Magnetotail Changes in Relation

to the Solar Wind Magnetic Field

and Magnetospheric Substorms

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Abstract

An attempt is made to understand some of the magnetotail dynamics by using simultaneous observations from several satellites: Explorers 33 and 35 in the solar wind, IMP 4 in the near magnetotail (30 R_E), ATS 1, and OGO 5 in the magnetosphere. We observed that in the main lobes of the tail the magnetic field increases slowly when the interplanetary magnetic field turns southward, and can decrease slowly after a substorm. The plasma sheet changes indicate a thinning when the interplanetary magnetic field turns southward and an expansion when it turns northward. When combined with the plasma sheet expansion, which has been observed by several authors to follow a substorm, these results allow us to draw a schematic view of the relations between the changes in the orientation of the solar wind magnetic field, the substorms, and the changes in the tail parameters.

1. Introduction

Many attempts have been made recently to understand the cause of magnetospheric substorms. Because of the major role it plays in the various theories which are presently available, the magnetotail region has been particularly well investigated by a number of experimenters. Particle observations have shown that in the tail at 17 Re from the earth 45 kev electrons in the plasma sheet disappear before, and reappear coincident with or after the sharp maximum of the bay in the auroral zone (Hones et al., 1967). Hones (1969) has clearly demonstrated that this signature is produced by a thinning of the plasma sheet in the initial phase of substorms and then a subsequent expansion.

During the thinning, the border of the plasma sheet has been shown in one occasion to move toward the neutral sheet at a velocity of 6 km/s. In contrast, the expansion is characterized by a velocity away from the neutral sheet ranging from 5 to 20 km/s (Hones et al., 1970, Akasofu et al., 1970).

Magnetic field observations between 10 Re and 40 Re behind the earth have shown two main kinds of variation of the tail magnetic field namely, slow increase or decrease of the field at a rate of some gammas per hour, and rapid increase or decrease of the field at a rate which can be as high as several gammas per minute (Anderson and Ness 1966, Heppner et al., 1967, Fairfield and Ness 1970, Camidge and Rostoker 1970, Brody and Holzer 1970, Russell et al., 1970). The typical substorm signature in the tail is a slow increase of the field followed by a rapid decrease. This sharp decrease in the field is generally considered to be due to a spatial phenomenon namely the expansion of the plasma sheet observed by Hones (1969), Hones et al. (1970), and Akasofu et al. (1970). Since the time of this rapid decrease can be accurately measured, many authors have tried to relate it to the best defined feature of the auroral substorm, the onset of the expansion phase. The results vary considerably from one author to another: the field decrease can be seen to coincide roughly with the beginning of the expansion phase of the substorm (Camidge and Rostoker 1970, Rostoker 1970) or to occur within a well defined delay (14 to 15 minutes as observed by Heppner et al., 1967). By studying about 20 substorms when the OGO A satellite was in the tail, Brody and Holzer (1970) found that the field decrease occurs on the average 54 minutes after the onset of the expansion of the auroral substorm. More recently Russell et al. (1970) found that the tail changes occurred coincident with some weak magnetic activity on the ground but did not find any precise relation between the magnetic field variation on the ground and in the tail. The reason for these divergent results is that, as will be shown in this paper, the rapid decrease of the tail field is quite often not at all related to substorms. In the present study we have separated the rapid and slow variations of the tail field and tried to find which of them, if any, is directly related to substorms.

Observations of changes in the tail magnetic field were provided by the published data from IMP-4 (Fairfield and Ness 1970). We have sought an explanation of these changes either in the solar wind or in the inner magnetosphere. The solar wind plasma parameters were obtained by the MIT experiment on board Explorer 33 and Explorer 35 (Dr. Binsack); the interplanetary magnetic field were obtained with the NASA Ames magnetometer on board these two satellites (Dr. Sonett) and were provided by the Space Data Center. The occurrence of substorms in the inner magnetosphere was determined from the UCLA magnetometer on board the synchronous satellite ATS 1 and various ground magnetograms (obtained from World Data Center A for Geomagnetism.)

These data show that the tail can respond directly to the solar wind in the following ways:

- when the interplanetary field turns southward the magnetic field increases in the main lobe of the tail and the plasma sheet thins,
- when the interplanetary field turns northward the plasma sheet expands.

These variations due to the solar wind only, must be combined with those due to substorm expansions: decrease of the magnetic field in the main lobe and expansion of the plasma sheet.

We shall present three examples illustrating the tail response in each of the above cases. The first one, on

February 13, 1968, occurred when IMP 4 was in the main lobe of the tail, and shows mainly the slow variation of the magnitude of the tail field: increases due to the solar wind magnetic field being southward, decreases due to the substorms. The second example on February 14 shows the thinning and expansion of the plasma sheet caused by reversals of the solar wind magnetic field without the intervention of substorms. In the third example on March 28, 1968, the two types of behavior are combined and displayed in their most typical sequence: slow increases and rapid decreases of the field. Moreover on this particular day the data from the OGO 5 satellite in the dawn magnetosphere allows the correlation between the magnetosphere and tail perturbations to be made.

2.1 <u>February 13, 1968</u>

We choose this day because the observations made by IMP 4 in the tail were relatively free of the influence of the rapid expansion of the plasma sheet (except after 1800 UT) and this allows us to analyse the slow increases and decreases of the tail field. Fig. 1 presents the solar wind data from Exp. 35 namely the hourly averages of the streaming energy density ρV^2*, the thermal energy density NkT, as well as the variation of the 80 sec averages of the angle α between the interplanetary magnetic field and the GSE equatorial plane. The tail magnetic field (total field and component along the GSM Z axis) as well as the latitude and longitude angles θ and ϕ of this field,

*(protons only are supposed to be present).

measured by IMP 4 at a distance Z' from the expected position of the neutral sheet (Russell and Brody 1967) are also presented in this figure. There is no apparent correlation between the solar wind energy densities (kinetic or thermal) and the amplitude of the tail field.

Rostoker (1968) has shown that the direction of the interplanetary field in the solar equatorial plane has an influence on the substorm activity; consequently for the examples presented here we checked this direction (however as it did not change very much we did not have it plotted). On February 13 between 1100 and 2100 UT the longitude angle remained between 90^{o} and 180^{o} (0^{o} is toward the sun, 90^{o} along the dusk meridan, 180^{o} away from the sun, etc).

In Fig. 2 the variation versus time of the solar wind magnetic field orientation, the ground magnetic activity and the increases or decreases of the tail field are shown schematically. We shall use the same format for all examples and it is worth discussing in some detail. In regard to the solar wind data presented on the left we represent differently the time intervals where the orientation is southward (S), northward (N), or horizontal (with or without fluctuations). In the tail data shown at the right, we represent the time intervals with slow increases or decreases of the field with vectors of appropriate slope. The rapid decreases (increases) considered to be due to the expansion (thinning) of the plasma sheet are indicated by EXPANS. (THINNING). Finally the magnetic activity measured from the ground observatories and the ATS satellite is shown in the center: each substorm sequence from the growth phase till the end is delineated by dashed lines and in each sequence the approximate onsets of the expansion phases (EP) are indicated. As the timing of substorm from ground magnetograms can be very controversial the data from 17 ground observatories used in this study are shown in the Appendix (Fig. A2). At the bottom of the figure the relative positions of the satellites Exp. 33, IMP 4 and ATS 1 are shown by projections on the GSE equatorial Plane. On February 13 Explorer 33 was about 65 Re in front of the earth and IMP 4 about -25 Re behind the earth. The relative spacing in Fig. 2, of the vertical lines labelled EXP. 33, Earth and IMP 4 reproduces this configuration. We used the velocity of the solar wind as measured by the MIT plasma experiment on board Explorer 33 (hourly averages 480 to 515 km/sec during this time interval) to trace the trajectory of any reversal of the interplanetary field from EXP. 33 to the earth and IMP 4: the oblique lines in Fig. 2 represent such a trajectory when the decrease in velocity behind the bow shock is neglected.

It appears from Fig. 2 that the tail magnetic field far from the plasma sheet (Z' is larger than 6 Re) increases slowly when the interplanetary field turns southward (around 1100 UT), or horizontal with fluctuation (around 1410 UT) and that it decreases slowly following (without more precision) the onset of the expansion phase of substorms (around 1230 and

1610 UT). It should be emphasized that these slow decreases of the field start roughly coincident with substorm expansions, and precede the change in solar wind magnetic field thus establishing the association of this effect with substorms only.

2.2 February 14, 1968

Fig. 3 present the original data for this event in the same format as discussed for Figure 1. In regard to the solar wind magnetic field orientation a word of caution is necessary. The Ames magnetometer was at this time working in "error mode" and measured "instead of the total vector, one half of the vector component lying in the spin plane" (Colburn, 1969). So the angle β in Fig. 3 is different from the angle α in Fig. 1; but as the spin plane of Explorer 33 is normal to the ecliptic plane, both angles have the same sign and a negative (positive) β angle means a southward (northward) interplanetary magnetic field. Due to this error mode, the longitude of the interplanetary magnetic field could not be measured. Fig. 4 presents schematically the variation of the solar wind magnetic field orientation, ground magnetic activity and amplitude of the tail field using the same format as in Fig. 2.

The event of February 14 shown in Figures 3 and 4 has been selected because it provides a sharp contrast to the two slowly varying events of February 13. A sudden increase in field magnitude at 2120 and a sudden decrease at 2350 are the distinguishing features of this event. From Fig. 3 there is again no obvious correlation between the solar wind kinetic energy and thermal energy density and the tail field. The convection velocity of the solar wind, 410 to 470 km/sec during this time interval, was used to draw the oblique lines in Fig. 4. As already noted by Fairfield and Ness (1970) the interplanetary field remained northward from 0300 till 2000 UT; during this same time there was no magnetic activity on the ground and the tail data show that from at least 0600 UT (Fig. 3) IMP 4 remained in a thick plasma sheet. Accordingly the diagram in Fig. 4 has been limited to the interval 2000 to 2400 UT. It appears from Fig. 4 that the rapid increase of the magnetic field at 2120 followed the reversal of the interplanetary field from northward to southward. The rapid decrease at 2350 UT followed a reversal from south to north. Between 2130 and 2400 UT weak magnetic activity was recorded on the ground; however no distinct substorm expansion could be identified, (Fig. A3). The increased stability of the field between the times of the rapid increase and decrease suggests that IMP 4 was in the lobe of the tail rather than the plasma sheet. Furthermore, it should be emphasized that the rapid increase and decrease of the field occurred at rates of about 0.5γ per minute in contrast to a rate of less than 0.1γ per minute on February 13 (Fig. 1), when IMP 4 was definitely in the lobe. Because these rates are so much greater than those characteristic of the lobe we attribute the sudden changes to passage through a spatial boundary, i.e., the boundary of the plasma sheet. Furthermore, since no distinct substorm could be identified in the ground data we conclude that the thinning of the plasma sheet at 2120, and the expansion at 2350 UT, were responses to the direction of the interplanetary magnetic field rather than substorm activity.

An additional example of this same phenomenon occurred at 1810 on February 13 (Fig. 1). A sudden decrease in field magnitude and a sudden appearance of turbulence in the field indicates that IMP 4 was engulfed in an expanding plasma sheet. Ground magnetograms, Figure A2, show no substorm expansion occurred at this time. However, the solar wind data shows that the interplanetary magnetic field did switch northward. The plasma sheet after 1800 UT (Fig. 1) was about 18 Re thick.

In summary, from the observations of rapid changes on February 13 and 14 we conclude that the plasma sheet thins when the interplanetary field turns southward and it expands when it turns northward.

2.3 March 28, 1968

We chose this event because it is a good example of the most typical signature in the tail at the time of substorms: namely a combination of a slow increase before the substorm and a sharp decrease after the substorm. Figure 5 presents the solar wind data as before. During this same interval the longitude of the interplanetary magnetic field fluctuated between 270^{o} and 320^{o}. From Fig. 5, no correlation appears between the variation of the tail field and the variation of the solar wind plasma parameters. In Fig. 6 the sequences of events in the solar wind, the magnetosphere and the magnetotail are represented schematically in the usual way; the ground magnetograms are shown in Fig. A4. In Fig. 6 we observe the classical features already described for the data from February 13 and 14, namely the tail field increases slowly when the solar wind magnetic field turns southward (0330 UT) and the plasma sheet expands when the solar wind magnetic field turns northward (0420 and 0800 UT). At 0650 UT we cannot determine which part of the field variation at IMP 4 is due to the crossing of the border of the plasma sheet and which part is truly a temporal increase.

For March 28 we have additional information provided by the UCLA magnetometer on the OGO 5 satellite outbound in the dawn meridian between 9.5 Re and 16.5 Re. (See bottom of Fig. 6). This OGO-5 data will enable us to present an overall view of what is going on simultaneously in the solar wind, the far magnetosphere at dawn (OGO-5), the inner magnetosphere at dusk (ATS 1) and the tail at -30 Re (IMP 4). In Fig. 7 the ATS 1 and OGO 5 data are presented versus universal time. At the very top the orientation of the solar wind magnetic field (south or north) is indicated schematically; vertical lines allow one to visualize the possible effect of the solar wind magnetic field reversals and of the onsets of substorm expansion phases on the various parameters. In regard to the ATS 1 data, panel 1 shows the deviation of the total field from the dipole field and panel 2 the total rms fluctuations. Below, the OGO 5 data is represented in the same manner as already used by Russell et al. (1970) namely: the difference between the measured and the expected field (Jensen and Cain 1962 model), the rms fluctuations, the inclination (the angle of the field with respect to a plane perpendicular to a radius vector through the satellite, this angle is positive when the field points below this plane) the declination (the angle between the projections in this same perpendicular plane of the north dipole and observed field) and finally the B_z (GSM) component of the measured field.

Three types of information drawn from the OGO 5 data are shown schematically in Fig. 6. First between 0330 and 0720 UT OGO 5 was in the magnetosphere and measured a positive declination (See Fig. 7). This is the distortion expected for a swept back field line. We shall associate the changes in this distortion with changes in the solar wind, the tail magnetic field as well as with the substorms. At 0720 UT OGO 5 crossed the magnetopause and we note that the magnetosheath field was indeed southward as could be expected from the orientation of the solar wind magnetic field. After 0720 OGO 5 recorded successive positions of the expanding magnetopause. Let us first comment on this expansion of the magnetopause.

The first of three main magnetopause crossings occurred at 0720 UT. The position of OGO 5 in GSM at this time was

X=0.5, Y=-11, Z=+8 (in earth radii), i.e., at high latitude on the dawn meridian. A second crossing occurred around 0830 (X=1.1, Y=-11.7, Z=9.0) and the last crossing (not shown on Fig. 7) was recorded at about 1020 UT (X=2.0, Y=-12.7, Z=10.1). The geocentric distances D of these three main crossings are indicated on Fig. 6. Although there was considerable magnetic fluctuations and multiple crossings during this time interval, the solar wind plasma experiment on board OGO 5 shows that the outbound OGO 5 satellite was indeed in the magnetosheath from 0720 till about 0830 UT, then in an expanding magnetosphere from 0830 till 1020 UT. After this time it definitely entered the magnetosheath (Neugebauer, personal communication, 1970). It appears that starting some time before 0830 UT the geocentric distance of the magnetopause on the dawn meridian increased from 13.6 Re to 16.5 Re in less than 2 hours.

We may comment now on the observations made by OGO 5 and ATS 1 inside the magnetosphere prior to 0720 UT. From Fig. 7 the most variable parameter as measured by OGO 5 was the declination which represents the twisting of the field line out of the dipole meridian. The average rate of variation of this angle in degrees per hour can be measured using the dashed lines in Fig. 7, and these rates after 0330 UT are indicated schematically by cross hatching in Fig. 6. Due to the many sources of information available on March 28, 1968 we shall present a chronology of the two sequences of events from 0330 to

0500, and from 0630 to 0900 UT. The accuracy of these chronologies is not claimed to be better than some minutes. In each sequence the events are grouped in three sets A, B and C associated with the reversal of the interplanetary field to southward, or northward or with the substorm activity. The indicated times of arrival of the solar wind refer, the first, to the arrival at the dawn dusk meridian, the second, to the arrival at 30 Re behind the earth. As explained above the slowing down of the solar wind flow behind the bow shock is neglected and it is why we use the expression "predicted earliest time..."; we refer to the ATS 1 observations as "dusk (6.6 Re)" observations and to the OGO 5 ones as "dawn (10 Re)" observations.

First Sequence

A. 0322-0330: predicted earliest time of arrival of the southward interplanetary field.

0330-0335: increase in the rate of change of the field depression at dusk (6 Re) and of the field declination at dawn (10 Re); onset of increase in the tail field magnitude at -30 Re.

0335: onset of magnetic noise at dusk (6 Re); onset of a substorm expansion phase at Great Whale River (Local time about 2230). (Not shown in Fig. 7).

B. 0410-0420: predicted earliest time of arrival of the northward interplanetary field.

0410: the declination stops increasing at dawn (10 Re).

0416-0418: drop of the field magnitude at -30 Re interpreted as an expansion of the plasma sheet.

0415: second rapid increase in the depression at dusk (6 Re); (note that between 0400 and 0430 a very irregular recovery phase is in progress at Great Whale River, Fig. A4).

C. 0430: onset substorm expansion phase at Great Whale River (Local time about 2330).

0434: B_z begins to increase at -30 Re into the tail.

0437: B total (F in Fig. 5) begins to decrease at -30 Re into the tail.

0430-0440: onset recovery at dusk (6 Re); onset rotation magnetic field and arrival $E \geq 40$ kev electrons (M. Kivelson, personal communication 1970) at dawn (10 Re).

0448: end substorm expansion phase at Great Whale River.

Second Sequence

A. 0640 : increase in the rate of change, of the field depression recorded by ATS 1 at 2100 LT (6 Re) and of the field declination recorded by OGO 5 at dawn (13 Re). Onset of the increase in the tail field; (as IMP 4 is not in the main lobe at the beginning this increase is probably partly due to a thinning of the plasma sheet.

(Note that the solar wind data is missing at this time but at 0720 UT, OGO 5 reached the magnetosheath where a southward magnetic field is recorded).

B. 0650: onset expansion phase of a substorm at Great Whale River (about 0200 LT).

0707: recovery at 2100 LT (6 Re) simultaneous with the onset of a recovery in H at Fredericksburg (about 0200 LT). This is the time selected for the vertical line in Fig. 7.

0750-0800: drop of the field at IMP 4 interpreted as a crossing of the plasma sheet border.

C. 0752-0758: predicted earliest time of arrival of the northward interplanetary field.

0802: observed time of change of orientation of the magnetosheath field (southward to horizontal) at dawn (OGO 5). That is why the vertical line corresponding to the reversal in Fig. 7 is drawn between 0800 and 0810.

0815: first partial magnetopause crossing showing that the magnetosphere boundary is getting disturbed at OGO 5.

0830: the magnetopause at dawn has begun to move outward.

0833: the plasma sheet expansion reaches 6 Re from the neutral sheet at a distance of -17 Re (Vela 4A; Akasofu et al., 1970).

A remark can be made about the crossing of the plasma sheet border at 0750. The expansion phase of a substorm was in progress at Great Whale River from about 0700 UT until 0812 UT. The crossing of the plasma sheet border occurred too early (by about 10 minutes) to be explained by an expansion due to the solar wind magnetic field change. As this crossing occurred at only 0.3 Re from the expected position of the neutral sheet we suggest that it was a crossing of a motionless (or slowly moving) border, the real expansion beginning about 10 minutes later at the arrival of the change in the interplanetary magnetic field (about 0805 if we note that the change in the field orientation occurred at 0802 in the dawn magnetosheath) and reaching Vela 4 after about 30 minutes (20 km/sec).

From these two sequences we want to emphasize that:

a) the action of a southward field is

- to increase the tailward distortion of the line of force in the far magnetosphere at dawn.
- to depress the magnetic field at a geostationary orbit (nightside).
- to increase the tail field (and to thin the plasma sheet.

b) the action of a northward field is to expand the plasma sheet.

The asymmetry of these two effects is obvious: the magnetic field in the magnetosphere does not return to its normal configuration when the interplanetary field turns back to northward, and the paragraph C in the first sequence shows that this return to dipole occurs through a substorm.

Let us note that an expansion of the dawn magnetopause (about 2 Re in 2 hours) is observed to follow at about 0830 UT the reversal of the interplanetary field to northward.

3. Discussion and Conclusion

We have shown examples of slow and rapid variations of the tail field at about 30 Re behind the earth at the time of change in the interplanetary magnetic field orientation. If we assume that the slow variations are temporal and the rapid ones are due to the crossing of the plasma sheet boundary then we can summarize our observations as follows:

- The tail magnetic field increases slowly when the interplanetary field is southward or horizontal with fluctuations; on two occasions (March 28) the OGO 5 data show that this is accompanied in the dawn meridian by a rapidly increasing distortion of the magnetic field wherein field lines are increasingly swept back with respect to a magnetic meridian plane. The tail magnetic field decreases slowly in association with substorms.

- The plasma sheet thins rapidly, immediately following a reversal of the interplanetary field from north to south and expands immediately when the interplanetary field turns northward.

These results are not based on any statistical study; moreover at some times the magnetic field in the tail does not seem to react as expected (for instance the plasma sheet expansion which should occur on February 14 at 22.20 UT is not observed); whether this is due to the position of the satellite at this time or some other cause we cannot determine. Additionally we are aware that the near tail magnetic field can depend also on other solar wind parameters as the kinetic energy density and the longitude angle of the interplanetary field; our analysis and our conclusions are limited to situations when these other parameters remain roughly constant (and assuming sufficiently large kinetic energy density and a longitude angle different from zero namely an interplanetary magnetic field not pointing toward the sun). We shall now discuss these results comparing them with those of other authors.

Temporal or Spatial Character of the Slow Increases of the Tail Magnetic Field

Lazarus et al. (1968) have reported a situation where the tail magnetic field increased and decreased slowly and have shown that the total pressure increased and decreased slowly with the field. In contrast they have interpreted as rapid spatial variations (crossing of a border), situations where the pressure remained constant when the field varied. Consequently in keeping with this philosophy we prefer a temporal interpretation of the slow variation. However an important problem remains unsolved: these temporal variations cannot occur with the same amplitude throughout the entire tail. Indeed in a previous paper (Aubry et al., 1970) evidence was presented for a flux transfer of about 10^{16} Maxwells from the eroded dayside to the tail; during this same event the IMP 4 magnetometer recorded a tail field increase from 15γ to 24γ which if occurring uniformly throughout a 20 Re radius tail implied an increase by 4.5×10^{16} Maxwells of the tail flux. So although the erosion of the day-side as reported in this paper was fairly dramatic, the flux transfer was lower than 4.5×10^{16} Maxwells and could not account for a uniform increase of the tail field. On February 13 the increase of the tail field from 20 to 30γ between 1400 to 1600 UT (Fig. 1) implies the same difficulty. We do not mean that our estimates of the flux transfer are very accurate, we want only to point out that a model in which the flux removed from the dayside is distributed uniformly in the whole section of the tail is maybe oversimplified; it seems quite probable that the slow increases in tail field if they are purely temporal, either depend on the distance from the neutral sheet or are enhanced by a simultaneous decrease of the radius of the tail. We presently have no arguments to rule out an interpretation in terms of a mixture of spatial and temporal variations.

Temporal or Spatial Character of the Slow Decreases of the Tail Magnetic Field

Hones et al. (1970) have shown that the particle pressure in the plasma sheet can decrease by a factor of two during a substorm. This observation and the one of Lazarus et al. (1968) showing a slow decrease of the tail magnetic field and total pressure after a substorm expansion supports our interpretation of the slow decrease as being temporal.

Thinning of the Plasma Sheet Following a Reversal of the Interplanetary Field Turning Southward

One more example of this phenomenon can be found in Hones et al. (1970). They report that on August 25, 1967 the satellites VELA 3A and 4A ($X_{SE} \sim -18$ Re) recorded the plasma sheet thinning from 2215 UT with a velocity of about 6 km/sec. We checked that at Explorer 33 ($X_{SE} \sim 10$ Re, $Y_{SE} \sim 12$ Re) the interplanetary magnetic field turned slowly southward after 2124 UT and was 90° southward after 2218 UT, (data not shown).

Expansion of the Plasma Sheet Following a Reversal of the Interplanetary Field Turning Northward or a Substorm

In the examples presented above there was quite often no substorm activity to account for the observed expansion and so we think that this relation between the expansion and the arrival of the northward interplanetary field is well confirmed. For instance on February 13 at 1810 UT (time of the expansion) the recovery phase of the substorm is nearly finished and on February 14 there is only a very weak ground disturbance during the interval 2100 - 2400 UT. However it is obvious that substorms themselves can trigger expansions of the plasma sheet. Examples of rapid variations of the tail field associated with substorm expansion onset have been presented by Camidge and Rostoker (1970) and Brody and Holzer (1970). (See Fig. 3 in this last paper). These variations could correspond to temporary expansion of the plasma sheet. As a confirmation of this interpretation recall that Hones et al. (1970) presented evidence for plasma sheet expansion after the onset of the substorm and <u>before</u> the reversal of the interplanetary field to northward.

Quite often however it is impossible to separate the contribution of the substorm and of the interplanetary field reversal to the plasma sheet expansion: For instance on August 15, 1968, at 0714 UT OGO-5 recorded an expansion of the plasma sheet coincident with the reversal of the interplanetary field turning northward and with the onset of a substorm

(McPherron et al., 1970). At other times the influence of the substorm and of the interplanetary field reversal could be contradictory: this could explain the tail signature observed on March 27, 1968 at 0740 UT (Aubry et al., 1970, Fig. 5). At this time an expansion of the plasma sheet occurred in association with the onset of a substorm and with the reversal of the interplanetary field turning southward.

Expansion of the Dawn Magnetopause Following a Reversal of the Interplanetary Field Turning Northward

This phenomenon was observed on March 28 after 0800 UT. We do not know if a large part of the magnetopause was involved, and it is not clear if the plasma sheet expansion observed by VELA 4A at 0833 UT (Akasofu et al., 1970) and this local magnetopause expansion are part of a global expansion triggered by the arrival of a northward interplanetary field. But as in a former paper (Aubry et al., 1970) we emphasize the large changes in the magnetopause position occurring under quiet solar wind conditions.

The indirect dependence of the tail characteristics on the solar wind through the substorm process has been shown by many authors (Heppner et al., 1967, Hones et al., 1967, Lazarus et al., 1968, Hones et al., 1968, Hones 1969, Akasofu et al., 1970, Hones et al., 1970, Fairfield and Ness 1970, Brody and Holzer 1970, Meng and Anderson 1970, Camidge and Rostoker 1970). We have shown in this paper that the tail characteristics depend also directly on the interplanetary field and that the tail at 30 Re reacts immediately to the changes in the motion electric field

(VxB) associated with changes in the solar wind magnetic field orientation. In particular we have shown that the slow increase in tail field and thinning of the plasma sheet systematically reported before substorms is produced by the arrival of a southward interplanetary field. We have shown also that the highly variable correlation between substorms and plasma sheet expansions is due to the fact that these expansions are frequently produced by the arrival of a northward solar wind magnetic field.

It would be unfair to claim that we understand each intermediate step in this picture. Hereafter we list some of the most obvious problems.

- What are the relative importance of spatial and temporal variations in the slow increase and decrease of the tail field?
- Although we claimed that the tail reacts "immediately" to the change in solar wind orientation, imprecisions of various kind restrict us in identification of a particular mechanism. In particular, we still cannot decide if the motion electric field (VxB) is transferred through an imperfectly conducting magnetopause (Nishida 1968) or along the lines of force of an open tail model (Van Allen 1970).

However from the simultaneous observations by several satellites presented above, we can infer a gross picture of the relations between the changes in the solar wind magnetic field orientation and the changes in the magnetosphere and the magnetotail before and after substorms (Fig. 8). First we have to assume that except for the vertical component of the interplanetary magnetic field (IMF), everything remains constant at some reasonable average value in the solar wind (velocity $\sim$ 400 km/sec, density $\sim 5\ cm^{-3}$, $B \sim 5\gamma$) and in order to avoid the longitude effect reported by Schatten and Wilcox (1967) and Rostoker (1968), we do not consider situations where the interplanetary magnetic field is directed exactly toward the sun.

On the left of Fig. 8 the sequence of events following the onset of a southward IMF is presented schematically. The high drag and the erosion of the dayside have been reported by Aubry et al. (1970). The other effects in the magnetosphere and in the magnetotail (box #1) are those reported above; by the "tailward orientation of the field at dawn", we mean the rapid increase in the declination as shown in Fig. 7. These changes (in box #1) are a part of the substorms growth phase. Some time later the substorm expansion phase starts and some of its consequences are listed (in box #2). If the IMF remains southward a closed loop of events is set up (white line), the substorms being the only way to release the stress imposed on the magnetosphere by the southward IMF. Such a closed loop in fact can lead to a magnetic storm. Such an event occurred on February 11, 1968 between 0300 and 0900 UT. Fairfield and Ness (1970) show the successive thinning and expansions of the plasma sheet. (See their Fig. 9). Our examination of Explorer 33 and 35 magnetometer data (not shown) indicate that the IMF remains southward during this interval. (However one must note also that the IMF amplitude was over 10γ and that the density of the solar wind varied between 10 and 17 cm^{-3}).

If the IMF turns northward the sequence on the right is set up. Depending on the energy stored in the magnetosphere and tail before the reversal, a substorm can be observed at this time but from our very limited observations (February 14, 1968 before 2100 UT: Fig. 3) and from statistical studies it seems that the substorm activity should end rapidly (Rostoker and Falthammar, 1967, Schatten and Wilcox, 1967, Zelwer et al., 1967, Rostoker, 1968). When the vertical component of the IMF reverses the magnetospheric sequence switches from one regime to the other (dark lines); since this can happen at anytime in the sequence, this means that the vertical positions of the points A and B, origin of the dark lines, are arbitrary.

Consequently when the time interval between the IMF reversals is smaller than the "time constant of the magnetosphere" (time constant of the loop on the left for instance) one never observes a simple magnetospheric sequence (left or right) but parts of the sequence on the left and parts of the sequence on the right combined randomly by the reversals of the interplanetary magnetic field.

The main consequence of this statement is that for any future studies of magnetospheric dynamics it becomes imperative that simultaneous measurements be made of the parameters of the solar wind (reasonably close to the earth), the near tail

(<50 Re) and the magnetosphere. We have shown that the presently available data are adequate to begin this study.

ANNEX

In order to support the magnetospheric substorm pattern sketched in Figs. 2, 4 and 6, we show in this annex the ground magnetograms of 17 magnetic observatories. Their position at 00.00 UT is shown in Fig. A1. In Figs. A2, A3 and A4 the deviation of the H component from the quiet day trace is shown for each of these stations.

The names of the stations are from the top:

SO: Sodankyla

LR: Leirvogur

GW: Great Whale River

ME: Meanook

SI: Sitka

CO: College

SJ: San Juan

FR: Fredericksburg

DA: Dallas

TU: Tucson

HO: Honolulu

GU: Guam

KA: Kakioka

GN: Gnangara

TA: Tashkent

MR: Hermanus

MB: M'Bour

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Fig. 1 Variation versus universal time of the solar wind (Explorer 33) and magnetotail (IMP 4) data. At the top solar wind kinetic energy density and thermal energy density as well as angle α between the solar wind magnetic field and the ecliptic plane. At the bottom magnetotail total field F and component of this field along the Z GSM axis; θ and ϕ are the usual latitude and longitude angle of the tail field. Z' is the distance between IMP 4 and the expected position of the neutral sheet (Russell and Brody, 1967). The magnetotail data (from Fairfield and Ness 1970) and the solar wind data have been shifted by 20 minutes relatively to each other. This time delay is required to convey any solar wind perturbation along the 90 Re between Explorer 33 and IMP 4.

Fig. 2 Sketch of the association between the solar wind magnetic field orientation (S: Southward, N: Northward), the existence of substorms (each isolated sequence of substorm is delineated by a dashed line; EP: onset of the expansion phase) and the variation of the tail total magnetic field ("Expans." and "thinning" refer to the rapid decreases or increases of this field considered to be due to the expansion or thinning of the plasma sheet; the shaded area correspond to the slow increases or decreases of the total field. The oblique lines in this position-versus-time reference system represent the propagation of the solar wind perturbations from Exp. 33 to the earth and IMP 4. At the bottom the projection of the various satellites in the XY_{SE} plane is shown. For the ATS 1 orbit, universal time at the beginning and the end of the orbit are indicated.

Fig. 3 Variation versus universal time of the solar wind (Explorer 33) and magnetotail (IMP 4) data. For further details see the caption of Fig. 1. The meaning of the angle β is explained in the text.

Fig. 4 Sketch of the association between the solar wind magnetic field orientation, the existence of substorms and the variation of the total magnetic field in the tail. For further details see the caption of Fig. 2.

Fig. 5 Variation versus universal time of the solar wind (Explorer 35) and magnetotail (IMP 4) data. For further details see the caption of Fig. 1.

Fig. 6 Sketch of the association between the solar wind magnetic field orientation, the existence of substorms and the variation of the total magnetic field in the tail. Some data from OGO 5 in the dawn meridian are shown schematically: namely the rate of change of the declination angle before 0720 UT, the orientation

(Southward) of the magnetosheath field from 0720 till 0800 UT and the various magnetopause positions recorded by the satellite. For further details see the caption of Fig. 2.

Fig. 7 Variation versus universal time of the magnetic field at ATS-1 and OGO-5 on March 28, 1968. From the top: the orientation of the solar wind magnetic field (S: South, N: North) as it would be observed at the distance of the earth; the difference ΔB between the total fields measured and expected at ATS-1 as well as the rms fluctuations (δ) of the measured field; these two same quantities ΔB and (δ) for OGO-5; the inclination, declination and vertical component B_z (GSM) of the field at OGO-5. Vertical lines point the influence of the solar wind magnetic field orientation, and of the substorm expansion phases on these various parameters. The vertical line at about 0640 UT when there is no solar wind data, correlates with the beginning of the increase in the depression at ATS-1 and the declination at OGO-5.

Fig. 8 Diagram of the two different sequences of events in the magnetosphere associated with the southward or northward orientations of the solar wind magnetic field. The white lines correspond to purely magnetospheric regimes when the solar wind magnetic field does not change. The dark lines show how the reversals of the vertical component of this solar wind magnetic field allow the magnetosphere to switch randomly from one regime to the other (the vertical positions of the points A and B are arbitrary). Except for the vertical component of the interplanetary magnetic field it is assumed that everything remains constant in the solar wind ($V \sim 400$ km/sec, $N \sim 5\ cm^{-3}$, $B \sim 5\gamma$, and oriented away from the sun).

Acknowledgments

We are very grateful to Drs. C.P. Sonett and D.S. Colburn for providing us with the Explorer 33 and 35 Ames magnetic field observations, to Dr. J. Binsack for the Explorer 33 and 35 MIT plasma data, and to Dr. C.T. Russell for the OGO-5 UCLA magnetic field data. We wish to thank M. Neugebauer who gave us very useful information obtained from the JPL solar wind experiment on board OGO-5 and D.H. Fairfield for additional comments about the published IMP 4 magnetic field data. Helpful discussions with P.J. Coleman, F. Coroniti, C. Kennel and C.T. Russell are gratefully acknowledged.

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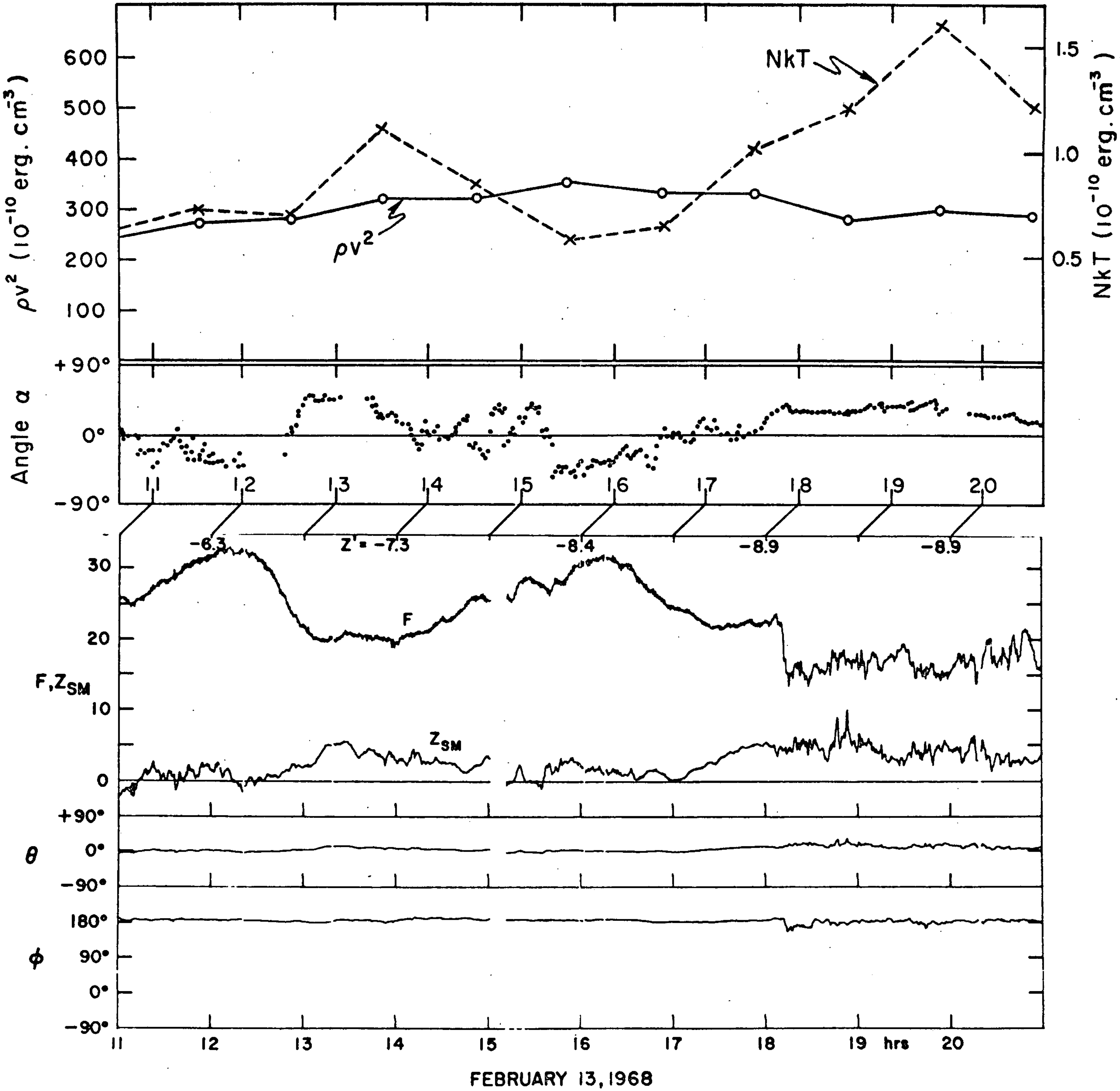

NkT
ρv^2 (10^{-10} erg. cm^{-3})
NkT (10^{-10} erg. cm^{-3})
ρv^2
Angle α
+90°
0°
-90°
1.1 1.2 1.3 1.4 1.5 1.6 1.7 1.8 1.9 2.0
-6.3
Z' = -7.3
-8.4
-8.9
-8.9
F
F, Z_{SM}
Z_{SM}
θ
ϕ
hrs
FEBRUARY 13, 1968

Fig. 1

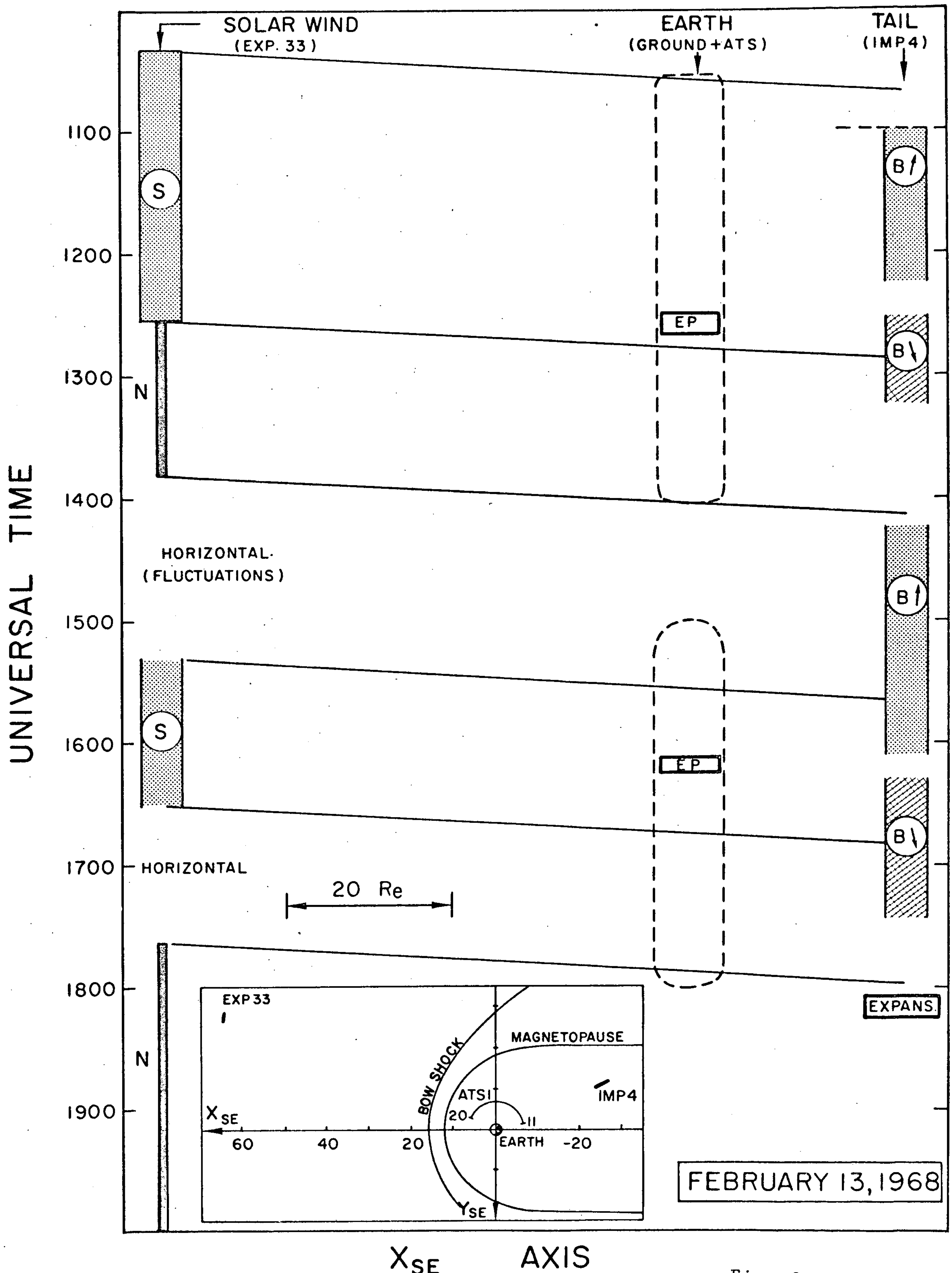
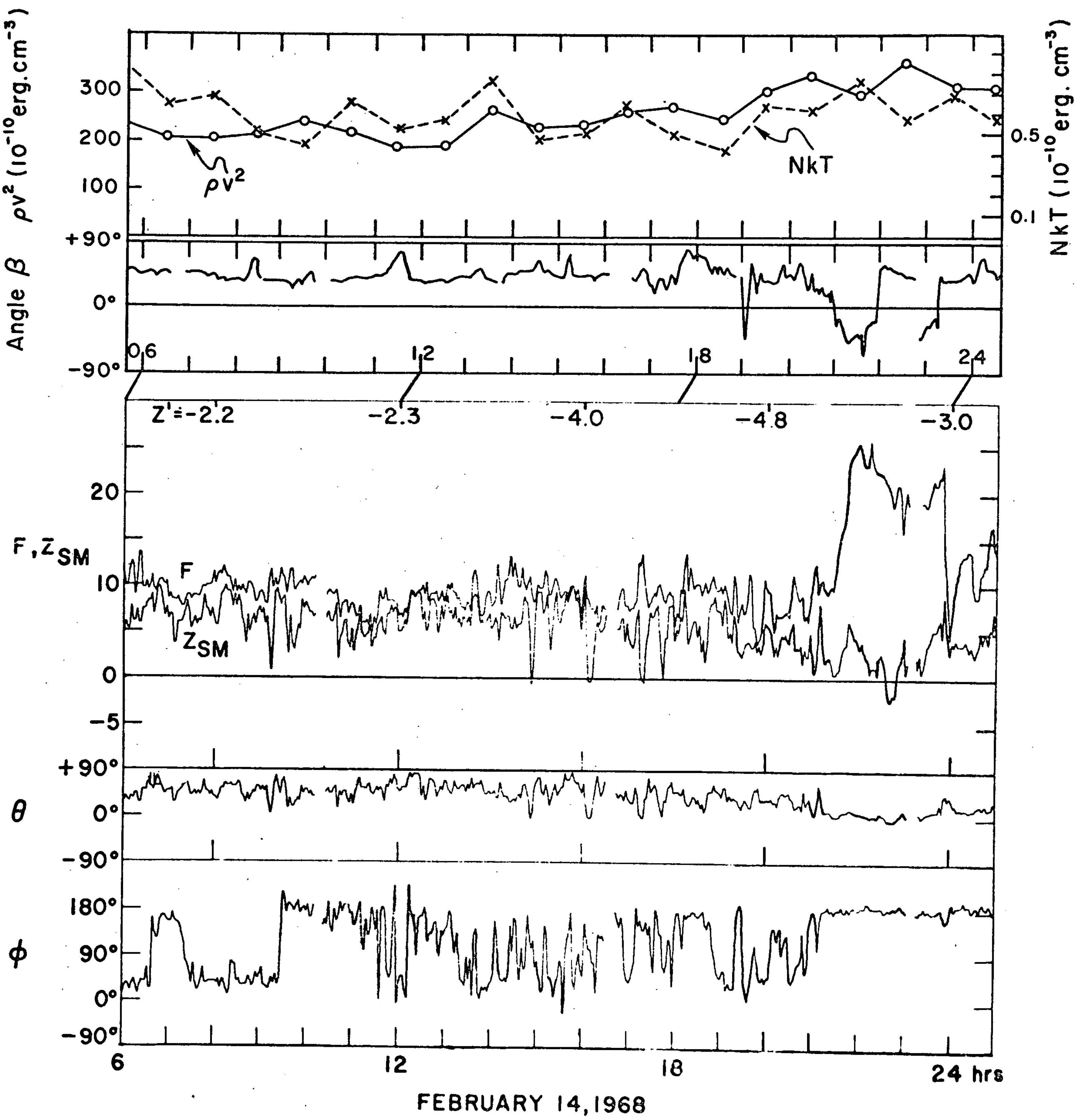
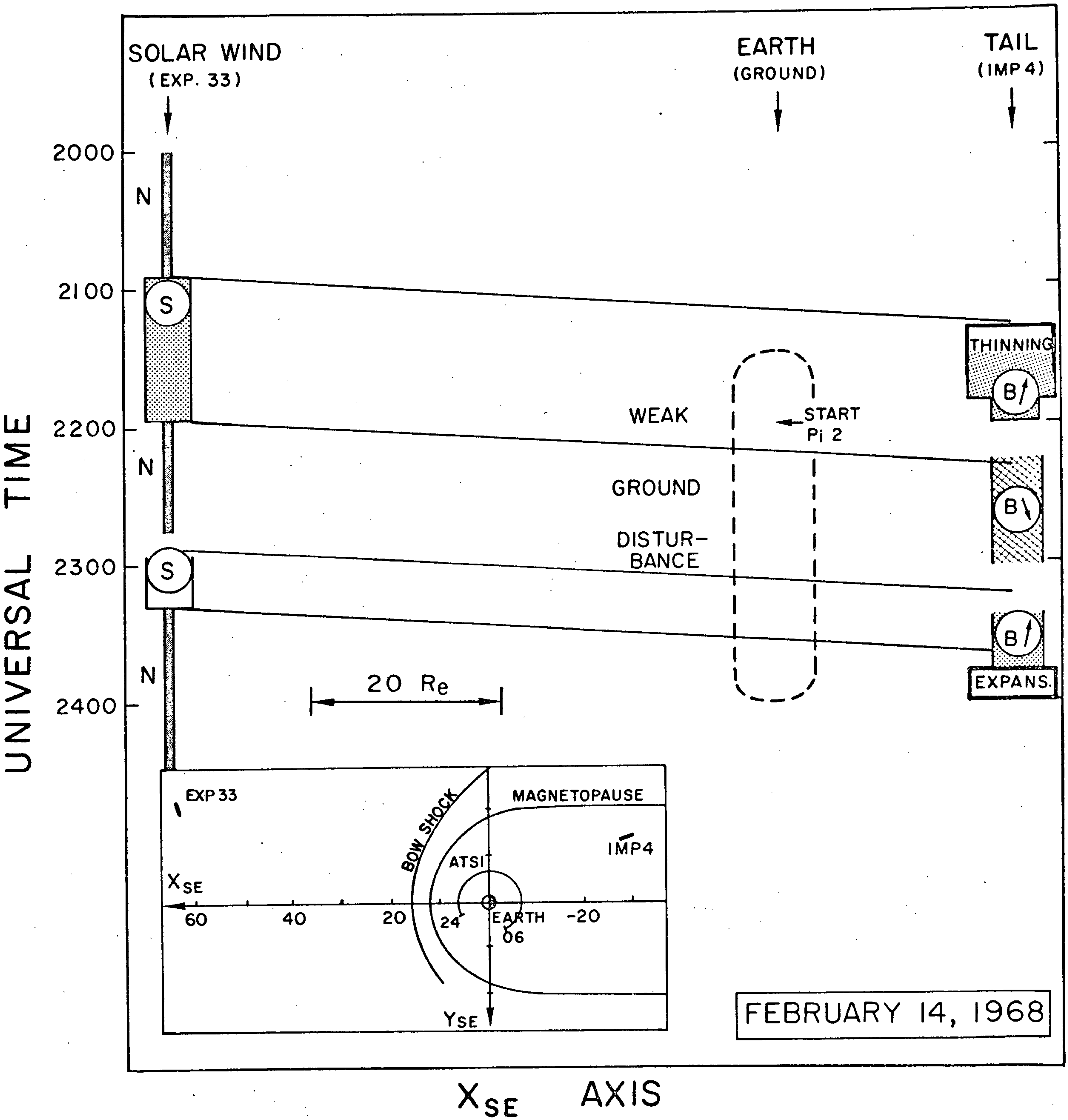

SOLAR WIND
(EXP. 33)
EARTH
(GROUND+ATS)
TAIL
(IMP4)
UNIVERSAL TIME
1100
1200
1300
1400
1500
1600
1700
1800
1900
S
N
B
EP
HORIZONTAL
(FLUCTUATIONS)
S
EP
B
HORIZONTAL
20 Re
N
EXPANS.
EXP33
BOW SHOCK
MAGNETOPAUSE
ATS1
IMP4
X_{SE}
20
11
60
40
20
EARTH
-20
Y_{SE}
FEBRUARY 13, 1968
X_{SE} AXIS

Fig. 2



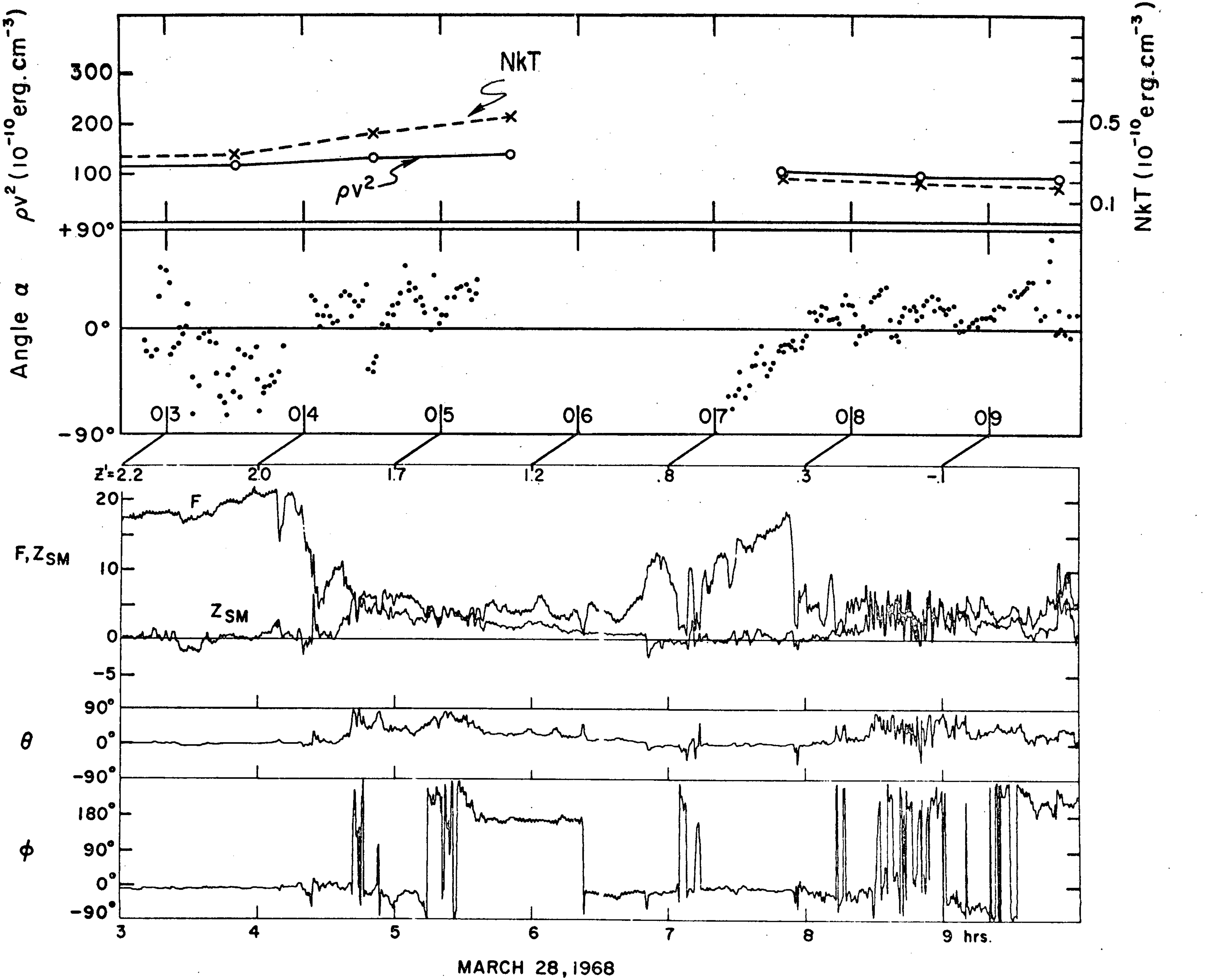
ρv² (10⁻¹⁰erg.cm⁻³)
NkT (10⁻¹⁰erg. cm⁻³)
300
200
100
0.5
0.1
ρv²
NkT
Angle β
+90°
0°
-90°
0.6
1.2
1.8
2.4
Z' = -2.2
-2.3
-4.0
-4.8
-3.0
F, Z_SM
F
Z_SM
20
10
0
-5
θ
+90°
0°
-90°
φ
180°
90°
0°
-90°
6
12
18
24 hrs
FEBRUARY 14, 1968

Fig. 3



SOLAR WIND
(EXP. 33)
EARTH
(GROUND)
TAIL
(IMP 4)
2000
2100
2200
2300
2400
N
S
N
S
N
THINNING
B
WEAK
START
Pi 2
GROUND
B
DISTUR-
BANCE
B
EXPANS.
20 Re
EXP 33
BOW SHOCK
MAGNETOPAUSE
IMP4
ATSI
XSE
60
40
20
24
EARTH
06
-20
YSE
FEBRUARY 14, 1968
UNIVERSAL TIME
XSE AXIS

Fig. 4



ρv² (10⁻¹⁰erg.cm⁻³)
300
200
100
NkT
ρv²
NkT (10⁻¹⁰erg.cm⁻³)
0.5
0.1
+90°
Angle α
0°
−90°
0|3
0|4
0|5
0|6
0|7
0|8
0|9
z'=2.2
2.0
1.7
1.2
.8
.3
-.1
F
Z_SM
F, Z_SM
20
10
0
−5
90°
θ
0°
−90°
φ
180°
90°
0°
−90°
3
4
5
6
7
8
9 hrs.
MARCH 28, 1968

Fig. 5

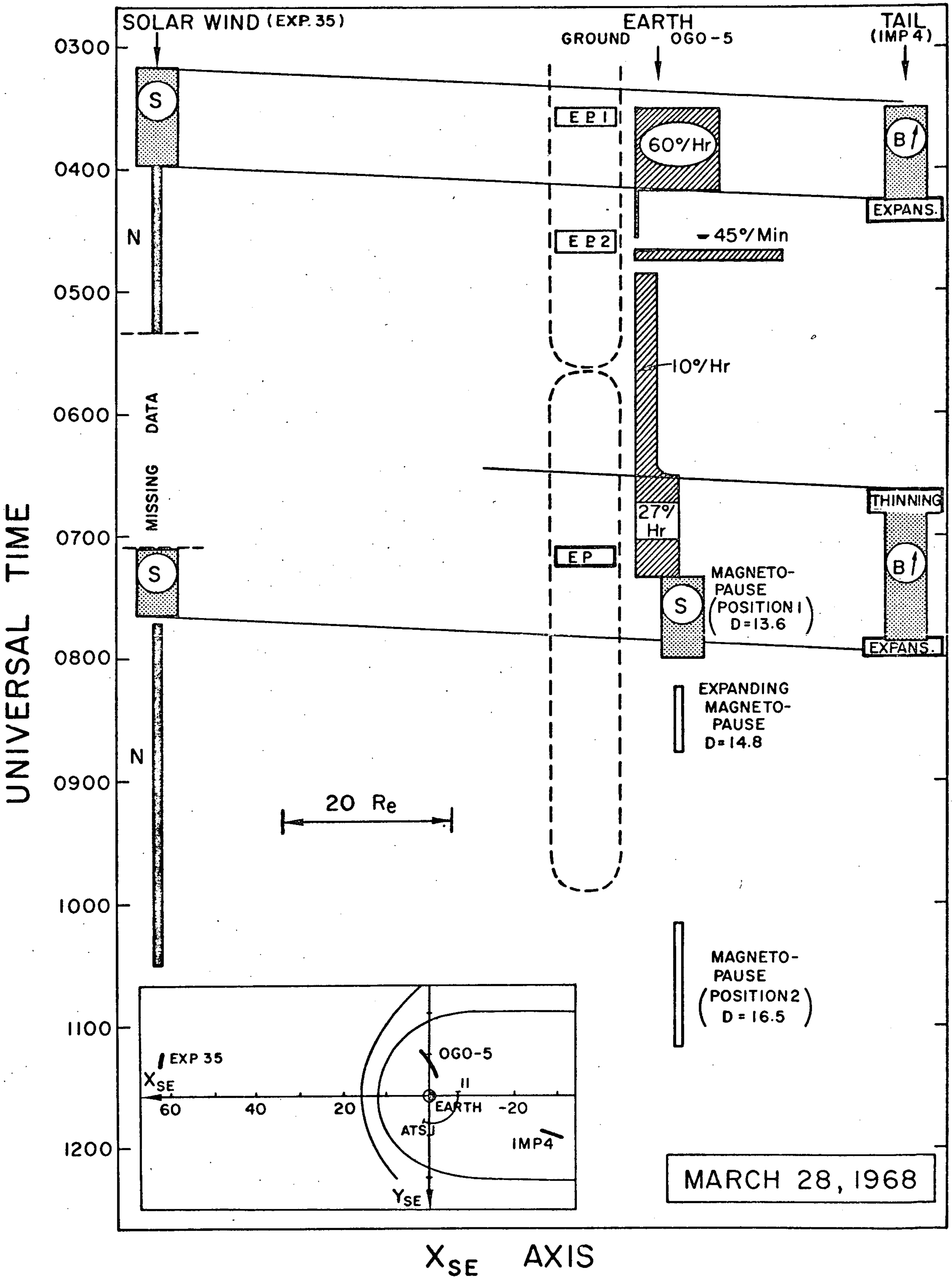

SOLAR WIND (EXP. 35)
EARTH
GROUND
OGO-5
TAIL (IMP 4)
0300
0400
0500
0600
0700
0800
0900
1000
1100
1200
UNIVERSAL TIME
S
N
DATA MISSING
EP1
EP2
EP
60%/Hr
45%/Min
10%/Hr
27%/Hr
B
EXPANS.
THINNING
MAGNETO-PAUSE (POSITION 1 D=13.6)
EXPANDING MAGNETO-PAUSE D=14.8
MAGNETO-PAUSE (POSITION 2 D=16.5)
20 Re
EXP 35
OGO-5
X_{SE}
60
40
20
EARTH
-20
ATS
IMP4
Y_{SE}
MARCH 28, 1968
X_{SE} AXIS

Fig. 6

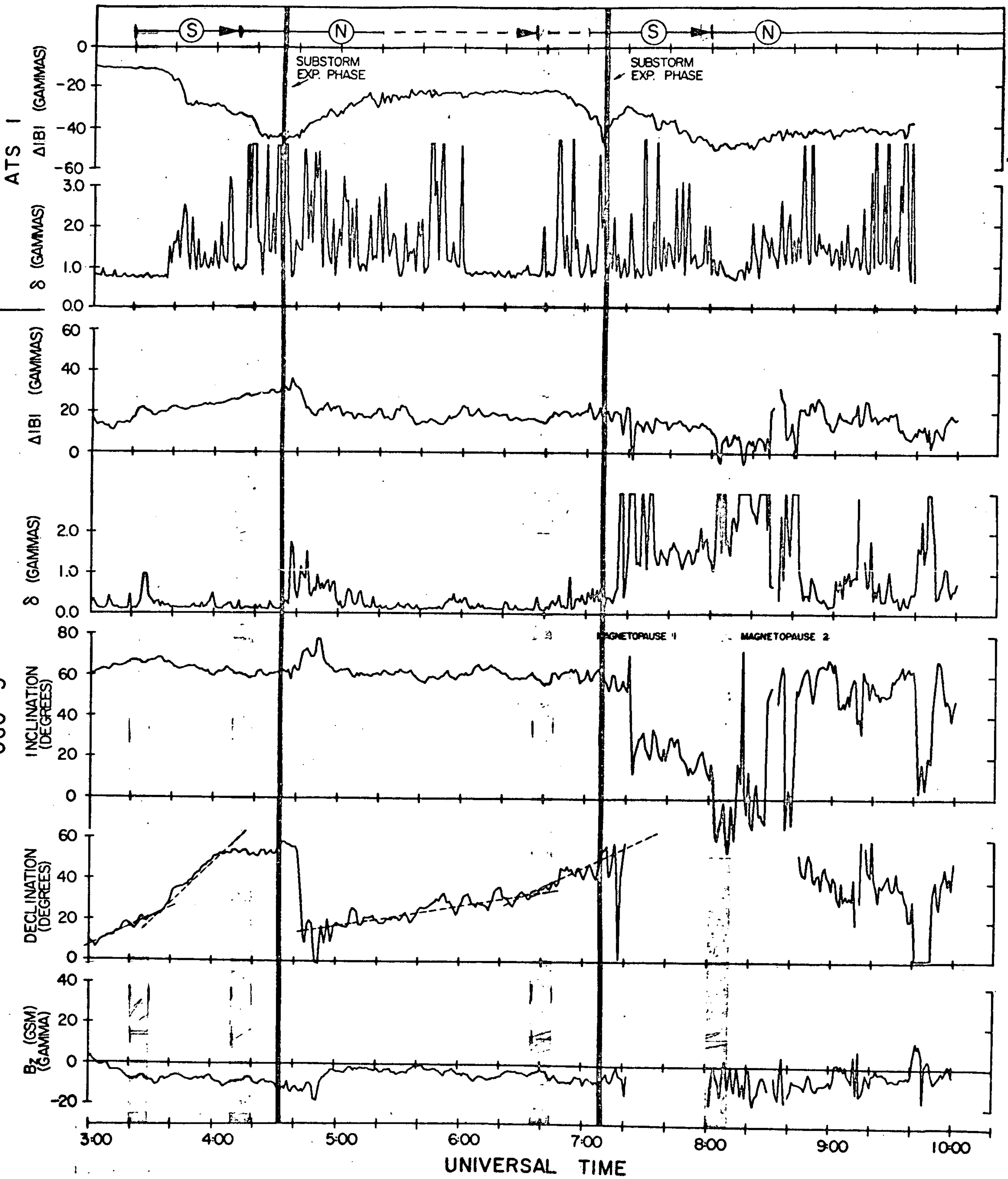
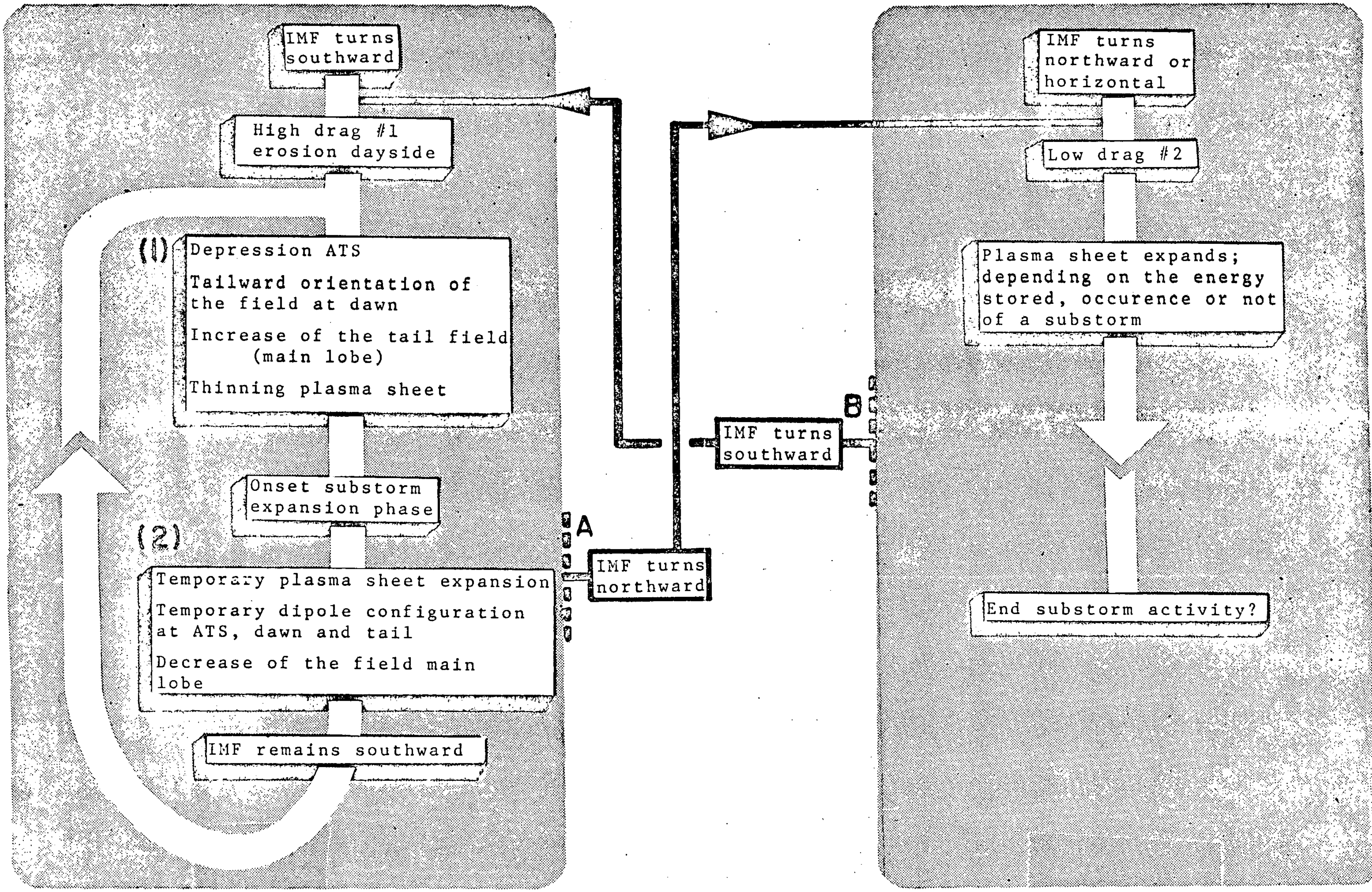

ATS 1
ΔIBI (GAMMAS)
δ (GAMMAS)
SUBSTORM EXP. PHASE
SUBSTORM EXP. PHASE
OGO 5
ΔIBI (GAMMAS)
δ (GAMMAS)
INCLINATION (DEGREES)
MAGNETOPAUSE 1
MAGNETOPAUSE 2
DECLINATION (DEGREES)
Bz (GSM) (GAMMA)
UNIVERSAL TIME

Fig. 7



SUBSTORM RELATION TO THE INTERPLANETARY MAGNETIC FIELD

Fig. 8

LOCATION OF MAGNETIC OBSERVATORIES
GEOGRAPHIC-NORTH POLAR PROJECTION
0000UT

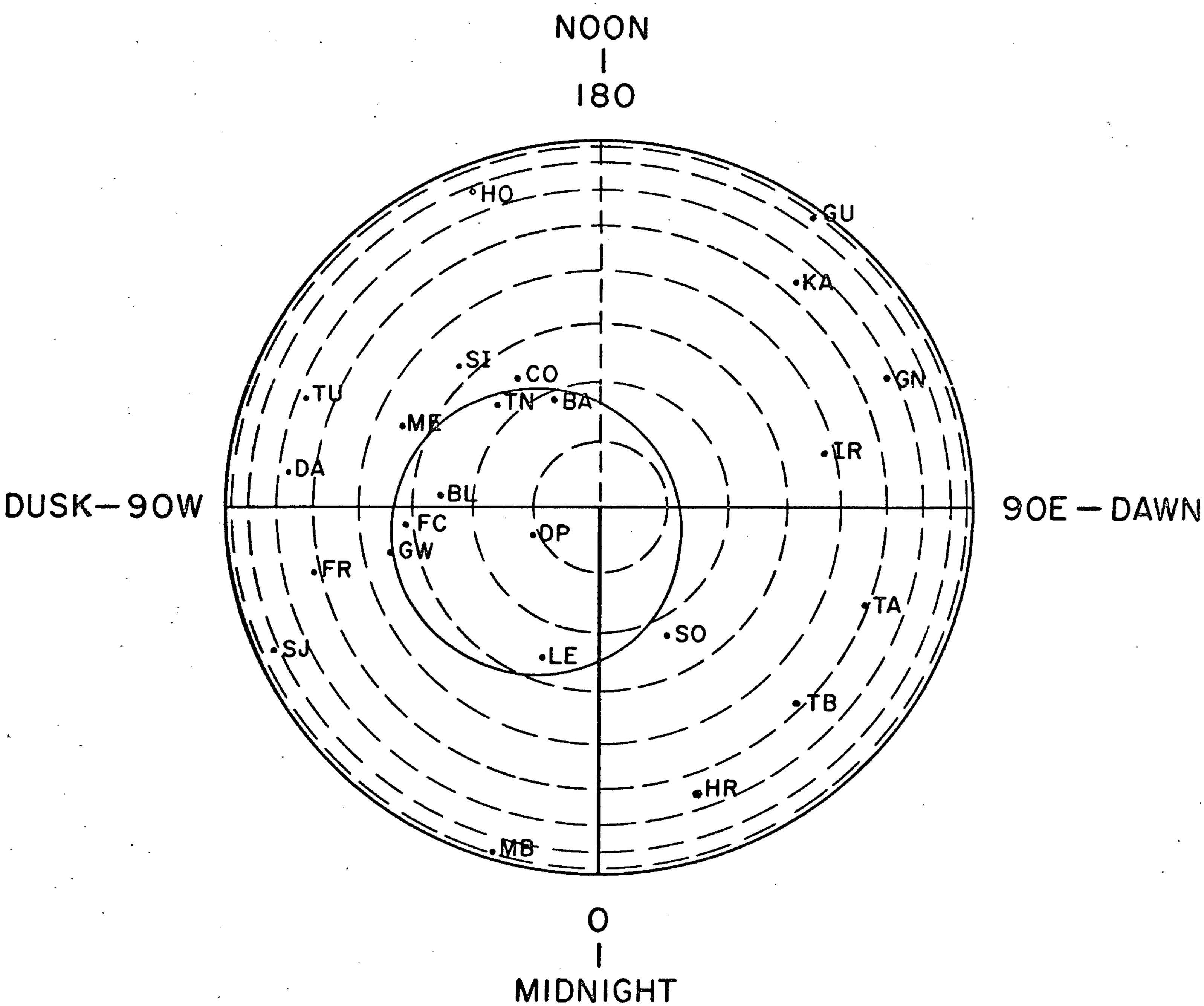


Fig. A1

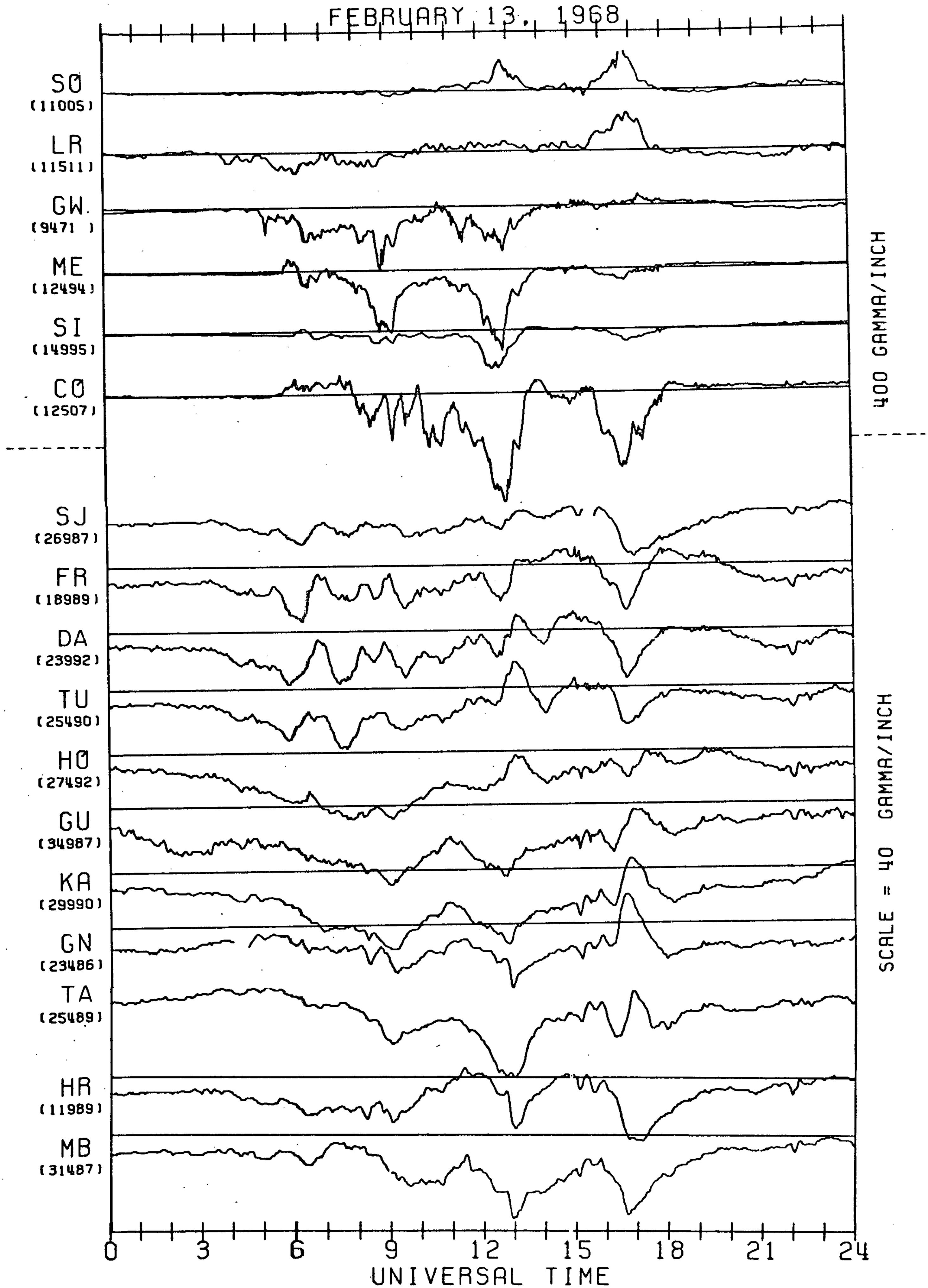
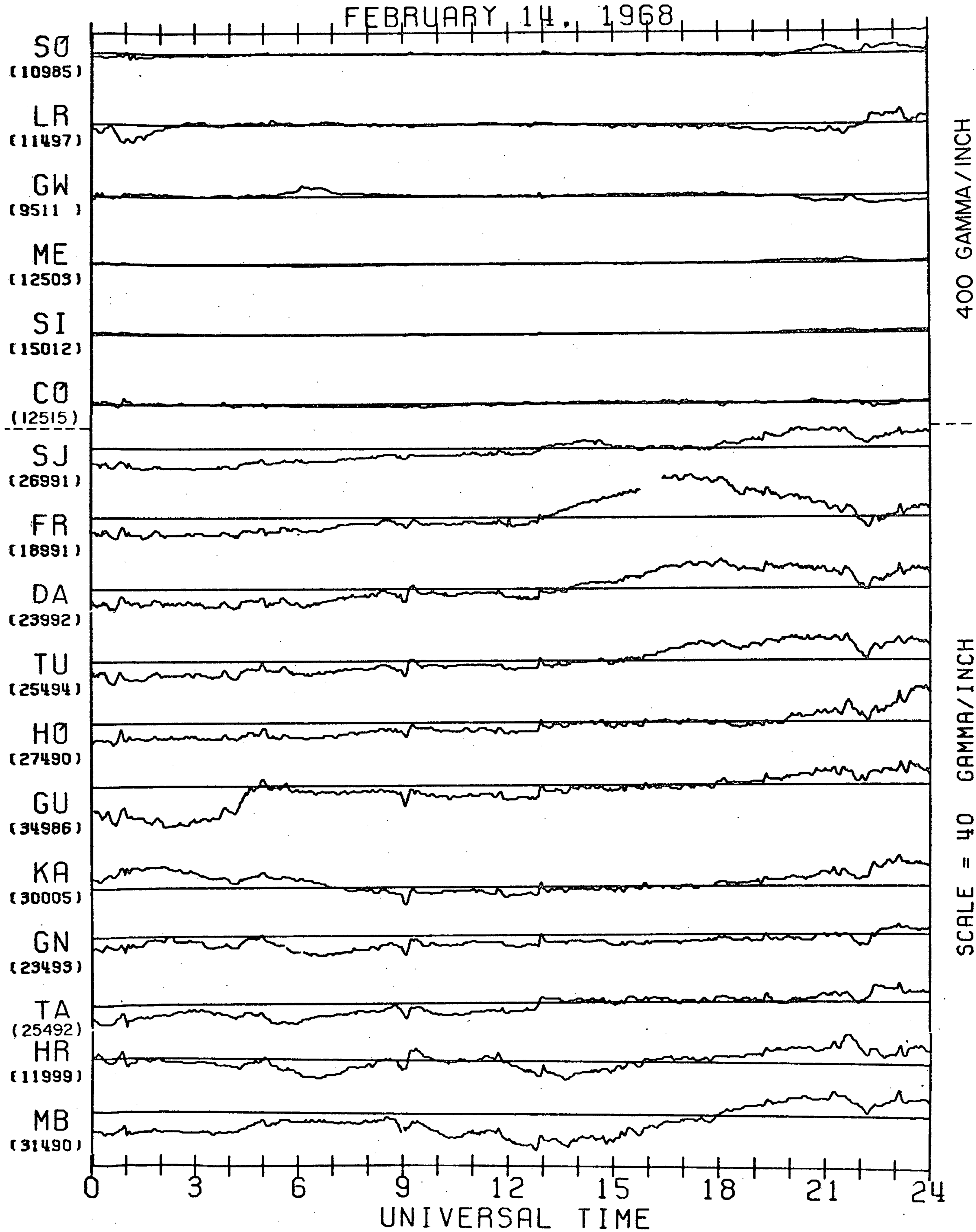

FEBRUARY 13, 1968
SØ
(11005)
LR
(11511)
GW
(9471)
ME
(12494)
SI
(14995)
CØ
(12507)
SJ
(26987)
FR
(18989)
DA
(23992)
TU
(25490)
HØ
(27492)
GU
(34987)
KA
(29990)
GN
(23486)
TA
(25489)
HR
(11989)
MB
(31487)
400 GAMMA/INCH
SCALE = 40 GAMMA/INCH
0
3
6
9
12
15
18
21
24
UNIVERSAL TIME

Fig. A2


FEBRUARY 14, 1968
SØ
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LR
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GW
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ME
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SI
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GU
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KA
(30005)
GN
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TA
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HR
(11999)
MB
(31490)
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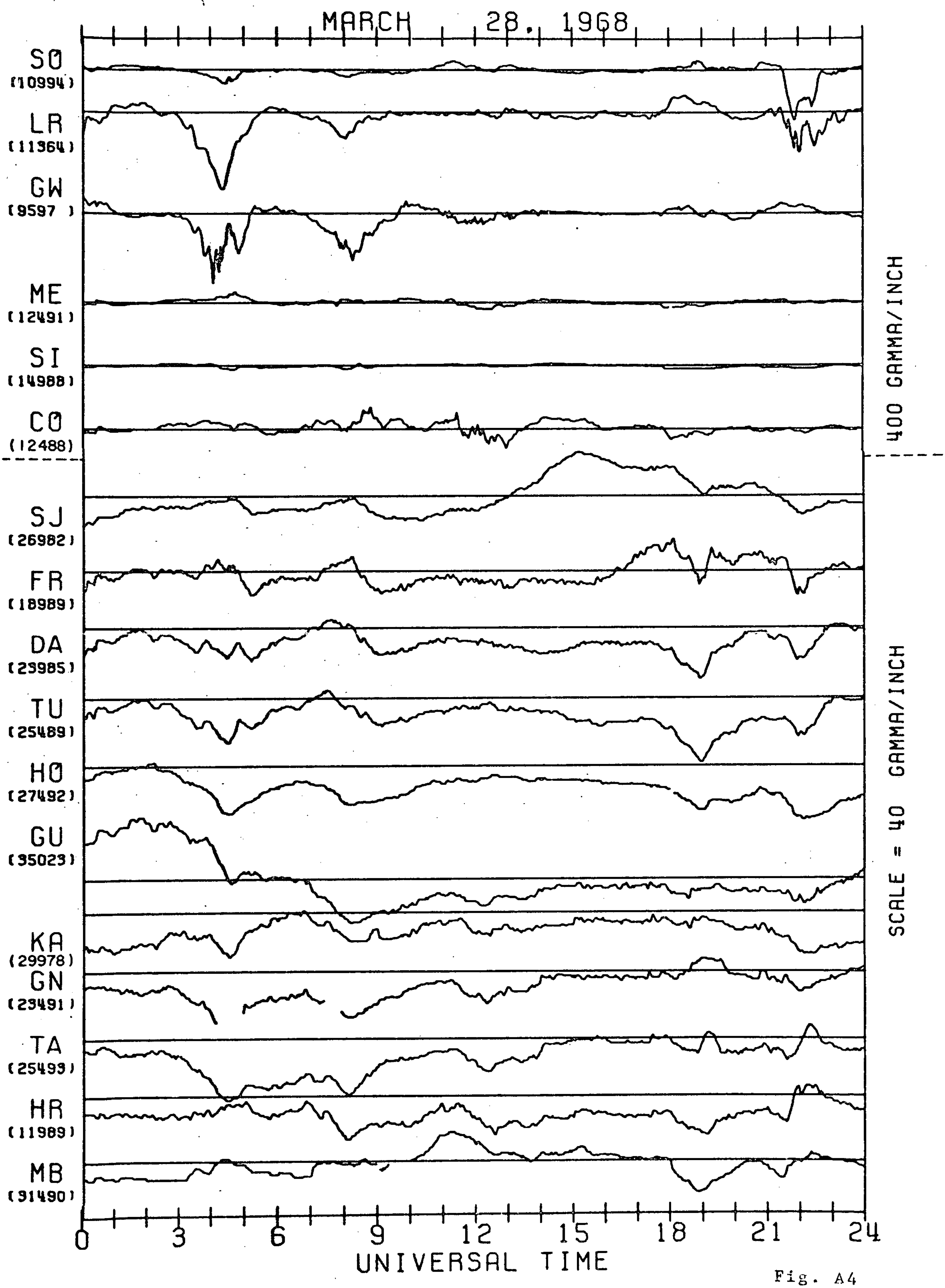
SCALE = 40 GAMMA/INCH
0
3
6
9
12
15
18
21
24
UNIVERSAL TIME

Fig. A3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TU (25489)
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TA (25493)
HR (11989)
MB (31490)
400 GAMMA/INCH
SCALE = 40 GAMMA/INCH
0
3
6
9
12
15
18
21
24
UNIVERSAL TIME

Fig. A4