NASA

Technical Memorandum 79637

First Results from the Six-Axis Electron Spectrometer on ISEE-1

K. W. Ogilvie and J. D. Scudder

(NASA-TM-79637) FIRST RESULTS FROM THE SIX-AXIS ELECTRON SPECTROMETER ON ISEE-1 (NASA) 27 p HC A03/MF A01 CSCL 04A

N78-32635

Unclas

G3/46 33094

September 1978

National Aeronautics and
Space Administration

Goddard Space Flight Center
Greenbelt, Maryland 20771

FIRST RESULTS FROM THE SIX-AXIS ELECTRON SPECTROMETER ON ISEE-1

by

K. W. Ogilvie
and
J. D. Scudder
NASA/Goddard Space Flight Center
Laboratory for Extraterrestrial Physics
Greenbelt, MD 20771

TO BE SUBMITTED TO: Space Science Reviews

ABSTRACT

A survey, using results from the first 25 orbits of ISEE-1, has been made of some aspects of electrons in the dawn magnetosheath. There are indications that the flow of plasma is not uniformly turbulent over this region. The electron heat flux is observed to be directed away from the shock and to have an average value of about twice the interplanetary heat flux. Many magnetopause crossings were observed and usually resemble abrupt transitions from one well-defined plasma state to another. The ejection of plasma from flux tubes convected up against the magnetopause is observed for about half the time, and its thickness and dependence on the solar wind mach number agrees with theoretical predictions. A full traversal of the whole forward hemisphere of the magnetosheath is required to fully confirm these deductions.

INTRODUCTION

In this paper the aim is to illustrate the capabilities and operation of this instrument and the data reduction system by conducting a preliminary partial survey of the magnetosheath using appropriate data obtained during the first 25 orbits of ISEE-1. This survey, which is confined to the region of the sheath between the subsolar point and the dawn meridian, will be concerned with observations of the electron distribution functions, and the flow of heat, and also the behavior of the plasma density in the region adjacent to the magnetopause. Examples of magnetopause crossings will be given, and the discussion of this data set indicates that the picture of a magnetosheath unstable to the mirror instability, with large amplitude slow-mode hydromagnetic waves, and bounded by a magnetopause whose surface carries wave-like disturbances is generally applicable. The reductions of density adjacent to the magnetopause are found to be consistent with the theory of Zwan and Wolf (1977), and result from the expulsion of plasma from flux tubes as these are convected up to the magnetopause. Such reductions occur in at least half of the traversals and seem to depend weakly if at all upon the angle between the interplanetary magnetic field and the solar wind flow direction.

THE INSTRUMENT

The instrument forms the subject of a separate paper (Ogilvie, Scudder and Doong, 1978); we therefore give only a very condensed description here. In order to determine the distribution function of electrons in three dimensions, it measures the electron spectrum along both senses of three perpendicular directions fixed in the coordinate system of the spacecraft. One such 6-axis measurement is taken for every sixty degrees of spacecraft rotation, which takes approximately one-half second. From the 36 spectra taken during each spin, the velocity distribution function is derived and its velocity moments obtained. This process is much simplified because simultaneous measurements are taken in each sense along each of the three axes. There are three energy ranges, 7.6 to 512 eV, 11 to 2062 eV, and 109 to 7285 eV, but only the first two were used in the present work. (The third energy range is designed to be used for the study of solar electron events.) An individual data point always has the same time resolution, and when the spacecraft is operating at high bit-rate (16 Kb/s) the telemetry system can transmit a complete measurement for every spin. At the low bit-rate (4 Kb/s for 80% of the time) the instrument obtains a measurement every fifth spin and is inoperative while this is being transmitted. Each of the six cylindrical electrostatic analyzers has two channeltron detectors, and the present measurements were made using both, in order to improve counting statistics at the higher energies. The angular field of view of each analyzer is 8.5 x 11 degrees, and sixteen energy steps are sampled with 5.5% FWHM energy resolution.

OBSERVATIONS

Figure 1 shows an example of a complete outbound traversal of the magnetosheath, on October 30, 1977, from the magnetopause at 0045 U.T. to the bow shock at 0250 U.T. In this plot we show the density and bulk speed, the azimuth and latitude angles describing the bulk speed direction, the temperature, temperature anisotropy, the heat flux (in the rest frame of the plasma) and two angles defining its direction. We use this figure to illustrate qualitatively some general features of the data. Average conditions ($n = 8\ cm^{-3}$, $U = 425$ km sec^{-1}, $T_e = 2.2 \times 10^{5}$ °K) were indicated in the solar wind, across the bow shock these parameters jump to ($n = 22\ cm^{-3}$, $U = 250$ km sec^{-1}, $T_e = 5.5. \times 10^{5}$ °K). The directional changes are of the correct magnitude and in the correct direction to agree with the aerodynamic model of the magnetosheath flow. The heat flow is towards the sun outside the bow shock, and towards the earth inside the magnetosheath. Upstream heat flows have been previously described by the Los Alamos and GSFC groups (Feldman et al., 1973; Scudder et al., 1973), and are seen as a matter of course when measurements are made at a point connected to the bow shock by the interplanetary magnetic field. The flux of heat in the magnetosheath, larger in magnitude than that in the interplanetary medium, seems not to have been previously evaluated and discussed.

A feature commonly seen in the present magnetosheath traversals is the presence of a region or regions of space where the flow is less turbulent than the flow in the magnetosheath as a whole. In the present example one such region may be seen from about 0207 U.T. to about 0244 U.T. The temperature and flow directions are seen to be more constant and the heat flux both larger and more constant there than elsewhere along the trajectory. These regions of less turbulent flow are usually seen in the mid-magnetosheath between the disturbed region immediately downstream of the bow shock, and the region of slow-mode waves adjacent to the magnetopause. Another region of low turbulence, observed when the spacecraft was in the high bit-rate mode, is shown in Figure 2. A change in the magnetic field and heat flux directions occurred at 0317 U.T. and the plasma became less turbulent, remaining so until 0335 U.T., and during this interval both the density and heat flux decreased. The form of the distribution function changed during these intervals corresponding to the change in density and heat flux as shown in Figure 3; the heat is carried by electrons with energies above 50 eV. The magnetosheath heat flux magnitude, which normally lies between 5×10^{-3} and 5×10^{-2} ergs/cm^2/sec, and has a mean value for the present observations of 1.7×10^{-2} ergs/cm^2/sec, is considerably larger than the interplanetary heat flux of $\sim 8 \times 10^{-3}$ ergs/cm^2/sec (Feldman et al., 1975). Striking a particle energy balance across the bow shock requires extensive detailed simultaneous measurements of solar wind and upstreaming ions and electrons, and of protons and electrons in the magnetosheath, and this cannot be carried out here. However, inserting average values into the equation

$$\left[\text{K.E. flux} + \text{Enthalpy flux} + Q_p + Q_e \right] = 0.$$

indicates that approximate balance can be obtained to $\sim 20\%$ accuracy, assuming that Q_e dominates over Q_p in the sheath as it does in the solar wind.

The electron temperature anisotropy usually changes from less than unity to greater than unity when the magnetopause is crossed, Figure 1, and a density reduction, present in 25 of the 48 traversals examined to date, is clearly seen as the magnetopause is approached. At the magnetopause crossing, in this example situated 37.5 degrees from the subsolar point in the ecliptic plane and 25 degrees above it, the flow direction changes, and the flow speed U, calculated from the relation

$$U = \frac{\int f_e(\bar{v})\ \bar{v}\ v^2 d\omega\ dv}{\int f_e(\bar{v})\ v^2\ d\omega\ dv} \tag{1}$$

apparently increases. These changes are in qualitative agreement with the presence of a boundary flow. However apparent flow speeds of order hundreds of km sec^{-1} are often calculated deep inside the magnetosphere, where they persist for distances of many earth radii. Furthermore their apparent direction is approximately perpendicular to that of the magnetic field, leading one to suspect that here Equation (1) does not predict the true bulk speed of the plasma. If one makes a scatter plot of U from Equation (1) against $(T/n)^{1/2}$, which is proportional to the radius of the Debye sphere, approximate proportionality is found. Figure 4 shows this result, and also that the apparent speed U decreases for increasing density in a constant temperature plasma. Montgomery et al. (1973) have discussed low energy electron measurements with Vela spacecraft, noting the spacecraft potential was inversely related to the incident electron flux and that there was an asymmetry in the photo-electron flux while in the dilute plasma sheet. The ISEE spacecraft were constructed in such a way as to make their surfaces approximate equipotentials, but the resistivity of, for example, the InO coating on the solar panels, is sufficiently high to allow the presence of a potential difference of 1-2 volts between the sunlit and shadow sides. Such a potential difference, increasing in magnitude with that of the spacecraft potential, could account for these apparent anti-solar bulk flows. We thus consider that the apparent bulk speeds calculated inside the magnetosphere using Equation (1) are probably not physical, at least near the sub-solar point. At large angles to the sub-solar point, where there is a strongly anti-solar flow in the boundary layer, care must be taken with the interpretation as asymmetry due to such flows adds vectorially to asymmetry due to any effect of the spacecraft potential. As may be seen in Figure 4 the calculated values of U tend towards a number greater than zero for low temperatures and high densities. At large angles to the sub-solar point, the significance to be attributed to an individual value depends upon conditions at the time of measurement, and they will often represent real flows in the boundary layer and plasma mantle. In the solar wind and magnetosheath we see from Figure 4 that the effect we describe will be less than $\sim$ 25 km sec^{-1}, and our values of U may be freely interpreted as the plasma bulk speed to at least that accuracy. Direct checks with results from other experiments show agreement to an accuracy of a few km sec^{-1}.

In Figure 5 we see four further sets of magnetopause crossing observations; the magnetosheath is characterized by densities of 10-30 and temperatures of 3-4 x 10^{5} °K and is on the right in the figure. The outer magnetosphere typically has much higher temperatures and lower densities; $kT_{e/n}$ changes from $\sim$ 2 to $\sim$ 200 in crossing the magnetopause. The upper two crossings show density reductions adjacent to the boundary, and significant wave activity (Crooker, Eastman and Fairfield, 1977; Crooker and Siscoe, 1977). Between 1005 and 1020 U.T. on November 1 (third and fourth panels) we can see quasi-sinusoidal oscillations with n and T in phase (but out of phase with B). Multiple magnetopause transitions are very common, and these frequently have, in the electron data, the appearance of transitions between two definite stable states. This is consistent with the motion of a surface carrying waves whose amplitude is large compared to its thickness as suggested for the magnetosphere by (Aubry et al., 1971).

DISCUSSION

A prominent feature of the magnetosheath is the density reduction which occurs adjacent to the magnetopause on about half of the traversals. This effect has been studied by Cummings and Coleman (1968) and Freeman (1968), and modeled by Zwan and Wolf (1976). Observations by the plasma analyzer and magnetometer on IMP-6, analyzed by Crooker, Eastman and Fairfield (1977), exhibited such a density decrease in eleven of the seventeen crossings studied. It is of interest because it is a hydromagnetic effect (models without a magnetic field predict a density maximum at the magnetopause), and because the process is inconsistent with the occurrence of large-scale magnetic merging. Crooker and Siscoe (1977) have pointed out that this effect is a likely cause for a pressure anisotropy, in the sense of $P_{\parallel} < P_{\perp}$, in the dayside magnetosheath. The magnetosheath crossing shown in Figure 1 is a typical sample from the present measurements, and it can be seen that the electron temperature anisotropy A (= $T_{\parallel}/T_{\perp}$) usually lies between 0.8 and 1.2. During the quiet periods it is characteristically less than unity, and in the region of waves adjacent to the magnetopause it is usually greater than unity. In the magnetosheath, the ions make a somewhat greater contribution to the pressure than do the electrons, so there is no contradiction in the present observations to the picture of Crooker and Siscoe (1977) of an inner magnetosheath, unstable to the mirror instability over a large portion of the dawn sector.

Density reductions were observed adjacent to the magnetopause in 25 out of 48 magnetosheath traversals and we can compare their magnitude with the model of Zwan and Wolf (1976). Table I shows parameters for 15 cases for which sufficient information has been obtained to make an approximate quantitative test of the relation between D, the effective thickness of the layer of reduced density and the Alfvén mach number of the solar wind. This relation predicts that the higher the mach number characterizing the solar wind flow, the thinner the layer of reduced density will be. D is defined as the distance from the magnetopause to the point where the density is half of the eventual value. The mach number is that obtained from the observations made in the solar wind a short distance upstream of the bow shock. Since the magnetopause is in motion, and all the necessary quantities change with time, we cannot expect to achieve a highly precise test, but approximate agreement and the correct slope of the dependence will increase our confidence in the correctness of the physical mechanism suggested to explain the effect. Figure 6 displays the data from Table I, together with the prediction of Zwan and Wolf. The theoretical curves marked σ = 1.00 and σ = 1.25 show the predicted effect of magnetic tension. The value σ = 1.00 represents the case in which the magnetic field line approximates a great circle on the magnetopause and the tension has no effect in accelerating the flux tube along the boundary, σ = 1.25 represents the case where there is a component along the boundary. There is considerable scatter among the points in Figure 6, and this is comparable to the distance between the two theoretical curves, but both the order of magnitude of D and the slope of its variation with the mach number are in agreement with the theory. Since as a result of the average direction of the interplanetary magnetic field, the dawnside shock tends to be parallel and therefore more often unstable or pulsating than the shock on the duskside, data from the dusk magnetosheath may improve the precision of this work when it becomes available, since the same phenomenon should occur on each side of the noon meridian.

Figure 7 shows an example of a magnetopause crossing not showing a density reduction. The crossing takes place abruptly, although there is an indication of wave motion in the three-minute period immediately before the crossing. Examples can be found where there are multiple crossings of the magnetopause during a magnetosheath passage and some of these exhibit density reductions, while the others do not.

CONCLUSIONS

As a result of this preliminary survey of electron data obtained in the dawn magnetosheath it is hardly appropriate to draw other than tentative conclusions, with the understanding that they must be confirmed by future work. When that is understood, one can put down some features of these observations which appear to be correct and also to be relevant to understanding of the magnetosheath and magnetopause.

1). The flow is not uniformly turbulent all over the magnetosheath, regions of quiet flow often occurring sandwiched between turbulence associated with the two boundaries, the bow shock and the magnetopause.

2). The average electron heat flux in the magnetosheath is about twice that in the solar wind and is directed away from the bow shock.

3). Magnetopause crossings observed by the behavior of the low energy electrons often have the appearance of rather sharp transitions between two definite states. Although this is not always observed, it indicates that the magnetopause is often a thin boundary in motion or carrying large amplitude surface waves.

4). The density reduction, predicted as a result of plasma flowing out of flux tubes as they are convected up against the magnetopause, is observed to occur for about 50% of magnetosheath traversals. The width of this depletion layer, and its variation with solar wind mach number, are approximately as predicted by theory. Large amplitude waves are observed in the depletion layer. None of these features of the data necessarily occur in a given crossing, but all are frequently observed. Since it takes approximately four hours for the spacecraft to cross the magnetosheath it is not to be expected that Figure 1, for example, represents anything like a time-stationary situation. The present observations do, however, provide support for the theoretical models of Zwan and Wolf (1975) and Crooker and Siscoe (1977). Since the presence of a depletion layer is inconsistent with large scale reconnection, these observations favor the idea of the predominance of locally confined merging processes, as suggested by Haerendel <u>et al</u>. (1978).

ACKNOWLEDGMENTS

The authors wish to thank Dr. C. T. Russell for his cooperation in supplying magnetic field data in advance of publication. There are many others to whom we are indebted for assistance, principal among them being Mr. H. Doong and Mr. F. Ottens of GSFC for their work on the instrument and data analysis programs respectively.

REFERENCES

Aubry, M. P., M. G. Kinelson and C. T. Russell, "Motion and Structure of the Magnetopause", J. Geophys. Res., 76, 1673, 1971.

Crooker, N. U. and G. L. Siscoe, "A mechanism for Pressure Anisotropy and Mirror Instability in the Dayside Magnetosheath", J. Geophys. Res. 82, 185, 1977.

Crooker, N., T. Eastman, and D. Fairfield, "Observations of Plasma Depletion in the Magnetosheath at the Dayside Magnetopause", Preprint 1977.

Cummins, W. D. and P. J. Coleman, "Magnetic Fields in the Magnetopause and Vicinity at Synchronous Orbit", J. Geophys. Res., 73, 5699, 1968.

Fairfield, D. H., "Structure of the Magnetopause: Observations and Implications for Reconnection", Space Sci. Rev., to be published.

Feldman, W. C., J. R. Asbridge, S. J. Bame and M. D. Montgomery, "Solar Wind Heat Transport in the Vicinity of the Earth's Bow Shock", J. Geophys. Res., 78, 3697, 1973.

Feldman, W. C., J. R. Asbridge, S. J. Bame, M. D. Montgomery, and S. P. Gary, "Solar Wind Electrons", J. Geophys. Res., 80, 4181, 1975.

Freeman, Jr., J. W., C. S. Warren and J. J. McGuire, "Plasma Flow Directions at the Magnetopause on January 13 and 14, 1967", J. Geophys. Res., 73, 5719, 1968.

Haerendel, G., G. Paschmann, N. Sckopke, H. Rosenbauer, and P. C. Hedgecock, "The Front Side Boundary Layer of the Magnetosphere and the Problem of Reconnection", J. Geophys. Res., 83, 3195, 1978.

Montgomery, M. D., J. R. Asbridge, S. J. Bame and E. W. Hones, "Low Energy Electron Measurements and Spacecraft Potential, Vela 5 and Vela 6", Proton and Particle Interactions with Surfaces in Space, 247, R. J. L. Grard (ed)., D. Reidel, 1973.

Ogilvie, K. W., J. D. Scudder, and H. Doong, "The Electron Spectrometer Experiment on ISEE-1", Geoscience Electronics, July 1978.

Paschmann, G. Haerendel, W. Sckopke and H. Rosenbauer, "Plasma and Magnetic Field Characteristics of the Distant Polar Cusp near Local Noon: The Entry Layer", J. Geophys. Res., 81, 2883, 1976.

Scudder, J. D., D. L. Lind, and K. W. Ogilvie, "Electron Observations in the Solar Wind and Magnetosheath", J. Geophys. Res., 78, 6535, 1973.

Zwar, B. T. and R. A. Wolf, "Depletion of Solar Wind Plasma near a Planetary Boundary", J. Geophys. Res., 81, 1636, 1976.

TABLE I

DD	HR	$Z^2 + Y^2$	B_T	B_Z	M_A	D	$\cos^{-1} X/_R$
302	0047	10.00	9.4	+2.1	6.0	1800	62.5
304	0949	10.35	5.6	0.9	9.6	1920	65.7
306	0804	5.94	3.0	-0.5	15.0	742	26.2
308	1716	5.44	8.3	3.2	5.4	1700	26.3
313	2239	11.08	8.6	4.2	6.3	400	73.6
315	2300	4.13	10.0	-	8.5	650	26.0
316	0825	10.55	6.5	-	7.5	1890	77.6
320	1524	6.99	5.5	-	12	970	34
327	1947	8.15	5.3	-2.0	8.4	1440	40.0
332	1509	6.42	2.5	-2.0	19	340	34.5
337	0820	9.29	4.5	-	13.5	580	47.8
338	0123	15.9	7.5	-	7.9	700	88
339	1844	8.94	5.0	0.5	9.8	850	50
349	0645	12.00	7.5	-	6.0	1400	60
351	1639	11.44	5.5	6.0	8.0	1360	61

FIGURE CAPTIONS

Figure 1 A complete traversal of the magnetosheath on October 30, 1977, showing the variation of density, bulk speed, bulk speed azimuth and elevation angles, temperature and temperature anisotropy, and the heat flux and its azimuth and elevation angles. Note the especially stable period between 0200 and 0244 UT.

Figure 2 A period of low turbulence observed on December 9, 1977, between 0317 and 0335 UT.

Figure 3 Distribution functions observed during the period shown in Figure 2, along and perpendicular to the average magnetic field direction.

Figure 4 A plot of the value of U, see text, versus 0.15 $(T^{\frac{1}{2}}/_n)$, dots; also the value of U vs. density for $T = 3 \times 10^{6\,o}K$ shown as circled points.

Figure 5 Four examples of observations of crossings of the magnetopause. The magnetosphere is on the left in the diagram.

Figure 6 Measured values of D, the thickness of the depletion layer adjacent to the magnetopause, plotted against the solar wind Alfvén mach number determined at the nearest shock crossing.

Figure 7 A magnetopause crossing which did not show a depletion layer.

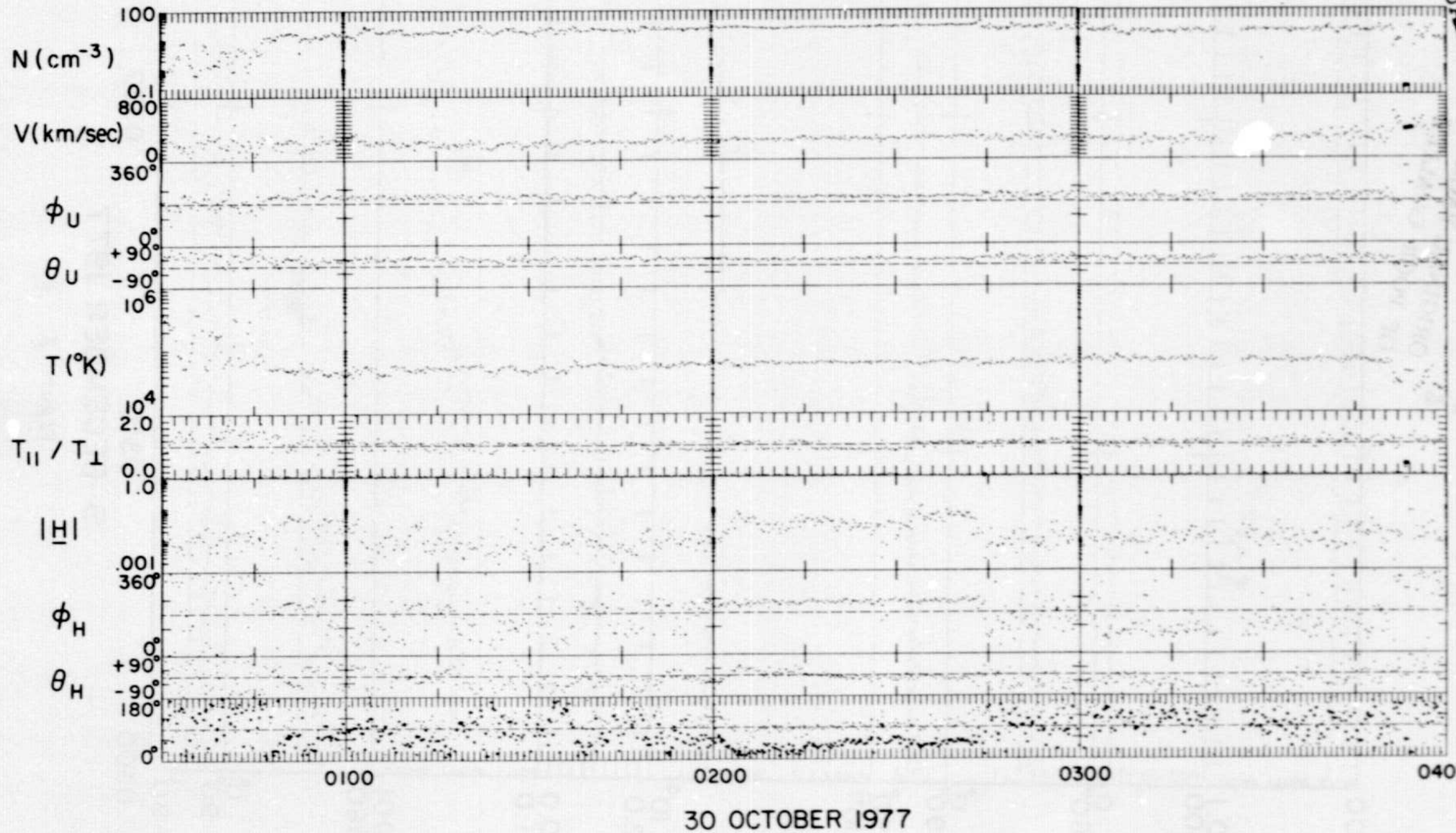

100
N (cm⁻³)
0.1
800
V(km/sec)
0
360°
ϕ_U
0°
+90°
θ_U
-90°
10^6
T(°K)
10^4
2.0
$T_{II} / T_{\perp}$
0.0
1.0
|H|
.001
360°
ϕ_H
0°
+90°
θ_H
-90°
180°
0°
0100
0200
0300
0400
30 OCTOBER 1977

Figure 1

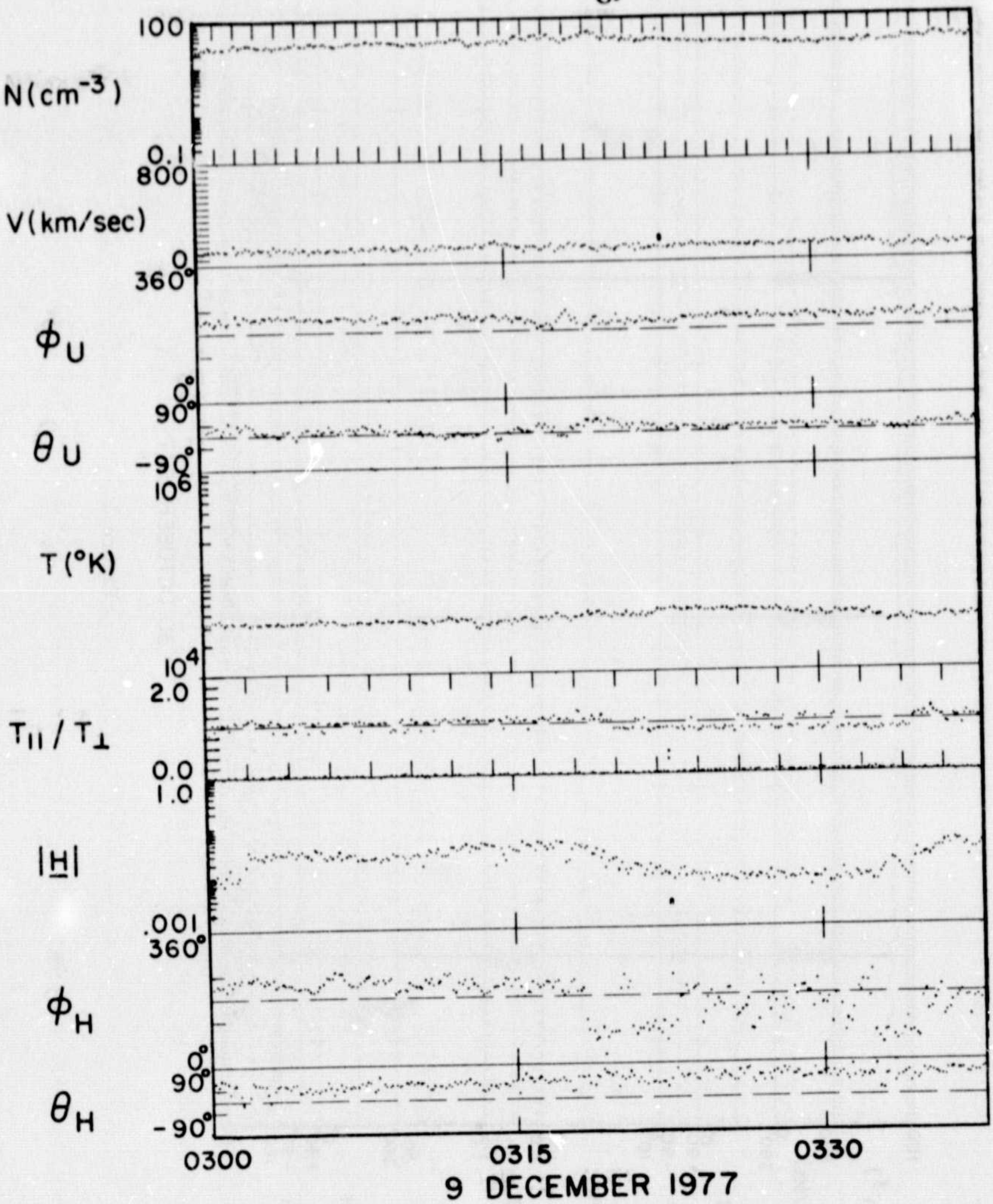
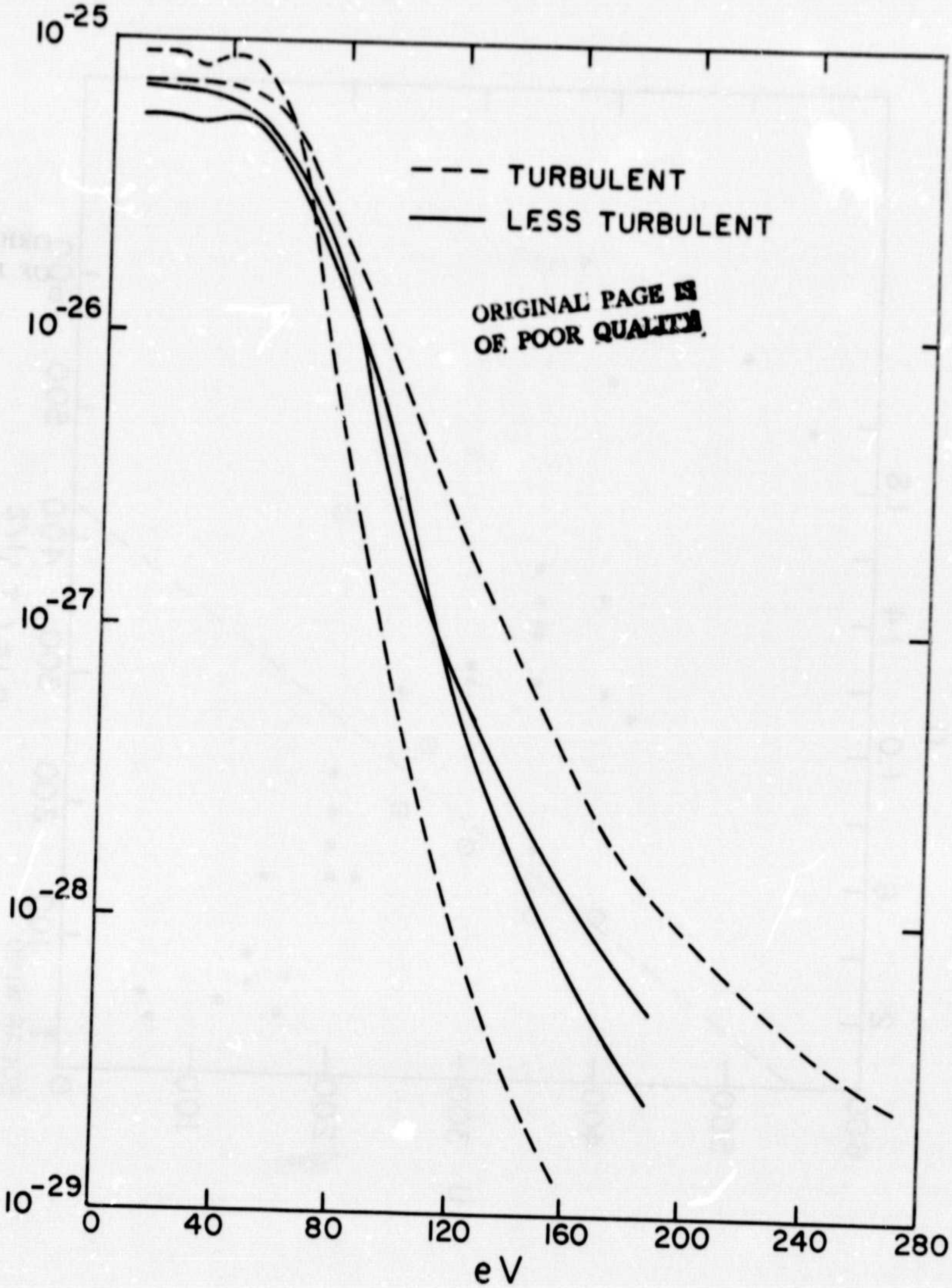

100
N(cm⁻³)
0.1
800
V(km/sec)
0
360°
φU
0°
90°
θU
-90°
10⁶
T(°K)
10⁴
2.0
T∥ / T⊥
0.0
1.0
|H|
.001
360°
φH
0°
90°
θH
-90°
0300
0315
0330
9 DECEMBER 1977

Figure 2



10^{-25}
TURBULENT
LESS TURBULENT
ORIGINAL PAGE IS
OF POOR QUALITY
10^{-26}
f
10^{-27}
10^{-28}
10^{-29}
0
40
80
120
160
200
240
280
eV

Figure 3

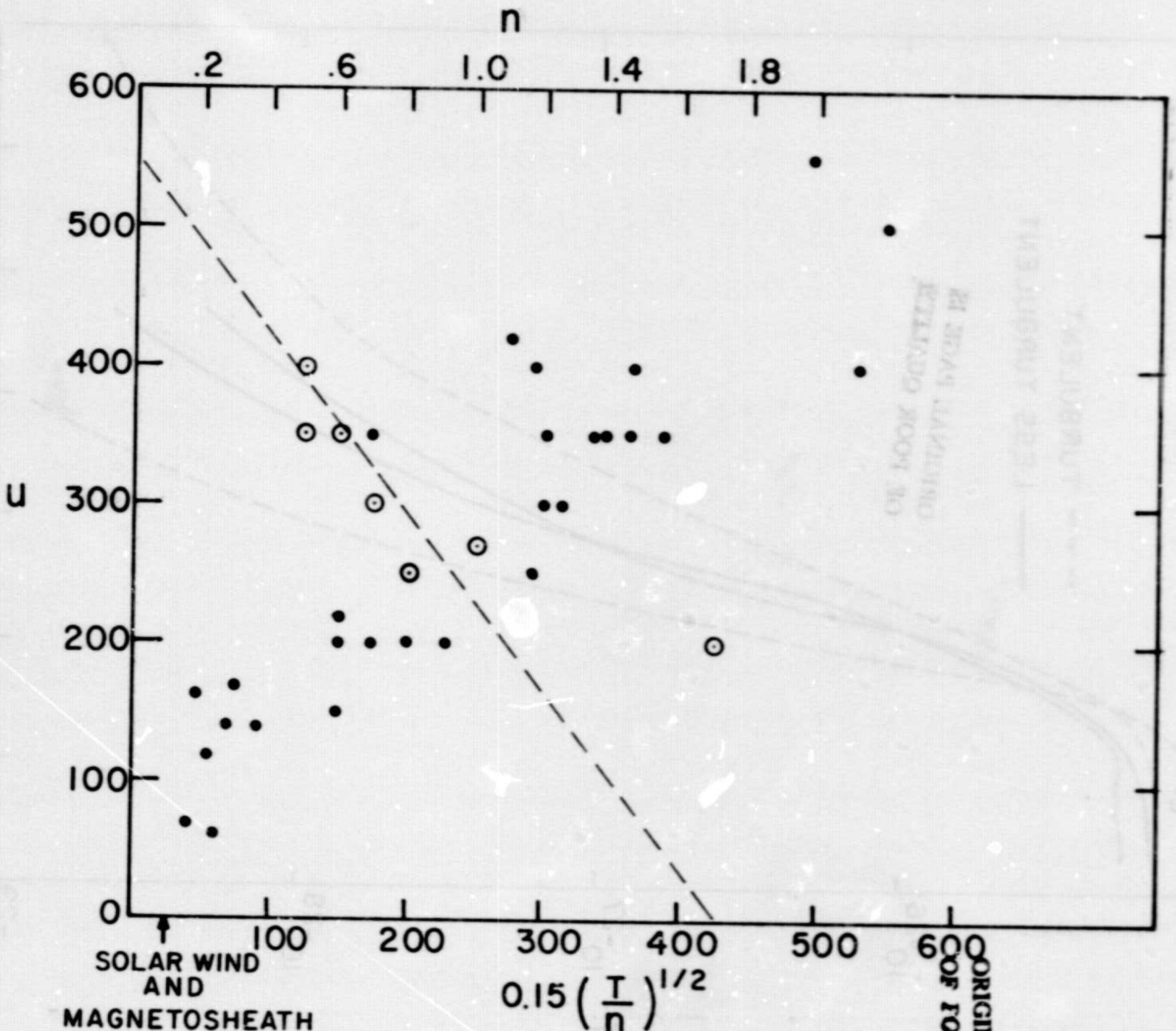

n
.2
.6
1.0
1.4
1.8
600
500
400
u
300
200
100
0
100
200
300
400
500
600
SOLAR WIND
AND
MAGNETOSHEATH
0.15 (T/n)^1/2

Figure 4

ORIGINAL PAGE IS
OF POOR QUALITY

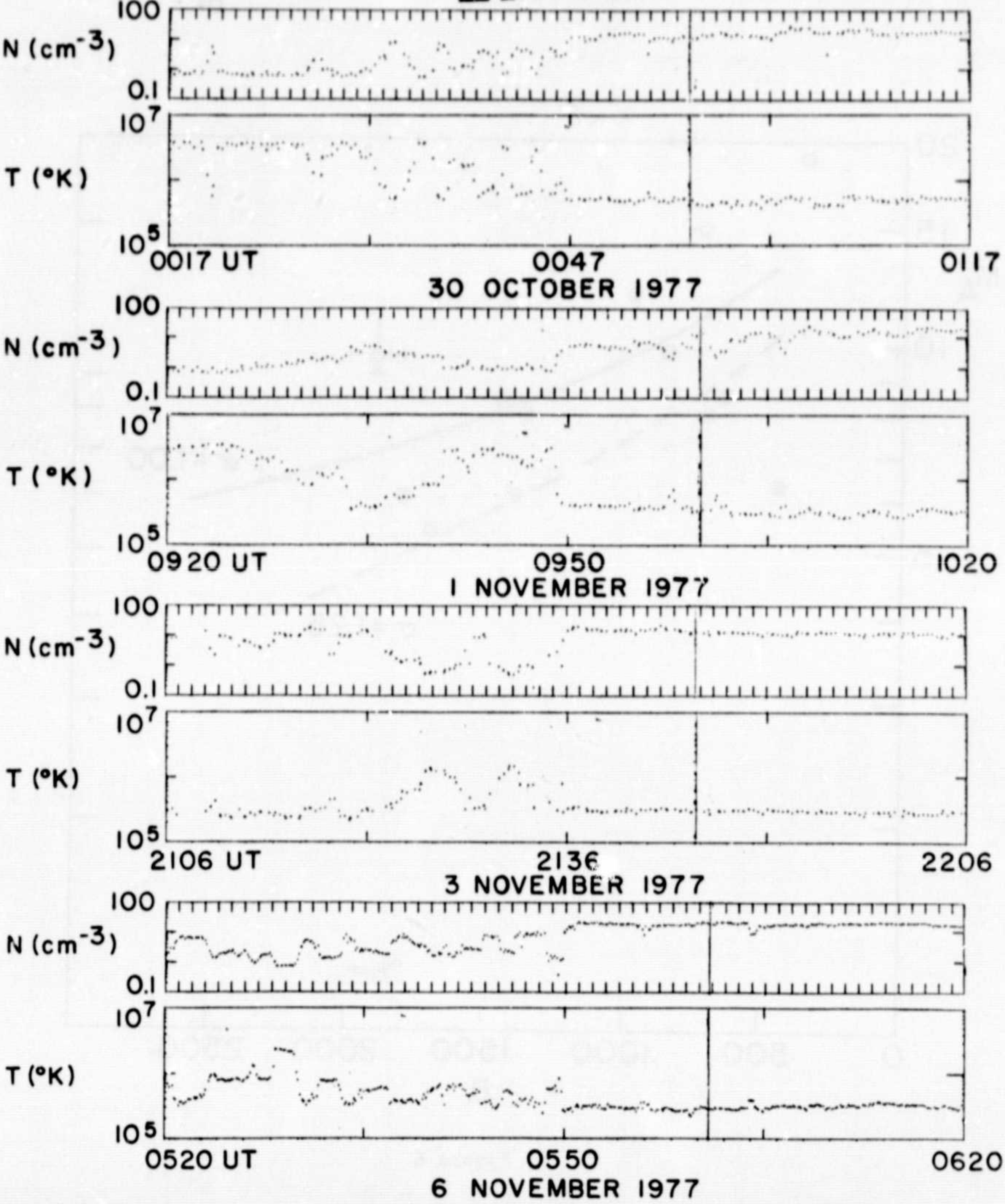


Figure 5

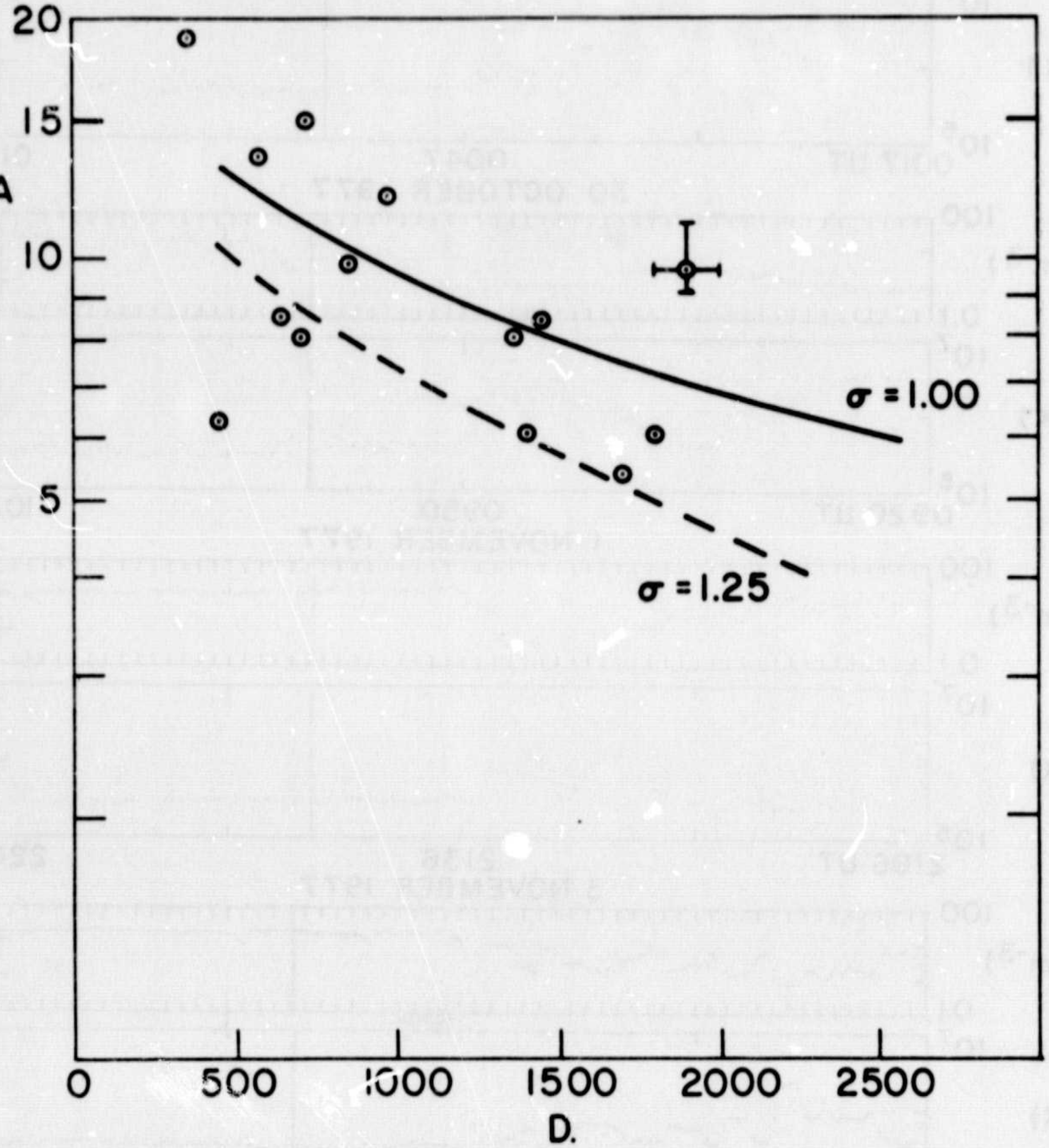


Figure 6

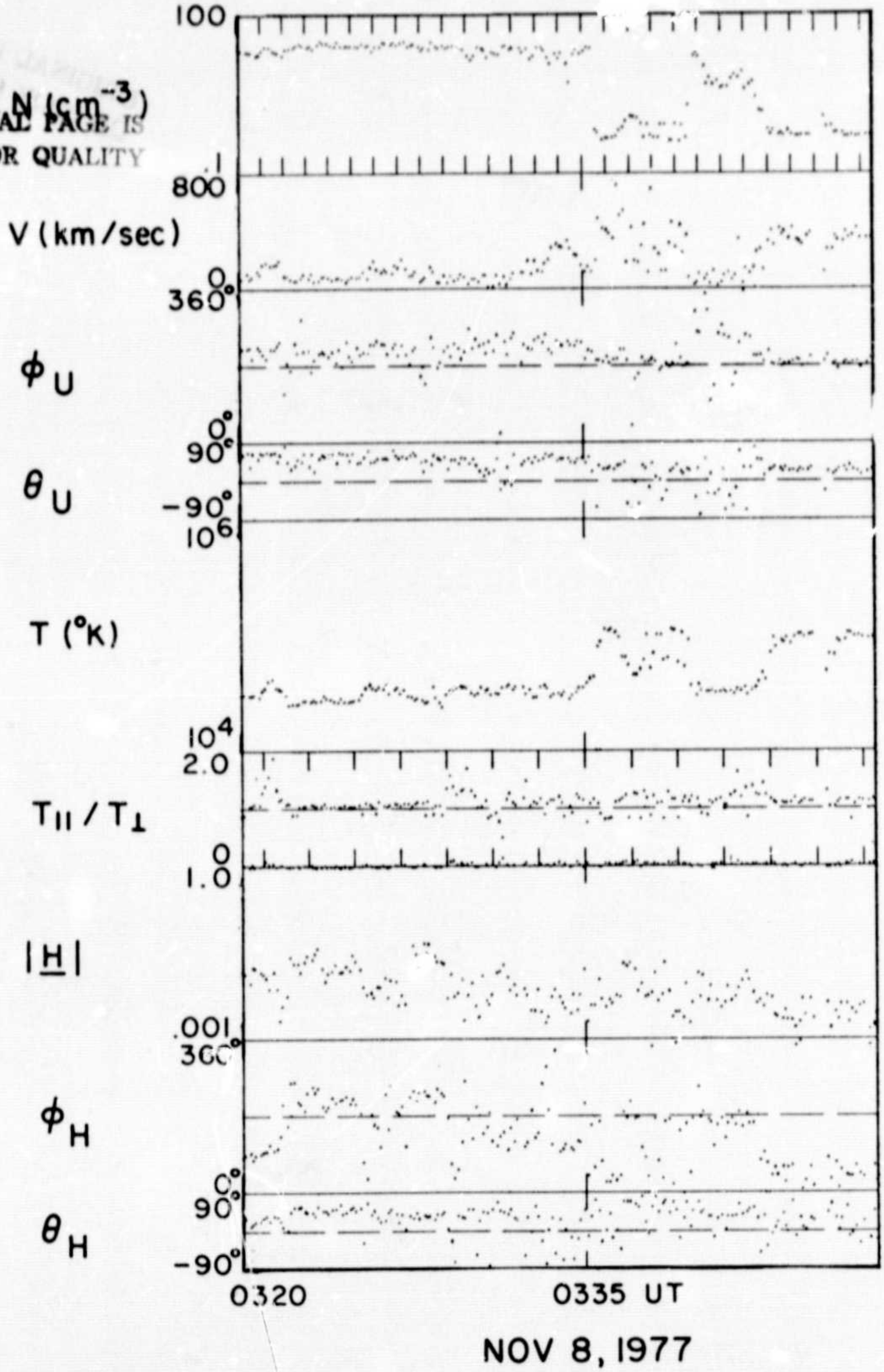

N (cm⁻³)
100
1
V (km/sec)
800
0
ϕ_U
360°
0°
θ_U
90°
-90°
T (°K)
10⁶
10⁴
T∥ / T⊥
2.0
0
|H|
1.0
.001
ϕ_H
360°
0°
θ_H
90°
-90°
0320
0335 UT
NOV 8, 1977

Figure 7