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To be presented at London COSPAR Proton Flare Project, July 27-28, 1967.

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LABORATORY FOR SPACE SCIENCES
NASA-GODDARD SPACE FLIGHT CENTER
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**NAS-NRC Postdoctoral Resident Research Associate

Introduction

This note discusses simultaneous observations of the interplanetary magnetic field by three widely separated satellites: Explorers 28, 33, and Pioneer 6 during 4-12 July 1966. These data establish the general macrostructure of the field in cislunar space and include the micro-structural feature of the shock wave associated with the geomagnetic sudden commencement (SC) at 2102 on July 8, 1966. Preliminary results and analyses reveal a remarkable correspondance of the measurements by the geocentric satellites Explorers 28 and 33. The very limited data coverage by Pioneer 6 precludes a similar comparison, but is included because the satellite was separated in heliocentric longitude by + 44° (with respect to the earth). Thus it provides unique data relative to the region on the Sun (N34, W45) where a class 2B flare occurred on 7 July 0022. Van Allen and Ness (1967) have presented an analysis of the simultaneous energetic particle and magnetic field observations of the interplanetary shock wave detected on 8 July by Explorer 33.

Satellites and Instrumentation

The NASA satellite Explorer 28 (IMP-3) was launched on 29 May 1965 into a highly eccentric Earth orbit with an initial apogee of approximately 42 R_e (Earth Radii = 6378.2 Km) and an orbital period of 5.8 days. A single monoaxial fluxgate magnetometer on the spin stabilized spacecraft measures the vector magnetic field once every 40.96 seconds with an accuracy of $\pm$ 1 gamma. The instrumentation and analysis of the data is similar to that of the earlier IMP-1 (Ness et al, 1964) and IMP-2 (Fairfield and Ness, 1967). During the period of interest the IMP-3 apogee for orbits 69, 70, and 71 was approximately 90^o east of the sun (ϕ_{se} = 90^o). Thus the measurements obtained correspond to a local time of 1800.

The NASA satellite Explorer 33 was launched into an extremely high apogee-high perigee orbit on 1 July 1966. The initial apogee of 70 R_e was beyond the moon (60 R_e) and occurred on 7 July at a solar ecliptic longitude (ϕ_{se}) of 242^o, corresponding to a local time of 0400. The orbital period of the satellite is approximately 14 days so that during the period of interest the satellite is at least 40 R_e or more from the Earth. A triaxial fluxgate magnetometer on the spin stabilized spacecraft measures the vector magnetic field every 5.12 seconds with an accuracy of $\pm$ 0.25 gamma. The NASA-GSFC experiment and initial results detecting the Earth's magnetic tail and neutral sheet at distances up to 80 R_e on subsequent orbits has been reported by Ness et al (1967) and Behannon (1967).

The NASA deep space probe Pioneer 6 was launched December 16,1965 into an heliocentric orbit with perihelion of 0.81 AU and aphelion of 1.01 AU. A monoaxial fluxgate magnetometer measures the vector magnetic field approximately once every 1.5 seconds (dependent upon telemetry bit rate) with an accuracy of $\pm$ 0.25 gamma. The experiment and early results revealing the filamentary nature of the interplanetary magnetic field have been presented by Ness et al (1966). Simultaneous data with IMP-3 (Ness, 1966) gave evidence for the spatial uniformity of the interplanetary magnetic field on a cislunar distance scale and also the co-rotation of the interplanetary magnetic field on larger distance scales. During early July 1966 Pioneer 6 was located approximately 44^{o} ahead of the Earth in heliocentric longitude and 0.83 AU from the sun. The Earth-Pioneer 6 distance ranged between 1.04-1.10 x 10^{8} Km. while the Earth-Sun-Probe angle ranged between 42.7^{o}-45.1^{o}. The theoretical co-rotation time for such macro-structure features as sector boundaries (Wilcox and Ness, 1965) is 2.8 days assuming a steady solar wind velocity of 400 Km/sec.

Data Presentation

Each of the experiments on the three satellites measures the magnetic field at a different rate dependent upon the telemetry format and bit-rate. The data presented in this note represents hourly averages computed from the original data as follows. The three orthogonal components of the vector field are linearly averaged for 5.46 minutes for Explorer 28 (6 samples), 81.9 seconds for Explorer 33 (16 samples) and 30 seconds for Pioneer 6 (20 samples). The component averages are then used to construct an average field magnitude and direction. If the magnetic field varies appreciably during these basic time intervals then the average field is not necessarily a good representation of the instantaneous field.

The hourly averages are computed in a similar fashion, linearly averaging the average components (10-11 for Explorer 28; 43-44 for Explorer 33 and 120 for Pioneer 6). These are then used to construct an average magnetic field for the hour interval. In addition to the magnitude computed from the component averages, a linear average of the basic magnitudes is also computed. The difference in these two manners of computing magnitudes depends on the level of fluctuations. If the direction changes frequently during the hour, then there will be a large difference between the two magnitudes. If the direction is very steady, then the two magnitudes will be approximately the same.

The data contained in this note illustrate this point very clearly. The two magnitudes are presented and the difference between them is graphically shaded so that the existence of an interval of fluctuating magnetic field is readily detected. During those times the average direction is not always a good representation of the instantaneous field direction.

Observations

The magnetic field as observed by Explorer 28 during 4-12 July 1966 is presented in Figure 1. Since the satellite is in a geocentric orbit it continuously monitors the interplanetary field only when it is outside the earth's bow shock. 100% interplanetary data is presented as a solid curve. On the basis of a study by Fairfield (1967), the average field in the magnetosheath is found to be closely alligned in direction with the interplanetary field. Thus magnetosheath field directions can be used to indicate the direction of the interplanetary field. Figure 1 includes magnetosheath field directions to provide as continuous a set of measurements as possible with this satellite.

The tendency of the interplanetary field direction to closely parallel the average spiral directions (ϕ_{se}=135^{o}, 315^{o}) and divided into intervals of constant sense is evident in these data. Two sector boundaries are observed during this period, one corresponding to a change from - to + polarity of field sense (+ out of sun) at 1600 on July 4 and an accompanying one from + to - at $\sim$ 0500 on July 8. The + sector thus extends in time for $\sim$ 4 days. The flare occurs at a time when the interplanetary field of 4 gamma at 1 AU is directed along the general Archimedean spiral in a sense away from the sun ($\phi \sim 135^{o}$). The characteristic increased field magnitude following a sector boundary (Wilcox and Ness, 1965) is observed where the field rises from 5 gamma to 15 gamma. The SC associated shockwave produces increased fields at 2100 on 8 July.

The corresponding observations for Explorer 33 are shown in Figure 2. Here the data coverage is more continuous and provides an improved monitor of the interplanetary field during and following the flare event on 7 July. Note that the sector boundary (- to +) observed on July 4 in the interplanetary medium by Explorer 28 when 37 R_e East of the Earth-Sun line is clearly observed in the magnetosheath by Explorer 33 while it is 60 R_e West of the Sun-Earth line. Fluctuating fields are observed near the sector boundary and following the shock wave and are identified by the large differences (up to 5 gamma) in the two magnitudes presented. In general all the macrostructural features observed by Explorer 28 are simultaneously detected by Explorer 33. Indeed a direct overlay of Figures 1 and 2 reveals a remarkable agreement to within a gamma in magnitude and 5^{o}-10^{o} in direction at most times. The agreement of the field in these data shows that the interplanetary magnetic field is generally uniform on cislunar distance scales, i.e. < 0.01 AU. However, in the case of microstructural features such as the shock wave observed at 210 July 8 there appear to be significant differences, as will be discussed shortly.

The limited data obtained by Pioneer 6 is presented in Figure 3. Unfortunately the telemetry acquisition by DSIF ground stations at this time was very poor and extended data gaps exist. This precludes any direct comparison of the macrostructural features of sectors. From the data it appears that a sector boundary (from - to +) is observed on July 9 at ~1600. However, the delay time for co-rotation of a stationary sector pattern from the earth to Pioneer 6 is ~ 3 days dependent upon solar wind velocity. This yields a predicted sector boundary at 1600 July 7. The extended 3 day data gap in Pioneer 6 includes this time ± 1.5 days. The nature of the apparent sector boundary, as analyzed in a finer time scale for Pioneer 6 shows that there appear to be several filaments close to the boundary because the field switches polarity back and forth (from + to - and - to +) several times. Since θ is very large and ϕ is far from the ideal spiral angles of 130^{o} and 310^{o}, this may not be a real sector boundary but only a complex interplanetary structure.

<u>The Interplanetary Shock</u>

The shock wave associated with the sudden commencement (SC) on earth at 2102 on July 8 was observed at IMP-3 and Explorer 33 simultaneously (within the resolution of the instruments). The actual times were: IMP-3 - 2106 ± 20.5 seconds, Explorer 33 - 2105:42 ± 6 seconds. Thus at that time, the line between the two satellites lay in the plane of the shock surface. The geometry is shown in Figure 4.

The observed field changes were essentially identical at the two satellites. The magnitude discontinuously increased from 12 gamma to 21 gamma. The directional changes were relatively small being from $\theta = -6^\circ$, $\varphi = 305^\circ$ to $\theta = 0^\circ$, $\varphi = 293^\circ$ for IMP-3 and from $\theta = -10^\circ$, $\varphi = 310^\circ$ to $\theta = -18^\circ$, $\varphi = 300^\circ$ for Explorer 33.

Using the fact that the component of the field vector, $\vec{B}$, normal to the discontinuity surface must be conserved so that the change vector, $\Delta\vec{B}$, $(= \vec{B}_1 - \vec{B}_2)$ must also lie in the plane of the discontinuity, we can calculate the surface normal. The results in geocentric solar ecliptic coordinates are as follows: IMP-3, $\theta = +16^\circ$, $\varphi = 160^\circ$; Explorer 33, $\theta = 16^\circ, \varphi=163^\circ$. Normals computed using the coplanarity theorem (valid in the case of a true shock wave) give similar results: IMP-3, $\theta = 24^\circ$, $\varphi = 158^\circ$; Explorer 33, $\theta = -27^\circ$, $\varphi=182^\circ$. The discrepancy in θ appears to be real and may be a consequence of the fact that Explorer 33 was located in behind the moon relative to the sun (see Figure 5). A negative change in the latitude angle of the normal is what would be expected if the shock motion were impeded by the presence of the moon since Explorer 33 is 9.4 R_m (R_m = 1738 km) "above" the Moon. (Its position relative to the moon is selenocentric solar ecliptic coordinates in $X_{sse} = -19.6\ R_m$, $Y_{sse} = -5.1\ R_m$, $Z_{sse} = +9.4\ R_m$.)

A knowledge of the orientation of the shock then allows a refined calculation of its velocity in the vicinity of the earth. If it is assumed that the onset time of the SC at the earth corresponded to the passage of the shock at the earth the velocity is:

$$v' = \frac{5.4 \times 10^4 \text{ km}}{210 \text{ sec}} = 250 + 40 \text{ km/sec} .$$

Because this is less than the solar wind velocity it appears that the propagation velocities through the magnetosphere and magnetosheath are significantly different from the interplanetary value. An upper limit on the velocity may be estimated by assuming that the onset time of the SC at earth corresponded to the arrival of the shock at the bow shock. This assumption yields:

$$v < \frac{1.5 \times 10^5 \text{ km}}{210 \text{ sec}} = 710 \pm 50 \text{ km/sec} .$$

In any event the velocity of the shock by the time it reaches the earth is clearly less than the average velocity of the shock out from the sun which was 950 km/sec (see Van Allen and Ness, 1967). A knowledge of plasma velocities and densities on both sides of the shock would enable one to calculate the shock velocity unambiguously.

The most prominent event which we can tentatively identify as a shock in the Pioneer 6 records occurred at 1822 on July 10. At this time the field magnitude increased from 9 gamma to 22 gamma and the direction changed by about 10° from $\theta = 48^\circ$, $\varphi = 270^\circ$ to $\theta = 41^\circ$, $\varphi = 61^\circ$ in spacecraft centered solar ecliptic coordinates. The outward shock normal calculated using the coplanarity theorem was $\theta = 40^\circ$, $\varphi = 204^\circ$. It is not clear whether this shock was associated with the flare of July 7 or not. It is of interest to note that viewed from Pioneer, this flare was located less than 5° from the central meridian of the sun. Although there were no other flares of comparable (or greater) importance observed during the days from July 7 through July 10, it is not impossible that Pioneer observed the effects of flares invisible to observers on the earth, since it is separated significantly in heliocentric longitude.

Summary and Conclusions

During the period of July 4 to 12, 1966, two sector boundaries and a flare associated shock wave were observed by the magnetometers on IMP-3, Explorer 33 and Pioneer 6. In the preceeding 27 days, IMP-3 measured two other sector boundaries so that the interplanetary sector structure at the time of the flare on July 7 can be deduced to be as shown in Figure 6. (400 km/sec steady solar wind is assumed.) There were four distinct sectors with sizes 1/7, 2/7, 2/7, 2/7 solar rotation as found in the earlier study by Wilcox and Ness (1965).

The flare apparently occurred near the + to - sector boundary which passed the earth on July 8. A possible configuration of the shock generated by the flare is sketched in Figure 6b. This sketch conforms with the shock normals deduced from the measured fields both at IMP-3 and Explorer 33 near Earth and also at Pioneer 6. Although the gaps in the data coverage on Pioneer preclude an unambiguous association of the July 10 shock at Pioneer 6 with the July 8 SC at Earth, such an association seems plausible. This then implies that the shock propagated more rapidly out along the spiral magnetic field (and the sector boundary) than transverse to it. The reason for this behavior hopefully will become clear in future studies when both the plasma and the magnetic field data can be studied together.

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LIST OF FIGURES

6a. 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.

6b. 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 tensity and velocity).

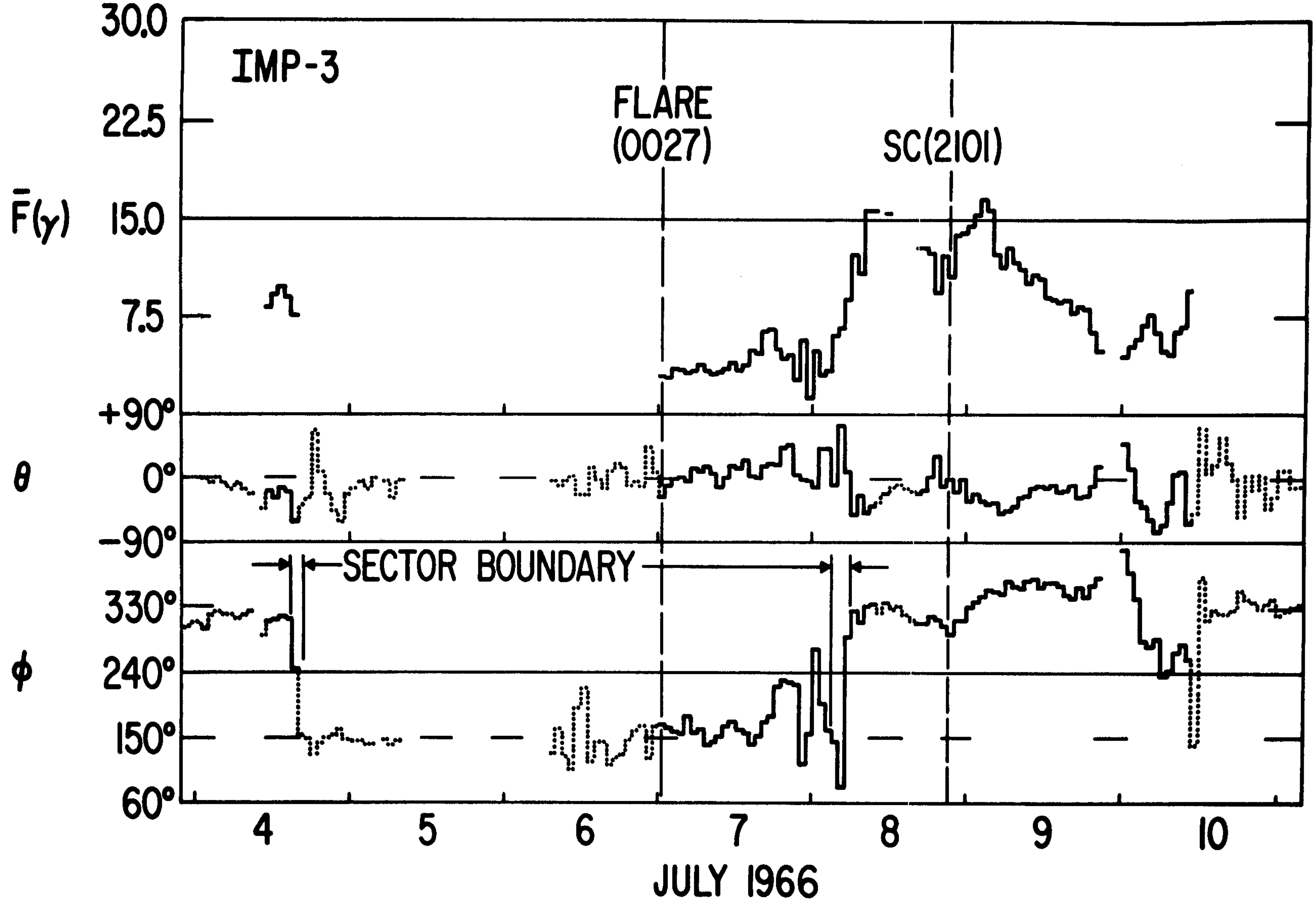
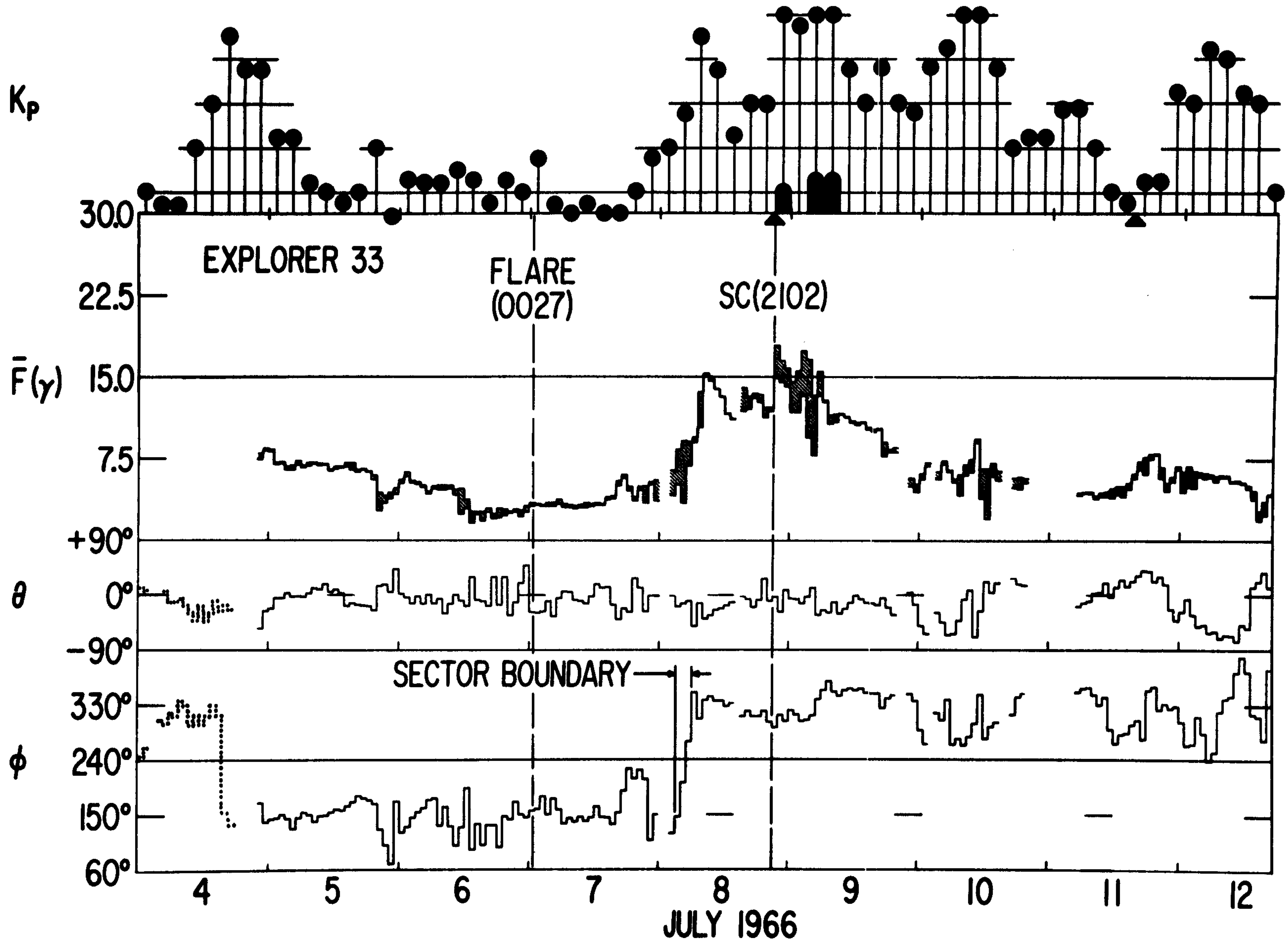

IMP-3
FLARE
(0027)
SC(2101)
F̄(γ)
θ
φ
30.0
22.5
15.0
7.5
+90°
0°
-90°
330°
240°
150°
60°
SECTOR BOUNDARY
4
5
6
7
8
9
10
JULY 1966

Figure 1



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

Figure 2

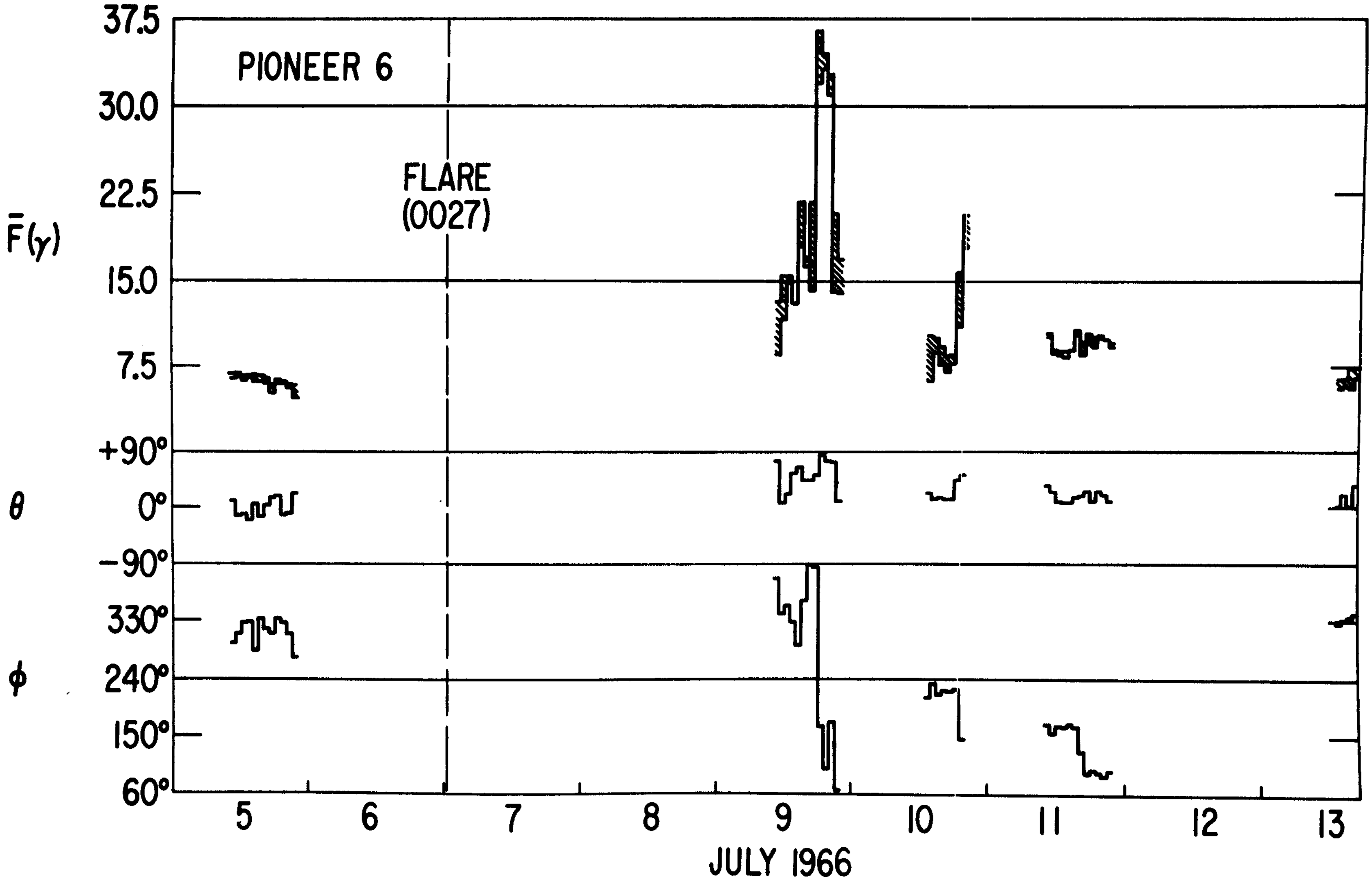

PIONEER 6
FLARE
(0027)
$\bar{F}(\gamma)$
37.5
30.0
22.5
15.0
7.5
θ
+90°
0°
−90°
ϕ
330°
240°
150°
60°
5
6
7
8
9
10
11
12
13
JULY 1966

Figure 3

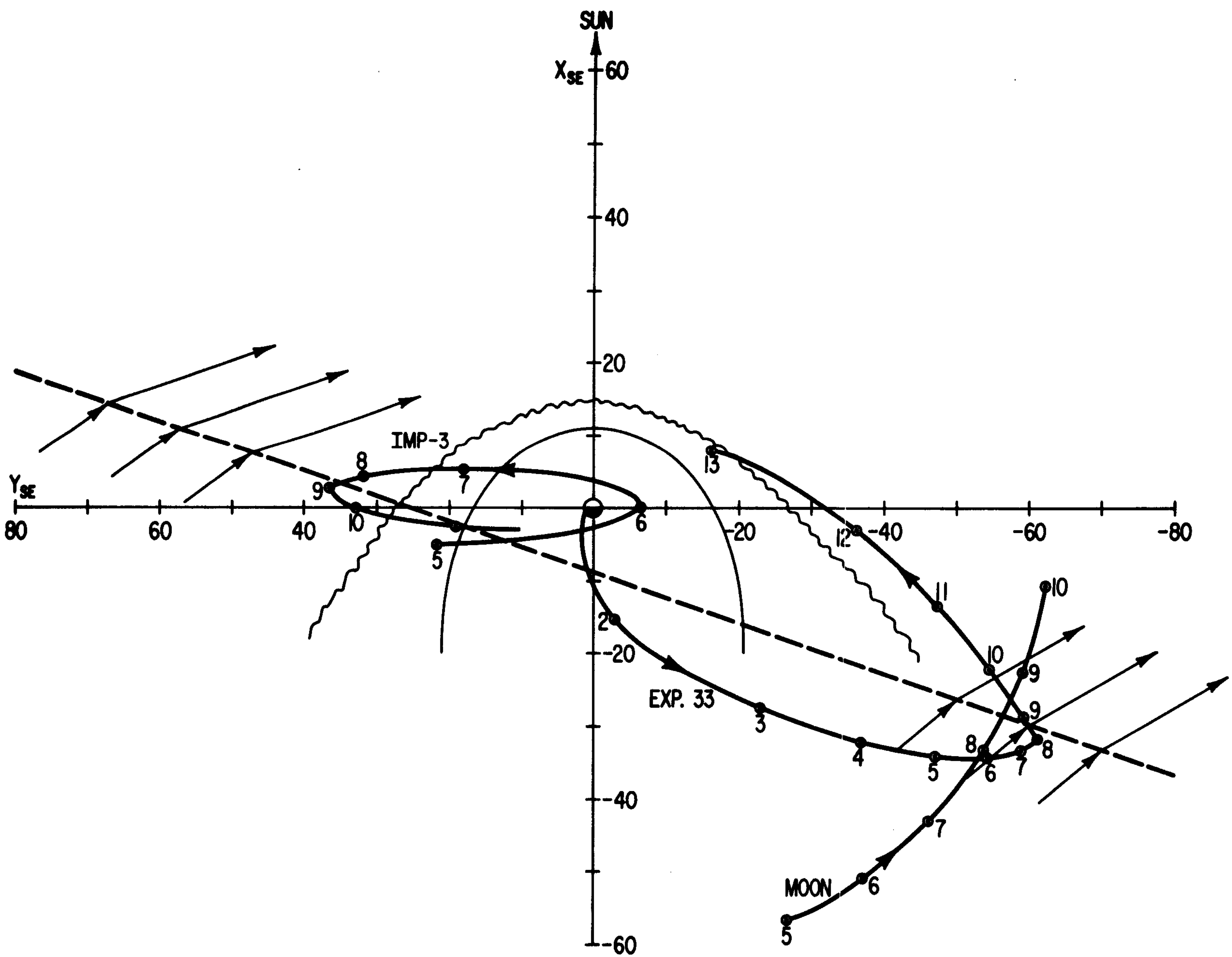


Figure 4

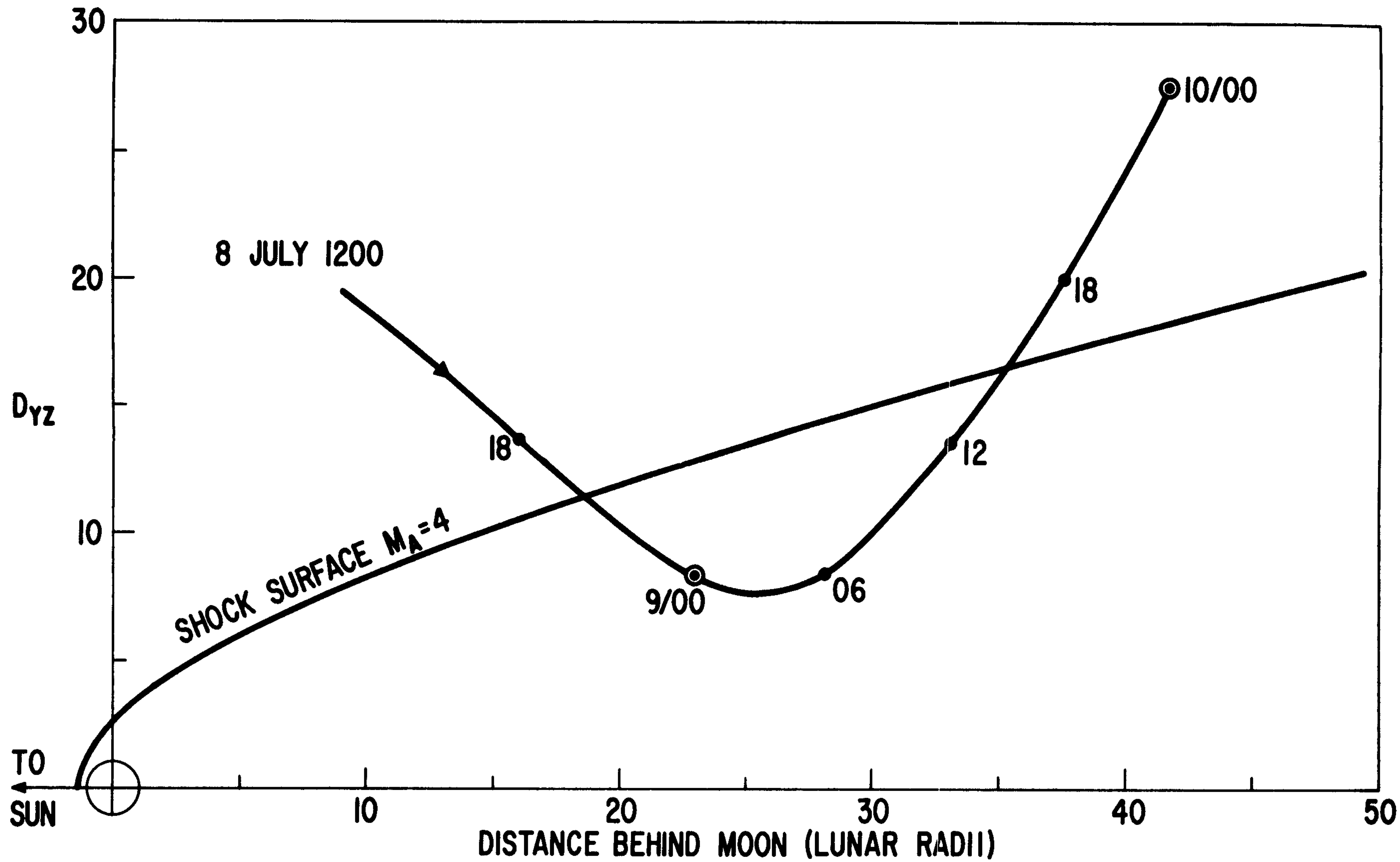

30
20
10
D_{YZ}
TO
SUN
10
20
30
40
50
DISTANCE BEHIND MOON (LUNAR RADII)
8 JULY 1200
18
9/00
06
12
18
10/00
SHOCK SURFACE M_A=4

Figure 5

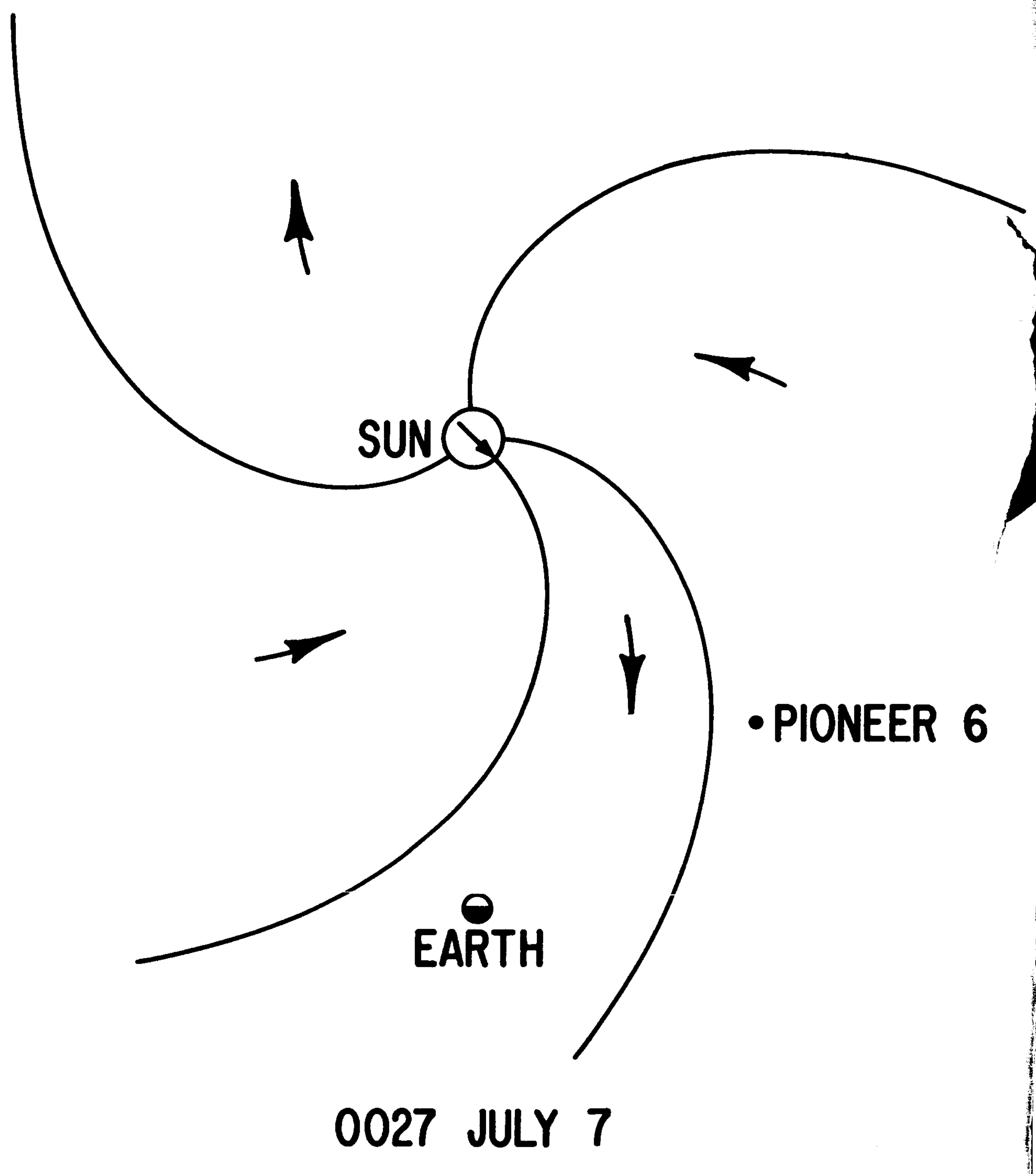


Figure 6a

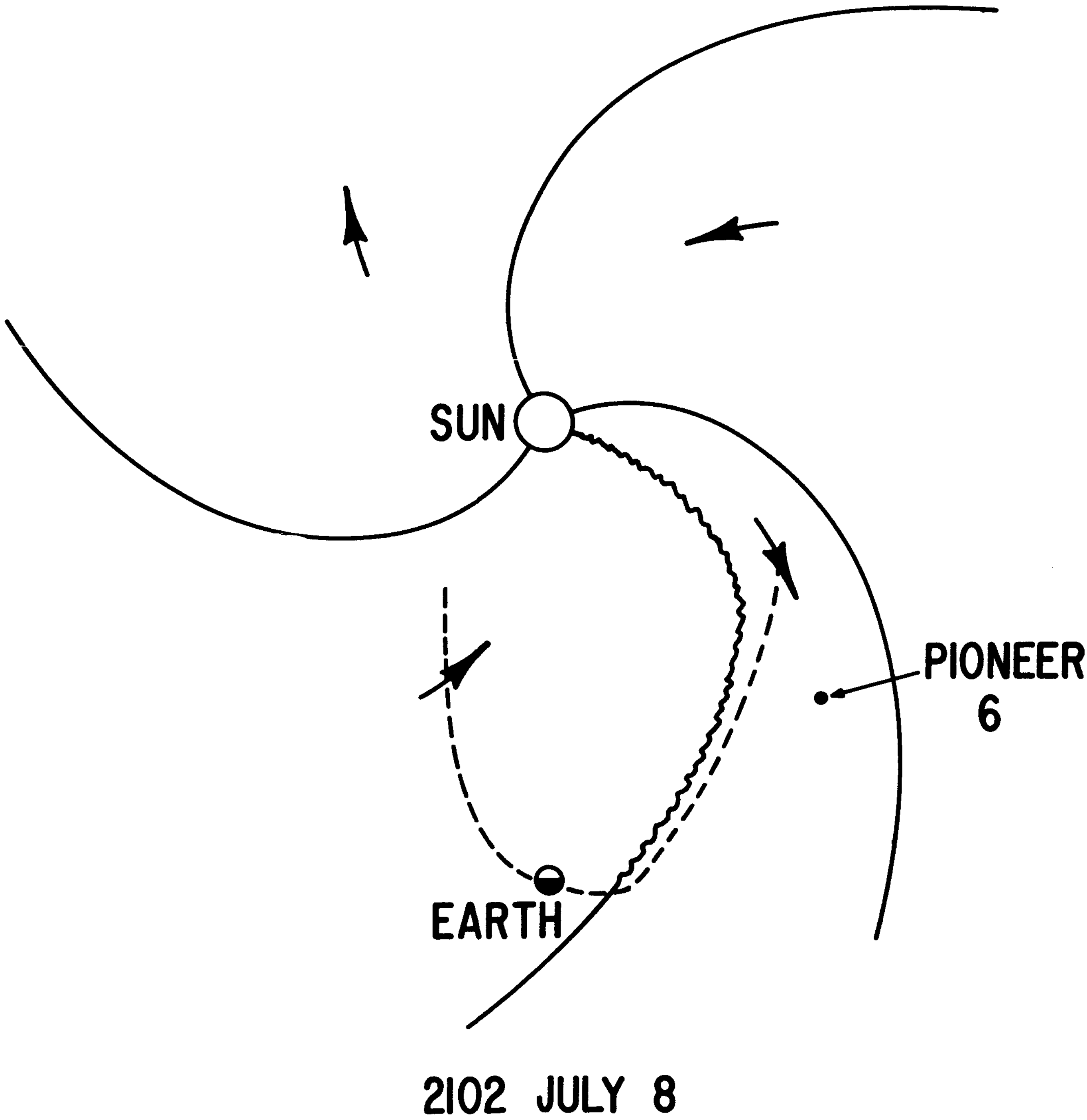


Figure 6b