NASA TECHNICAL
MEMORANDUM

N74-10776
NASA TM X- 62,313

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DISTANT BOW SHOCK OBSERVATIONS BY EXPLORER 33

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September 1973

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Abstract

Locations, orientations and magnetic field changes are given for 135 bow shock crossings at distances downstream from Earth between 84 and 117 Earth radii. The shock locations are dependent on the spacecraft trajectory and agree with locations calculated for the hypersonic analogue by Dryer and Heckman for a Mach number of 3.8. The shock normal vectors have been calculated using magnetic coplanarity. The average normal vectors have a greater inclination by $\sim 17 \pm 5$ deg from the symmetry axis than the Dryer and Heckman shock orientations for a 3.8 Mach number. Over a range of downstream distances from 60 to 115 Earth radii, the median magnetic field magnitude jump across the shock changes from 1.90 to 1.70 times.

Introduction

Explorer 33 was launched on July 1, 1966 into a highly elliptical Earth orbit, with an initial apogee of 69.04 R_E (Earth radii). A close passage near the Moon on January 19, 1969 (to 32,900 km selenocentric distance) caused the apogee distance to increase to 128.2 R_E on February 14, 1969, and to 138.6 R_E on March 28, 1969. After March 1969, successive apogees decreased so that by the end of 1970 they had returned to the same range of values as prior to the January 1969 lunar perturbation. Crossings of Earth's bow shock were observed at the most distant apogee. At least 135 bow shock crossings are identified as abrupt field magnitude changes by a factor of ~ 2 in Explorer 33 Ames magnetometer data at distances along the antisolar direction from Earth between 84 and 117 R_E during February 2 to May 15, 1969, including also one crossing on March 2, 1970. These distant bow shock crossings are at geocentric distances from 103.5 R_E out to the maximum of 138.6 R_E.

Experiment

The Ames magnetometer on Explorer 33 has been described by Sonett et al. [1968]. This experiment uses a triaxial fluxgate assembly with one sensor always oriented parallel to the spacecraft spin axis and the other two sensors in a plane perpendicular to the spin axis. Synchronous spin demodulators within the experiment remove the spacecraft spin modulation from the signals of the sensors in the plane perpendicular to the spin axis. Sensor offsets are measured about once per day by 90° rotation of two of the sensors.

Results

Observed locations of crossings of Earth's bow shock by Explorer 33 are indicated by solid circles on Figure 1 for three different ranges of distance, -X, downstream in the solar wind from Earth: 84 to 95, 95 to 105 and 110 to 117 R_E. The Figure shows projections in the geocentric solar ecliptic Y-Z plane. The dashed lines give the locations where magnetometer data is available from Explorer 33, for the indicated ranges of -X. Numerals indicate more than one bow shock crossing for a single symbol where the crossings occur too close together to use separate symbols. For each of the three ranges of downstream distance, an arrow with a line on either side gives an average shock orientation projected onto the Y-Z plane and its uncertainty. These average shock orientations are discussed further later.

Among the shock observations are two events which probably are actually abrupt increases in the ambient magnetic field magnitude associated with interplanetary disturbances that produced sudden commencements reported from ground magnetogram data on February 2 and March 19, 1969. The February 2 event is indicated by a cross on the left half of the top section of Figure 1. The March 19 sudden commencement is probably associated with one of the three northernmost Explorer 33 observations near Y=0 on the bottom section of Figure 1.

Four of the observations of distant bow shock crossings by Pioneer 8 at ~ 100 to ~ 170 R_E downstream [Bavassano et al, 1971] are also given on the bottom two sections of Figure 1. Two further observations of the distant bow shock by Pioneer 7 are also given on the bottom section of Figure 1. These Pioneer 7 observations are presented later in this report.* Open circles on the top two sections of Figure 1 give magnetopause crossings observed by Explorer 33.

Each section of Figure 1 also gives calculated locations for the distant bow shock shape [Dryer and Heckman, 1967] assuming a 4.3 deg observation and cylindrical symmetry. The calculated shock locations are given for the two limits of each range of antisolar distances.

Discussion

The Explorer 33 distant bow shock observations span wide ranges of transverse distance from an assumed aberrated axis of cylindrical symmetry. This result is summarized in Table 1, in which the units of

*The Pioneer 7 and 8 trajectories are not given explicitly on Figure 1 but are nearly perpendicular to the Y-Z plane as indicated by the series of Pioneer 8 shock observation locations that is given on that Figure.

Table 1.

EXPLORER 33 DISTANT BOW SHOCK OBSERVATIONS

DOWNSTREAM DISTANCE	RANGE OF TRANSVERSE DISTANCE, FROM AXIS	NUMBER OF OBSERVATIONS
-110—-117	53.6—84.5	39
-95—-105	57.1—85.8	51
-84—-95	61.6—79.9	45

distance are R_E. The most distant range from 110 to 117 R_E downstream includes times of disturbed solar wind and the bow shock is observed in this range at transverse locations that differ by more than 30 R_E of transverse distance from an aberrated symmetry axis. The 95 to 105 R_E downstream observations are found over a range of almost 30 R_E of transverse distance. The average K_p for these two groups of observations is the same, 3-. Part of the more distant observations (110 to 117 R_E) were made during the largest geomagnetic storm of 1969 as indicated by the K_p values. Of course, the spacecraft trajectory chiefly determined where these bow shock observations occurred.

The bow shock normals for which projections are given on Figure 1 are averages of 16 to 27 normals calculated from consecutive separate bow shock crossings using magnetic coplanarity [Colburn and Sonett, 1966]. Table 2 gives locations, time intervals, the numbers of vectors and the average K_p for four average shock normal calculations, along with the deviation of the average normal from the normal to the calculated bow shock shape [Dryer and Heckman, 1967]. The average normals are given in solar ecliptic coordinates. Observations from February 24, 1970 at ~ 60 R_E downstream are included with the other more distant observations for comparison. Holzer et al. [1972] have suggested that magnetic coplanarity should not be expected to be valid for typical observations of these shocks. The results presented here cannot supply firm evidence for or against the validity of magnetic coplanarity for the cases presented. However, one must note from Figure 1 that the projections of the average magnetic coplanarity shock normals on the solar ecliptic Y-Z plane agree within the statistical uncertainties with the corresponding normals to the calculated bow shock shapes also given on the Figure. On the other hand, the average inclination of these average magnetic coplanarity shock normals to the symmetry axis of the calculated bow shock is greater by $\sim 17 \pm 5$ deg than the inclinations of the calculated bow shock normals. An increase of the free stream Mach number from 3.8 to 8.5

Table 2. Explorer 33 Distant Bow Shock Normal Vectors

Downstream Distance, R_E	Solar Ecliptic Transverse Location, R_E Y	Z	Range of Transverse Distance, R_E
-112.4 - -115.4	-24.8 - -30.7	-72.7 - -73.6	80.0 - 83.3
-95.8 - -101.4	39.0 - 47.1	-69.0 - -70.3	77.0 - 79.7
-84.4 - -90.2	51.5 - 54.5	-62.6 - -66.1	79.0 - 79.9
-59.6 - -62.9	25.4 - 28.4	-52.7 - -54.8	57.9 - 58.6

Δt, hr	Number of Vectors	Average Normal X	Y	Z	Deviation of Normal, deg	Correl- ation	Av. K_p
54.1	16	0.0178	-0.0467	-0.9987	26±19	-0.90	3-
73.8	27	0.3062	0.1617	-0.9381	25±11	-0.18	2_o
38.0	21	0.5281	0.6434	-0.5542	22±9	-0.19	2+
13.6	18	0.7298	0.2217	-0.6467	24±8	-0.65	1+

(and of γ, the ratio of specific heats, from 1.2 to 1.67) increases the inclinations of the calculated bow shock normal by $\sim$ 6 deg for an aligned field condition and identical magnetopause shapes (M. Dryer, personal communication). Under the 8.5 Mach number conditions the distance to the shock surface from the symmetry axis is reduced by 6% at 100 R_E downstream.* A higher magnetoacoustic Mach number than 3.8 (sonic Mach number of 4.4), which is the published example of Dryer and Heckman [1967], should be more typical of the solar wind.

Table 2 also gives the correlation (pairwise) [Epp et al., 1971] of the set of individual magnetic coplanarity normal vectors used to calculate each of the four average shock normals. No correlation is indicated by this calculation.

In Table 3 the median and mean magnetic field magnitude ratios across the distant bow shock for the observations of Table 2 are given, as well as the median changes in field directions across the shock. There is a slight trend towards lower field magnitude jumps at greater distances based on the decrease in the median values. There is no trend with distances discernible in the field direction changes. Further studies of changes of magnetic field deflections and magnitude jumps across the distant bow shock as the downstream distance increases should be undertaken with samples for which changes in solar wind plasma and magnetic field parameters are excluded.

The Pioneer 8 distant bow shock observations were used in a test of consistency of magnetic field jumps and field direction changes across the shock with the Rankine-Hugoniot relations for confirmation that the events were shocks [Bavassano et al., 1971; 1973]. Since the observations given here form a clearly defined continuous set in location and type with the bow shock crossings observed by both Explorer 33 and other spacecraft closer to Earth, these tests have not been applied

*The magnetopause flares more than the shape used by Dryer and Heckman [Mihalov et al., 1970].

Table 3. Magnetic Field Magnitude and Direction Changes Across the Distant Bow Shock

Downstream Distance, R_e	B_2/B_1 median	B_2/B_1 mean	median $\cos^{-1}(\vec{B}_2 \cdot \vec{B}_1)$, deg
-112.4 - -115.4	1.70	1.75	11.5
- 95.8 - -101.4	1.87	1.86	10.7
- 84.4 - - 90.2	1.88	1.85	16.9
- 59.6 - - 62.9	1.90	1.84	8.5

here. This eliminates the need to guess the upstream sound and Alfvén velocities and sonic Mach numbers for these cases. Plasma parameters from the Explorer 33 plasma experiment are available on both sides of five of these shock observations. The Explorer 33 plasma experiment aperture is not directed toward the plasma flow for cases where plasma parameters are not available. When the Explorer 33 plasma parameters are available they further confirm these as bow shock observations, as discussed below in connection with the Pioneer 7 observations.

Pioneer 7 Observations

The Pioneer 7 bow shock observations plotted in Figure 1 are presented in Figure 2. Both plasma and magnetic field data are given. In the magnetic field data, bow shock crossings are noted as abrupt jumps in magnetic field magnitude at 1122 and 1353 UT (114.6 and 116.0 R_E downstream, respectively). At these times in the plasma data there are corresponding abrupt changes in the number density, but no corresponding large change in plasma bulk velocity is discernible. A jump in magnetic field magnitude at 1324 is preceded by a steady decline in magnetic field magnitude rather than a more steady level, and it is not known if this jump corresponds to a bow shock crossing. The dots and horizontal brackets on Figure 2 correspond to data obtained from two different instrument modes of the Pioneer 7 Ames plasma analyzer, the "maximum flux" and "full scan" modes. These modes and further description of the instrument and its operation are given in Wolfe and McKibbin [1968]. Note that a polar flow angle determination is not currently made from "maximum flux" mode data, other than to assign one of the three values, 0 or ±2.5 deg. The 0 deg dots were not entered on the Figure. Also the "maximum flux" mode azimuthal flow angle is estimated from the azimuthal angle of the peak flux. The azimuthal flow angle near and downstream from the distant shock characteristically fluctuates over at least a ±5 deg range on the ~1 min sampling time scale of these measurements.

Positive polar flow angles correspond to southward flow; positive azimuthal flow angles correspond to flow toward the same direction as the normal aberration due to Earth's heliocentric motion.

Conclusions

The 135 distant bow shock crossings observed by the Ames magnetometer on Explorer 33 agree with the locations calculated by Dryer and Heckman [1967]. The average observed normal vectors obtained using magnetic coplanarity are more inclined to the symmetry axis of the calculated bow shock by ~17±5 deg than the calculated bow shock normals, but the projections in the Y-Z plane of both the calculated and the average observed normal vectors agree within statistical uncertainty. An increased flow Mach number would increase the inclination to the symmetry axis of the calculated bow shock normals. At times of moderate geomagnetic disturbance the distant bow shock (95 to 105 R_E downstream) is observed over an ~30 R_E range of distance transverse to an assumed symmetry axis. Without restrictions of the interplanetary magnetic field orientation or the solar wind plasma conditions, the median ratio of the downstream to the upstream magnetic field magnitude decreases from 1.90 to 1.70 over the 60 to 115 R_E range of downstream distance.

Acknowledgments. Dr. C. P. Sonett, Principal Investigator for the Explorer 33 Ames magnetometer experiment, granted use of the data for this study. The National Space Science Data Center supplied the complete Explorer 33 plasma data and, in addition, 30 second average Pioneer 7 magnetometer data from launch to February 1967, on magnetic tapes. Mrs. S. C. Lathrop calculated the pairwise vector correlations.

References

Bavassano, B., F. Mariani, U. Villante, and N. F. Ness, Multiple crossings of the Earth's bow shock at large geocentric distances, J. Geophys. Res., 76, 5970, 1971; Corrections, J. Geophys. Res., 77, 2004 and 4902, 1972.

Bavassano, B., F. Mariani, and N. F. Ness, Pioneer 8 observations and interpretations of sixteen interplanetary shock waves observed in 1968, J. Geophys. Res., 78, 4535, 1973.

Colburn, D. S., and C. P. Sonett, Discontinuities in the solar wind, Sp. Sci. Rev., 5, 439, 1966.

Dryer, M., and G. R. Heckman, On the hypersonic analogue as applied to planetary interaction with the solar plasma, Planet. Space Sci., 15, 515, 1967.

Epp, R. J., J. W. Tukey, and G. S. Watson, Testing unit vectors for correlation, J. Geophys. Res., 76, 8480, 1971.

Mihalov, J. D., D. S. Colburn, and C. P. Sonett, Observations of magnetopause geometry and waves at the lunar distance, Planet. Space Sci., 18, 239, 1970.

Holzer, R. E., T. G. Northrop, J. V. Olson, and C. T. Russell, Study of waves in the Earth's bow shock, J. Geophys. Res., 77, 2264, 1972.

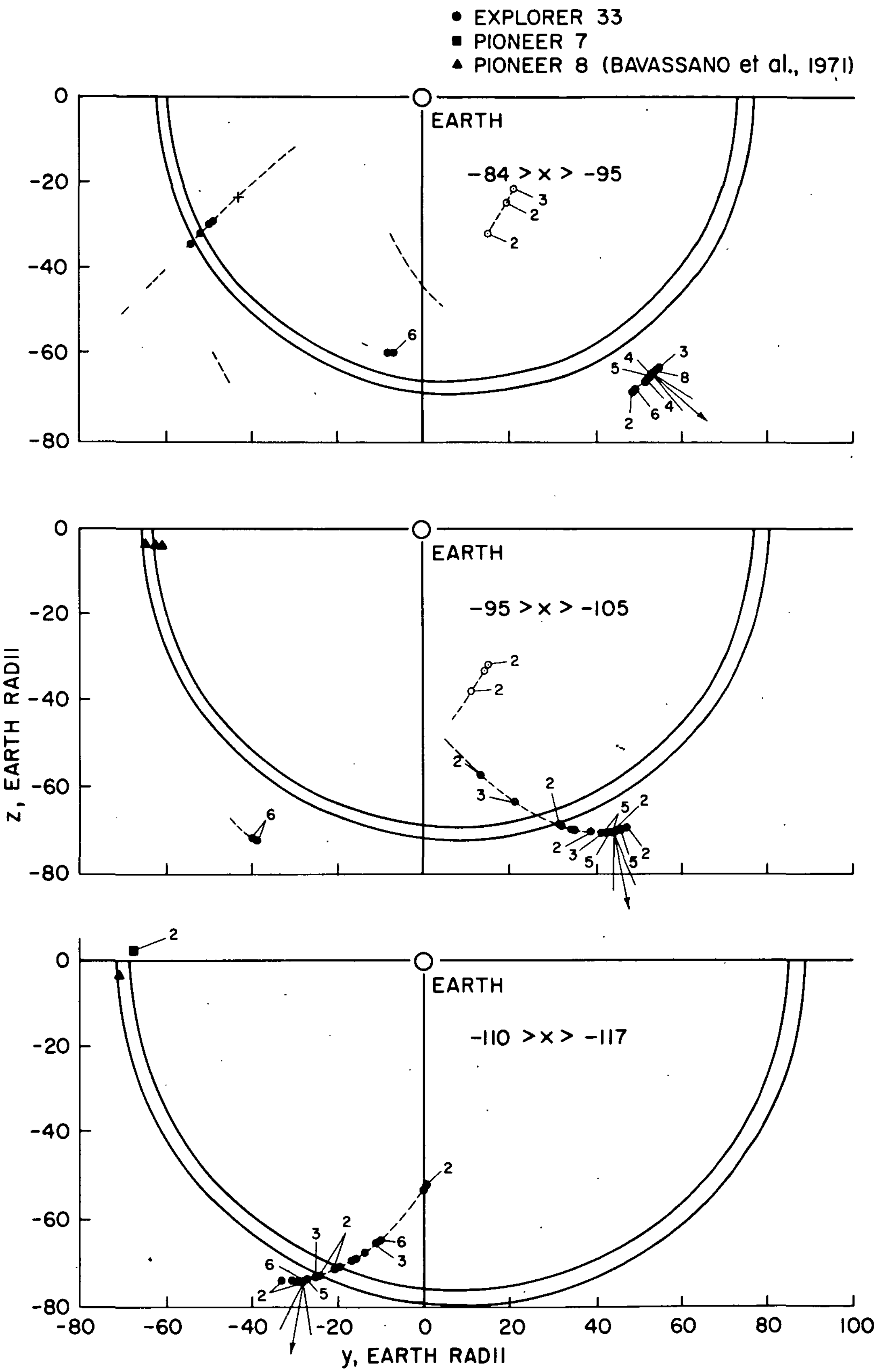
Sonett, C. P., D. S. Colburn, R. G. Currie, and J. D. Mihalov, The geomagnetic tail: Topology, reconnection and interaction with the moon, in Physics of the Magnetosphere, edited by R. L. Carovillano, J. F. McClay, and H. R. Radoski, p. 461, D. Reidel, Dordrecht, Netherlands, 1968.

Wolfe, J. H., and D. D. McKibbin, Pioneer 6 observations of a steady-state magnetosheath, Planet. Space Sci., 16, 953, 1968.

Figure Captions

Figure 1. Locations of distant bow shock (solid circles) and magnetopause (open circles) crossings observed by Explorer 33 at three different ranges of distance downstream from Earth, projected into the solar ecliptic Y-Z plane. Theoretical bow shock locations [Dryer and Heckman, 1967], assuming a 4.3 deg aberration, are given for the limits of each of the three ranges of downstream distance. The locations of four additional distant bow shock crossings observed by Pioneer 8, and two by Pioneer 7, are also given.

Figure 2. Two distant bow shock crossings observed by Pioneer 7 at the location given on Figure 1. Plasma parameter samples from the Ames plasma analyzer are given in the top five plots. Pioneer 7 magnetic field magnitudes in the bottom plot are thirty sec averages.



EXPLORER 33
PIONEER 7
PIONEER 8 (BAVASSANO et al., 1971)
EARTH
-84 > x > -95
-95 > x > -105
-110 > x > -117
z, EARTH RADII
y, EARTH RADII

Fig. 1

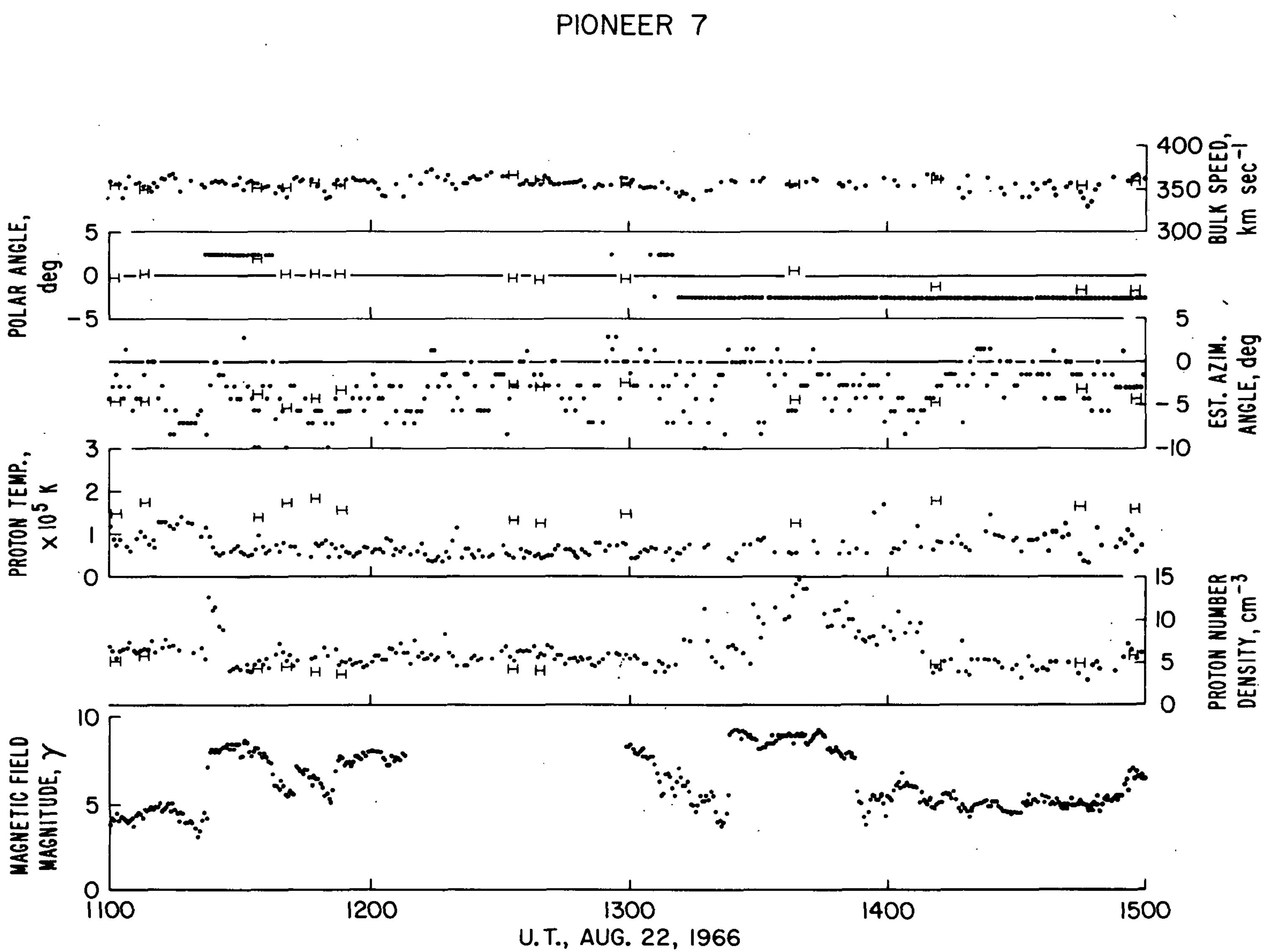

PIONEER 7
400
350
300
BULK SPEED, km sec^{-1}
POLAR ANGLE, deg
5
0
-5
EST. AZIM. ANGLE, deg
5
0
-5
-10
PROTON TEMP., $\times 10^5$ K
3
2
1
0
PROTON NUMBER DENSITY, cm^{-3}
15
10
5
0
MAGNETIC FIELD MAGNITUDE, γ
10
5
0
1100
1200
1300
1400
1500
U.T., AUG. 22, 1966

Fig. 2