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Extremely high speed solar wind: October 29-30, 2003

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Abstract. On October 29-30, 2003, the SWEPAM instrument on the 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. Although the proton temperatures were higher than typical for a CME in the solar wind at 1 AU, the proton densities were moderate, leading to low to moderate proton beta. The solar wind dynamic pressure reached 50 nPa, again not unusual for large events, but, when coupled with the large negative $\mathrm{B_z}$, sufficient to cause intense geomagnetic disturbances.

1. Introduction

In two coronal mass ejection (CME) events observed on October 29 and October 30, 2003, the SWEPAM instrument on the ACE spacecraft measured solar wind speeds of > 1850 km/s and 1700 km/s. 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.

Extremely fast solar wind, with speeds >1500 km/s, has been directly measured near 1 AU on only one previous occasion, August 4–5, 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.

Previous high-speed events include the Sept 1, 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 Aug 4, 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.

In this paper, we present solar wind plasma and magnetic field observations from October-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 in the space 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

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.,* 1998] and magnetic field observations from the Magnetic Fields Experiment (MAG) [*Smith et al.,* 1998] on ACE.

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.

The SWEPAM ion instrument collects data in two modes, each of which requires 64 seconds 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 minutes) 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.

Two issues affected the SWEPAM data during the October-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 October 28 through 0051 UT on October 31, and again from 0225 to 1956 UT on November 3), 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 $\sim$33 minute time resolution are available during these periods. The high background does not appear to adversely affected the search mode data. No evidence of instrument saturation was observed in any of the measurements, and peak counts were at least an order of magnitude above the background level at all times. It thus does not appear that the calculated moments were significantly affected by the penetrating radiation background, although 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 October 29.

Secondly, for several of the highest-speed points on October 29-30, 2003, the high energy part of the solar wind beam exceeded the search mode energy range. Figure 1 shows flux spectra from SWEPAM on October 29. Although several of the flux spectra in Figure 1 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 (not shown) was within the measured energy range. At these highest-speed times, estimates of the proton speed, density, and temperature at these times were obtained from Maxwellian fits to the velocity distribution function f rather than from moment integrals. Both 1-dimensional (1D) Maxwellian fits (to f as a function of speed) and 3-dimensional (3D) 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 3D and 1D fits are generally in good agreement. In the figures which follow, fitted data are used on October 29 from 0620 to 1150 UT (11 data points), and on October 30 from 1740 to 1840 UT (3 data points).

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 1D Maxwellian fit to these three data points gives a solar wind speed of 2100 km/s. A 3D Maxwellian fit to the full 3D measurement gives an even higher speed, 2500 km/s. In this paper, we use the 1D 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.

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 October 28, 1200 UT to October 29, 1300 UT, from October 29, 2300 UT to October 31, 0030 UT, and from November 02, 1800 UT to November 04, 0700 UT. At times when the electron measurements are available, the suprathermal electron distributions are helpful for identifying CME material.

3. Observations

The unusually high solar wind speeds on October 29-30, 2003 were part of a series of events observed in the solar wind during October and November, 2003. Figure 2 shows an overview of plasma and magnetic field measurements from October 21 to November 7, 2003 and provides context for the high speed events. The most unusual features in Figure 2 are the two high speed intervals on October 29 and 30. However, many solar wind disturbances were observed in this period. We have identified 8 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 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 October 28–30, making CME identification and timing difficult. Solar wind composition provides another CME signature, as discussed for these events by *Zurbuchen et al.* [2004].

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 October 23, October 24, and October 31–November 2. 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%. The magnetic field showed an increase at each shock, reaching values >25 nT at shocks 1, 5, 6, and 7, with typical values of ∼5 nT between events.

To examine the highest speed events more closely, Figures 3, 4, and 5 show plasma and magnetic field parameters for four days surrounding these events. The solar wind speed exceeded 1500 km/s during two intervals, following the shocks on October 29 and October 30, with the highest speeds observed ∼2 hours following each shock. On October 29, a top solar wind speed of >1850 km/s, with a best fit value of 2100 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 1000 km/s for 26 hours. The maximum solar wind speed on October 30 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.

Proton temperatures were also unusually high, exceeding 10^7 K following the October 29 shock and reaching 5×10^6 K following the October 30 shock. Such temperatures are far higher than typically observed in the solar wind. 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. Unusually high $\mathrm{He}^{++}/\mathrm{H}^{+}$ density ratios were observed in the CME driving the October 30 shock, reaching values of 20–40% on October 31–November 2. The proton density was relatively low during the high-speed events, briefly exceeding 15 cm^{-3} prior to the October 29 shock, but typically ranging from 1–5 cm^{-3} during most of the high-speed period. In addition, several periods of unusually low density, ranging from 0.2–1 cm^{-3} were observed on October 30–31.

The magnetic field B showed an increase at each of the shocks, and was particularly enhanced following the October 29 shock, briefly reaching 68 nT. The $\mathrm{B_z}$ component briefly reached −68 nT, but generally was only moderately southward or even northward during this interval. Following the October 30 shock, B reached values of 40 nT, with minimum $\mathrm{B_z}$ of −35 nT, and southward $\mathrm{B_z}$ for only a few hours. The magnetic field direction showed smooth rotations with reduced fluctuation levels on October 29 and October 31.

The relatively low proton density resulted in a moderate dynamic pressure, even at the highest speed times. The proton dynamic pressure reached 50 nPa on October 29, a high but not atypical value. Similar values were observed following the October 24 shock, in much lower speed solar wind. Note that the dynamic pressure shown here includes only the protons, but that the He^{++} contribution to dynamic pressure was also significant, at times (e.g. during the October 31 – November 2 CME) equal to the proton pressure.

The Alfven speed was very high during portions of these events, >1000 km/s, with particularly high values during the declining speed period late on October 29 and on October 30–31. 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–November, 2003 events. However, we note that when both protons and He^{++} were observable, e.g. October 31–November 2, 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.

The high proton temperatures produced a high proton thermal pressure, exceeding 1 nPa following the October 29 shock. The proton beta covered a wide range of values, from 10^{-3} to approximately 10, with typical values of 0.1 during the highest speed intervals. The very low densities in the October 31 CME led to periods of very low proton beta, ~ 0.001. With the exception of the very highest speed times, the magnetic field dominated the proton pressure during these events. 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. However, the proton beta was sufficiently low during most of this interval that it is highly likely that the magnetic field dominated the total static plasma pressure as well.

4. Discussion

Given the large increase in solar wind speed on October 29, it seems clear that the magnetic field discontinuity at 0600 UT must be a shock. One unusual feature in Figure 3 is that the proton density appears to drop at this shock. The drop appears to be real, rather than a measurement artifact. To examine this feature more closely, Figure 6 shows the plasma and field parameters for 5 hours surrounding the October 29 shock. Vertical dotted lines mark the times of the SWEPAM plasma measurements, and the shock is indicated by a vertical dashed line. It is clear that the shock was not well-resolved by the SWEPAM measurements. However, the density drop is still surprising. We would expect that the very fast solar wind would compress material ahead of it, leading to a density increase at the shock. The fact that this density increase was not observed suggests that SWEPAM did not measure the compressed material swept up ahead of the CME and thus implies a very short time delay from shock passage to CME onset of less than the half hour between SWEPAM data points. This is an unusually short delay, but is consistent with the extremely high solar wind speed.

Gosling [1990] reported a CME observed at ISEE-3 with a two-hour delay, corresponding to a shock/CME separation width of $\sim$0.03 AU. A similar delay was observed at ACE on July 15, 2001 [*Smith et al.,* 2001]. If we take the ~1400 km/s speed measured by SWEPAM following the October 29 shock as the speed of the shocked plasma, a 30-minute delay corresponds to a shock/CME separation distance of ~0.02 AU. *Gosling et al.* [1987] performed a statistical study of shock/CME delay times using 49 events observed by ISEE 3 in 1978–1979. They found a mean separation of 0.16 AU, with 5% of the events having separations of less than 0.05 AU. The current observation is at the edge of, but is consistent with, this distribution. In addition, such a short shock-to-CME delay is consistent with the MAG observations, which show only a short interval of very high magnetic field. Note that each of the SWEPAM measurements in Figure 6 occurred at times when the magnetic field was relatively low, lending support to the idea that SWEPAM did not measure the compressed material ahead of the CME.

On the other hand, the unusually high temperatures after the shock suggest that the low-density material immediately following the shock was compressed. Since compression typically also extends into the leading portion of the CME, SWEPAM may have observed compressed CME material at this time. Since this CME had a low density, compressed CME material might also have had a relatively low density, and so could be difficult to distinguish based on density alone. Although we feel it less likely, 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.

The CME which drove the October 30 shock also had a low density, with density dropping well below 1.0 cm^{-3} in several intervals. In addition, this CME was running into the previous low density CME. It is thus perhaps not surprising that no density signature was observed at the October 30 shock.

Unusually high solar wind proton temperatures and $\mathrm{He}^{++}/\mathrm{H}^{+}$ ratios 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 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 August 4, 1972 very high speed event and with the July 15, 2000 (Bastille Day event) and March 31, 2001 CMEs. The August 4, 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.

The solar wind speeds in 1972 and 2003 appear to be 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 they 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. The 2000 and 2001 events both showed more typical transient speeds of 1100 and 850 km/s, respectively, and peak temperatures near 10^6 K. The high proton temperatures in October 2003 and August 1972 led to high proton thermal pressures of ∼1.5 nPa. For comparison, pressure during the July 15, 2000 event reached 0.9 nPa and during the March 31, 2001 CME reached 0.2 nPa. All of these CMEs were magnetically dominated, with proton $\beta < 1$.

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 August 4, 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 two-hour period on July 15, 2000 and $B_z < -30$ nT for 7 hours on March 31, 2001.

In contrast to the 2003 CMEs, 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 July 15, 2000 CME had a low density, around 1 cm^{-3}, while the March 31, 2001 CME had a higher density, on average ∼10 cm^{-3}. The low proton densities in the October 2003 CMEs led to a moderate dynamic pressure of <10 nPa throughout most of the event and a peak of 50 nPa. Similar dynamic pressure was observed in the July 15, 2000 event, with higher dynamic pressure, ∼100 nPa, in the August 4, 1972 and March 31, 2001 CMEs.

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 October 29 shock and −400 nT following the October 30 shock. However, an even larger storm occurred three weeks later, with Dst reaching −465 nT on November 20, 2003 when the solar wind speed was only ∼750 km/s. Comparable storms were produced by the July 15, 2000 and March 31, 2001 CMEs. The 1972 high speed event produced only a moderate geomagnetic storm, with Dst of −125 on August 5. This contrast between solar wind and geomagnetic activity levels can be explained by considering the variability of solar wind plasma parameters. Even in this extremely fast event, the solar wind speed is only 5 times larger than average, and only 2–3 times faster than typical for large solar wind transients. 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 low-density October 2003 events thus did not lead to unusually large changes in solar wind dynamic pressure, as compared to other large transient events. When coupled with only moderately southward IMF, even solar wind with such extreme speed need not lead to particularly unusual geomagnetic conditions.

Concerning the frequency of extremely high-speed solar wind, we note that flare/storm correlations, and most spacecraft measurements to date, only refer to the fraction of solar events which are Earthward-directed. It thus is likely that extremely high-speed solar wind is more common than is suggested from Earth or L1 observations. This point was emphasized by the 1972 observations, in which the Pioneer spacecraft, separated from the Earth by 45 degrees in longitude, observed top speeds of only ∼1100 km/s [*Intriligator,* 1976]. Similar results are suggested by the 2003 observations, with Ulysses (separated from the Earth by nearly 90° in longitude) measuring normal solar wind speeds from the solar activity which produced the events discussed in this paper, but observing unusually high speed wind from a solar event several days later [*deKoning et al.,* 2004].

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Table 1. Shocks from October 21 – November 6, 2003. Columns give the shock time, shock normal angle θ_{Bn} in degrees, Mach number $\mathrm{M_A}$, and magnetic field compression ratio $\mathrm{R_B}$.

#	Date	Time	θ_{Bn}	$\mathrm{M_A}$	$\mathrm{R_B}$
1	Oct 24	1448	57	3.1	2.1
2	Oct 26	0809	–	–	–
3	Oct 26	1832	100	1.3	1.4
4	Oct 28	0131	68	–	–
5	Oct 29	0558	14	–	–
6	Oct 30	1619	54	–	–
7	Nov 04	0559	43	4.4	2.4
8	Nov 06	1919	114	3.0	2.2

Table 2. CMEs from October 21 – November 6, 2003, with identifying characteristics.

Start Time	End Time	CME signatures
Oct 22, 0200 UT	Oct 24, 1445 UT	E;[a] T_p;[b] He^{++};[c] B[d]
Oct 24, 2200 UT	Oct 25, 1400 UT	E, brief T_p and He^{++}
Oct 28, 0230 UT	Oct 28, 0830 UT	T_p, He^{++}
Oct 29, 0800 UT	Oct 30, 1600 UT	B, E[e]
Oct 31, 0200 UT	Nov 02, 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

Table 3. Comparison of the October 29–30, 2003 high-speed events with the August 4, 1972, July 15, 2000, and March 31, 2001 CMEs. 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).

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	15	50	60	190
B	68	115	60	70
B_z	−68	~−60	−60	−50
P_{dyn}	50	~100	50	100
P_p	1.5	~1.5	0.25	0.9
Dst	−400	−125	−300	−390

Figure 1. 1D flux spectra from the SWEPAM search mode on October 29, 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-second data point is obtained approximately every 33 minutes.

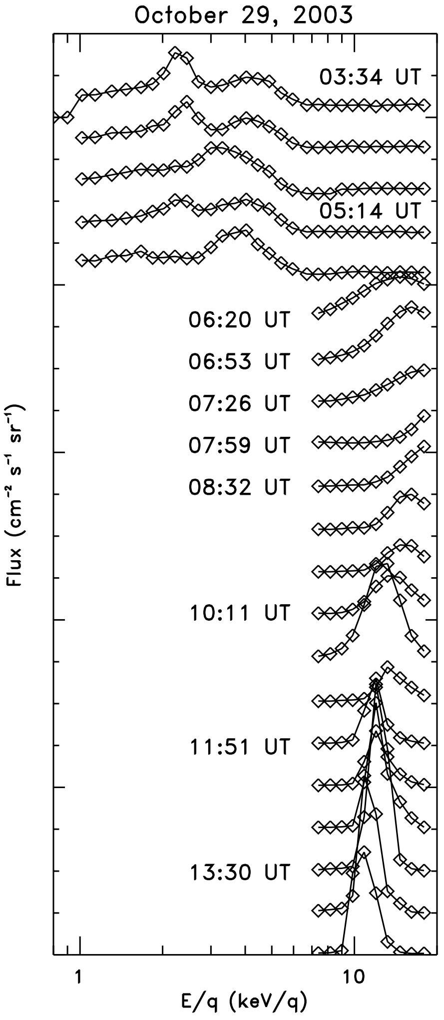
Figure 2. Plasma and magnetic field parameters for October 21 - November 11, 2003. From top to bottom, panels show proton speed, density, and temperature, $\mathrm{He}^{++}/\mathrm{H}^{+}$ density ratio, and magnetic field. Solid bars at the top of the figure indicate the presence of counterstreaming suprathermal electrons (∼70–1370 eV), and striped bars indicate periods with no valid electron measurements. Shocks are indicated by vertical dotted lines.

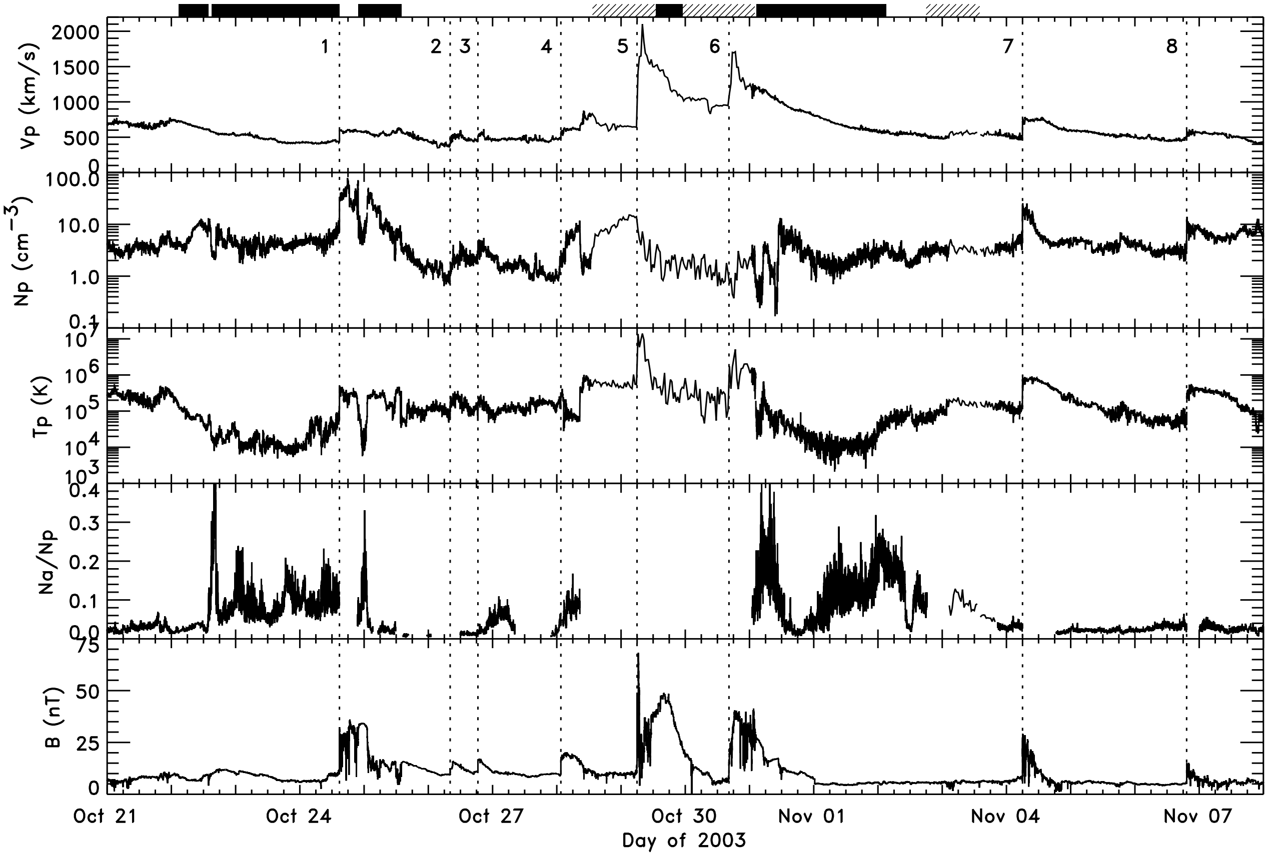
Figure 3. Plasma measurements for October 28–31, 2003. From top to bottom, panels show proton speed, density, and temperature, and $\mathrm{He}^{++}/\mathrm{H}^{+}$ density ratio. Shocks are indicated by vertical dotted lines.

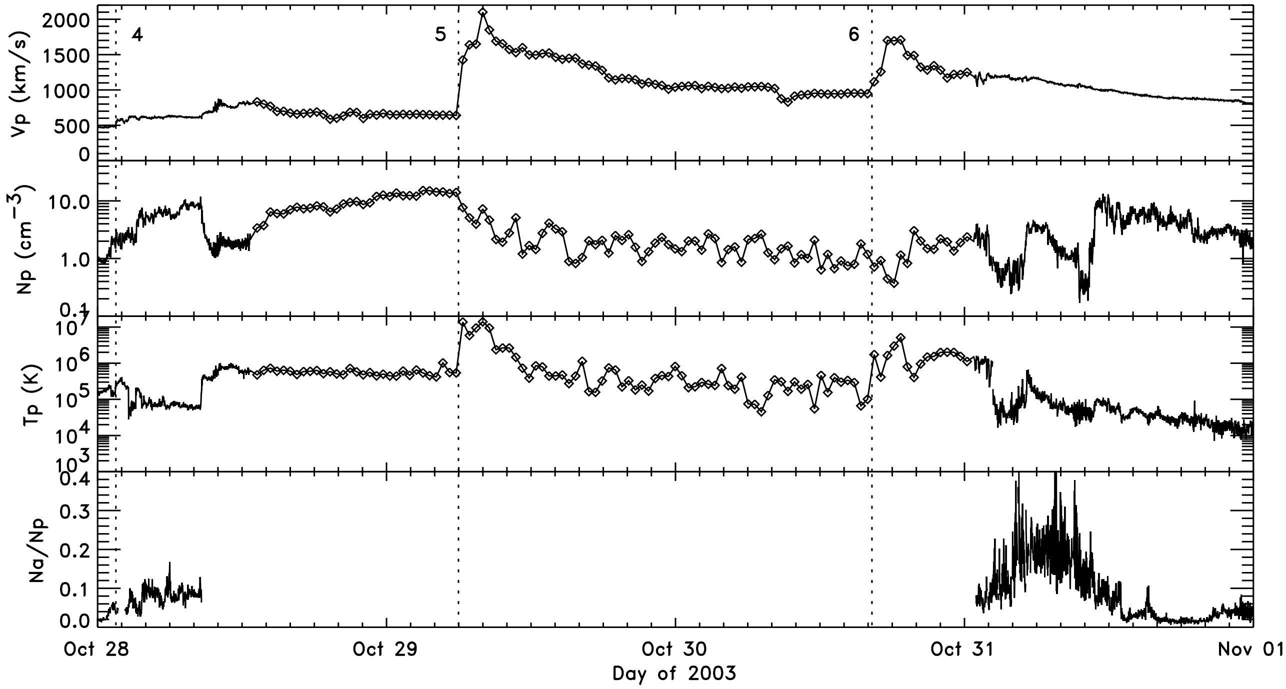
Figure 4. Magnetic field measurements for October 28–31, 2003 in the same format as Figure 3. From top to bottom panels show magnetic field magnitude, the GSE Z component of the magnetic field, and the magnetic field polar and azimuthal angles in GSE coordinates.

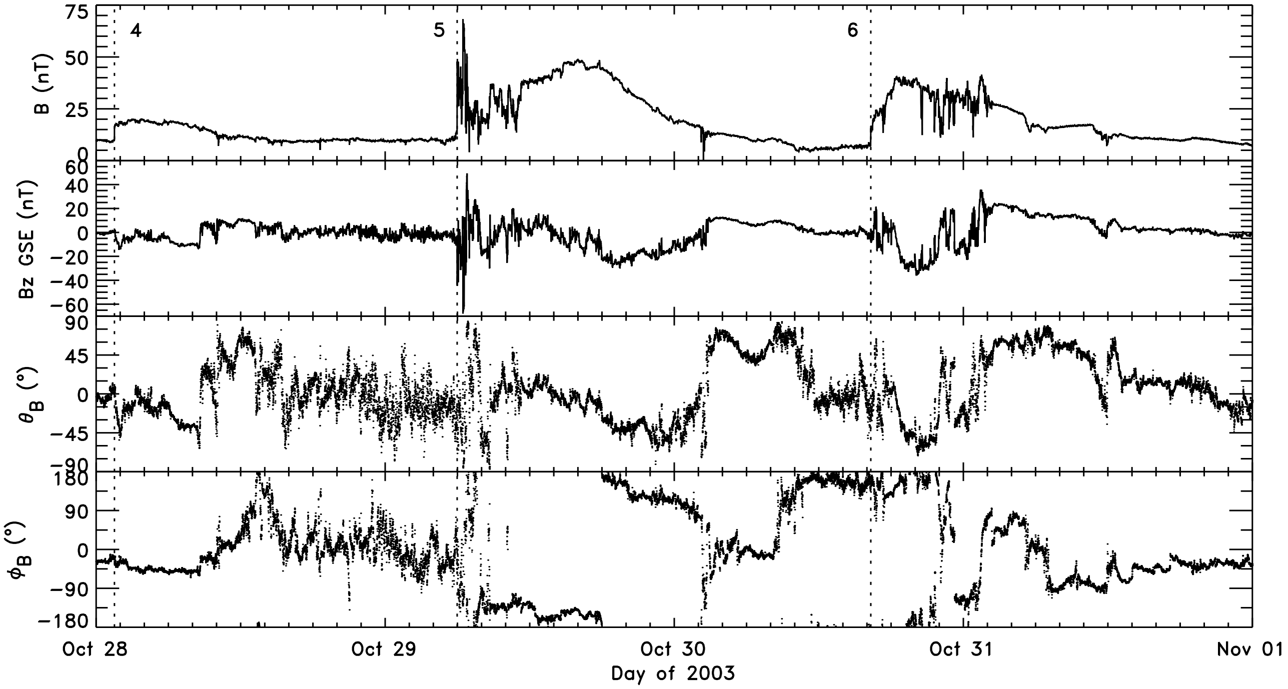
Figure 5. Plasma and magnetic field measurements for October 28–31, 2003 in the same format as Figure 3. From top to bottom, panels show solar wind dynamic pressure, Alfven speed, proton thermal and magnetic field pressures, and proton beta.

Figure 6. Plasma and magnetic field measurements for 5 hours on October 29, 2003. From top to bottom, panels show solar wind magnetic field, speed, density, and temperature. The shock is marked with a vertical dashed line. Vertical dotted lines mark the times of the SWEPAM data points.

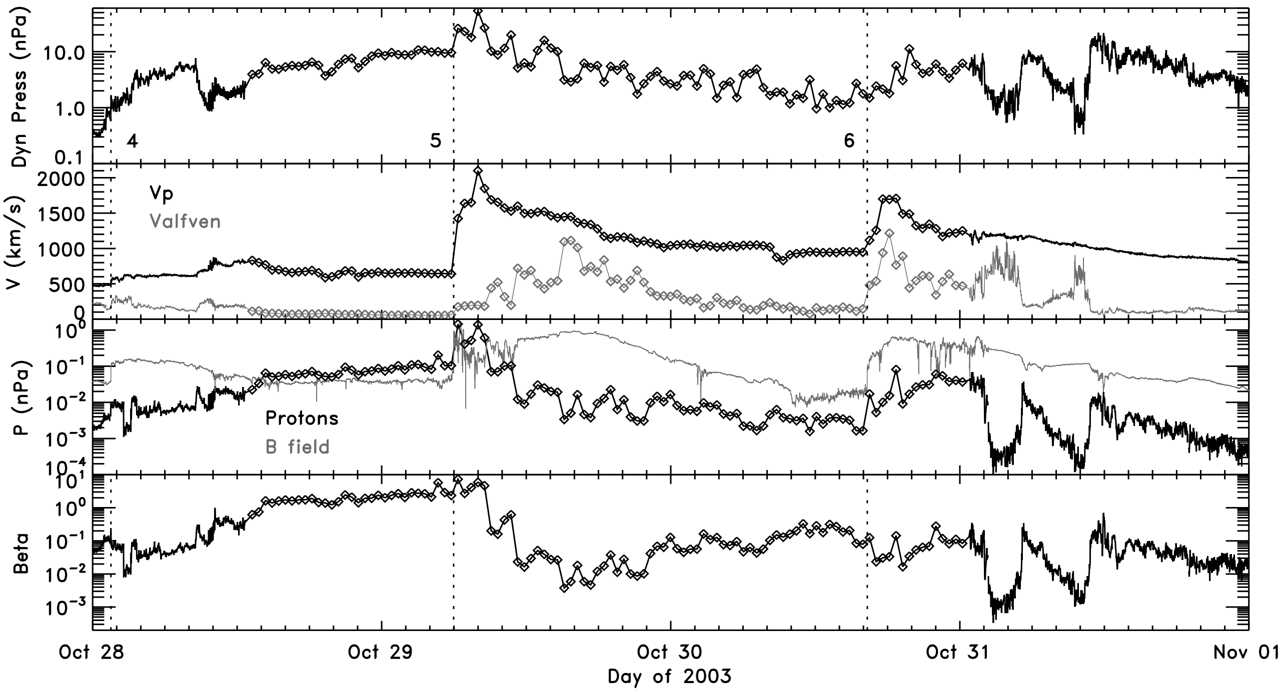

October 29, 2003
03:34 UT
05:14 UT
06:20 UT
06:53 UT
07:26 UT
07:59 UT
08:32 UT
10:11 UT
11:51 UT
13:30 UT
Flux (cm⁻² s⁻¹ sr⁻¹)
1
10
E/q (keV/q)

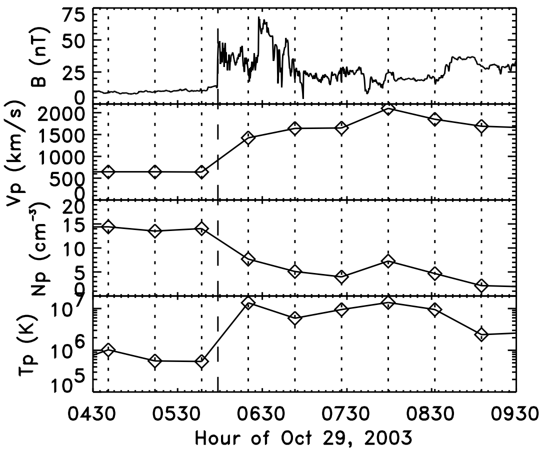

1
2
3
4
5
6
7
8
Vp (km/s)
2000
1500
1000
500
0
Np (cm^{-3})
100.0
10.0
1.0
0.1
Tp (K)
10^7
10^6
10^5
10^4
10^3
Nα/Np
0.4
0.3
0.2
0.1
0.0
B (nT)
75
50
25
0
Oct 21
Oct 24
Oct 27
Oct 30
Nov 01
Nov 04
Nov 07
Day of 2003


Vp (km/s)
2000
1500
1000
500
0
4
5
6
Np (cm^{-3})
10.0
1.0
0.1
Tp (K)
10^7
10^6
10^5
10^4
10^3
Na/Np
0.4
0.3
0.2
0.1
0.0
Oct 28
Oct 29
Oct 30
Oct 31
Nov 01
Day of 2003



4
5
6
B (nT)
0
25
50
75
Bz GSE (nT)
-60
-40
-20
0
20
40
60
θ_B (°)
-90
-45
0
45
90
ϕ_B (°)
-180
-90
0
90
180
Oct 28
Oct 29
Oct 30
Oct 31
Nov 01
Day of 2003


Dyn Press (nPa)
10.0
1.0
0.1
4
5
6
V (km/s)
2000
1500
1000
500
0
Vp
Valfven
P (nPa)
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
Protons
B field
Beta
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
Oct 28
Oct 29
Oct 30
Oct 31
Nov 01
Day of 2003


B (nT)
75
50
25
0
Vp (km/s)
2000
1500
1000
500
0
Np (cm⁻³)
20
15
10
5
0
Tp (K)
10⁷
10⁶
10⁵
0430
0530
0630
0730
0830
0930
Hour of Oct 29, 2003