Space Sciences Laboratory
University of California
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SOLAR WIND DISTURBANCES ASSOCIATED WITH FLARES*

John M. Wilcox

Technical Report

ONR Contract Nonr 3656(26), Project NR 021 101
Partial support from NASA Grants NsG 243 and
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*Ninth Invited Lecture, Symposium on Solar Flares and Space Research, COSPAR, Tokyo, May 10, 1968

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Abstract

The structure of the quiet solar wind and interplanetary magnetic field is reviewed to provide background and perspective for the discussion of solar wind disturbances associated with flares. Corotating structures with a recurrence period of about 27 days must be distinguished from structures directly produced by flares. Flare-induced discontinuities have been interpreted as low Mach number shock waves; in one such event (which appears to be fairly typical) the solar wind velocity increased from 340 to 385 km/sec, the density increased from 9 to 23 protons/cm^3, and the average temperature increased from 3×10^4 to 8×10^4 °K. In another event the interplanetary magnetic field strength increased from 12.2 to 20.8×10^{-5} gauss, and the rms deviation of the orthagonal components of the field approximately doubled. Many interplanetary shock waves appear to be decelerated as they expand and propagate through the solar wind plasma. The most reasonable interpretation appears to be in terms of an intermediate strength shock wave with an energy input in the range of 10^{30} to 10^{32} ergs.

During most of the interval in which the interplanetary medium has been observed by spacecraft the sun has been near the minimum of its 11-year cycle, and the opportunities for observing solar flare-induced disturbances have likewise been at a minimum. A discussion of flare-induced disturbances in the interplanetary medium must take into account its highly structured nature. During most of the observations the large-scale structure of the interplanetary magnetic field can be characterized in terms of sectors having appreciable angular extent. Within each sector the average field direction is approximately along the Archimedes spiral direction, but the sense of the field is predominantly either toward the sun or away from the sun. The evolution with time over an interval of several years of the interplanetary sector structure (1) is shown in Figure 1. In the preceding portion of a sector the solar wind velocity tends to increase and in the following portion of a sector the velocity tends to decrease. At the sector boundary there occur discontinuous jumps in the direction of the interplanetary magnetic field, and sometimes in other solar wind quantities. When an attempt is made to associate a particular disturbance in the interplanetary medium with a particular solar flare this structured nature of the medium must be considered. Many disturbances (some of them rather abrupt) corotate with the sun, and are not to be associated with a particular flare but rather with some quasi-stationary structure on the solar surface. Ballif and Jones (2) propose a model of the magnetic properties of solar streams, and make the following comments with regard to flare identification. "It is our view that although the energy spectrum of the particles leaving the sun becomes tremendously more energetic during a flare, the high velocity particles emitted at that time are primarily not responsible for the large-scale geomagnetic event that sometimes follows. Rather, as far as its relation to geomagnetic activity is concerned, the flare is usually just an indicator of active regions. Some of these active centers are associated with unipolar regions that have the characteristics necessary to produce the plasma stream responsible for geomagnetic activity." "Very likely many solar flares have been incorrectly related to specific geomagnetic storms. There are almost always several geomagnetic storm-producing streams engulfing the earth on each solar rotation. No matter where the flare occurs on the solar disk one need not wait long to observe an earth disturbance of some sort." The large-scale structure of the interplanetary medium has recently been reviewed (1), and we suggest that in the analysis of any flare-associated disturbance in the interplanetary medium the large-scale structure obtaining at the particular time must be carefully considered.

We proceed now to a discussion of several spacecraft observations of flare-associated disturbances. Gold (3) first pointed out that the abrupt change associated with a sudden commencement indicated the presence of a collisionless shock in the interplanetary medium. Parker (4) has discussed the propagation of flare-associated shock waves for several cases. In one model of a blast wave (i.e. the energy is deposited in the medium in a time short compared with the transit time to 1 AU) the interplanetary lines of force are swept up by a high velocity plasma stream. Further discussions have been given by Nishida (5) and Dryer (6). An extensive review of the magnetic shock wave structure has recently been given by Colburn and Sonett (7). These authors point out that a geomagnetic impulse need not be associated with a shock wave propagating through the solar wind, but can also be associated with a contact surface in the solar wind. There is a net flow of plasma through a shock, while there is no net flow of plasma through a contact surface. Thus a contact surface is a separation of two different plasma states, and is stationary in the sense that it does not propagate through the plasma. McCracken and Ness (8) have suggested that the interplanetary medium contains many well-defined filaments with diameters of the order of 10^6 km that connect back to specific regions on the solar surface. The boundary of such a filament may be an example of a contact discontinuity that can produce an abrupt change in the interplanetary medium.

The first observations of shock-like phenomena in interplanetary space by Pioneer 5 in 1961 and Mariner 2 in 1962 have been reviewed by Colburn and Sonett (7) and will not be further discussed here. We will discuss some observations obtained in the rising portion of the present sunspot cycle.

Interplanetary disturbances associated with the July 7, 1966 flare have been studied by Lazarus and Binsack (9), Ness and Taylor (10) and Van Allen and Ness (11). Observations of this event were available from earth satellites and also from Pioneer 6 which was considerably removed from the earth. Figure 2 shows the relative positions of Pioneer 6 and the earth as well as the interplanetary sector structure prevailing at the start of July 7. Magnetic observations from Explorer 33 during the interval of interest are shown in Figure 3. Notice that a sector boundary rotated past the spacecraft early on July 8 and was accompanied by a large increase in the magnitude of the interplanetary field. A discontinuous increase in field magnitude from 12 γ to 21 γ at 2106 UT on July 8 is associated with an interplanetary shock wave. A similar increase was observed on IMP-3 at the same time, and in fact the observations by IMP-3 and by Explorer 33 agreed during the interval under consideration at most times to within a γ in magnitude and 5° - 10° in direction. Since both satellites observed the shock at essentially the same time, the line between the satellites lay in the plane of the shock surface. Figure 4 shows the relative positions of the two satellites as well as the trace of the shock surface and the directions of the observed fields before and after the shock.

Parker (4) has pointed out that the shock thickness of an interplanetary blast wave might be of the order of the ion gyroradius. Van Allen and Ness (11) observed that the increase in the magnitude of the interplanetary field associated with this disturbance occurs within a period of five to ten seconds. Thus, at a velocity of propagation of 950 km/sec, the apparent thickness of the transition region at the shock front is $\leq 1 \times 10^4$ km. This thickness is $\leqslant$ 100 gyroradii for protons of the interplanetary medium.

At this time there were extended gaps in the telemetry acquisition from Pioneer 6 so that no observations were obtained on July 6, 7 and 8. At 1822 UT on July 10 the field magnitude observed on Pioneer 6 increased from 9 γ to 22 γ , and Ness and Taylor (10) suggest a plausible association with the July 7 flare. Of course, the extended gaps in Pioneer 6 coverage make this association somewhat uncertain. If this association is correct it would mean that Pioneer 6 observed the flare-associated shock wave considerably later than it was observed at the earth in spite of the fact that Pioneer 6 was closer to the sun. Ness and Taylor suggest that the shock may have had difficulty in propagating across the sector boundary and that the sector pattern at 2102 UT on July 8 may have looked as shown in Figure 5.

The solar wind plasma observations of this event by Lazarus and Binsack (9) with Explorer 33 are shown in Figure 6. The initial increase in density during the late hours of July 7 and in the early hours of July 8 is attributed to the passage of a magnetic sector boundary, rather than being related to the flare. The jump in velocity and density at 2106 UT on July 8, coincident in time with the magnetic changes previously discussed, is attributed to a moderate shock. The velocity increased from 320 to 430 km/sec and the proton density increased from 4 to $8/cm^3$, according to revised values given in (12). The high velocity plasma which extends for a period of three days following the shock is attributed to "pusher" gas emitted by the flare itself. The plasma observations on Pioneer 6 are shown in Figure 7. Lazarus and Binsack suggest that the fact that the velocity observed at Pioneer 6 became large only after July 10, combined with a long period of observation of high velocity plasma after the shock of July 8 at Explorer 33, tends to argue that the flare material was not missed because of the poor telemetry coverage. Lazarus and Binsack suggest that the flare particles were forced to push on the denser plasma contained in the sector boundary, and were thereby much delayed in their appearance at Pioneer 6. On July 11 Pioneer 6 observed a number density ratio of alphas to protons of approximately 0.12, an unusually high value. We shall find this intriguing feature in other spacecraft observations also. It does not seem to be possible to arrive at an unambiguous description of the interplanetary configuration that obtained at the time of these interesting observations, but they certainly illustrate the necessity for consideration of the large-scale interplanetary patterns in the analysis of flare-associated disturbances.

A recent report by Ogilvie et al. (13) describes interplanetary disturbances observed on Explorer 34 with a plasma detector that analyzes both energy per unit charge and velocity, and with a flux-gate magnetometer. This analysis has the considerable advantage that inasmuch as both plasma and field observations are considered it is possible to more closely define the physical conditions associated with disturbances. During some of the events, Explorer 34 was within the magnetosheath before the event and then in the interplanetary medium after the event, the interpretation being that the interplanetary disturbance has compressed the magnetosphere and returned the satellite to the interplanetary medium. This appears to be a very reasonable interpretation; still the possibility of effects related to proximity to the magnetosphere must be considered. This experiment shows that a complex structure may be associated with interplanetary disturbances. Both shocks and tangential discontinuities are observed. In some disturbances the proportion of helium in the plasma is variable and larger than that observed at quiet times. This is a most interesting observation, the physical significance of which is not understood at the present time; the helium could, for example, be associated with a driver gas. Some of the results of Ogilvie et al. are shown in Figure 8 which is a distance-vs-time representation of the plasma flow near 1 AU which displays plasma velocity (solid lines), wave speed (dashed line) and the time separation of events associated with a class 3 solar flare that began at 0525 UT on May 28, 1967. A mean speed for the shock to travel from the sun to the earth is found to be 735 km/sec. Several interesting structures trail behind the shock front. A tangential discontinuity trails the shock by about 0.05 AU; behind this, at roughly equal intervals of 0.02 AU are a second tangential discontinuity and the leading and trailing edges of a helium-rich plasma. The bulk velocity of the helium ion is equal to the bulk velocity of the protons to within a few percent, as shown in Figure 9. About 5 1/2 hours after the commencement of disturbances the helium/hydrogen ratio reached a value of 0.17, as compared with a typical range during quiet times of 0.02 to 0.05.

Gosling et al. (14) have given an analysis and interpretation of two interplanetary discontinuities observed with hemispherical plate electrostate analyzers on the Vela 3 satellites. Both discontinuities have been interpreted as shock waves, and both have been associated with solar flares. An interplanetary disturbance observed on January 20, 1966 is shown in

Figure 10. Across the discontinuity, the velocity increased from 340 to 385 km/sec, the density increased from 9 to 23 protons/cm^3, and the average temperature rose from 3×10^4 to 8×10^4 °K. The authors interpret these changes as being consistent with a low Mach number shock wave traveling at a velocity of 70 km/sec through the ambient solar wind. They suggest that the most likely association with this disturbance was a class 2b solar flare that began at 2253 UT on January 18. The only other flare of comparable size during this period occurred at 1032 UT on January 17. If the January 18 flare was the source of the interplanetary disturbance, the mean transit velocity of the disturbance from the sun to the earth was 1670 km/sec, while if the January 17 flare was the source then the mean transit velocity was 685 km/sec. For either flare, the computed mean transit velocity significantly exceeded the measured velocity of the shock past the satellite and the earth. A somewhat similar interplanetary event was observed on October 5, 1965 and is shown in Figure 11. Across the discontinuity the velocity increased from 330 to 380 km/sec, the density increased from 6 to 13 protons/cm^3, and the temperature rose from 3×10^4 to 7×10^4 °K. Again this disturbance is consistent with the changes to be expected from a low Mach number shock wave. The authors propose a flare-association with a class 2+ flare that began at 0946 UT on October 4. If the correct flare has been chosen, the mean transit velocity of the disturbance from the sun to the earth was 2500 km/sec, which greatly exceeded the measured velocity of the shock wave past the earth. Thus it appears that interplanetary shock waves are decelerated as they expand and propagate through the quiescent solar plasma.

In an earlier paper Gosling et al. (15) discussed several observations of discontinuities in the solar wind in which the velocity has no appreciable change. These are interpreted in terms of the tangential discontinuities reviewed by Colburn and Sonett (7), and are not specifically associated with solar flares.

Dryer and Jones (12) have analysed several of the flare-associated disturbances discussed previously in terms of classical blast wave theory for an ordinary gas. A strong shock would cause a density increase by a factor of four, whereas the actual measurements give a density increase of about two. This result clearly shows the shock to be of intermediate strength. Dryer and Jones estimate that the energy deposited in the solar wind by the events considered is of the order of 10^{30} to 10^{32} ergs.

Hundhausen and Gentry in a recent investigation (16) used the standard one-fluid hydrodynamic equations, assuming spherical symmetry about the sun. The forces due to solar gravity and the pressure gradient were included in the momentum equation. The energy equation was handled by the assumption of an adiabatic expansion, with $\gamma = 5/3$. The steady state solar wind at 1 AU was assumed to have a velocity of 395 km/sec, a proton density of $12/cm^3$ and a temperature of 5×10^4 °K. The inner boundary was placed at a heliocentric distance of 18 solar radii. In one case examined by Hundhausen and Gentry the shock wave was initiated at the inner boundary with a density jump of 4 (strong shock for $\gamma = 5/3$) and with a shock velocity (in a stationary frame) of 2000 km/sec. The total energy input was 1.6×10^{33} ergs over an interval of 4 hours. For these conditions the shock profile at 4.3 hours is shown in Figure 12 (velocity vs heliocentric distance) and in Figure 13 (density vs heliocentric distance). Figure 14 shows the heliocentric position of shocks of varying energy as a function of time. The shock shown in Figures 12 and 13 is the leftmost of this family. Probably most flare-induced shocks in the interplanetary medium would correspond to conditions at the right side of Figure 14, and would therefore have appreciable transit times to the earth.

It appears that in a flare-induced disturbance in the interplanetary medium we may expect the proton density to approximately double (typically from 5 to 10 protons/cm^3), the average temperature to approximately double (typically from 4 to 8 x 10^4 °K), and the velocity to increase by perhaps 50 to 100 km/sec (typically from 350 to 425 km/sec). The interplanetary field magnitude may increase by approximately a factor of two, and the deviations in the field increase considerably after the disturbance. The most reasonable interpretation appears to be in terms of an intermediate strength shock wave that is decelerated as it propagates through the quiescent solar wind plasma.

The region after the disturbance may have a rich structure including tangential discontinuities and a helium-rich region. At the present time too few flare-associated disturbances have been studied to permit a general description. We can anticipate in the coming year or two a considerable increase in our knowledge of this subject.

Acknowledgement

I thank Drs. A. J. Hundhausen and M. Dryer for discussions of work in progress, and Dr. Hundhausen for the loan of the motion picture shown in Tokyo. This work was supported by the Office of Naval Research under Contract Nonr 3656(26), and by the National Aeronautics and Space Administration under Grants NsG 243 and NGR 05-003-230, and by the National Science Foundation under Grant GA-1319.

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Figure Captions

Figure 1. Observed sector structure of the interplanetary magnetic field, overlayed on the daily geomagnetic character index C9, as prepared by the Geophysikalisches Institut in Göttingen. Light shading indicates sectors with field predominantly away from the sun, and dark shading indicates sectors with field predominantly toward the sun. Diagonal bars indicates periods of mixed polarity. An assumed quasi-stationary structure during 1964 is indicated (Reference 1).

Figure 2. The interplanetary sector structure at the time of the July 7 flare as deduced from preceding 27 days of IMP-3 measurements. The longitude of the flare on the sun is marked by an arrow (Reference 10).

Figure 3. Geocentric solar ecliptic hourly averages of the interplanetary magnetic field as observed by Explorer 33 on orbit number 1 during 5-12 July 1966. Gaps in data correspond to poor quality data reception. Dotted portions are magnetosheath measurements. K_p is plotted at the top (Reference 10).

Figure 4. Projection on ecliptic plane of trajectories of Explorers 28 and 33 during early July 1966, and average magnetopause and shock wave positions as observed by Explorer 28. Superimposed are the pre- and post-shock wave interplanetary magnetic field directions and the trace of the shock wave surface associated with the geomagnetic sudden commencement storm beginning at 2102 July 8 (Reference 10).

Figure 5. A possible configuration of the interplanetary shock (dashed curve) and sector structure at the time of the July 8 SC at Earth. The sector boundary is shown distorted in the way one might expect following a

sudden increase in a localized area of solar wind flux (both density and velocity) (Reference 10).

Figure 6. Hourly averages of preliminary values of plasma parameters measured at Explorer 33. The large density on July 8 is probably associated with the passage of a magnetic sector boundary. The velocity increase on July 8 corresponds to the passage of the shock. Note that the solar wind velocity stays high for several days afterwards (Reference 9).

Figure 7. Plasma data observed from Pioneer 6. The cross-hatched areas are times during which no data are available. The lines connecting the data points are linear interpolations and are dashed on July 10 to indicate the long time between measurements. The last data points on July 10 were obtained by hand processing of fractional spectra and error bars are included to show the uncertainty in the parameters. On July 11, the plasma is relatively cold and falls almost completely into one energy channel of the detector. The thermal speeds are most probable speeds assuming an isotropic, Maxwellian velocity distribution in a frame of reference moving with the plasma. Angular measurements North and South of the ecliptic plane are roughly quantized to 5^{o} intervals. Angular measurements in the ecliptic are uncertain within $\pm 1^{o}$. No correction for aberration has been made (Reference 9).

Figure 8. V_{α}, the center velocity of the helium velocity channel showing a non-zero flux, plotted against the proton bulk speed V_p deduced from curve fitting to data obtained at the same time, observed with Explorer 34 (Reference 13).

Figure 9. A kinematic diagram of conditions near 1 AU on May 30, 1967, observed with Explorer 34, illustrating the variety of structures that may

be associated with a flare-induced disturbance. Tangential discontinuities are labeled t a d. Note the helium-rich region following the shock front (Reference 13).

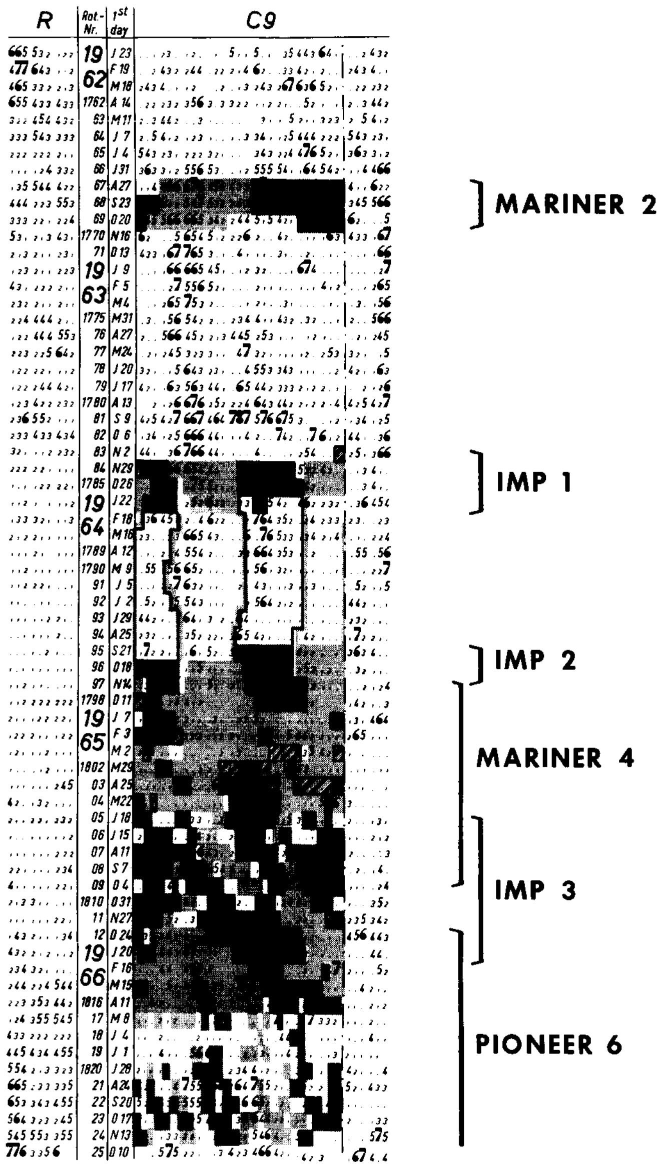
Figure 10. Plot of solar wind positive ion velocity, direction, density, and temperature on January 19-20, 1966, observed with the Vela 3 satellites. 0° flow direction is for flow radial from the sun. The representative error bars shown are estimates of the relative uncertainties involved in the various determinations. A trace of the horizontal component of the earth's field at Guam is shown in the lower part of the figure (Reference 14).

Figure 11. Plot of solar wind positive ion velocity, direction, density, and temperature on October 4-5, 1965, observed with the Vela 3 satellites. 0° flow direction is for flow radial from the sun. The representative error bars shown are estimates of the relative uncertainties involved in the various determinations. A trace of the horizontal component of the earth's field at Guam is shown in the lower part of the figure (Reference 14).

Figure 12. Velocity vs heliocentric distance for a particular shock (see text) calculated in Reference 16.

Figure 13. Density vs heliocentric distance for a particular shock (see text) calculated in Reference 16.

Figure 14. Heliocentric position of shocks of varying energy as a function of time (Reference 16).



R
Rot-Nr.
1st day
C9
MARINER 2
IMP 1
IMP 2
MARINER 4
IMP 3
PIONEER 6

Figure 1

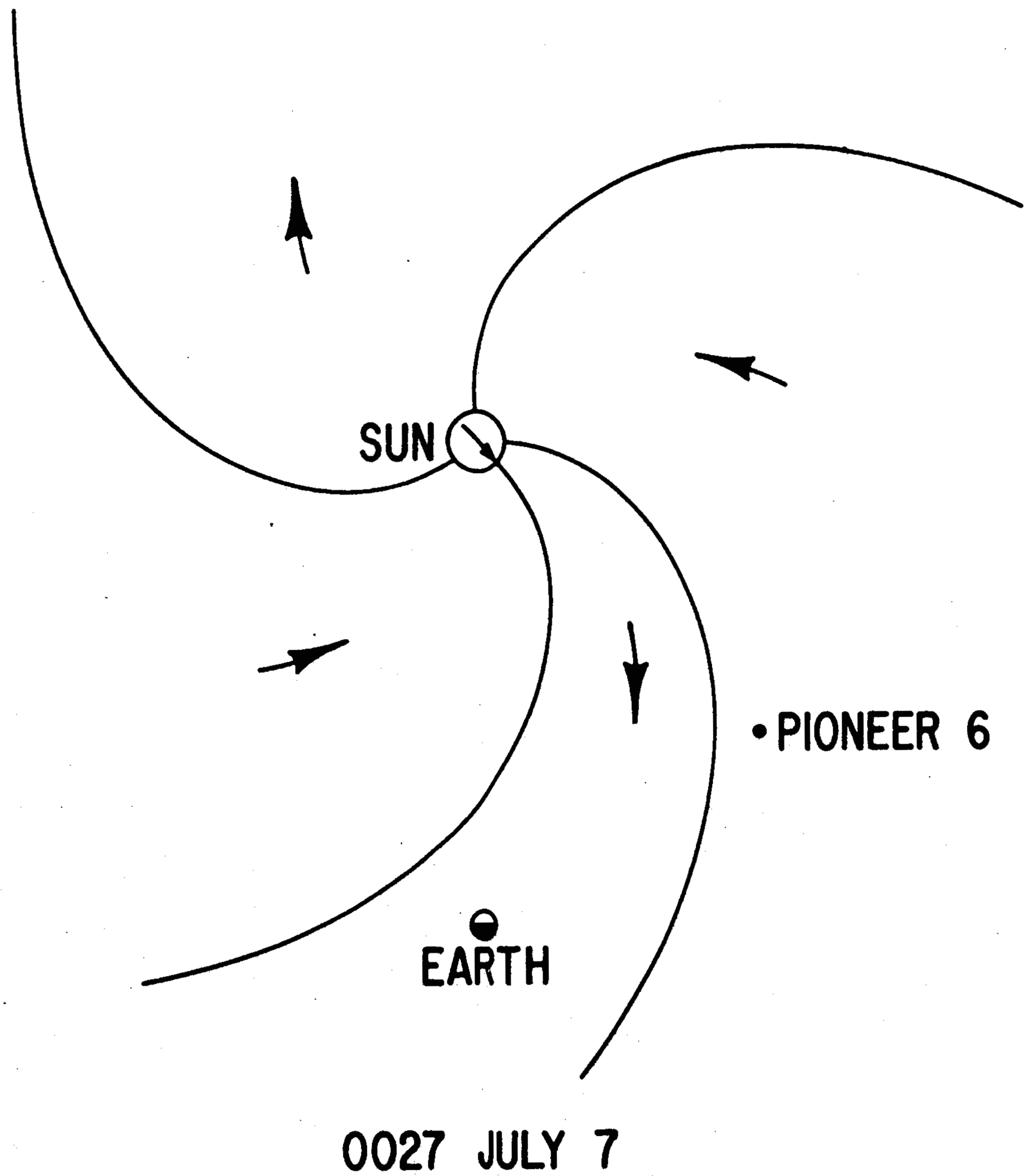
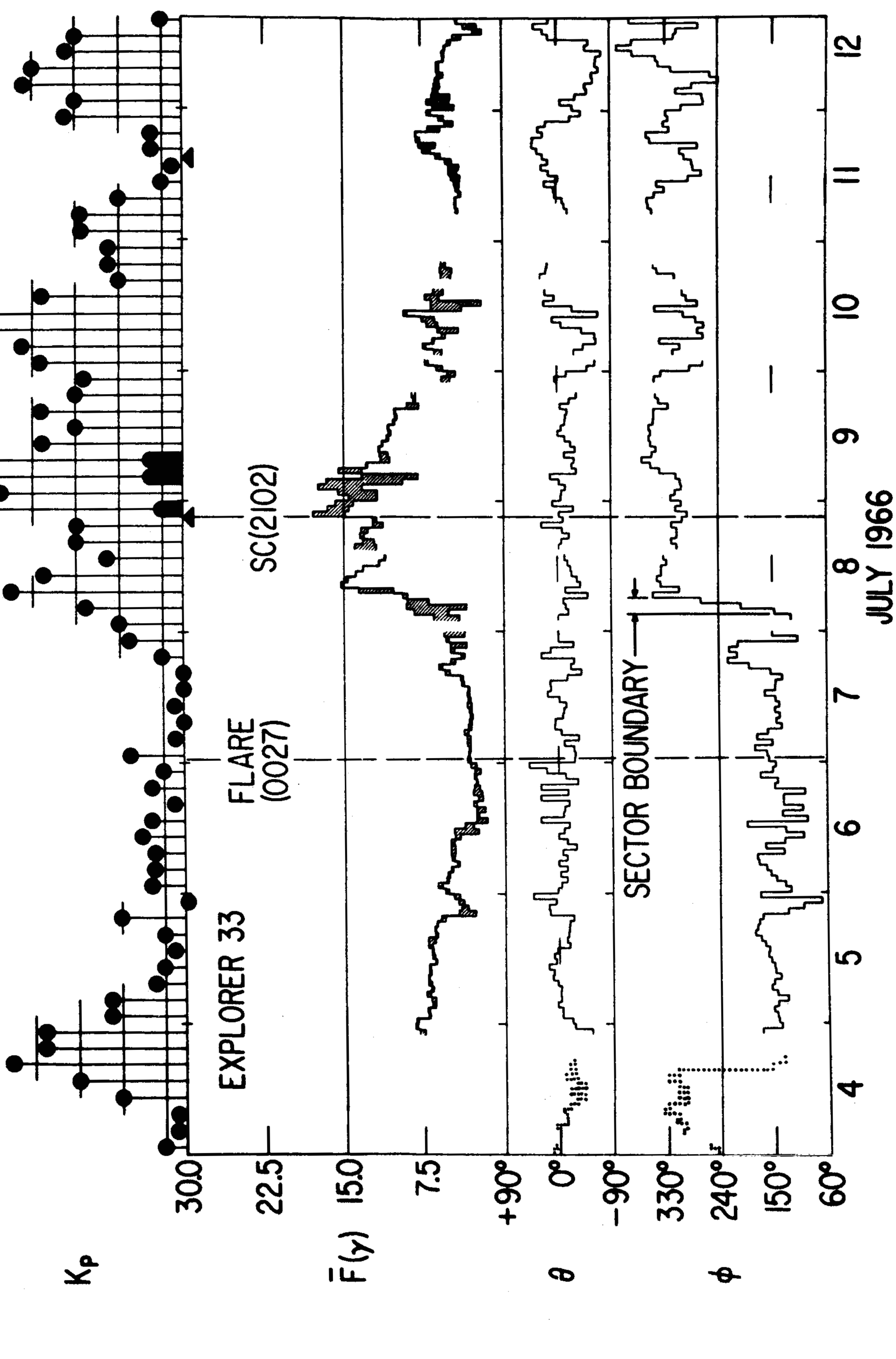


Figure 2



Kp
F̄(γ)
θ
φ
30.0
22.5
15.0
7.5
+90°
0°
-90°
330°
240°
150°
60°
EXPLORER 33
FLARE (0027)
SC(2102)
SECTOR BOUNDARY
4
5
6
7
8
9
10
11
12
JULY 1966

Figure 3

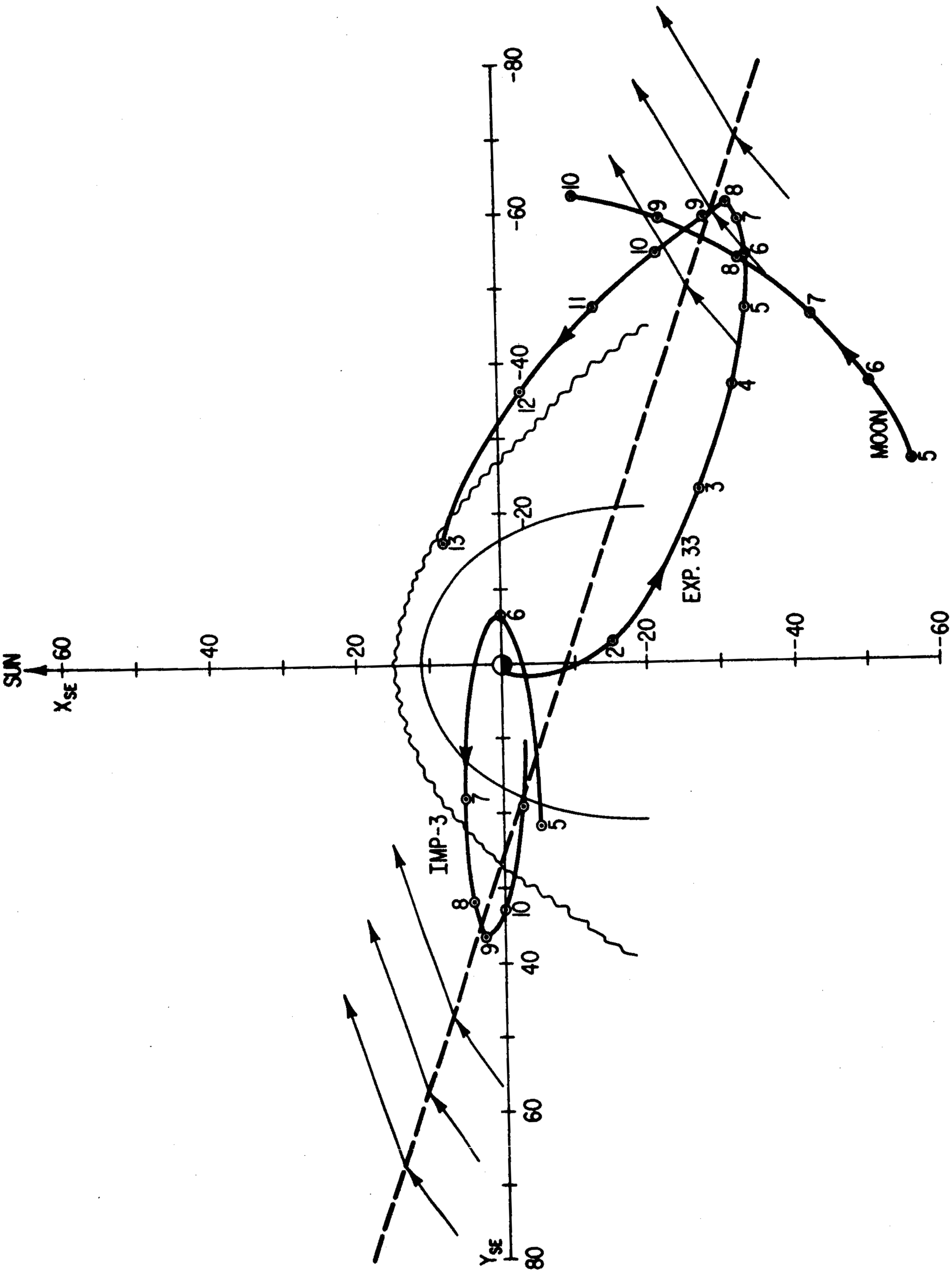


Figure 4

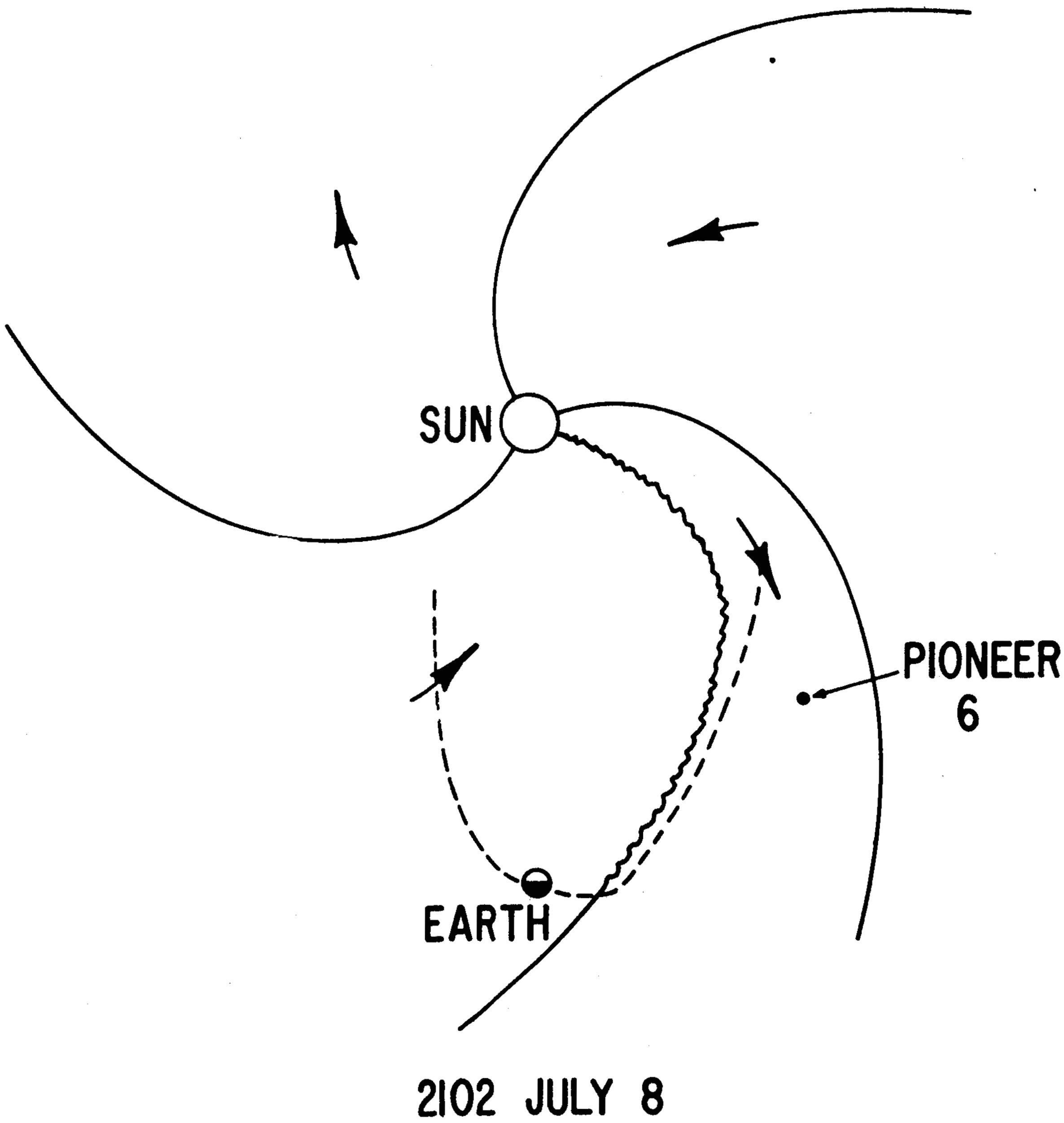
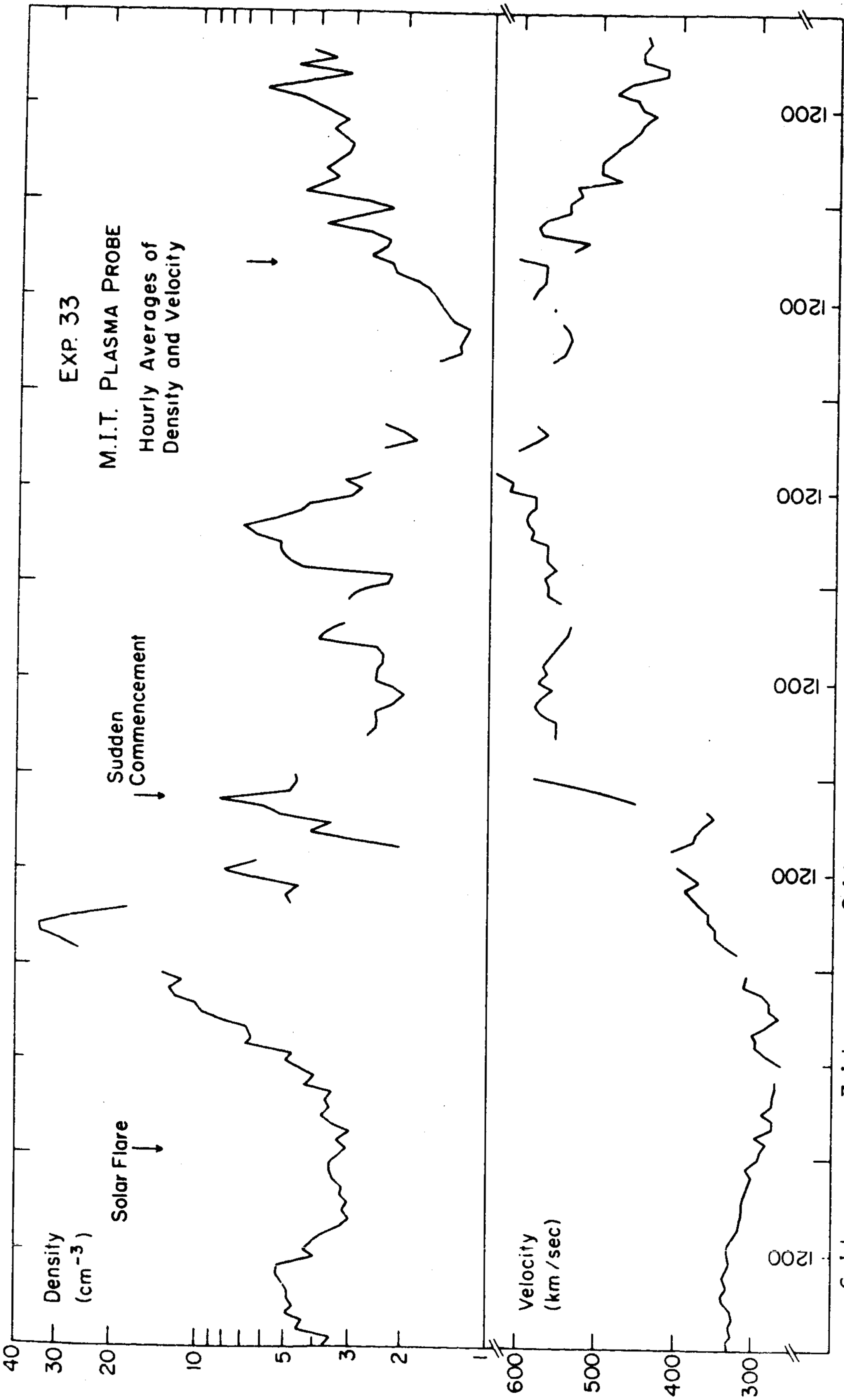
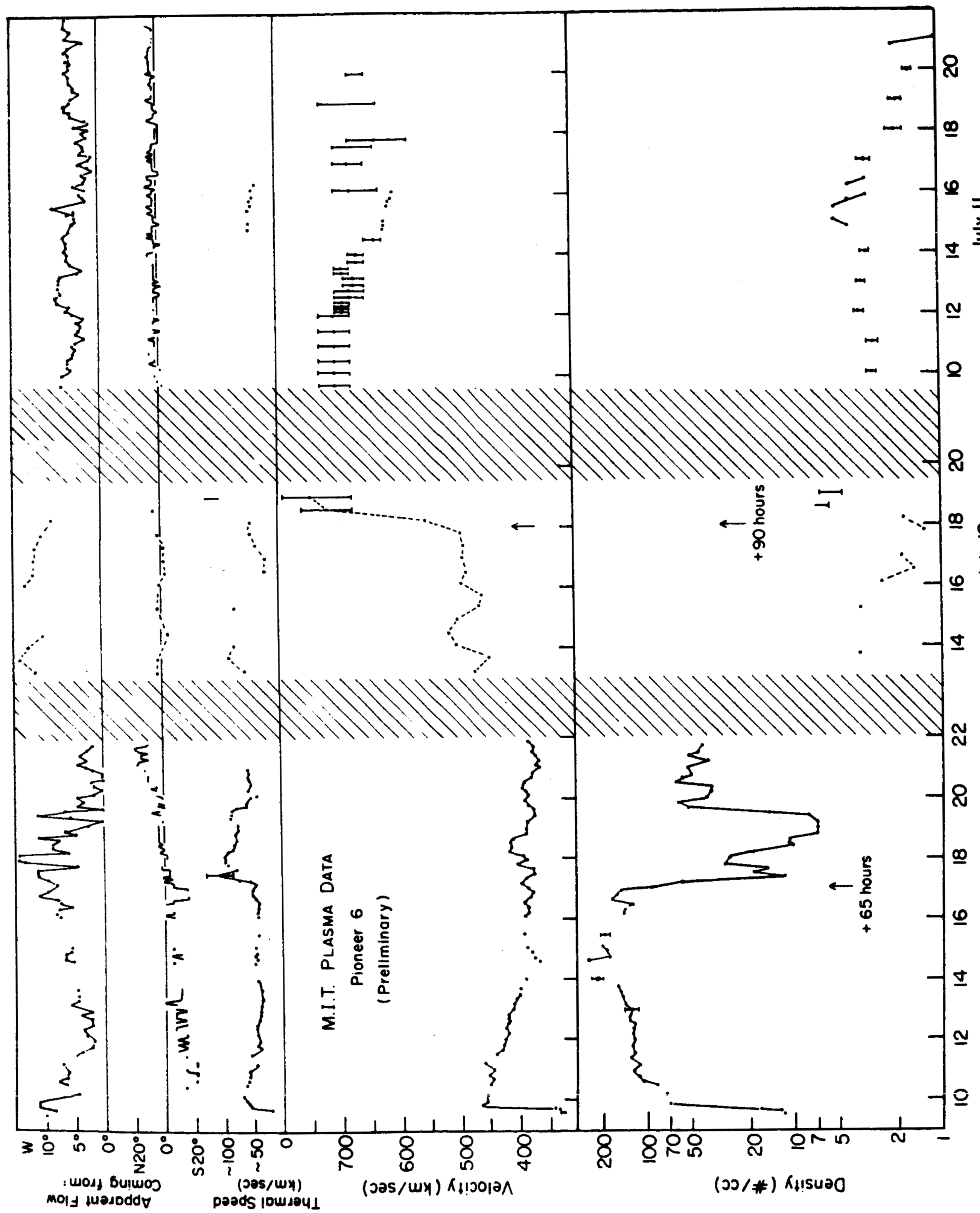


Figure 5



Exp. 33
M.I.T. Plasma Probe
Hourly Averages of
Density and Velocity
Solar Flare
Sudden
Commencement
Density
(cm-3)
Velocity
(km/sec)
40
30
20
10
5
3
2
1
600
500
400
300
1200
6 July
7 July
1200
8 July
1200
9 July
1200
10 July
1200
11 July
1200
12 July

Figure 6



M.I.T. Plasma Data
Pioneer 6
(Preliminary)
Apparent Flow
Coming from:
Thermal Speed
(km/sec)
Velocity (km/sec)
Density (#/cc)
+65 hours
+90 hours
July 9
July 10
July 11

Figure 7

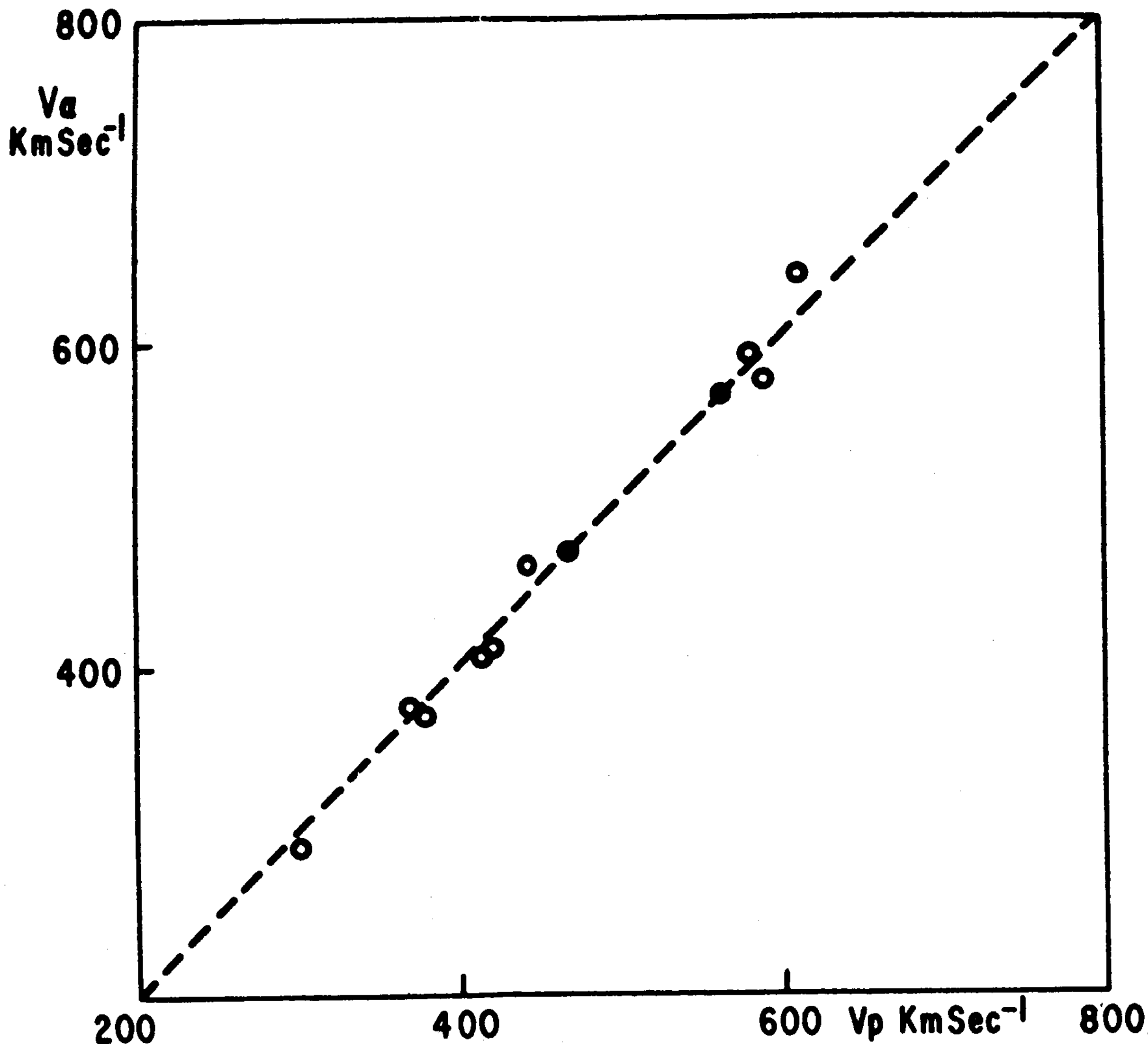
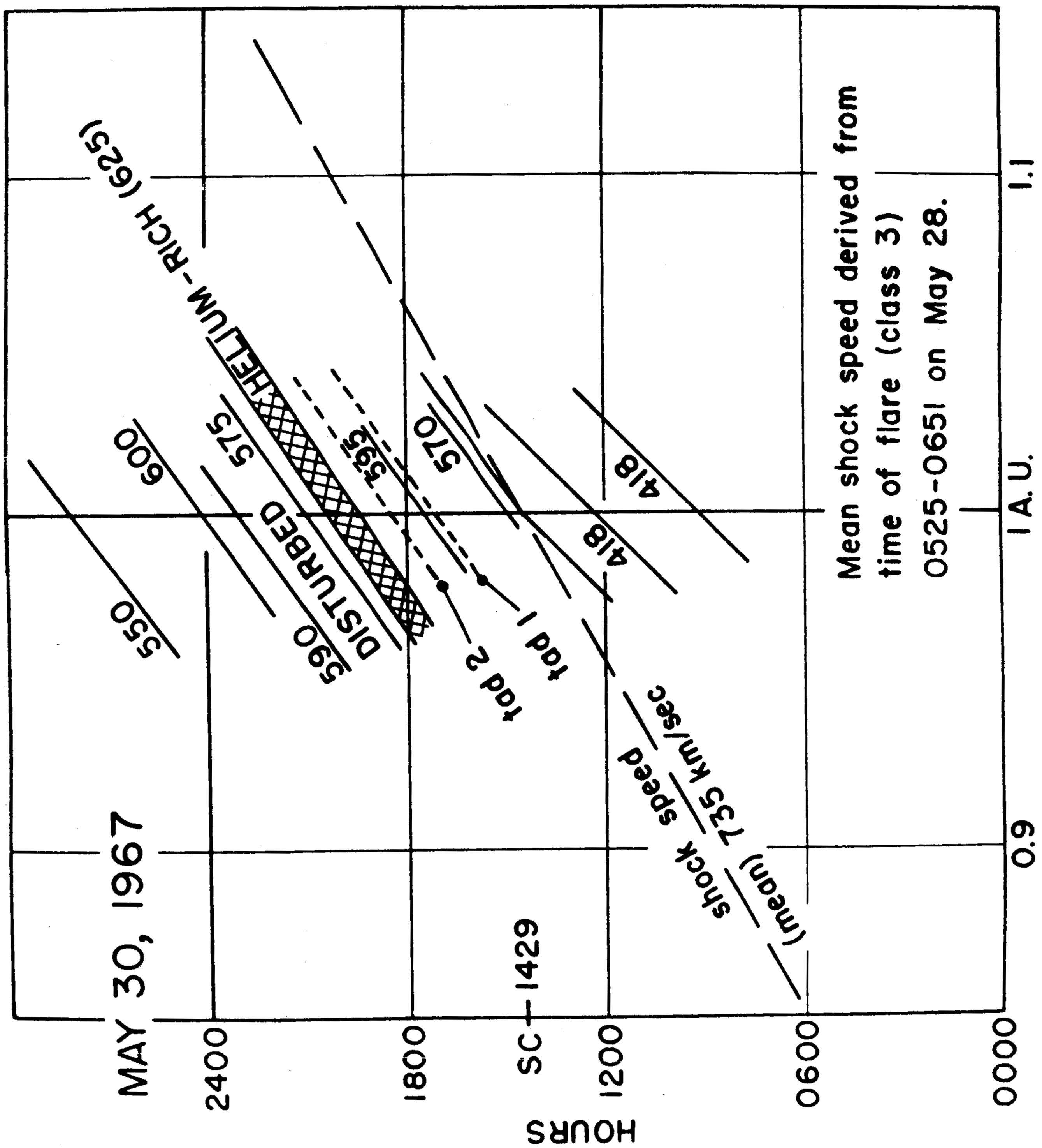


Figure 8



MAY 30, 1967
HOURS
0000
0600
1200
SC
1800
2400
SC—1429
0.9
I A.U.
1.1
550
600
590
575
DISTURBED
HELIUM-RICH (625)
595
570
418
418
tad 1
tad 2
shock speed
735 km/sec
(mean)
Mean shock speed derived from
time of flare (class 3)
0525-0651 on May 28.

Figure 9

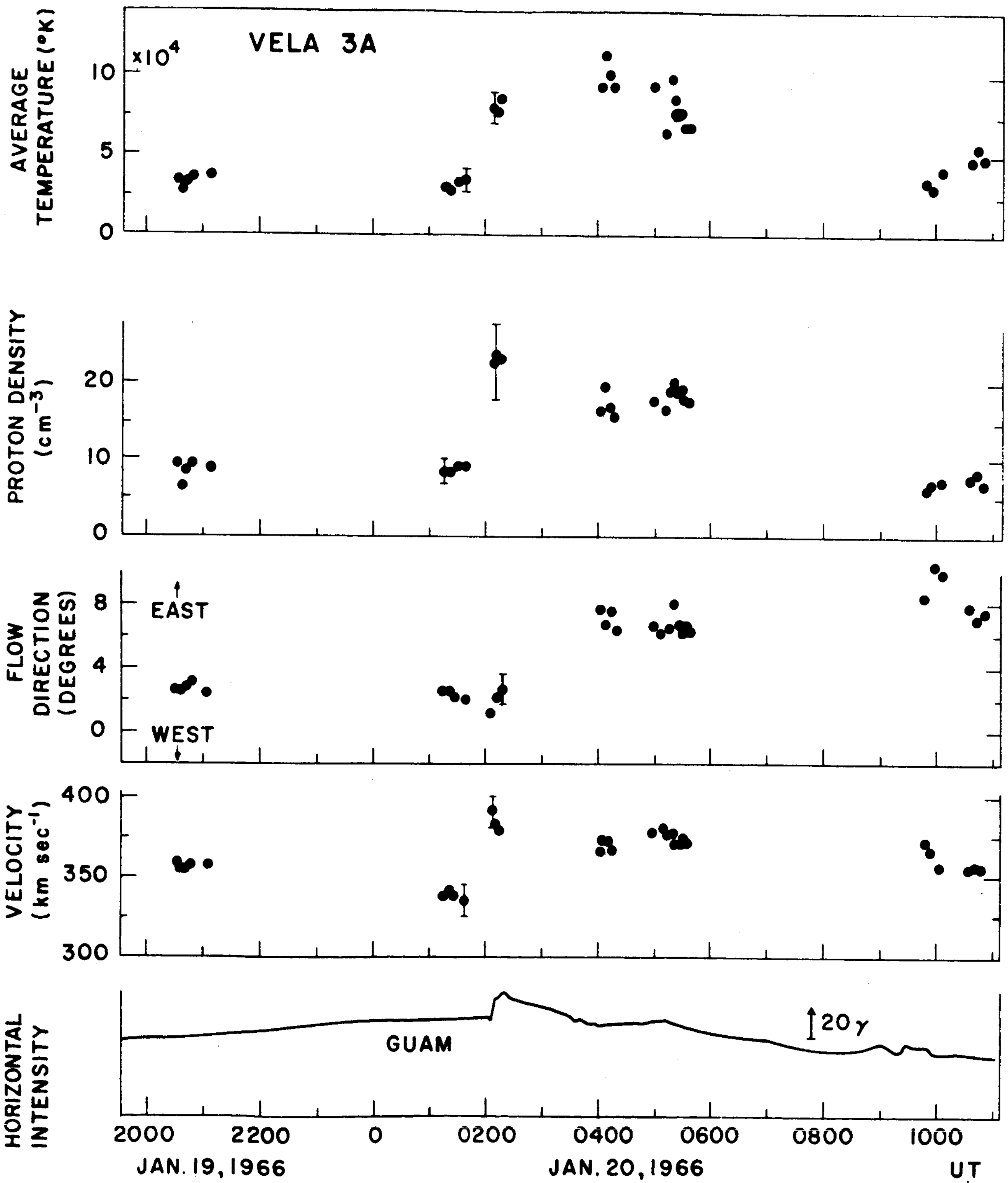

VELA 3A
AVERAGE TEMPERATURE (°K)
x10^4
10
5
0
PROTON DENSITY (cm^-3)
20
10
0
FLOW DIRECTION (DEGREES)
8
4
0
EAST
WEST
VELOCITY (km sec^-1)
400
350
300
HORIZONTAL INTENSITY
GUAM
20γ
2000
2200
0
0200
0400
0600
0800
1000
JAN. 19, 1966
JAN. 20, 1966
UT

Figure 10

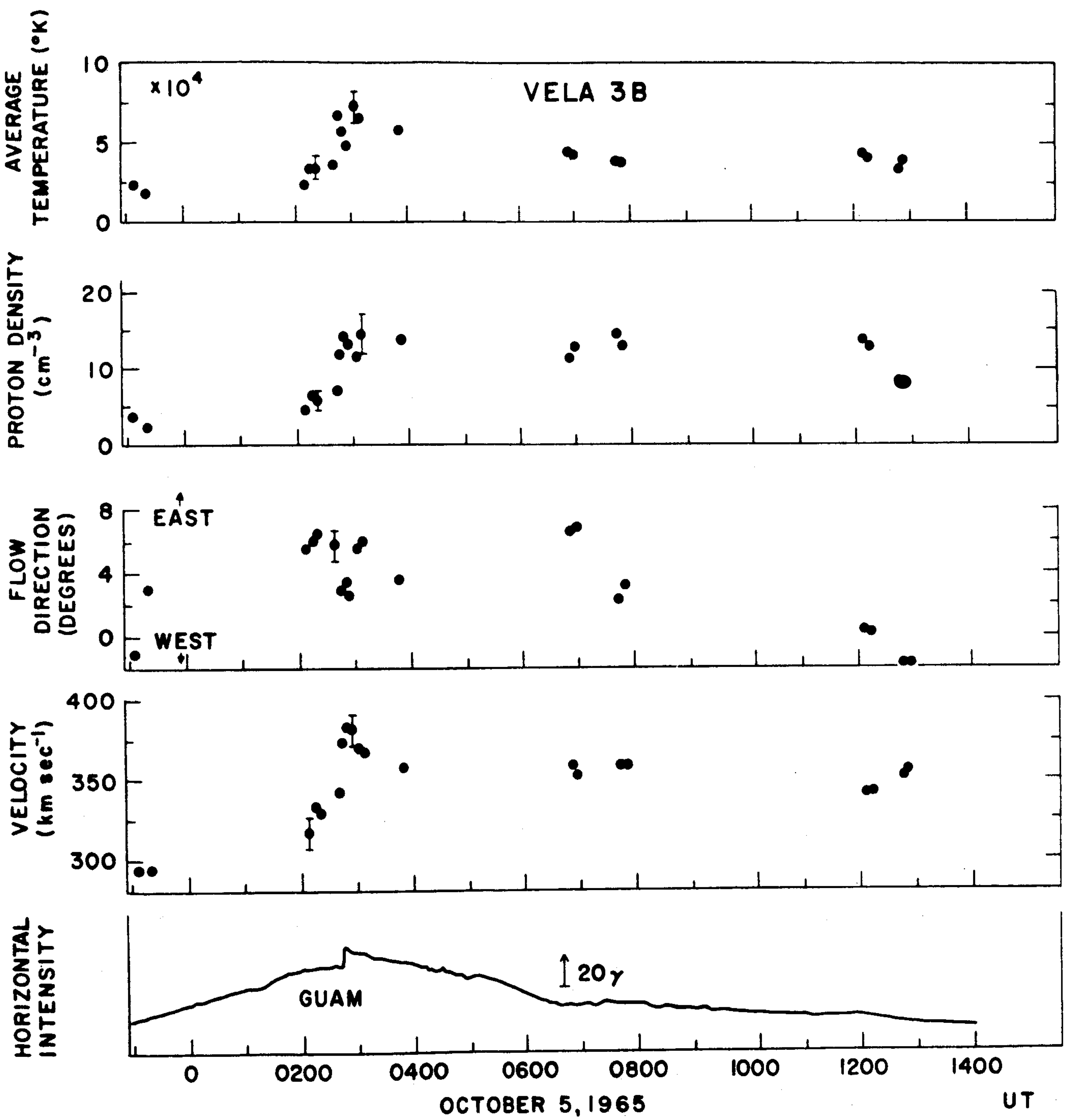

AVERAGE TEMPERATURE (°K)
x10^4
VELA 3B
PROTON DENSITY (cm^-3)
FLOW DIRECTION (DEGREES)
EAST
WEST
VELOCITY (km sec^-1)
HORIZONTAL INTENSITY
GUAM
20γ
0
0200
0400
0600
0800
1000
1200
1400
OCTOBER 5, 1965
UT

Figure 11

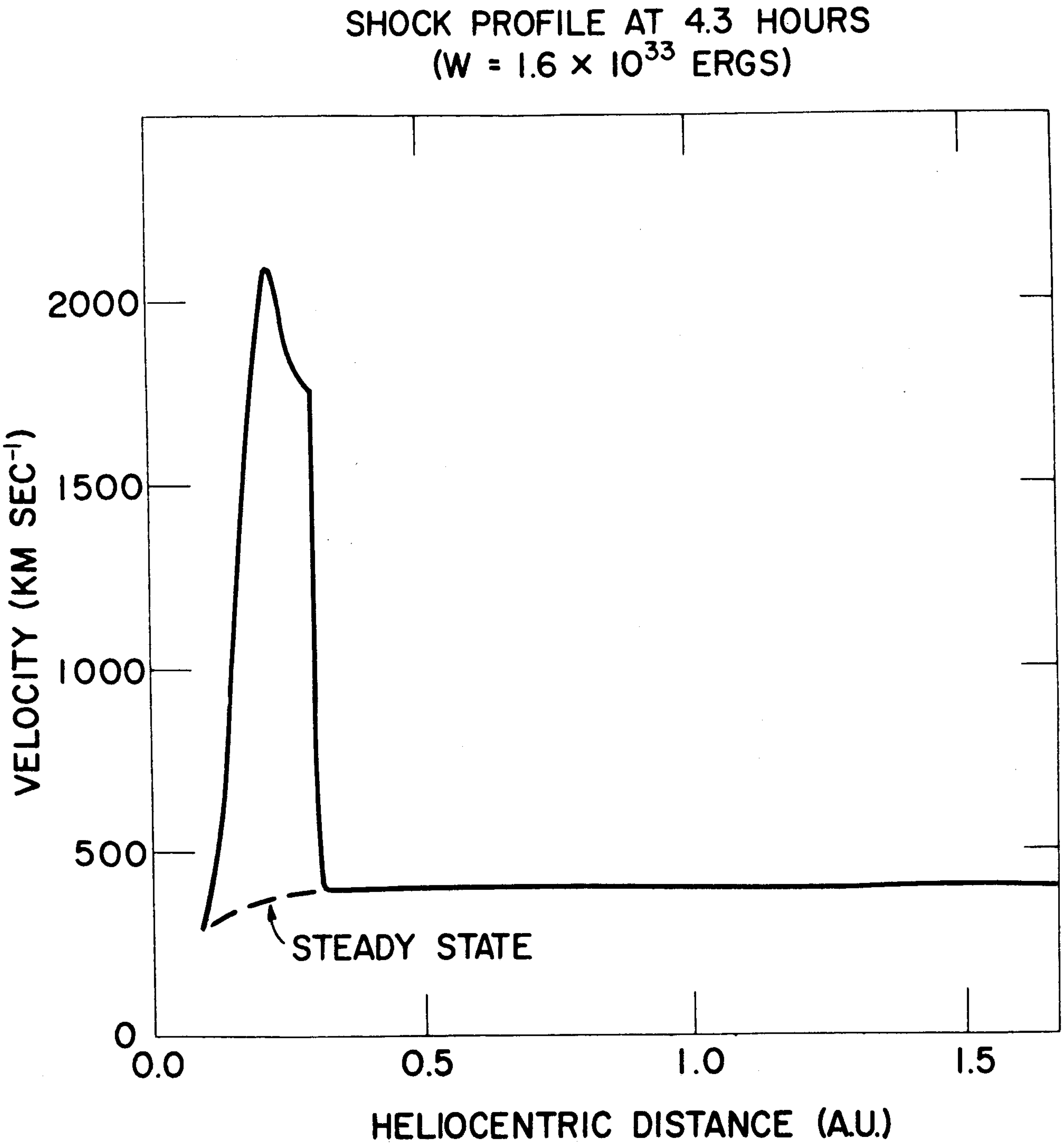

SHOCK PROFILE AT 4.3 HOURS
(W = 1.6 × 10^33 ERGS)
VELOCITY (KM SEC^-1)
2000
1500
1000
500
0
STEADY STATE
0.0
0.5
1.0
1.5
HELIOCENTRIC DISTANCE (A.U.)

Figure 12

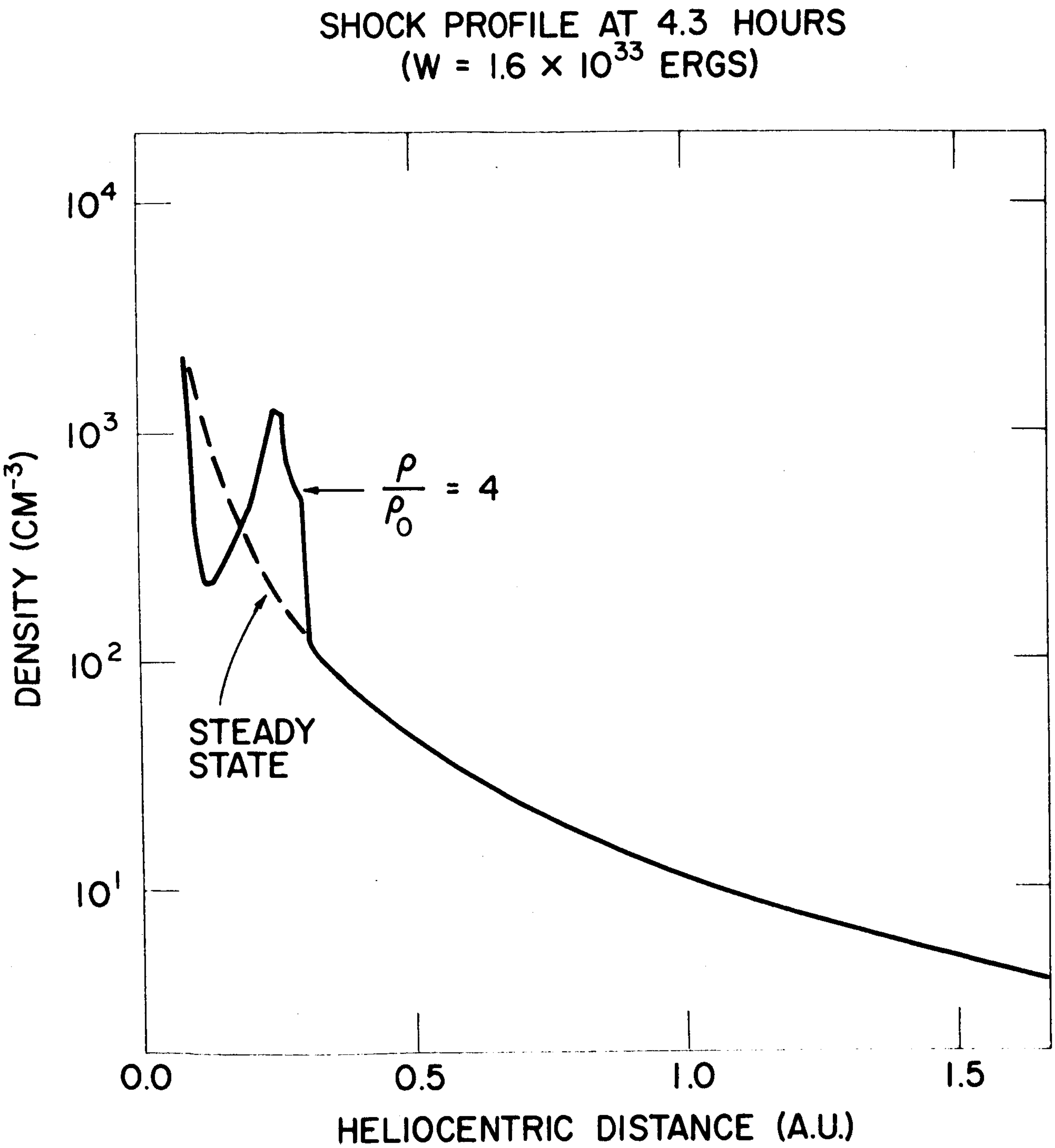

SHOCK PROFILE AT 4.3 HOURS
(W = 1.6 × 10^33 ERGS)
DENSITY (CM^-3)
10^4
10^3
10^2
10^1
ρ/ρ0 = 4
STEADY STATE
0.0
0.5
1.0
1.5
HELIOCENTRIC DISTANCE (A.U.)

Figure 13

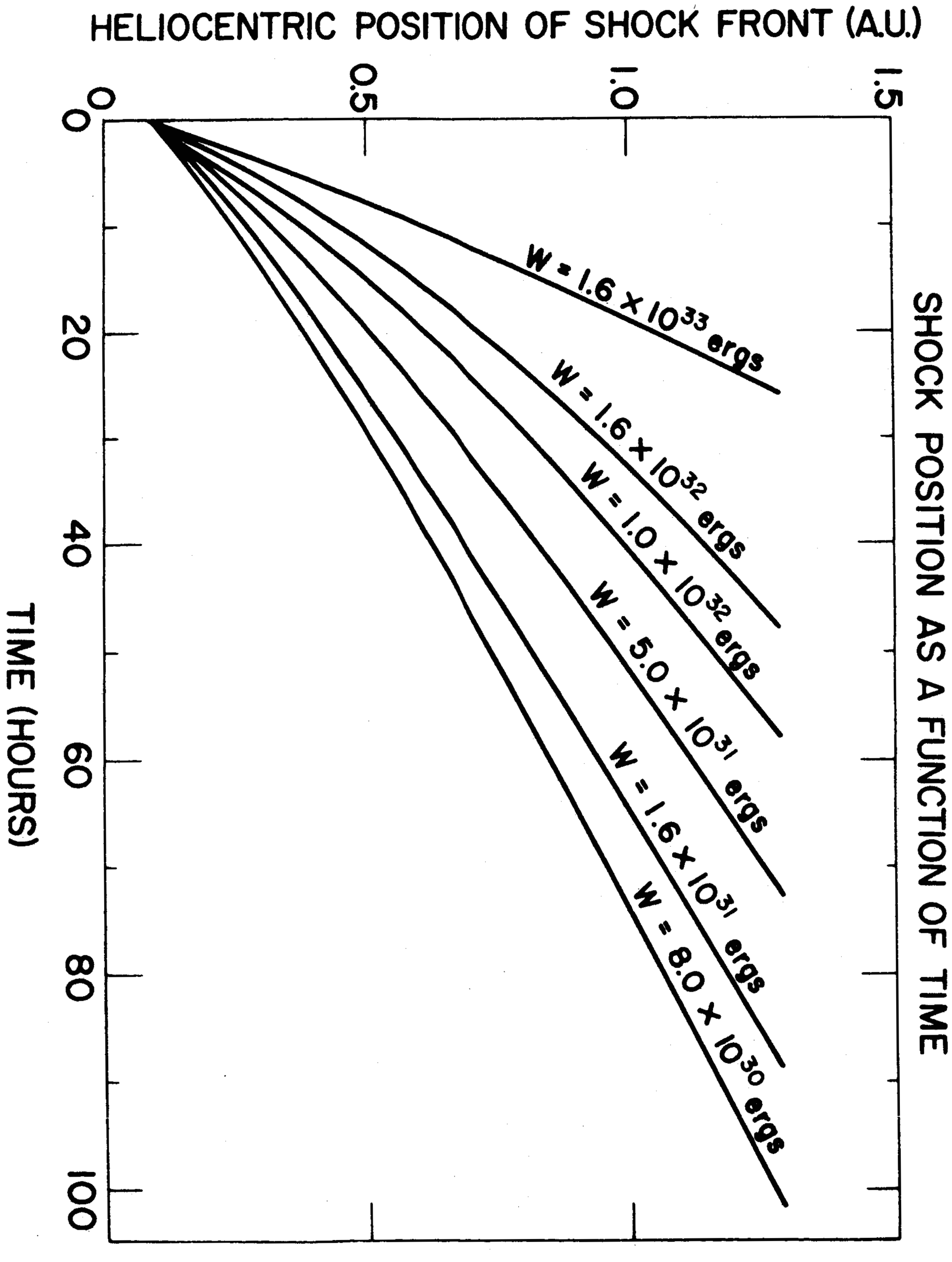

SHOCK POSITION AS A FUNCTION OF TIME
HELIOCENTRIC POSITION OF SHOCK FRONT (A.U.)
TIME (HOURS)
0
0.5
1.0
1.5
0
20
40
60
80
100
W = 1.6 × 10^33 ergs
W = 1.6 × 10^32 ergs
W = 1.0 × 10^32 ergs
W = 5.0 × 10^31 ergs
W = 1.6 × 10^31 ergs
W = 8.0 × 10^30 ergs

Figure 14

UNCLASSIFIED

Security Classification

DOCUMENT CONTROL DATA - R&D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author) Space Sciences Laboratory University of California Berkeley, California 94720	2a. REPORT SECURITY CLASSIFICATION Unclassified 2b. GROUP

3. REPORT TITLE

SOLAR WIND DISTURBANCES ASSOCIATED WITH FLARES

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)
Technical Report

5. AUTHOR(S) (Last name, first name, initial)

Wilcox, John M.

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
May 6, 1968	16	15

8a. CONTRACT OR GRANT NO. ONR Contract Nonr 3656(26) NASA Grants NsG 243 and NGR 05-003-230 NSF Grant GA-1319	9a. ORIGINATOR'S REPORT NUMBER(S) Series No. 9, Issue No. 24
b. Project No. ONR NR 021 101	9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report)

10. AVAILABILITY/LIMITATION NOTICES

Qualified requesters may obtain copies of this report from DDC.

11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY Nuclear Physics Branch Office of Naval Research Washington, D. C. 20360

13. ABSTRACT

The structure of the quiet solar wind and interplanetary magnetic field is reviewed to provide background and perspective for the discussion of solar wind disturbances associated with flares. Corotating structures with a recurrence period of about 27 days must be distinguished from structures directly produced by flares. Flare-induced discontinuities have been interpreted as low Mach number shock waves; in one such event (which appears to be fairly typical) the solar wind velocity increased from 340 to 385 km/sec, the density increased from 9 to 23 protons/cm^3, and the average temperature increased from 3×10^4 to 8×10^4 °K. In another event the interplanetary magnetic field strength increased from 12.2 to 20.8×10^{-5} gauss, and the rms deviation of the orthagonal components of the field approximately doubled. Many interplanetary shock waves appear to be decelerated

(continued)

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