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Abstract

In January 1968, Pioneer 8 passed through the extended geomagnetic tail region at 470-580 R_E downstream of the solar wind interaction with the geomagnetic field. Magnetic field observations suggest detection of the geomagnetic tail similar in characteristics to that observed by Pioneer 7 at 1000 R_E, but for a higher percentage of time when in the region of an extended, aberrated tail.

Introduction

The NASA interplanetary space probe Pioneer 8 was launched from the Eastern Test Range, Cape Kennedy, Florida on 13 December 1967 at 14H 08M UT. The heliocentric orbit achieved possesses an aphelion of 1.088 AU, perihelion of 0.9892 AU, inclination to ecliptic plane of 0.0578° and an orbital period of 386.6 days. The trajectory was so chosen that as the spacecraft lagged behind the earth, with respect to heliocentric longitude, it would pass near the anticipated extension of the geomagnetic tail at a geocentric distance of ~500 R_E. Previously Pioneer 7, launched into a similar trajectory, passed through the same region at a distance of ~1000 R_E (Ness et al., 1967b). Figure 1 shows the projection of both the Pioneer 7 and 8 trajectories on the ecliptic plane.

Observations of the extended geomagnetic tail have been made previously by several spacecraft. See Ness (1969) for a comprehensive review of the experimental studies of the geomagnetic tail. Existence of an ordered tail and its imbedded neutral sheet was established by Explorer 33 to distances of 80 R_E (Ness et al., 1967a, Behannon 1968; Mihalov et al., 1968). At larger distances, the measurements by Pioneer 7 (Ness et al., 1967b; Wolfe et al., 1967) at 1000 R_E suggested that certain of the observed field lines were connected to the earth in the shape of intermingled filamentary tubes. Fairfield (1968) in a detailed study of simultaneous magnetic field data from earth orbiting spacecraft and Pioneer 7 concluded that possibly an ordered tail was also consistent with the observed results.

In this paper we present preliminary results obtained by the NASA-Goddard Space Flight Center magnetic field experiment on Pioneer 8 in January 1968 as it passed through the extended geomagnetic tail region.

The monoaxial magnetometer, its geometry and its operation are similar to those used on the Pioneer 6 and 7 spacecrafts (Scearce et al., 1968); however, an automatic range switch was added providing a high range of $\pm 96\gamma$ with a sensitivity of $\pm 0.375\gamma$ and a low range of $\pm 32\gamma$ with a sensitivity of $\pm .125\gamma$. All data used in this paper have been obtained with the magnetometer operating in the low range. The spin period of the spacecraft was approximately 1 sec. at the time of the tail crossing with a vector measurement obtained once every 1.5 seconds.

Shown in Figure 2, in an enlarged scale, is the trajectory in the expected tail region projected on the X_{SE}-Y_{SE} and X_{SE}-Z_{SE} planes. Also shown are the distances Z_{SM} from the X_{SM}-Y_{SM} plane of the solar magnetospheric system and the expected distance $Z_{neutral}$ of the neutral sheet from the magnetospheric equatorial plane. The neutral sheet plane is defined according to the statistical results from IMP 1 (Speiser and Ness, 1967). $Z_{neutral}$ is computed by $Z_{neutral} = d \sin \chi_{ss}$, where χ_{ss} is the magnetic latitude of the subsolar point and d is taken to be 10 R_E. In the time interval between January 17 and 30 the daily variation of the angle χ_{ss} was approximately between 9^o and 32^o South. The interval within which a tail would be expected to be observed according to the simple model of an aberrated (5^o) cylindrical tail of diameter 40 R_E is also indicated in Figure 2.

Observations

The data presented are based on linear averages of the individual data points computed over time intervals of either 10 or 30 seconds, from which averages over longer times have been obtained. The number of data points in each average is initially respectively 7 or 8 and 23 or 24. The field intensity $\bar{F}$, defined as $\sqrt{(\bar{X})^2+(\bar{Y})^2+(\bar{Z})^2}$, and the angles θ (inclination of the field with respect to the ecliptic) and φ (azimuth in the ecliptic) are presented. The average intensity $\bar{\bar{F}}$ is also shown and is obtained by averaging the field intensities of individual data points.

The quantity $\delta = [\delta\overline{X}^2 + \delta\overline{Y}^2 + \delta\overline{Z}^2]^{\frac{1}{2}}$ is defined in terms of $\delta\overline{X}$, $\delta\overline{Y}$, $\delta\overline{Z}$, the RMS deviations of the individual components. This quantity is an invariant of the coordinate system and during most of the time is about 0.3 gammas, i.e., close to the level expected taking into account the quantization error of the measurements. It is particularly sensitive to direction variations. When $\delta\overline{F}$ and $\bar{\bar{F}}$ are known, the variance δ^* of the magnitudes of the individual field vectors is obtained from the relationship

$$\delta^* = [\delta^2 + \overline{F}^2 - \bar{\bar{F}}^2]^{\frac{1}{2}}$$

The magnetic activity on the ground between January 16 to 28, 1968 is expressed by values of the planetary magnetic activity index Kp and is less than 5-. January 25, for which ΣKp = 9+ and Ap = 4, is the quietest day after January 9 (ΣKp = 5-, Ap = 3). Geomagnetic activity is generally low except on January 26, when a ssc was reported on the ground at 1441 UT (ESSA, 1968b), followed by a perturbed field during the next few hours. A similar event was detected almost simultaneously with the ground event on Explorers 33 and 35, and delayed by 1.86 hours on Pioneer 8. This corresponds to a velocity from earth to Pioneer 8 of 540 km/sec. Flare and X-ray activity were also not higher than normal, a few flares of importance 2 being observed in the period (ESSA, 1968a). Simultaneous measurements of the interplanetary magnetic field by Explorer 33 are also useful in establishing the polarity of the field during the period of January 17-27 as positive, i.e., on average $\phi_{SE} = 135^{\circ}$.

A first inspection of the data using hourly averages in Figure 3 did not show a well ordered tail for long intervals (>several hours). Thus 20 minute averages were used to provide a higher time resolution. These averages are shown in Figures 4, 5 and 6 for time intervals with fields at orientations close to those expected for the tail, i.e., parallel or antiparallel to the earth-sun direction. These are indicated in Figure 5 by T or T* respectively.

Identification of the tail has been made on the basis that the field intensity $\overline{F}$ is relatively high, between 4-10γ, the variance is small (less than 1.0γ) the azimuth φ is $\approx 0^{\circ}$ or 180° and the inclination θ is zero or near to zero. Some tens of such tail observations have been made and also several crossings of a neutral sheet, which is identified by a field intensity very near zero as the azimuth changes rapidly from 0° to 180° or vice versa. The most significant of them are indicated in Figure 5. Shown in Figures 4 and 6 are two sections of data typical for the week preceding and the week following the tail observations.

The tail is not as well ordered as it appears in the Explorer 33 observations at 80 earth radii. In order to interpret the results, an estimated cross-section of the aberrated magnetosphere, symmetric on both sides of the neutral sheet plane, is shown in Figure 7. The diameter of the magnetosphere is taken equal to 40 R_E; the daily variation of the intersection of the ideal neutral sheet with the Y_{SE}-Z_{SE} plane is also indicated at four different times of the day. According to this ideal situation the expected field lines should point toward the earth at all times (i.e., in the northern portion of the magnetosphere). Thus, the observation of field lines at $\phi = 0^\circ(T)$ within a positive polarity sector can be considered very strong evidence for that field line connecting back to the north polar cap of the earth and hence representing the extended geomagnetic tail.

It is clear that a majority of tail observations occurs in correspondence to its expected position with a 5° aberration. Near zero magnitude fields are evident generally in correspondence to azimuth reversals, with characteristics expected for a neutral sheet. A section of a plot of 10 sec averages is shown in Figure 8 to illustrate this last point. It also appears that in most cases, a tail orientation is observed no longer than for a few tens of minutes.

The total time spent in the geomagnetic tail between January 16 and 27 is about 33 hours; in about 55% of this time field lines toward the earth were observed. The corresponding figures for the three day interval when the model tail was expected are about 18 hours, i.e., 25% of the total time; for about 12 hours the field lines were directed toward the earth. The percentage of time spent in the tail by Pioneer 7 was about 7% (Fairfield, private communication). On the other hand, Pioneer 8 was in a more favorable condition than Pioneer 7 to observe the tail, since the corresponding distances from the ecliptic plane were about 10 and 25 R_E respectively.

It is interesting to compare the magnetic field measured by Pioneer 8 with that measured in different places by other satellites simultaneously in orbit, in particular Explorer 33, launched on July 1, 1966, and Explorer 35 (Lunar Anchored IMP) launched on July 19, 1967. Figure 9 shows the trajectories of these satellites projected on the ecliptic plane in the period to which our analysis is limited. For this comparison appropriate time shifts have been introduced to achieve the best correspondence of the angular discontinuities observed at the three spacecrafts.

General agreement in the orientations, similar to that observed by Fairfield (1968) from the data of Explorers 28, 33 and Pioneer 7, is apparent during the interplanetary portion of the Explorers' orbits when Pioneer 8 is far from the expected tail, i.e., in the days before January 20 and those after January 26. In the intermediate days, when the tail is observed or also only expected, the similarity disappears almost completely. A few examples of striking similarity of the field orientations for Explorer 33 and Pioneer 8 are shown in Figure 10.

If the subscripts 8 and 33 are used to distinguish corresponding quantities for Pioneer 8 and Explorer 33 we have approximately, for the examples A, B, C of Figure 10:

A	$\varphi_8 \approx \varphi_{33} + 25^\circ$	$\theta_8 \approx \theta_{33}$
B	$\varphi_8 \approx \varphi_{33}$	$\theta_8 \approx \theta_{33}$
C	$\varphi_8 \approx \varphi_{33} + 25^\circ$	$\theta_8 \approx \theta_{33} + 15^\circ$

Explorer 33 was inside the magnetosheath in the first case and in interplanetary space in cases B and C. For the intensities, only in case A are the variations similar; in cases B and C there is no particular similarity, F_{33} being almost constant and F_8 varying quite rapidly. In case B the field orientation is exactly the same at the two different locations, while in the other cases a constant change of orientation is apparent. Several other situations like those above outlined occur at other times.

Conclusions

The main conclusion of our analysis is that the magnetic tail extends itself in the form of identifiable field lines up to distances of 500 R_E. A complex structure is shown by tail observations near its expected position. The tail appears to be swept back and forth across the spacecraft trajectory, a consequence of temporal variations in the direction of the solar wind velocity. It is also possible that the geomagnetic tail is no longer an ordered entity at 500 R_E and in fact may be filamentary due to penetration of the tail by the magnetosheath plasma or connection between the field in the tail and the interplanetary magnetic field. Since the velocity vector changes are not yet known from the onboard plasma measurements, no unique determination of true tail geometry is possible at this time.

Some tail field lines are observed quite far from the average tail; in particular, a thick "filament" is seen on January 27 between 1600 and 2020 UT; for this last case a deviation from a direction closer to the other filaments could have been caused by the ssc of January 26. The orientation of the field before and after the tail region is encountered is quite similar to that observed in the upstream interplanetary regions by Explorers 33 and 35. On the other hand, at other times in the tail region, the correlation between the orientations is absent or very poor.

The interpretation of the magnetic tail structure will benefit very much when the corresponding plasma data will be available regarding the direction of the plasma bulk flow velocity, its number density, temperature and thermal anisotropy. Especially revealing shall be the separate results for ions and electrons which may permit a resolution of the question regarding an ordered tail or a filamentary tail.

Acknowledgements

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FIGURE CAPTIONS

Figure 1 Pioneer 7 and 8 trajectories projected on the ecliptic plane

Figure 2 Projection of Pioneer 8 trajectory near passage through syzygy. Also shown are the solar magnetospheric coordinate Z_{SM} of the spacecraft location and the estimated neutral sheet distance $Z_{neutral}$ from the X_{SM}-Y_{SM} plane.

Figure 3 Hourly averages of the magnetic field elements $\overline{F}$, $\overline{\overline{F}}$, θ, φ observed by Pioneer 8 in January 1968. Kp is superimposed at bottom.

Figure 4 Twenty minute averages of the magnetic field from January $17^d\ 0^h$ to $18^d\ 12^h$, before the tail observation.

Figure 5 Twenty minute averages of the magnetic field showing a section of data in the tail region, from January $22^d\ 12^h$ to $24^d\ 0^h$. In the upper portion the time intervals of tail observations are also indicated; T or T* respectively mean the field points toward the earth ($\varphi \cong 0^o$) or away ($\varphi \cong 180^o$).

Figure 6 Twenty minute averages of the magnetic field from January $29^d\ 12^h$ to $31^d\ 0^h$, after the tail observation.

Figure 7 Ideal tail cross-section and location of individual tail filaments observed along the trajectory. The shaded area includes all possible intersections of the neutral sheet with the expected tail cross-section. An aberration of 5^o has been assumed.

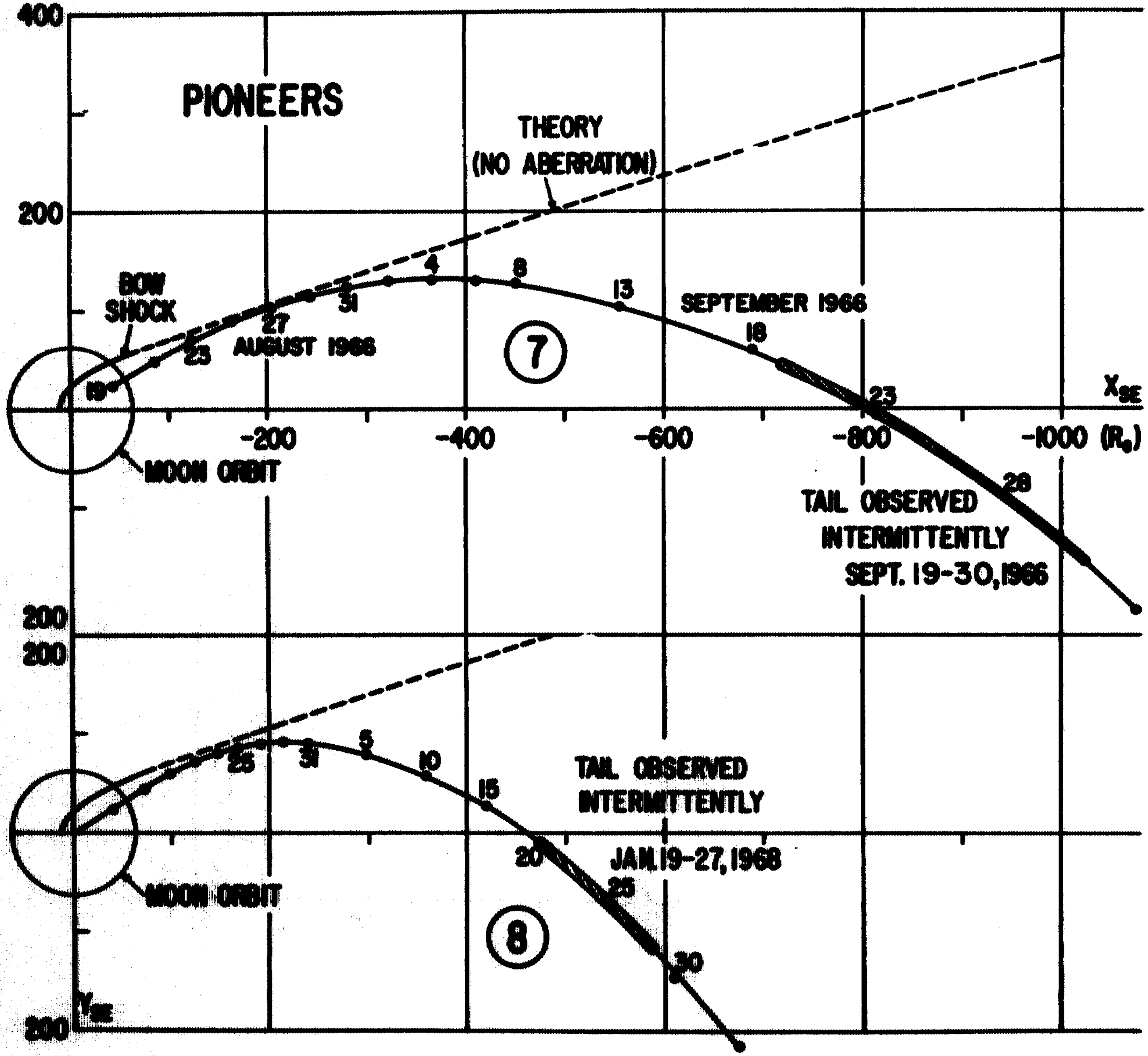
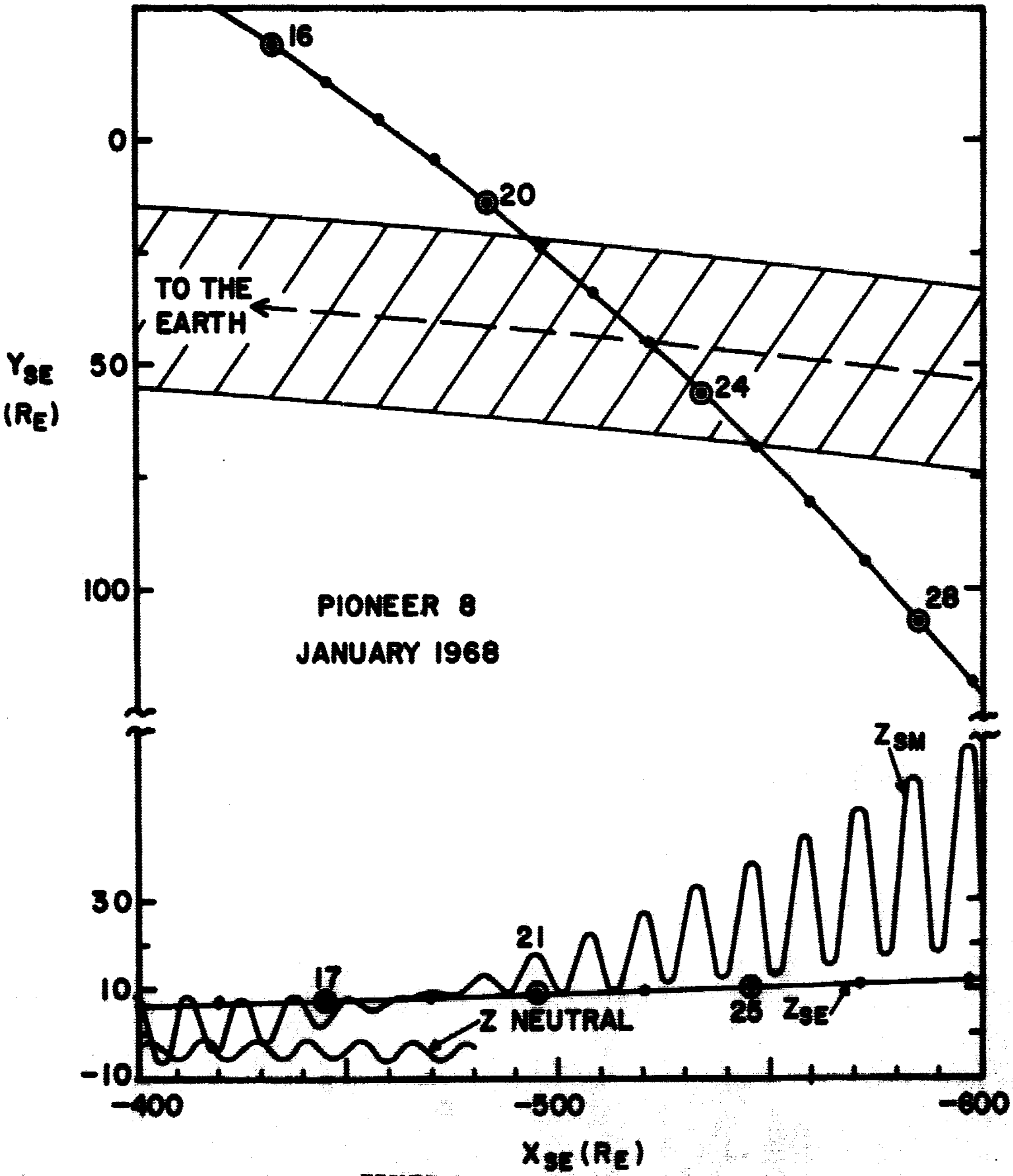
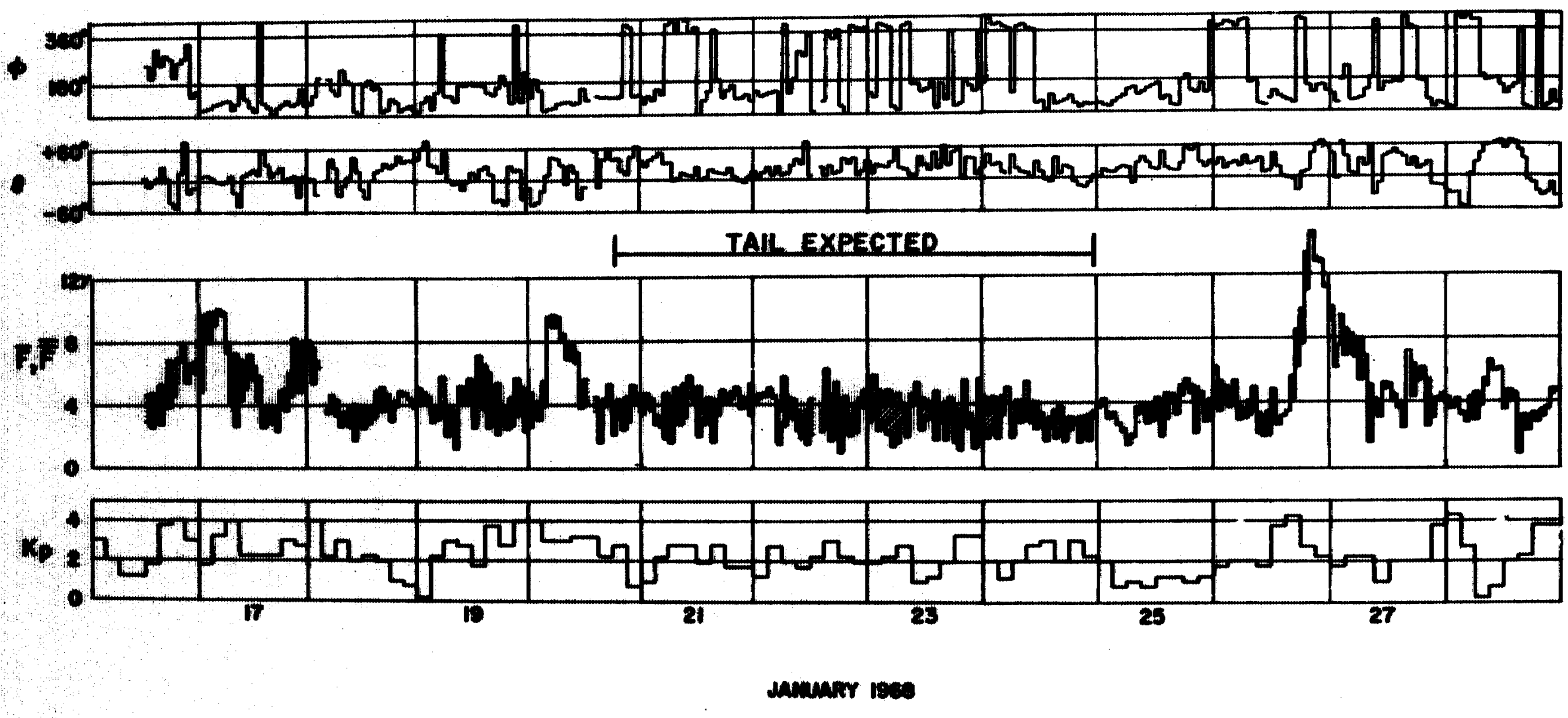

PIONEERS
THEORY
(NO ABERRATION)
BOW
SHOCK
MOON ORBIT
AUGUST 1966
SEPTEMBER 1966
TAIL OBSERVED
INTERMITTENTLY
SEPT. 19-30,1966
TAIL OBSERVED
INTERMITTENTLY
JAN.19-27,1968
7
8
-200
-400
-600
-800
-1000 (R$_e$)
400
200
X_{SE}
Y_{SE}

FIGURE 1



16
20
24
28
TO THE EARTH
Y_{SE} (R_E)
0
50
100
PIONEER 8
JANUARY 1968
Z_{SM}
30
10
-10
21
17
25
Z NEUTRAL
Z_{SE}
-400
-500
-600
X_{SE} (R_E)

FIGURE 2



φ
360°
180°
θ
+60°
-60°
TAIL EXPECTED
F, F
12γ
8
4
0
Kp
4
2
0
17
19
21
23
25
27
JANUARY 1968

FIGURE 3

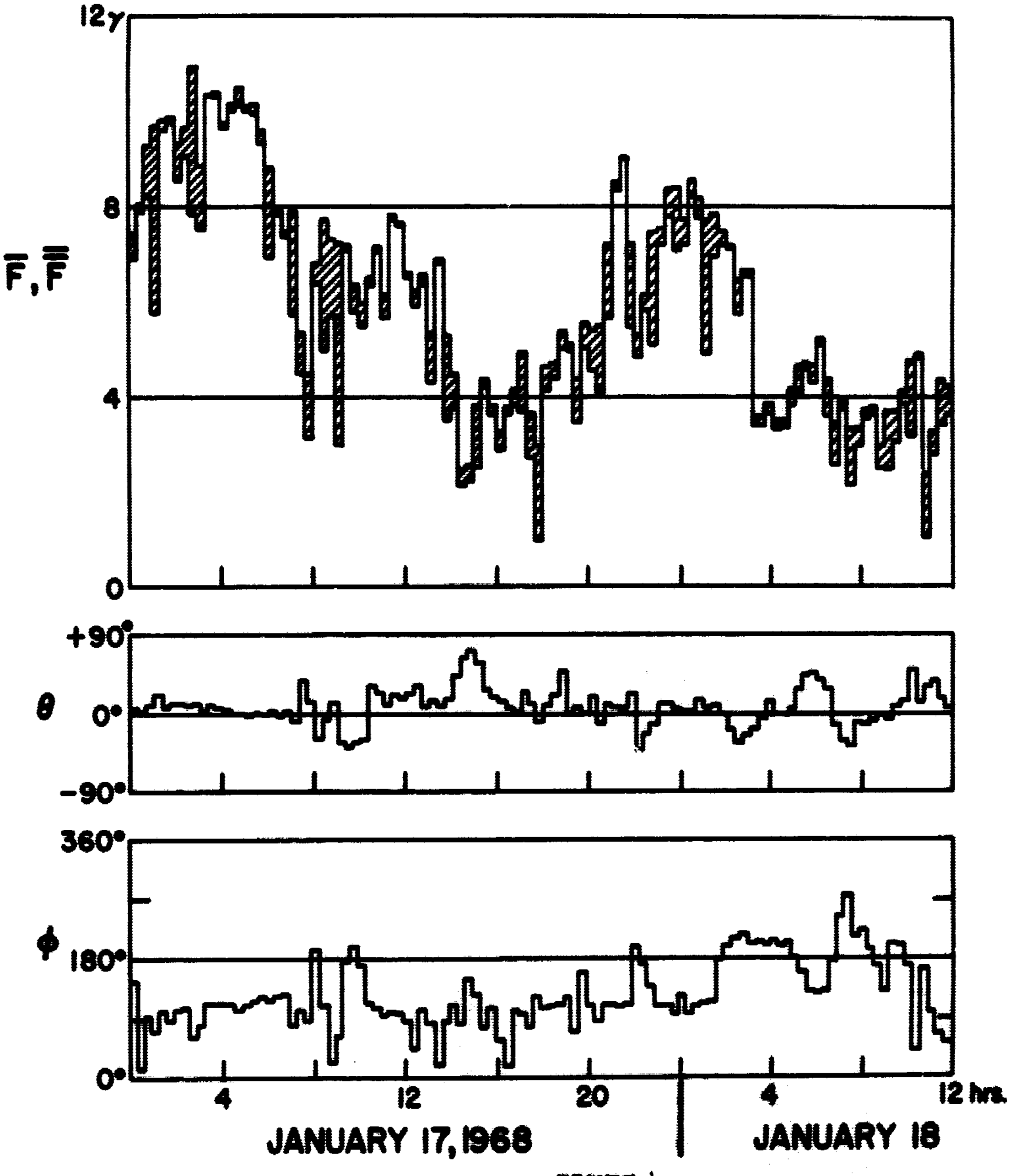
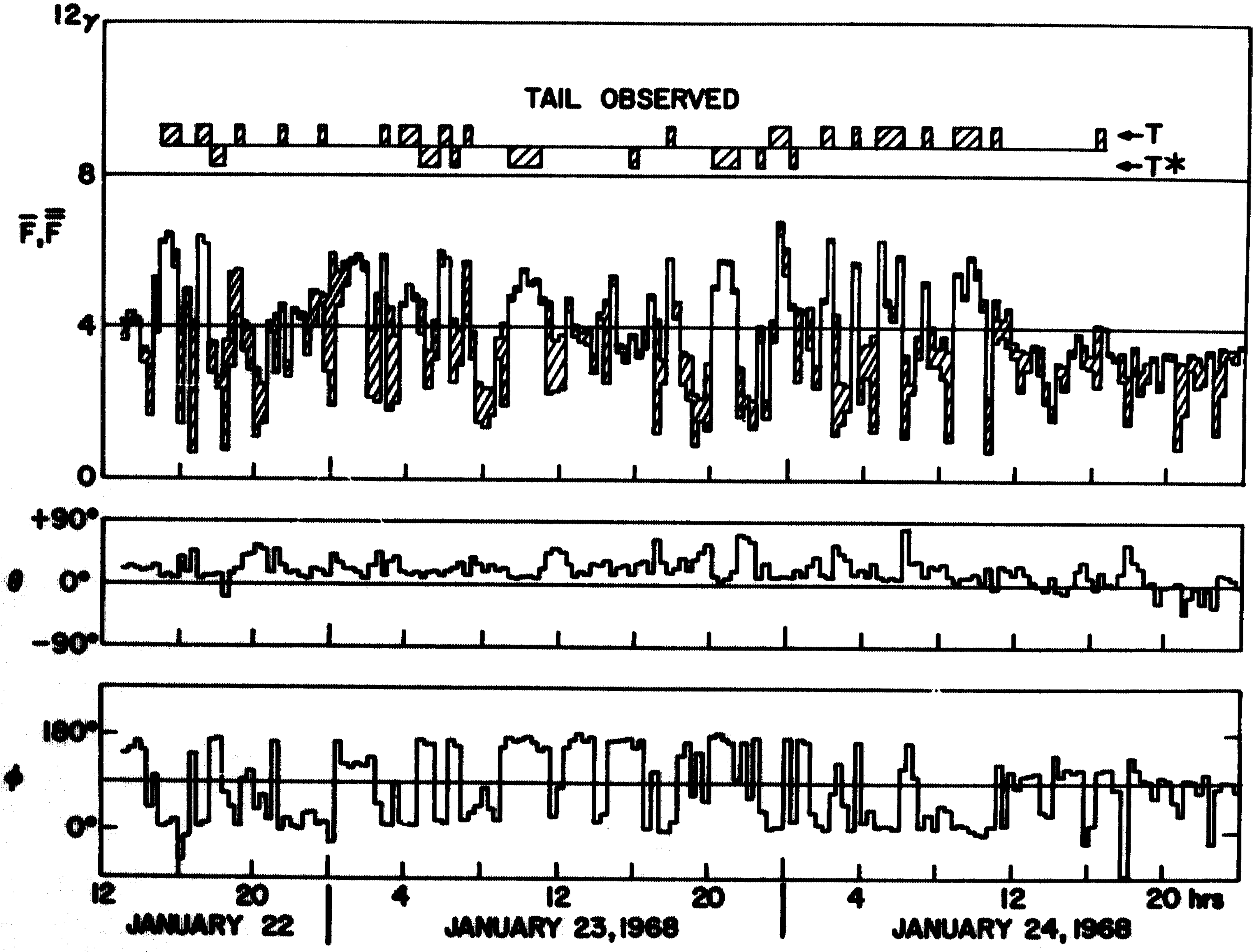

12γ
8
4
0
$\overline{F}, \overline{\overline{F}}$
+90°
θ
0°
-90°
360°
φ
180°
0°
4
12
20
4
12 hrs.
JANUARY 17, 1968
JANUARY 18

FIGURE 4



12γ
TAIL OBSERVED
←T
←T*
8
F̄, F̿
4
0
+90°
θ
0°
-90°
180°
φ
0°
12
20
4
12
20
4
12
20 hrs
JANUARY 22
JANUARY 23, 1968
JANUARY 24, 1968

FIGURE 5

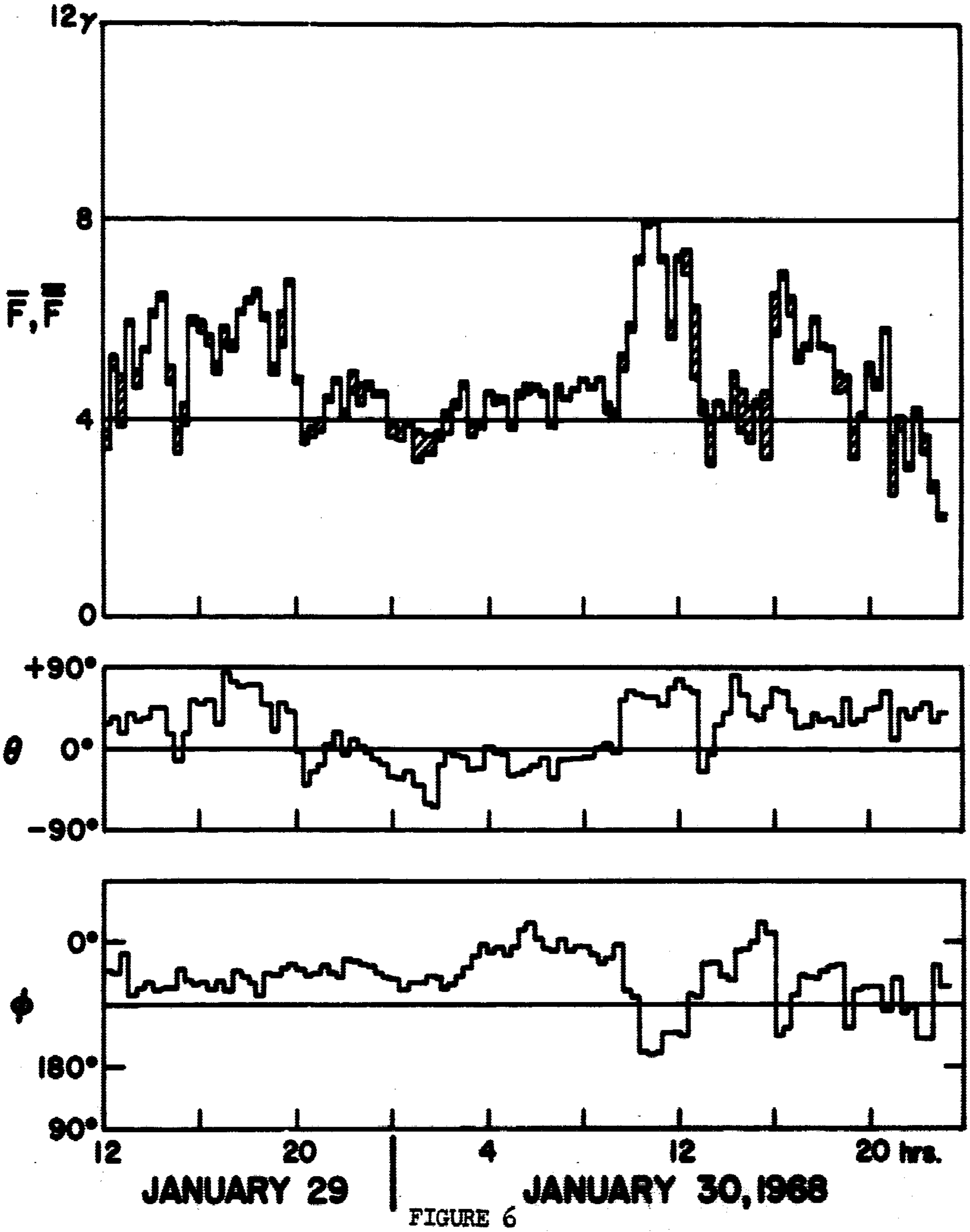
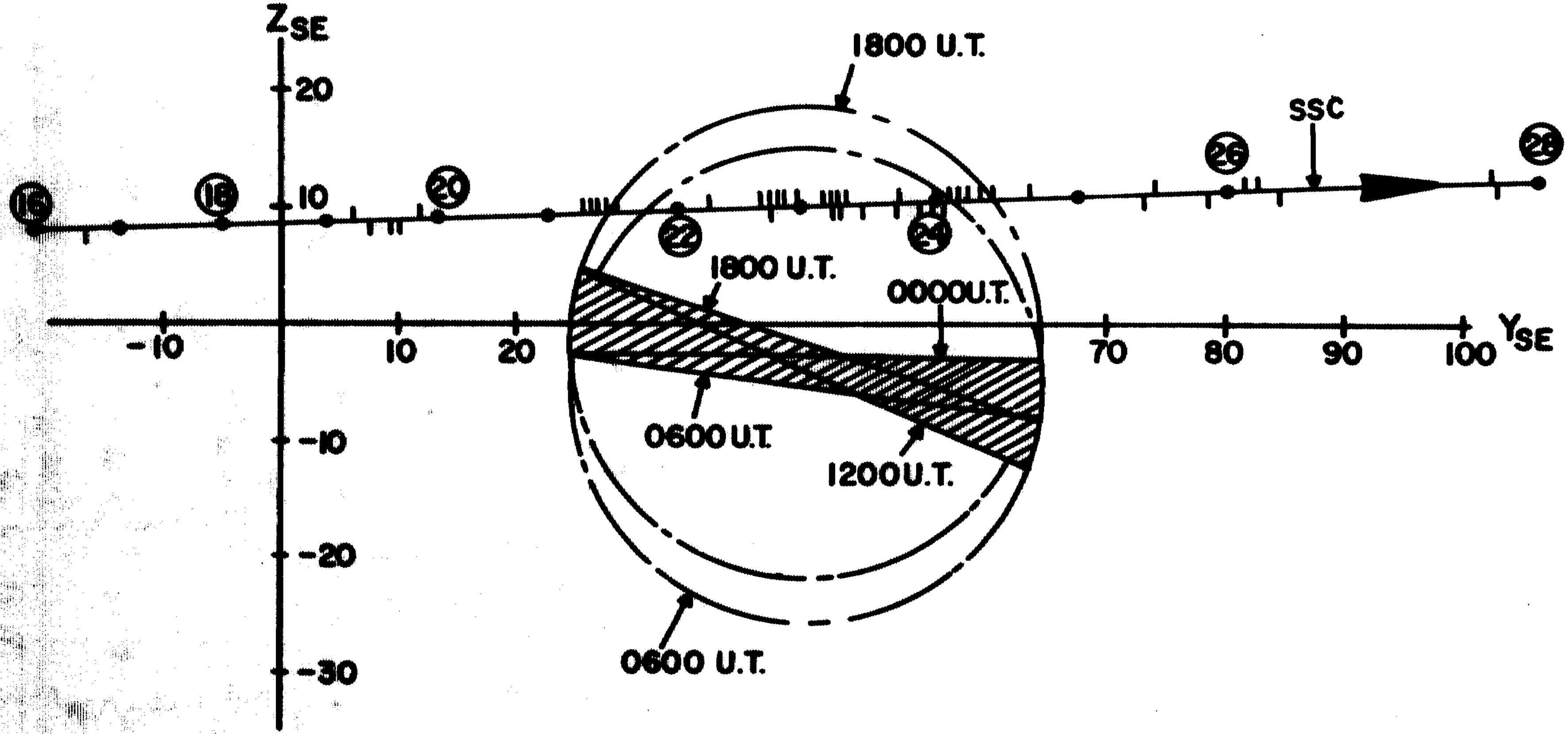

12γ
8
4
0
F̄, F̿
+90°
θ
0°
-90°
0°
φ
180°
90°
12
20
4
12
20 hrs.
JANUARY 29
JANUARY 30, 1968

FIGURE 6



Z_{SE}
20
10
-10
-20
-30
Y_{SE}
-10
10
20
70
80
90
100
16
18
20
22
24
26
28
SSC
1800 U.T.
1800 U.T.
0000U.T.
0600U.T.
1200U.T.
0600 U.T.

FIGURE 7

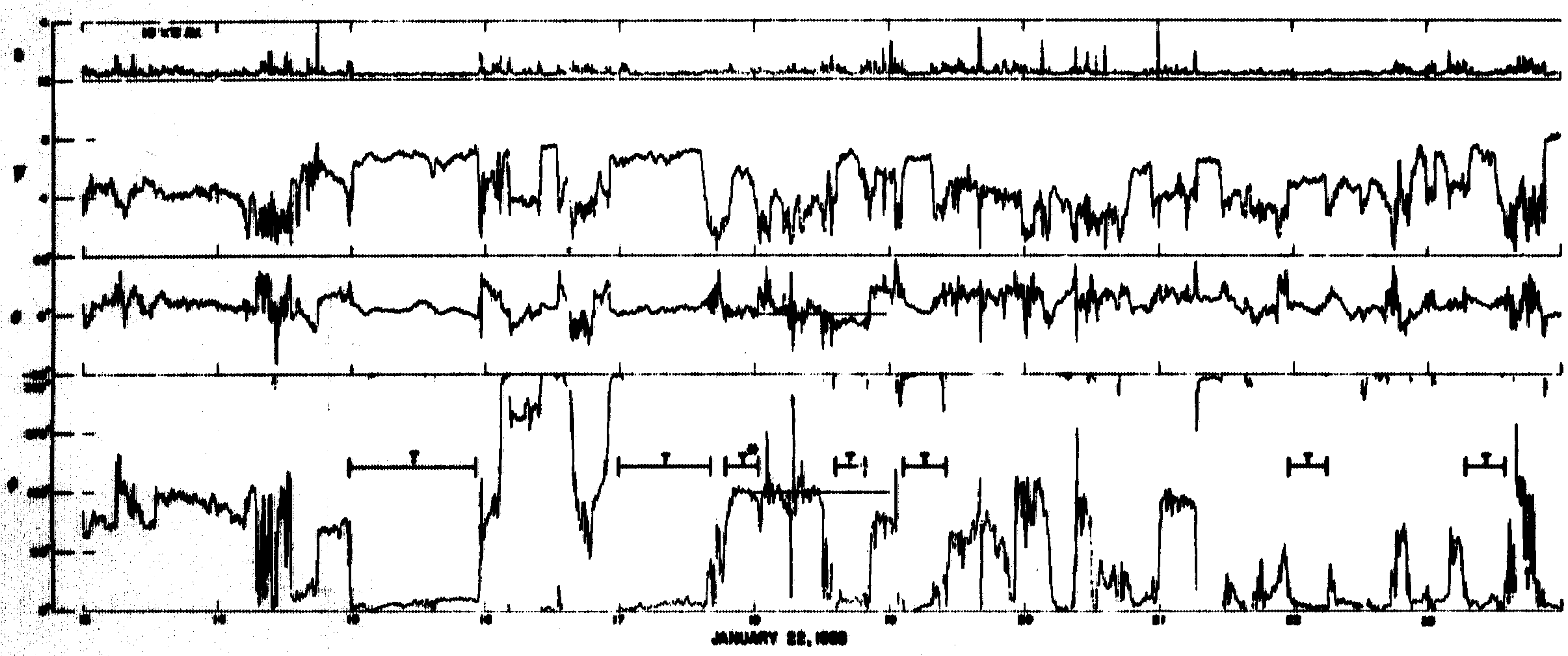
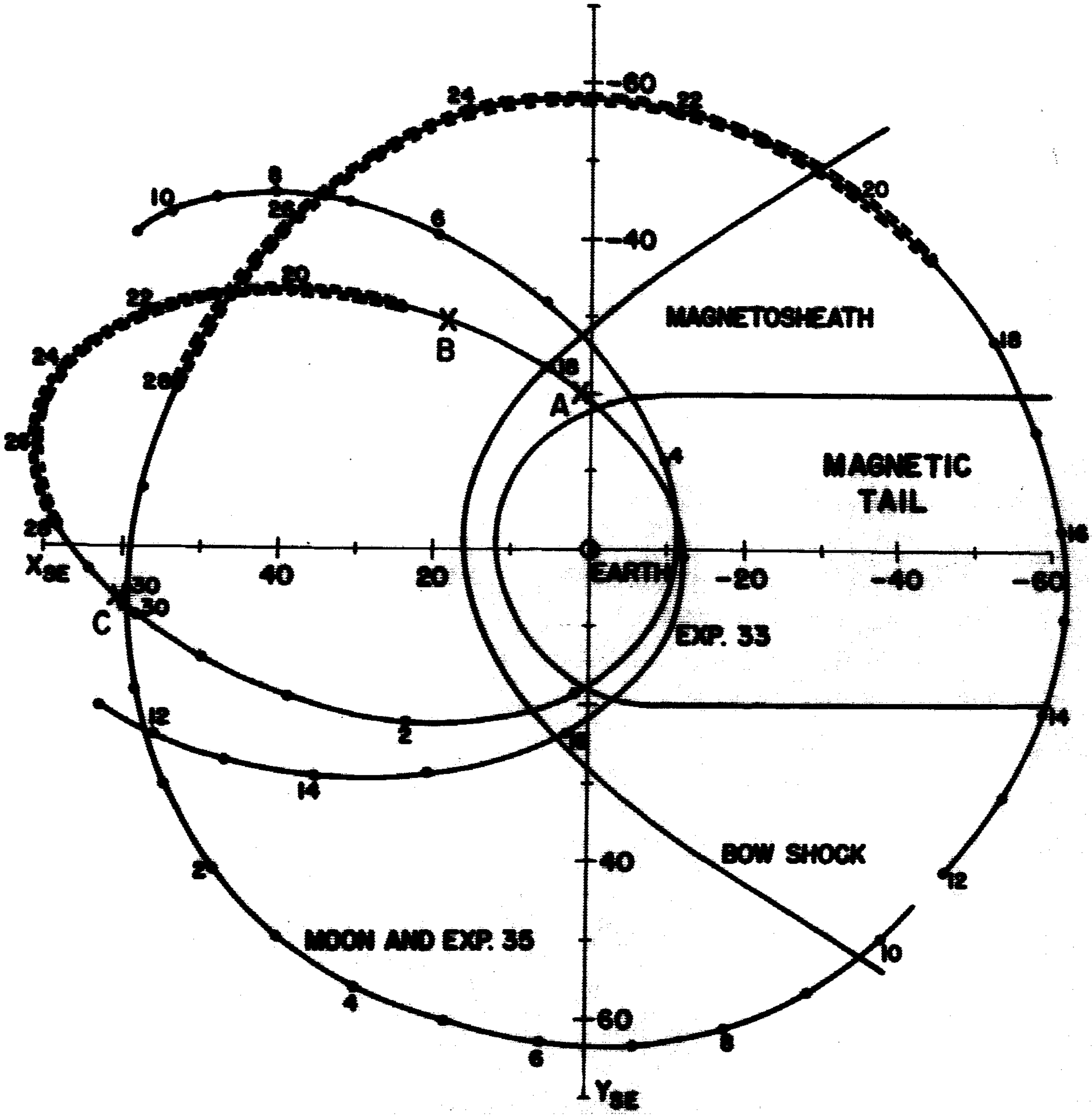
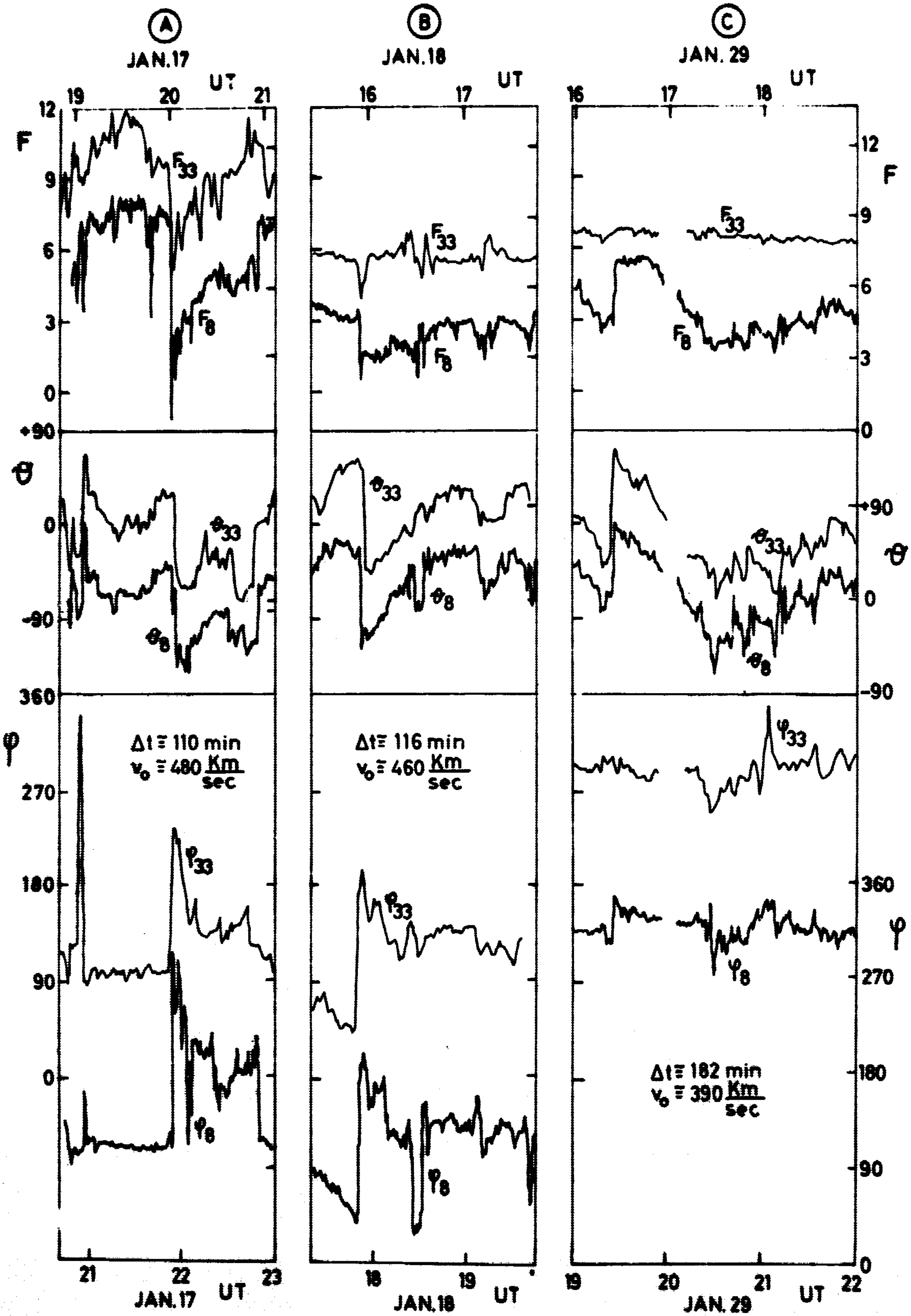


FIGURE 8



JANUARY-FEBRUARY 1968

FIGURE 9



A
JAN.17
UT
B
JAN.18
UT
C
JAN. 29
UT
F
F33
F8
ϑ
ϑ33
ϑ8
φ
φ33
φ8
Δt ≡ 110 min
v0 ≡ 480 Km/sec
Δt ≡ 116 min
v0 ≡ 460 Km/sec
Δt ≡ 182 min
v0 ≡ 390 Km/sec
JAN.17 UT
JAN.18 UT
JAN. 29 UT

Fig. 10