept up ahead of the CMEs. This would be an unusually short shock/CME separation but not inconsistent with the extremely high solar wind speed. At the measured speeds, a half hour delay corresponds to a shock/CME separation of 0.015–0.02 AU, on the tail of the distribution of previously observed separations [*Gosling et al.*, 1987]. For the 29 October event a short shock/CME separation is consistent with the MAG observations, which show only a short interval of very high magnetic field strength. In addition, each of the SWEPAM measurements on 29 October occurred at times when the magnetic field strength was relatively low. However, the magnetic field during the 30 October event was much less variable, and in fact the signatures used to identify the CME suggest a longer shock/CME separation (see Table 2).

[29] The CME which drove the 30 October shock did have a moderately low density, on the order of 10 cm^{-3} or less. In addition, this CME was running into the previous low-density CME, and this interaction of low-density objects may have contributed to the lack of density signature at the 30 October shock. It is also possible that there was a low-density plug of material immediately ahead of the shock and thus that compressed material ahead of the CME had a lower density than expected based on the upstream density.

[30] Unusually high solar wind proton temperatures (on 29 and 30 October) and He^{++}/H^{+} ratios (on 1–2 November) were observed in association with the October 2003 high-speed events. However, many other solar wind parameters, while unusual when compared with the solar wind as a

Table 3. Comparison of the 29–30 October 2003 High-Speed Events With the 4 August 1972, 15 July 2000, and 31 March 2001 CMEs[a]

Parameter	Oct 2003	Aug 1972	Jul 2000	Mar 2001
V_p	~2000	~2000	1100	850
T_p	1.4×10^7	1×10^7	1×10^6	9×10^5
N_p	~10–20[b]	50	60	190
B	68	115	60	70
B_z	−68	~ −60	−60	−50
P_{dyn}	~80b	~100	50	100
P_p	~2b	~1.5	0.25	0.9
Dst	−400	−125	−300	−390

[a]For each event, rows give the maximum proton speed V_p (km/s), maximum proton temperature T_p (K), maximum proton density N_p (cm^{-3}), maximum magnetic field B (nT), minimum B_z component (nT), maximum dynamic pressure P_{dyn} (nPa), maximum proton thermal pressure P_p (nPa), and minimum Dst (nT).
[b]Lower bound.

whole, were fairly typical of other large, transient events. It is interesting to compare the current observations with the only other directly measured, very high speed event and with other recent large CMEs. Table 3 gives a comparison of plasma and field parameters in the October 2003 CMEs with those in the 4 August 1972 very high speed event and with the 15 July 2000 (Bastille Day event) and 31 March 2001 CMEs. The 4 August 1972 CME was detected in the solar wind by the Prognoz 2 and HEOS 2 spacecraft, both located near the Earth [e.g., *Cattaneo et al.*, 1974; *Vaisberg and Zastenker*, 1976; *d'Uston et al.*, 1977; see also *Cliver et al.*, 1990]. The July 2000 [*Smith et al.*, 2001] and March 2001 [*Baker et al.*, 2002; *Ober et al.*, 2002; *Skoug et al.*, 2003] CMEs were detected by the ACE instruments.

[31] The solar wind speeds in 1972 and 2003 appear to have been comparable, on the order of 2000 km/s. The HEOS 2 plasma instrument suffered from a high background during the high-speed event [*Cattaneo et al.*, 1974] and was probably in the magnetosheath at the time of the highest-speed observations [*d'Uston et al.*, 1977] but reported speeds of ~1800 km/s [e.g., *Vaisberg and Zastenker*, 1976; *Cliver et al.*, 1990]. Prognoz 2 measured speeds up to ~1700 km/s, then saw a drop-out of the signal in both the Faraday cup and electrostatic analyzer instruments, which was interpreted as being caused by a drop in temperature and an increase in speed which took the solar wind beam out of the measurement range of the instrument [*Vaisberg and Zastenker*, 1976; *d'Uston et al.*, 1977]. A solar wind speed of ~2000 km/s, coupled with a proton temperature of 10^5 K, was inferred for the highest-speed interval [*d'Uston et al.*, 1977]. As in the 2003 events, unusually high proton temperatures, >10^7 K, were observed at the preceding shock. More typical transient speeds of 1100 and 850 km/s, respectively, and peak temperatures near 10^6 K were observed during the 2000 and 2001 events. The high proton temperatures in October 2003 and August 1972 led to high proton thermal pressures (~1.5 nPa in August 1972, with a lower bound of ~2 nPa on 29 October 2003). For comparison, pressure during the 15 July 2000 event reached 0.9 nPa and during the 31 March 2001 CME reached 0.2 nPa. All of these CMEs were predominantly magnetically dominated, with proton $\beta < 1$.

[32] Magnetic field values in October 2003 were high but not unprecedented, and the high magnetic fields lasted for only a short time. Significantly higher fields, up to ~115 nT, were observed following the 4 August 1972 shock, with 30–40 nT alternating northward and southward fields in the CME. Magnetic field values in the 2000 and 2001 events were similar to those observed in October 2003, with $B_z <$ −40 nT for a 2-hour period on 15 July 2000 and $B_z <$ −30 nT for 7 hours on 31 March 2001.

[33] Although the proton density calculated from the SWEPAM data is uncertain for much of the highest-speed interval, it is clear that the proton density was relatively low during the high-speed events, with maximum values on the order of <10–20 cm^{-3} and smaller densities in the CMEs. In contrast, the 1972 CME was a relatively high-density object, with densities ranging from 10 cm^{-3} to >20 cm^{-3} in the highest-speed region and ~50 cm^{-3} at the preceding shock. Even higher densities were observed following the 2000 and 2001 shocks. The 15 July 2000 CME had a low density, around 1 cm^{-3}, while the 31 March 2001 CME had an average density of ~10 cm^{-3}. The relatively low proton densities in the October 2003 CMEs led to a moderate dynamic pressure, even at the highest-speed times (lower bound of ~80 nPa). Slightly lower dynamic pressure was observed in the 15 July 2000 event, with higher dynamic pressure, ~100 nPa, in the 4 August 1972 and 31 March 2001 CMEs, in the second case in much lower speed solar wind.

[34] Because of the moderate dynamic pressure and short-lived large negative B_z, the October 2003 high-speed events were not unusually geoeffective. These events did produce large geomagnetic storms, with Dst of −360 nT following the 29 October shock and −400 nT following the 30 October shock. However, an even larger storm occurred 3 weeks later, with Dst reaching −465 nT on 20 November 2003 when the solar wind speed was only ~750 km/s. Comparable storms were produced by the 15 July 2000 and 31 March 2001 CMEs. The 1972 high-speed event produced only a moderate geomagnetic storm, with Dst of −125 on 5 August. This contrast between solar wind and geomagnetic activity levels can be understood by considering the variability of solar wind plasma parameters. Even in this extremely fast event, the solar wind speed was only 5 times larger than average and only 2–3 times faster than typical for large solar wind transient events. In contrast, the solar wind proton density in large transient events can exceed 100 cm^{-3}, more than an order of magnitude higher than the average density. The relatively low-density October 2003 events thus did not produce unusually large changes in solar wind dynamic pressure as compared with other large transient events. When coupled with only moderately southward IMF, even solar wind with such extreme speed need not result in particularly unusual geomagnetic conditions.

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