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PIONEER SOLAR PLASMA AND MAGNETIC FIELD MEASUREMENTS IN INTERPLANETARY SPACE DURING AUGUST 2–17, 1972

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Pioneer
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by

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ABSTRACT

Solar wind plasma and magnetic field measurements from Pioneers 9 and 10 during August 2 - 17, 1972, reveal complex and large-amplitude variations on a one-hour time scale and numerous discontinuities. During this time period an approximate radial alignment of the two spacecraft as seen from the Sun occurred with heliocentric distances of 0.8 AU for Pioneer 9 and 2.2 AU for Pioneer 10, both at 45 deg east of the Earth's solar longitude. The peak hourly average solar wind proton bulk velocity measured at Pioneer 9 was 990 km sec^{-1} during hour 0 UT of August 5. The peak hourly average proton number density was 62 cm^{-3} during hour 11 UT of August 3. The peak solar wind speeds are generally much reduced at Pioneer 10 compared with those observed at Pioneer 9. The peak 30 minute average magnetic field magnitude was 85 gamma during 1245 - 1315 UT of August 3. The Pioneer 9 data indicate passage of four fast forward interplanetary shocks, and one slow forward interplanetary shock.

Introduction

An unusual period of solar flare activity in early August, 1972, occurred at McMath Plage Region 11976. During August 2 to 10, two 3B and three 2B flares were reported (Solar-Geophysical Data, 1973). Intense and varied geophysical activity (cf. McKinnon, 1972) and high cosmic ray fluxes (cf. Pomerantz and Duggal, 1973) were observed at the Earth. Various spacecraft observations which also show unusually large fluxes of energetic solar particles and high-speed solar wind streams have also been given at the December 1972 and April 1973 American Geophysical Union meetings. This report presents interplanetary plasma data from the Ames Research Center solar wind plasma experiments on the Pioneer 9 and 10 interplanetary spacecraft, as well as interplanetary magnetic field data from the Ames Research Center magnetometer on Pioneer 9. The solar flares which probably were the source of the principal features in the plasma and magnetometer records are listed in Table 1. Note that the two spacecraft were near 45 deg east of the Earth's solar longitude during this time period.

TABLE 1. Large Solar Flares during Early August 1972 (*Solar-Geophysical Data*, 1973)

Day, August 1972	Time, UT (onset)	Class	Approx. Lat.	Approx. Long.
2	0505	2B	13N	35E
2	1958	2B	14N	28E
4	0617	3B	14N	8E
7	1449	3B	14N	37W

Experiment Details

The Pioneer 9 Ames solar wind plasma experiment utilizes 120 deg electrostatic deflection for energy per unit charge analysis, with three current collectors connected to electrometer amplifiers. Proton measurements are made at 30 logarithmically spaced intervals ranging from 210 to 15000 eV, for a proton energy/plate voltage difference ratio of 6. Similarly electron measurements are made at 14 logarithmically spaced intervals ranging from 13 to 1000 eV. The mean radius of the nearly hemispherical analyzer plates is 6 cm and their separation is 1/2 cm. The solar wind azimuthal flow direction measurements are performed by sampling $2\frac{13}{16}$ deg wide sectors of the spacecraft rotation. The spacecraft spin axis is perpendicular to the ecliptic plane. The polar flow direction measurements give the flow vector component approximately normal to the ecliptic plane, using the relative currents in the three collectors. The solar wind proton parameters presented here are obtained by a least-squares fit of the flight data to a convecting Maxwellian velocity distribution model with an isotropic temperature, using an instrument model derived from laboratory calibration data. This procedure is analogous to that used for the early Pioneer 6 and 7 Ames plasma probe data (Mihalov and Wolfe, 1971), although linear rather than non-linear least squares fits are done currently. The uncertainties in the plasma parameters for Pioneer 9 have not yet been completely evaluated but for similar instrument modes and solar plasma conditions they will be much smaller than those given by Mihalov and Wolfe (1971) for the Pioneer 6 and 7 data because the later instrument has significantly improved energy and angular resolution. The Pioneer 9 plasma experiment is almost identical to that on Pioneer 8 which has been described by Intriligator et al. (1969), and both experiments are similar in many respects to the Pioneer 6 and 7 plasma probes described by Wolfe and McKibbin (1968).

The Pioneer 9 Ames magnetometer is a triaxial fluxgate instrument with on board signal processing to preclude contamination of the measurement by vector aliasing (Sonett, 1966). Analog signals from the three sensors are prefiltered and then sampled at a high rate (27 sec^{-1}) relative to the 1 Hz spin frequency. Digital spin demodulation is performed on the spin plane components by mathematical transformation to a non-rotating coordinate system using the sun angle to obtain a high data rate representation of the field as would be measured by a non-spinning spacecraft. Digital filtering is then employed on each component to observe the Nyquist criterion prior to telemetry sampling. The filter constants are automatically adjusted to match any of 5 commandable telemetry bit rates. During the time of the magnetometer data presented here, the field sampling interval was 19 sec, except for $\sim$8 hr on August 6-7 when it was 2.3 sec. The digitization window is 0.4 gamma (one gamma = 10^{-5} G) in each component.

The Pioneer 10 Ames plasma experiment is similar in many respects to the Pioneer 6 and 7 experiments described by Wolfe and McKibbin (1968). Two independent sets of quadrispherical 90 deg electrostatic deflection plates are used in the Pioneer 10 experiment for energy analysis, but data from the higher resolution set which uses 26 Bendix continuous channel multipliers as detectors are not given in this report. The Pioneer 10 plasma analyzer views along the spacecraft spin axis which is directed toward Earth. The lower resolution assembly deflects incoming particles into five current collectors connected to electrometer amplifiers. The deflection plates have a mean radius of 12 cm and a 1 cm separation. The five current collectors provide a total angular acceptance of ± 70 deg from the normal to the instrument aperture. The central three collectors each have a 15 deg wide angular acceptance. The energy analysis for protons may be done at four different sets of energy intervals, the maximum number being 64 logarithmically spaced intervals ranging from 100 to 18000 eV for a proton energy/plate voltage difference ratio of 6. Similarly electrons are measured at 15 logarithmically spaced intervals that range from 2.1 to 500 eV. The solar wind flow directions are obtained from the combination of the relative currents on the five collectors together with identification of the particluar 0.70 deg wide spacecraft roll sectors in which the solar wind is detected.

The Pioneer 9 spacecraft was launched November 8, 1968 into a heliocentric orbit with a 298 day period. This spacecraft is spin stabilized at 60 rpm. The Pioneer 10 spacecraft was launched March 3, 1972 on a trajectory which, with subsequent corrections, permits encounter with the planet Jupiter on December 4, 1973. This spacecraft is spin stabilized at about 4.7 rpm. The Pioneer 10 mission is discussed in NASA (1971), in which some description of the spacecraft and experiments is also given.

During the times of these observations the Pioneer 9 and 10 spacecraft were at heliocentric distances of 0.8 and 2.2 AU respectively, approximately 45 deg east of the Earth's solar longitude. Pioneer 9 was located from 110,000 km to $\gtrsim$ 130,000 km north of the ecliptic plane during this time, while Pioneer 10 was 11-12 x 10^6 km south of the ecliptic plane.

Description of Observations

The hourly average solar wind proton bulk velocity, number density and temperature observed at Pioneers 9 and 10 are given in Figure 1. These results are presented with an arbitrary delay of the Pioneer 10 data by 3 days with respect to the Pioneer 9 data to achieve on the figure an approximate alignment of the most prominent features.

At both Pioneers 9 and 10, features often observed in association with interplanetary disturbances are seen, namely, fast velocity increases associated with increased proton temperatures (Wolfe, 1972). At the shocks in the data discussed here, the abrupt velocity increases are followed by peaks in the number density. An exception to this behavior is the event seen at Pioneer 9 at the beginning of August 5 which is not followed by a large density increase. A recent summary of theoretical calculations on post-shock conditions may be found in Dryer et al. (1972).

Another feature evident at both Pioneers is the gradual recovery of number densities over ~ 10 days from low values that follow the high density peaks seen on August 3 at Pioneer 9 and on August 7 at Pioneer 10 associated with the second shock of Table 2. One also notes that during the first few days of these events, a "background" proton temperature level which might be $\sim 10^5$ K from the Pioneer 9 records is even higher, or $\sim 3 \times 10^5$ K at Pioneer 10. If an adiabatic, quiescent solar wind expansion with an $r^{-4/3}$ temperature gradient were assumed, a 10^5 K temperature at Pioneer 9 at 0.8 AU would imply a 3×10^4 K value at Pioneer 10 at 2.2 AU. Here r refers to heliocentric distance. We speculate that convective energy has been transformed into thermal energy during this part of the disturbance, as the wind passed between 0.8 and 2.2 AU, because the Pioneer 9 high velocity peaks of 830 km sec^{-1} at 03h on August 4 and 990 km sec^{-1} at 0h and 01h on August 5 appear to be replaced at Pioneer 10 by a single reduced amplitude peak of 690 km sec^{-1} at 02h on August 7. Details of this apparent heating of the solar wind and the heating mechanism itself are topics for further study.

The plasma bulk velocities of Figure 1 have not been corrected for the spacecraft velocities. The Pioneer 9 spacecraft velocity at this time is 36 km sec^{-1} approximately normal to the solar direction in the direction of planetary motion and in the ecliptic plane. The Pioneer 10 spacecraft velocity at this time is 15 km sec^{-1} in the antisolar direction and 17 km sec^{-1} in the direction of planetary motion, parallel to the ecliptic plane.

Thirty minute averages of the Pioneer 9 magnetic field measurements during August 2 to 10 are given in Figure 2. The field latitude and longitude are given in the conventional ecliptic coordinate system with ϕ measured counterclockwise from the solar direction, looking from the north and θ measured from the ecliptic plane to the vector, with positive values corresponding to northward pointing field vectors.

There is a peak in the average magnetic field magnitude at 85 gamma during 1245 to 1315 UT on August 3. After the early part of August 4 the magnetic field magnitude is generally much smaller than 24 gammas. After the early part of August 6 until August 9 the field magnitude is at essentially the pre-disturbance value, less than 10 gammas.

Pioneer 9 Interplanetary Shock Observations

Five interplanetary shocks are observed in the Pioneer 9 plasma and magnetic field data. The times of these events, observed changes in magnetic field magnitude and calculated proton bulk velocity, and the shock type (Colburn and Sonett, 1966) are given in Table 2. The times are obtained from the magnetometer records and the identification to the minute is arbitrary in some of the cases with slower times on the order of a minute for the change in magnetic field magnitude. The shock types are deduced from examination of detailed data that is not presented here.

The best-fit calculation of Lepping and Argentiero (1971) has been performed for the August 3, 1117 event, excluding an error cone angle calculation. The results are given in Table 3. The notation of Table 3 follows that of Lepping and Argentiero (1971), with subscripts 1 and 2 denoting pre- and post-shock quantities. The coordinate system used is the conventional right handed, orthogonal solar ecliptic system with +x in the solar direction and +z northward. $\vec{W} = \vec{V}_2 - \vec{V}_1$ where $\vec{V}$ refers to the plasma (proton) bulk velocity. B_{ij} and n refer to the jth component of magnetic field and the proton number density, respectively. $\Delta p = p_2 - p_1$ where p refers to the thermal pressure, in this case due to protons and electrons alone. The solar wind helium is ignored in this calculation. σ here is an estimated uncertainty for each measured

TABLE 2. Interplanetary Shocks Observed by Pioneer 9 during Early August 1972.

Day, August 1972	Spacecraft time, UT	Solar wind proton bulk velocity change (km sec^{-1})	Interplanetary magnetic field magnitude change (gamma)	Type
3	0440	55	5.6	Fast Forward
3	1117	~210	55	Fast Forward
4	2323	240	14	Fast Forward
9	0707 ± 10min	~145	~15	Fast Forward
9	0958	85	~ - 3	Slow Forward

TABLE 3. Best-fit Calculation (Lepping and Argentiero, 1971) for Pioneer 9 Event of August 3, 1972, 1117 UT.

Parameter	Average Value	σ	Best Estimate Value
B_{1x}(gamma)	3.6	1.48	3.9
B_{1y}	-7.3	2.02	-6.1
B_{1z}	-19.4	1.66	-19.7
B_{2x}	-3.6	1.25	-3.6
B_{2y}	-15.0	5.76	-16.5
B_{2z}	-74.0	6.77	-73.3
W_x(km sec^{-1})	-196	11.	-194
W_y	52	15.	61
W_z	-21	20.	-26
n_1 (cm^{-3})	19.2	2.7	16.2
n_2	48.9	13.	58.4
Δp(10^{-10}dynes cm^{-2})	112		-55

parameter, including statistical variance and systematic sources. The measured pre- and post-shock electron temperatures are 7×10^5 K and 9×10^5 K respectively.

The best-fit shock normal is $\hat{n} = (-.938, .341, .064)$, with a 17 deg change from a shock normal based on average values. This shock normal is within 4 deg of the direction to the flare location from Pioneer 9 at the time of the event. An arbitrary preliminary 1.0 gamma northward instrumental offset magnetic field has been assumed for these calculations. Based on the best-fit shock normal the measured Alfvén, whistler and sonic shock Mach numbers (Tidman and Krall, 1971) are 9.5, 15 and 2.3 respectively.

Various estimates of shock speed are possible. The expression given by Lepping and Argentiero (1971) yields

$$V_s = \frac{(n_2\vec{V}_2 - n_1\vec{V}_1)}{n_2 - n_1} \cdot \hat{n} \sim 645 \text{ km sec}^{-1}.$$

Evolutionarity (Colburn and Sonett, 1966) yields $754 \text{ km sec}^{-1} < V_s \leq 788$ km sec^{-1}. These two estimates for shock speed are subject to experimental uncertainties that may be as large as ~ 10 percent but a final evaluation has not yet been done. The transit time between Pioneers 9 and 10 yields a mean speed of 787 km sec^{-1} along the direction between the locations of the two spacecraft at the times when this event was observed; this direction is ~ 27 deg west and ~ 7 deg south of the above shock normal. An indication of inaccuracy in the above shock normal is the negative calculated value for the thermal pressure difference Δp given in Table 3. Perhaps a more correct shock normal exists which would yield better agreement with this measured parameter which is not used in the best-fit calculation reported here. Agreement between the measured and calculated thermal pressure differences might be supposed if a large excess of momentum flux (~ 200 erg cm^{-3}) due to waves or turbulence were present upstream from the shock. This large an amount of extra momentum flux would seem unlikely, as no more than 1/30 this amount was inferred for any of 18 interplanetary shocks studied by Chao and Goldstein (1972), although only two of the 18 shocks they studied were of comparable Mach number to the event discussed here. Also, one would expect excess momentum flux due to waves or turbulence downstream rather than upstream from the shock.

Chao, J. K. and Goldstein, B. : 1972, J. Geophys. Res. 77, 5455.

Colburn, D. S. and Sonett, C. P. : 1966, Space Sci. Rev. 5, 439.

Dryer, M., Smith, Z. K., Endrud, G. H., and Wolfe, J. H. : 1972, Cosmic Electrodyn. 3, 184.

Intriligator, D. S., Wolfe, J. H., McKibbin, D. D., and Collard, H. R. : 1969, Planetary Space Sci. 17, 321.

Lepping, R. P. and Argentiero, P. D. : 1971, J. Geophys. Res. 76, 4349.

McKinnon, J. A. : 1972, NOAA Tech. Memo. ERL SEL-22, U.S. Department of Commerce, N.O.A.A. Environmental Research Laboratories, Boulder, CO.

Mihalov, J. D. and Wolfe, J. H. : 1971, Cosmic Electrodyn. 2, 326.

N.A.S.A.: 1971, The Pioneer Mission to Jupiter, SP-268, National Aeronautics and Space Administration, Washington, D.C.

Pomerantz, M. A. and Duggal, S. P.: 1973, Nature 241, 331.

Solar-Geophysical Data (comprehensive reports): 1973, No. 342-part II, U.S. Department of Commerce, Boulder, CO, p. 4.

Sonett, C. P. : 1966, R. L. Smith-Rose (Ed.), Space Research 6, Spartan Books, Washington, D.C., p. 280.

Tidman , D.A. and Krall, N. A.: 1971, Shock Waves in Collisionless Plasmas, Wiley-Interscience, New York.

Wolfe, J. H. : 1972, in C. P. Sonett, P. J. Coleman, Jr., and J. M. Wilcox (Eds.), Solar Wind, SP-308, National Aeronautics and Space Administration, Washington, D.C., p. 170.

Wolfe, J. H. and McKibbin, D. D. : 1968, Planetary Space Sci. 16, 953.

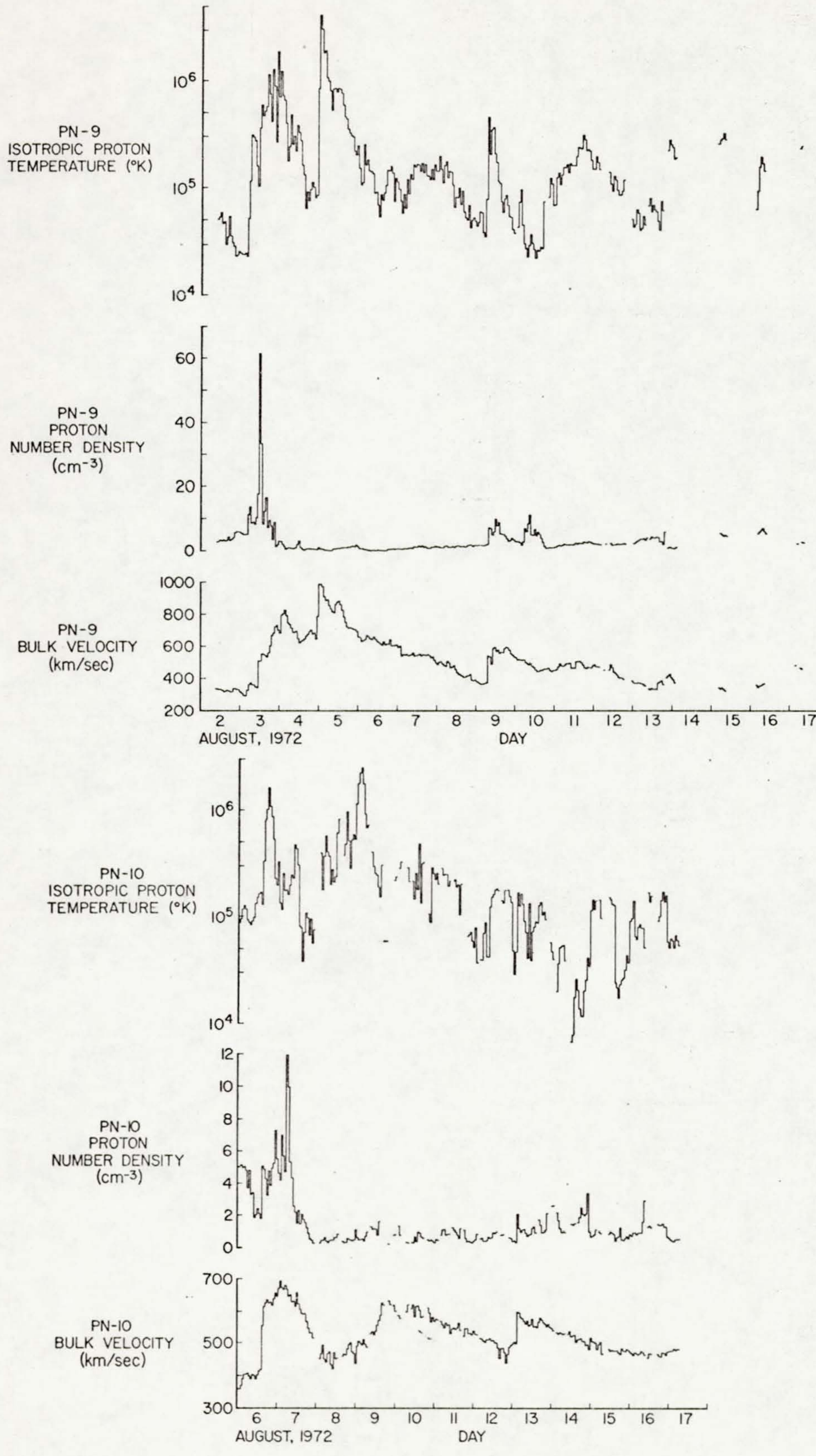

Figure 1. Hourly average plasma parameters from Pioneers 9 (top) and 10 (bottom). The UT times refer to the Earth, so that a ~ 6 min correction must be applied to obtain times at Pioneer 9, and a ~ 13 – 15 min correction for Pioneer 10. The Pioneer 10 plot is arbitrarily delayed three days with respect to the Pioneer 9 plot as indicated by the horizontal scales.

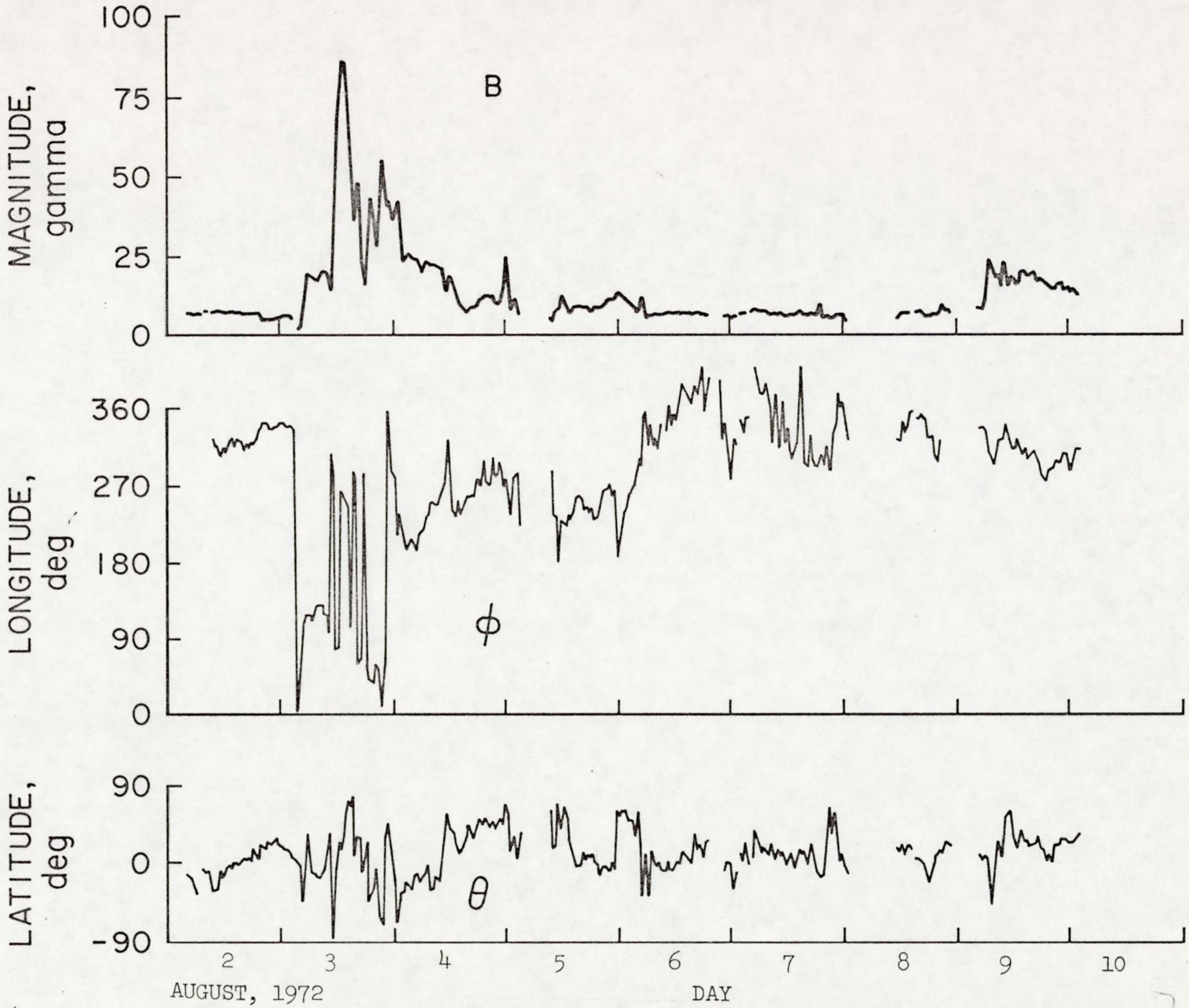

Figure 2. Thirty-minute average magnetic field measurements from Pioneer 9. The UT times refer to the spacecraft.