

SUDDEN IMPULSES IN THE GEOMAGNETOTAIL  
AND THE VICINITY<sup>+</sup>

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# ABSTRACT

Explorer 33 magnetic field observations have been analyzed to study the propagation of sudden impulses in the geomagnetic tail and the magnetosheath. Average speed of propagation in these regions is 760 km per sec with a range of 550 to 1230 km per sec. Most of the si's have propagation speed which is close to that of the shock wave observed in this region. Positive si is shown to have a positive change in the tail or magnetosheath and a negative si has a similar negative change. Nine out of thirteen correlated si's have their origin in the solar wind continuities, while four si's have possible origin in the perturbations of tail or magnetosheath field. It is found that the si propagation is not confined to the tail region but it has correlated effects in the magnetosheath also. The propagation region studied is in 2000 to 0200 local time sector.

## INTRODUCTION

Sudden impulsive changes in the geomagnetic field intensity have been studied on the surface of the earth and in the magnetosphere (Nishida and Jacobs, 1962; Matsushita, 1962; Nishida and Cahill, 1964; Patel, 1968; Ondoh, 1970). It is now well established that the sudden impulse (si) observed in the surface geomagnetic field is correlated to similar changes in the inner magnetosphere as well as far out in the magnetospheric tail. An si is defined as a sudden positive and negative change in the geomagnetic field which is not associated with a geomagnetic storm or high activity disturbance. In contrast, the sudden storm commencement (SSC) is a positive change in the field which is preceded by a storm. The si is called positive or negative depending on increase or decrease in the horizontal component in a mid-latitude or an equatorial magnetogram. The high latitude magnetograms show complicated changes in all three components of the geomagnetic field.

We also know that the large and well defined si has its origin in the sudden changes in the solar wind parameters, i.e., density and velocity and the interplanetary magnetic field (Gosling, et al., 1967; Burlaga and Ogilvie, 1969). However, it is still not clear that all of the interplanetary sudden changes which are responsible for

the si can be interpreted as shock waves. The present status of the si phenomenon is that the discontinuities or sudden changes in the solar wind density and velocity and the magnetic field cause the magnetopause movement. The resulting change in the magnetic field is transmitted through the magnetosphere down to the surface. This si perturbation then propagates into the geomagnetic tail (Dessler, 1964). Propagation studies of the si in the tail show that changes on the surface and in the geomagnetic tail are correlated out to 25 earth radii (Patel, 1968). It was also shown that the changes in the tail were found which had effects on the surface field after 5 to 10 minutes time delay. We have extended the study of si in the tail and magnetosheath out to 62 earth radii by using Explorer 33 magnetic field observations. More accurate propagation speeds have been calculated and correlated magnetic field variations are discussed for these events.

## ANALYSIS

The magnetometer experiment aboard Explorer 33 satellite provides accurate measurements (maximum error  $\pm 0.5$  gamma) of the vector magnetic field out to 80 earth radii. The data presented in this paper are 82-second sequence averages and also 20-second averages. In order to calculate the propagation speed of the si, 5 second averages of magnetic field data were used. Data in solar ecliptic coordinate,  $F, \theta, \phi$  for 1-1/2 hours before and after the si onset time were examined in making selection of satellite data for each event. For detailed study of the variations in the tail and magnetosheath field during si events, data in the solar-magnetospheric coordinates  $X, Y, Z$  were also used. Details on the flux-gate magnetometer instrumentation, data reduction and coordinate systems are described by Behannon (1968).

Selection of the si events included in this study was carried out as follows: We started with the list of si compiled in Solar Geophysical Data and selected si events which have clear effects at more than ten magnetic observatories. The period covered is July to December, 1966. From past experience of si analysis, we find that si occurring at few observatories does not show clear world-wide effect and may or may not have the correlated effect in the magnetosphere or in the tail. We have, therefore,

selected only well-defined si's occurring at ten or more observatories. Explorer 33 magnetic records were also examined for si-like changes and compared to ground magnetograms. Some satellite observations showed correlated changes at one or two observatories as we had found in IMP-1 study (Patel, 1968) and are not included in this study. Fourteen si events which were examined in rapid-run magnetograms from seven ground observatories (see Figs. 1 to 4) had corresponding Explorer 33 magnetic field observations available in the tail or magnetosheath region. Only one si (Oct. 17) did not show any effect in the satellite observations. The satellite was far out at solar magnetospheric position  $X = -54$ ,  $Y = 33$  and  $Z = 30.6$  earth radii ( $R_E$ ) and it is possible that si effect was not propagated in that region. The other thirteen events showed correlated effects far out to 62 earth radii. In Table 1, we give details about each event; onset time on the earth, delay time for the effect observed at the position of Explorer 33 in the solar-magnetospheric coordinates, etc. The onset times given in the Table were determined by using rapid-run magnetograms from the observatories shown in Figs. 1 to 4. An accuracy of 30 seconds is obtained but the onset times are given to the nearest minute. The delay times are obtained by taking a difference between onset time at satellite and at the

surface of the earth. The method followed in determining onset in the satellite data is described in the next section. In two events, because of local fluctuations near the si, it was not possible to uniquely determine onset times.



## RESULTS

The propagation of the si in the geomagnetic tail has been studied by using IMP-1 magnetic field observations (Patel, 1968). It was found that most of the si's originate in the solar-wind and propagate into the tail. However, a few of them showed a perturbation which occurred first in the tail and then arrived at the earth. In the present study we find that 4 events out of 13 correlated si's are observed first in the tail or magnetosheath. Nine events register si signatures first in the surface magnetograms and then into the tail or magnetosheath near the tail. These si's have their origin in the solar-wind discontinuities (Gosling et al., 1967; Burlaga and Ogilvie, 1969). We also find in this study that the si propagation from the sunward side is not confined to the tail. The si's are propagated into the magnetosheath and their effects are detected within 0200 to 2000 local time sector. We discuss their propagation speed and correlated field variations by illustrating four examples of the si's. Details about all thirteen correlated and one uncorrelated si's are given in Table 1.

#### A. Approximate speed of propagation

Onset times of the si on the earth and at the satellite position in the tail or magnetosheath have been determined. Because of the availability of larger number of events in this study, these results are a definite improvement over the preliminary si study with IMP-1 data which was carried out using 5.46 min and 20 sec average. Ground-based rapid-run magnetograms at seven observatories at various latitudes and longitudes have been examined. Onset time is determined to an accuracy of 30 sec following the method described by Nishida and Jacobs (1962), but have been listed in Table 1 to the closest minute. For each event, satellite data containing 5 sec averages were plotted on an expanded scale in the solar ecliptic coordinates  $F$ ,  $\theta$  and  $\phi$  and also in the solar-magnetospheric components  $X$ ,  $Y$ , and  $Z$ . (Plots are not shown in this paper because of large quantity of data). For events where magnitude  $F$  showed clear change, the onset times were determined by using this change. When the change in  $F$  is not clear (as is the case in some of the satellite observations in the magnetosheath), the largest change in any component  $X$ ,  $Y$ , or  $Z$  was used in determination of onset time. Some events in the tail showed very clear si associated variations for positive and negative si as shown in Figs. 1 and 3. However, local fluctuations near

the si may introduce an error of about 20 to 30 sec in the satellite onset time determination and should be considered in that approximation. The error in onset determination in the satellite data is of the same order as in the ground magnetograms.

Delay times for each event, i.e., onset-time at the satellite minus onset-time at the earth are obtained from the data and are shown in Table 1. The negative delay times indicate that the si change was seen first in the tail or the magnetosheath and the si effect was seen later on the earth. There are four such events out of the 13 correlated si's. These four si events which seem to have perturbations originated in the tail were further checked by using Explorer 28 (IMP-3) data in the interplanetary space. Explorer 28 was between the sun and earth region during these four events. If there is no corresponding si signature in Explorer 28 data, then it is possible that the si might have originated in the tail region. Simultaneous observations of the interplanetary magnetic field during these four events were examined by using 5.6 minute averages for one hour period around the si time. Three events had no clear effects observed prior to the onset time on the earth indicating that the origin of these si had no possible cause in the solar wind between the earth and the sun. One si (10/12/66) has some

indication that the si might have origin in the solar wind discontinuity. We should point out that the interplanetary data used were 5.6 minute averages because smaller time averages were not available in the NASA Data Center. A definite conclusion regarding possible origin of the si in the tail or the space beyond one AU still remains uncertain. More events with simultaneous observations at various locations in space with better time resolution are needed. The events discussed in this study with negative time delays and other results obtained in IMP-1 study (Patel, 1968) only point out the possibility of the si type disturbances originating in the tail. The movement of tail or the interaction of the geomagnetic tail with the moon can generate the hydromagnetic disturbances which might appear as si type disturbances on the surface of the earth.

Most of the events, 9 out of 13 have si registered first on the earth and then show the effect in the tail. The approximate speed of propagation of the si is calculated by using distance along X axis and the delay time. The average speed is about 760 km per sec with an approximate range of 550 to 1200 km per sec for various events. The values for all events are given in Table 1. For comparison, the Alfven speed in the tail region is  $\sim 690$  to 2000 km per sec for  $B \sim 10 \gamma$  and  $n = 0.1$  to  $.01$  protons per  $\text{cm}^3$ . Far in the tail or the magnetosheath near the tail, a Alfven speed

larger than 1000 km per sec is possible. We note that the previous estimate from IMP-1 study ranges from 870 to 1300 km per sec (Patel, 1968). We note that the sudden storm commencement (SSC) studied by Behannon(1968) on September 14, 1966 at  $X = -73.8 R_e$  in the tail had a speed of about 650 km per sec. While Sugiura et al., (1968) estimate SSC speed at 500 km per sec from OGO 3 observations at  $X = -10.1 R_e$  in the tail. They have noted that the Explorer 33 MIT plasma observations indicated a shock speed of 700 km per sec. Ondoh (1970) obtained propagation speeds which had a range of 677 to 1160 km per sec. He used OGO 3 and 5 magnetic field observations in the local time 0800 - 2200 hour region in the magnetosphere at 6.55 to 20  $R_e$ . Our calculations shown in Table 1 indicate that all si's with exception of two events, have propagation speed which corresponds to the shock wave speed. There is no systematic difference in the propagation speeds in the tail and the magnetosheath, or in the negative or positive si.

#### B. Magnetic field variations of si

First, we discuss field variation of the positive si in the tail and the magnetosheath. In Fig. 1, a positive si occurs at 0003 UT on August 1 and is seen on several ground magnetograms at low latitude and at high latitudes such as College and Wilkes. Explorer 33 data in solar ecliptic coordinates are plotted at 20 second intervals. The

satellite position at this moment in solar-magnetospheric coordinate is  $X = -48.5$ ,  $Y = 0.1$  and  $Z = 9.8$  in earth radii, in the tail. After a delay time of about 6.8 min, the tail field begins to increase with no changes in the angles  $\theta$  and  $\phi$ . An increase in the geomagnetic field at the surface is correlated to the increase in the tail field as noted by Behannon and Ness (1966) and Behannon (1968). The average propagation speed determined by using 5 sec averages is comparable to shock wave speed discussed by Sugiura, et al., (1968). An increase in the  $x$  component is consistent with their argument that more field lines are swept into the tail region.

A positive si event on August 31, shown in Fig. 2 illustrates the associated field changes in the magnetosheath near the tail. The si occurs at 1346 UT in the surface magnetograms at several observatories. The satellite at this time is located at  $X = -29.3$ ,  $Y = 31.5$ ,  $Z = 1.2$  in the magnetosheath. The data in solar-ecliptic coordinates are shown and a clear increase in the magnitude begins after the delay time of 4.3 min. The average speed obtained by using 5 sec averages is 727 km per sec. In the case of all positive si's (a total of six), the positive change at the surface of the earth is correlated to the positive change in the tail and the magnetosheath.

In the case of the negative si, the tail field shows a decrease in magnitude when the negative si is observed on the surface of the earth. An example shown (Fig. 3) illustrates the correlated field changes. The si on July 15 has onset time 2308 UT and has decrease in H component at the low latitudes. The high latitude variations are masked with the effects in the polar ionosphere. Explorer 33 was located in the tail at  $X = -45.0$ ,  $Y = -11.0$  and  $Z = 9.4 R_e$  and showed clear decrease in the  $F$ ,  $\theta$ ,  $\phi$  after delay of 7.0 min. The propagation speed from 5 sec averages is 686 km per sec which is comparable to the shock wave speed. However, other negative si's have speed close to the average Alfvén speed (see Table 1). In the magnetosheath the magnetic field is more variable than the tail region and sometimes it is difficult to determine exact onset time in the satellite data. But the general trend of the magnetic field during negative si event shows decrease. An example is shown in Fig. 4 which shows negative si on Sept. 24 at 1805 UT. Explorer 33 located in the magnetosheath at  $X = -47$ ,  $Y = 38.2$  and  $Z = -24.8 R_e$  observed decrease in the field magnitude after the delay of 5 minutes from the onset time. A total of seven negative si's has similar correlated field variations in the tail and the magnetosheath. The average speed has the same range as in the positive si which indicates the lower speed range of 600

to 700 km per sec comparable to shock wave speed and the higher range close to the Alfven speed of about 1200 km per sec.

### C. Field variation in the solar-magnetospheric coordinates

Sometimes magnetic field observations are more useful in the solar-magnetospheric coordinates to relate the changes in tail to the near-earth phenomena. Data for the fourteen si events are shown in these coordinates in Figs. 5a and 5b. The data are shown for a period of  $\pm 20$  min around the onset time of each si. We have used 20 second sequence averages in the solar-magnetospheric coordinates. Only one event (10/17/66) has no significant variations related to the si observed on the earth. Explorer 33 in this case was far out at  $X = -54$ ,  $Y = 33$  and  $Z = -30 R_e$ . With exception of this event the si related field variations in the magnetosheath show larger fluctuations than those observed in the tail. When the si is observed in the magnetosheath, it shows fluctuations in all three components, e.g., the si variations shown in Figs. 5a and 5b on September 1, 3 and 24.

In the tail region, the field shows steady behavior for several hours (Behannon, 1968) and the si shows maximum change in X component. This is understandable because the magnetic field is mainly directed along X axis in the tail.



Occasionally, there is a small perturbation in the Z component. The behavior of small Z component is of recent interest in understanding the polar disturbances. Fairfield and Ness (1970) and Camidge and Rostocker (1970) have shown that before the sub-storm starts the magnetic field in tail increases and then, after reaching a certain value, it collapses. In the decreased field period the Z component of the tail field increases indicating the merging of the field lines. We have searched for the similar effect in tail field during the propagation of the si's. It is known that sometimes a si occurs before the onset of the substorm and in such cases perhaps the si acts as an initiating process. In Fig. 5a we show si events on July 15, Aug. 1 and Aug. 18 which were observed in the tail. There is no significant change in the Z components during these si's which resemble the changes observed during sub-storm by Fairfield and Ness (1970) and Camidge and Rostocker (1970). Future studies of si and substorm should look into the connection between these phenomena. If si's are found to initiate certain substorms then a maximum field increase required in the tail and corresponding amplitude of the si can give quantitative information on conditions required to start such a substorm.

## SUMMARY

Study of si events in the tail and the magnetosheath by using Explorer 33 magnetic field bring out the following points:

- a) The positive or negative si propagates with the speed with the range of approximately 550 to 1200 km per sec.
- b) The si with the lower speed travel as hydro-magnetic discontinuities or weak shocks with average shock wave speed between 550 - 700 km per sec. The higher velocities ( $>700$  km per sec) corresponds to the local Alfven speed; and the si's propagate as a large amplitude wave in these cases.
- c) The delay times indicate that some fluctuations associated with the si (4 out of 13 events) appear first in the tail or in the magnetosheath near the tail region. This supports the initial results obtained from IMP-1 analysis (Patel, 1968). Magnetic field data in the interplanetary space between the sun and earth showed no significant effects in these events. For the si which appears first on the earth and then in the tail or the magnetosheath the origin lies in the discontinuities in the solar wind as shown by Burlaga and Ogilvie (1969) and Gosling, et al. (1967).

- d) The si propagation is not confined to the geomagnetic tail. Its effect is detected far out in the magnetosheath covering a local time sector between 2000 to 0200 hours.
- e) The variations observed in the tail for the increase in the field during the si's are not large enough to start a substorm. However, further study is required to see if certain si's can build up the tail field to a limit when the field collapses and the substorm in the tail is started.

#### ACKNOWLEDGMENTS

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TABLE 1

Date	Onset (UT)	Delay Time (min.)	Satellite Position ( $R_E$ )			Satellite Local Time	Region	Avg. Speed km/sec
			X	Y	Z			
7/15/66a	2131 N	-5.0	-44.5	-10.3	9.5	0050	Tail	682
7/15/66b	2308 N	+7.0	-45.0	-11.0	9.4	0053	Tail	686
7/20/66	0800 P	-12.0	-61.9	-36.6	19.1	0214	Sheath	550
8/1/66	0003 P	+6.8	-48.5	- 0.1	9.8	0004	Tail	745
8/10/66	0149 P	+7.0	-56.8	-40.0	-6.5	0217	Sheath	866
8/18/66	1726 N	-8.0	-54.2	14.3	6.9	2311	Tail	723
8/31/66	1346 P	+4.3	-29.3	-31.5	-1.2	0250	Sheath	727
9/1/66a	1212 P	+1.6	-12.2	-26.6	0.8	0408	Tail-Sheath Plasma Sheet	813
9/1/66b	1524 N	---	- 9.1	-25.0	-2.7	0428	Sheath	---
9/3/66	2114 P	+2.6	-16.5	24.3	6.8	2024	Sheath	620
9/24/66	1805 N	---	-47.0	38.2	-24.8	2122	Sheath	---
9/27/66	1517 N	5.5	-63.4	-30.4	-22.2	2158	Tail Sheath	1230
10/12/66	0607 N	-5.6	-39.3	33.9	-24.8	2013	Tail Sheath	730
10/17/66	1702 N	---	-54.0	33.0	-30.6	2129	Sheath	---

## FIGURE CAPTIONS

- Fig. 1 A positive si on August 1, 1966 at several ground observatories and corresponding Explorer 33 magnetic field observations in solar-ecliptic coordinates. All satellite data are 20 sec averages. The letters in right-hand corner designate the observatories with the following geomagnetic latitudes and longitudes: MO = MOCA (5.73, 78.57); HO = Honolulu (21.03, 266.43); TU = Tucson (40.43, 312.18); Fr = Fredericksburg (49.55, 349.84); MA = Macquarie Island (-61.07, 243.15); CO = College (64.66, 256.51); WI = Wilkes (-78.4, 179.02). Scale for each station and component is shown by arrows. Scale for the Explorer data has ranges for F: 0-25,  $\theta$ : 0 to 360 degrees,  $\theta$ : -90 to +90 degrees. Onset times of the si's on the ground and the satellite position in solar-magnetospheric coordinates are given in Table 1.
- Fig. 2. A positive si on August 31, 1966 and Explorer 33 magnetic field observations. Other details are similar to Fig. 1.
- Fig. 3 A negative si on July 15, 1966 and Explorer 33 magnetic field observations. Other details similar to Fig. 1.
- Fig. 4. A negative si on September 24, 1966 and Explorer 33 magnetic field observations. Other details are similar to Fig. 1.

Fig. 5a. Explorer 33 magnetic field observations in the solar-magnetospheric X, Y, Z coordinates using 20 second averages. For each si event the zero line corresponds to the onset time observed on the surface of the earth. XS values for each event shows satellite position in solar-magnetospheric coordinates. Complete coordinates for satellite position, and onset times are given in Table 1.

#### TABLE CAPTION

Table 1. Onset time on the ground, delay time for the si effect in the tail or magnetosheath magnetic field data of Explorer 33 position of the satellite in solar-magnetospheric coordinates satellite local time and average speed of propagation for each si event. The negative delay time indicates earlier effect in the satellite data in the tail and the vicinity. N and P near the onset time indicate negative and positive si in the surface magnetograms.

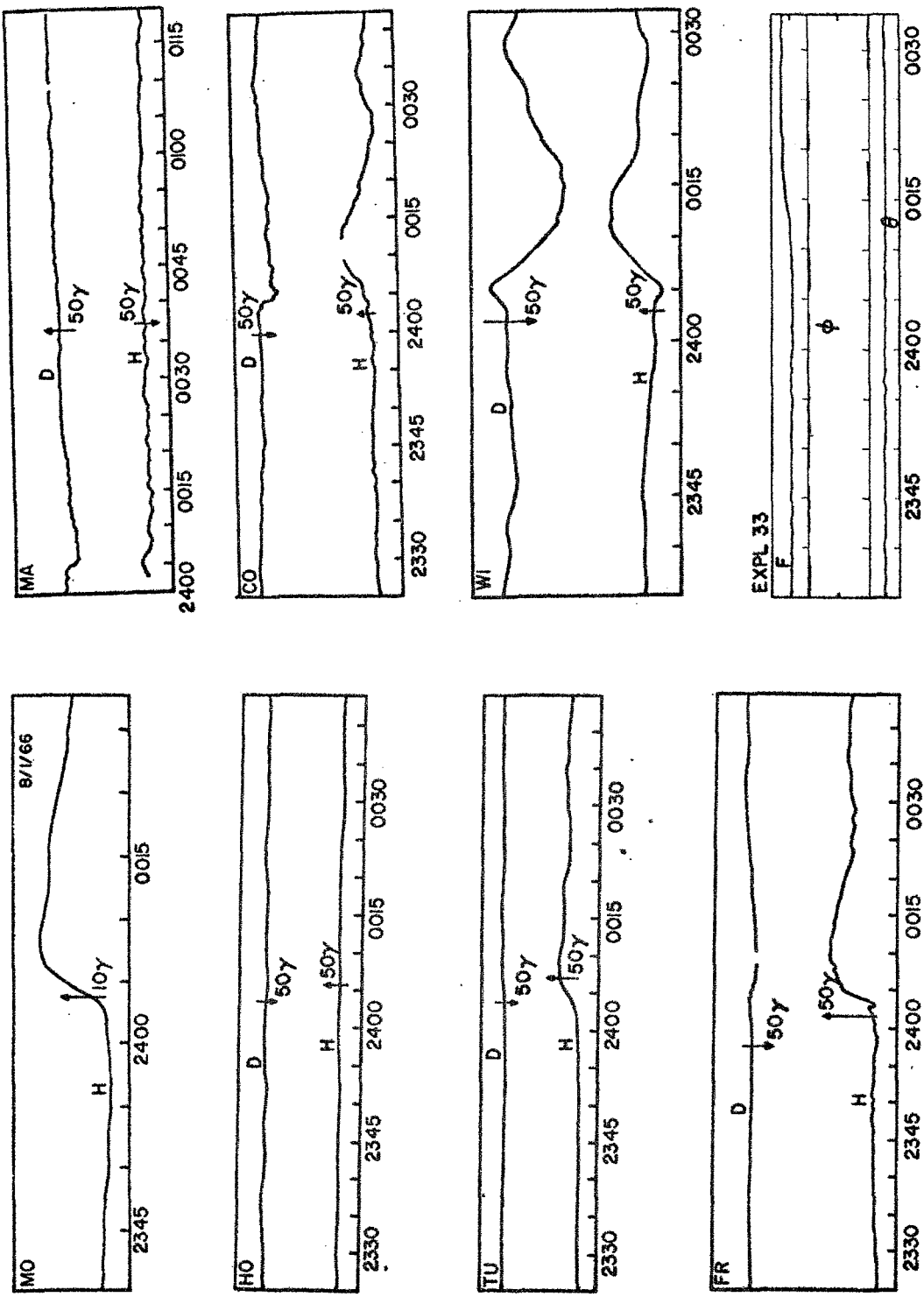


Fig. 1



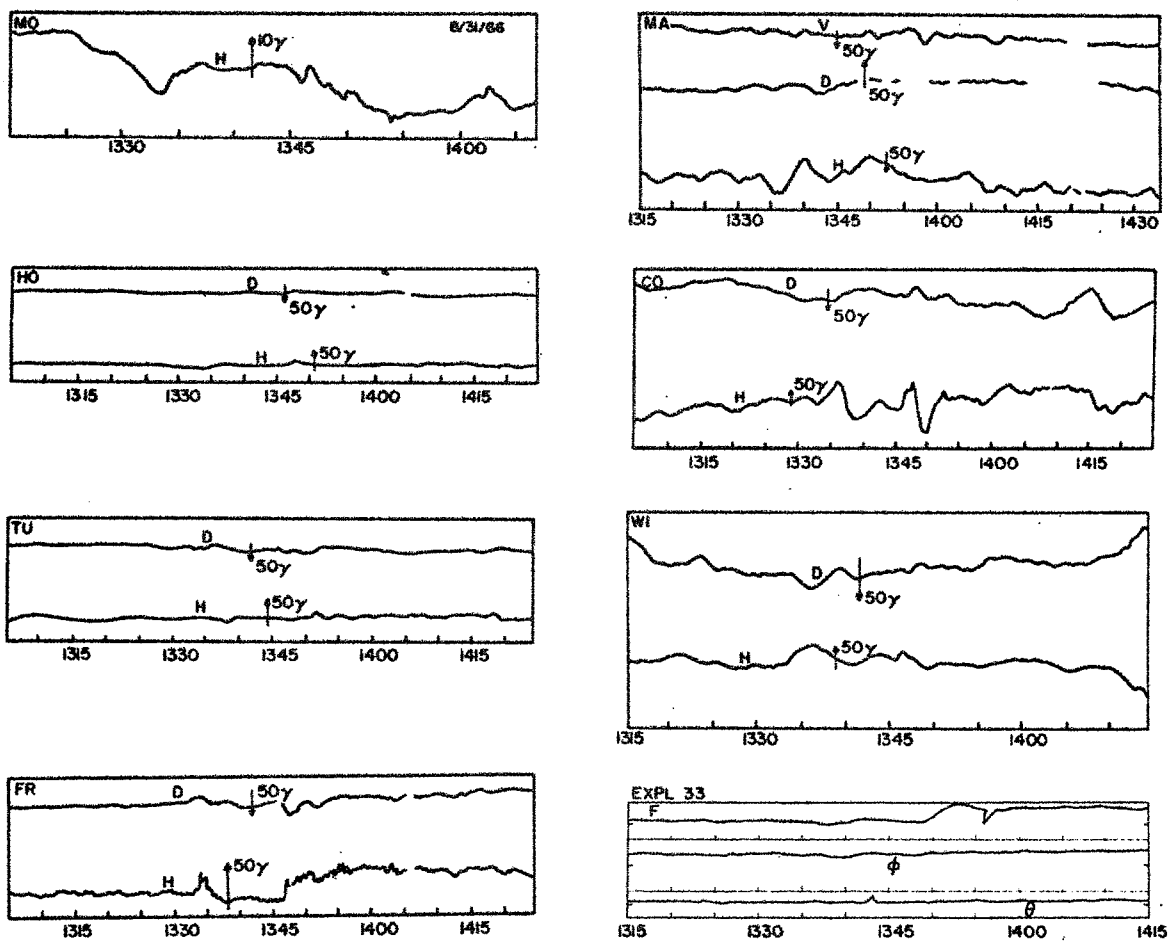


Fig. 2

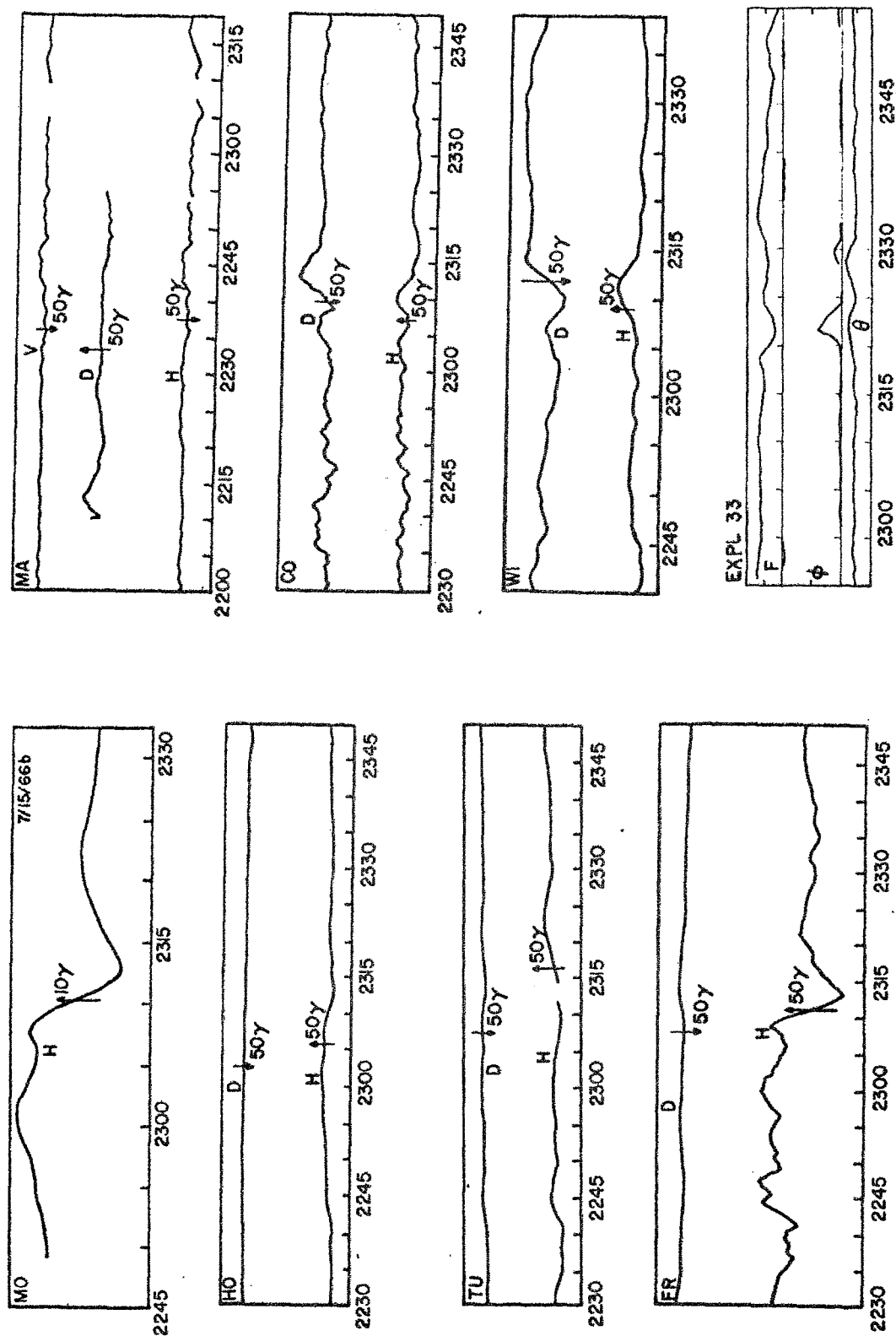


Fig. 3

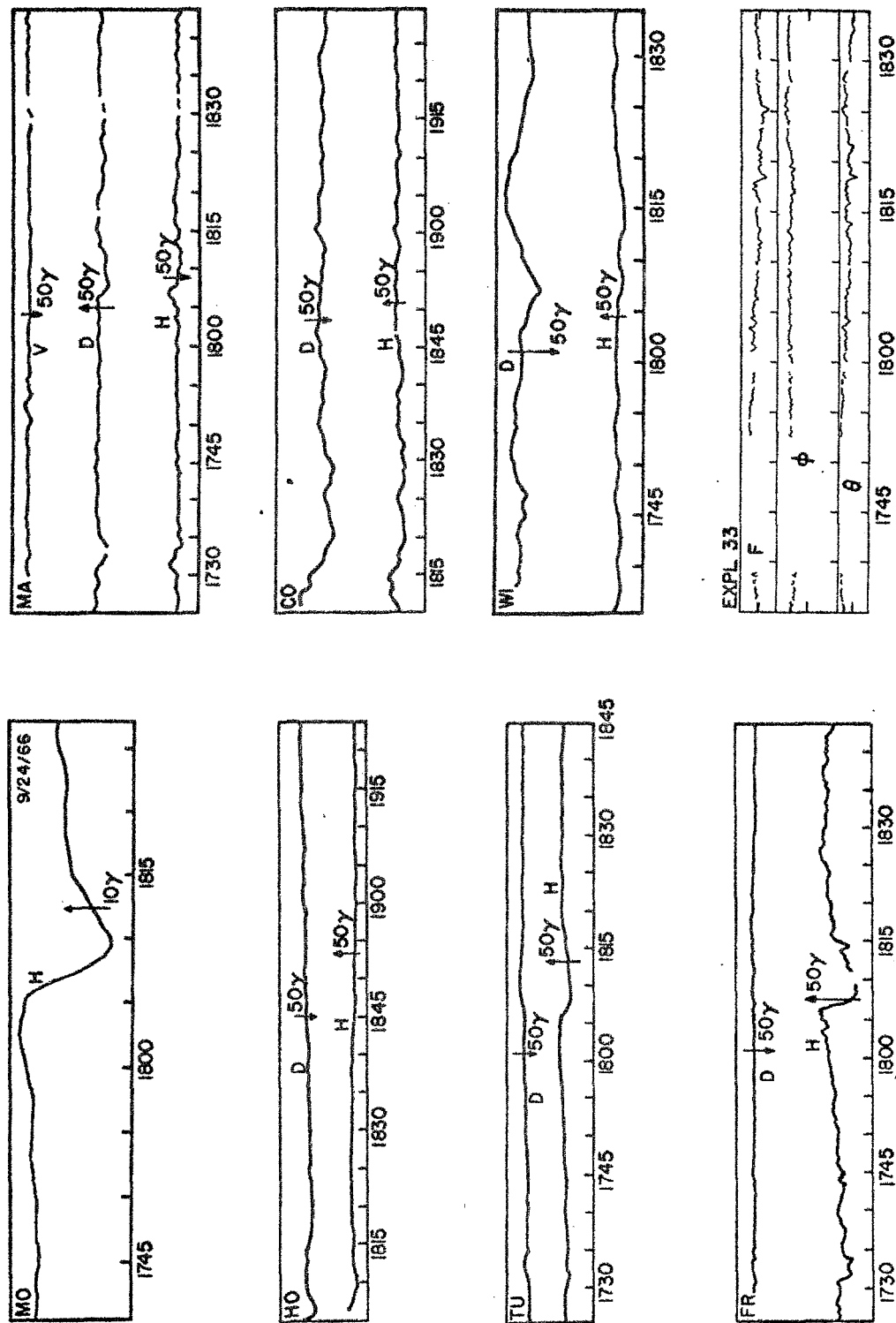


Fig. 4

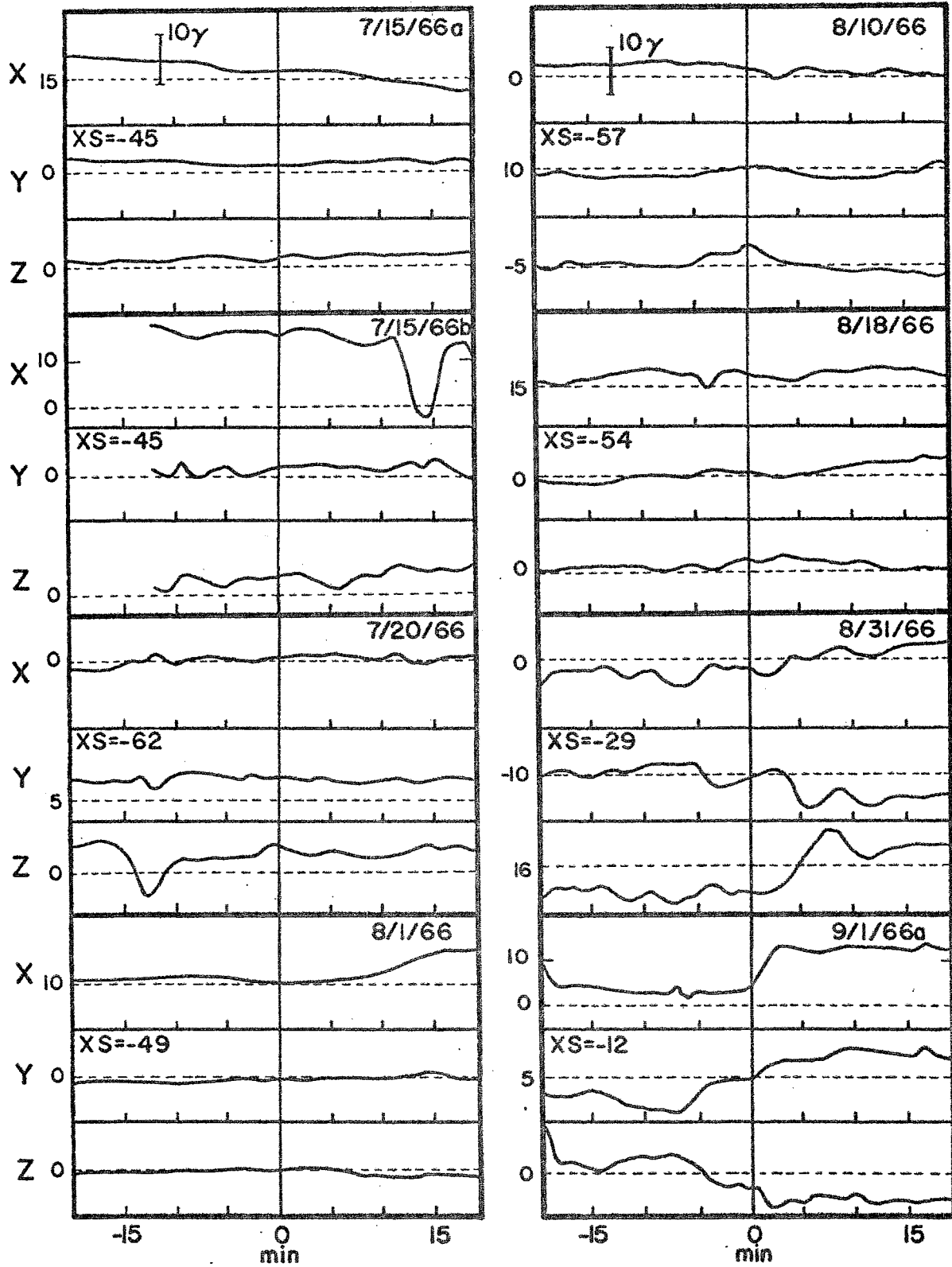


Fig. 5a

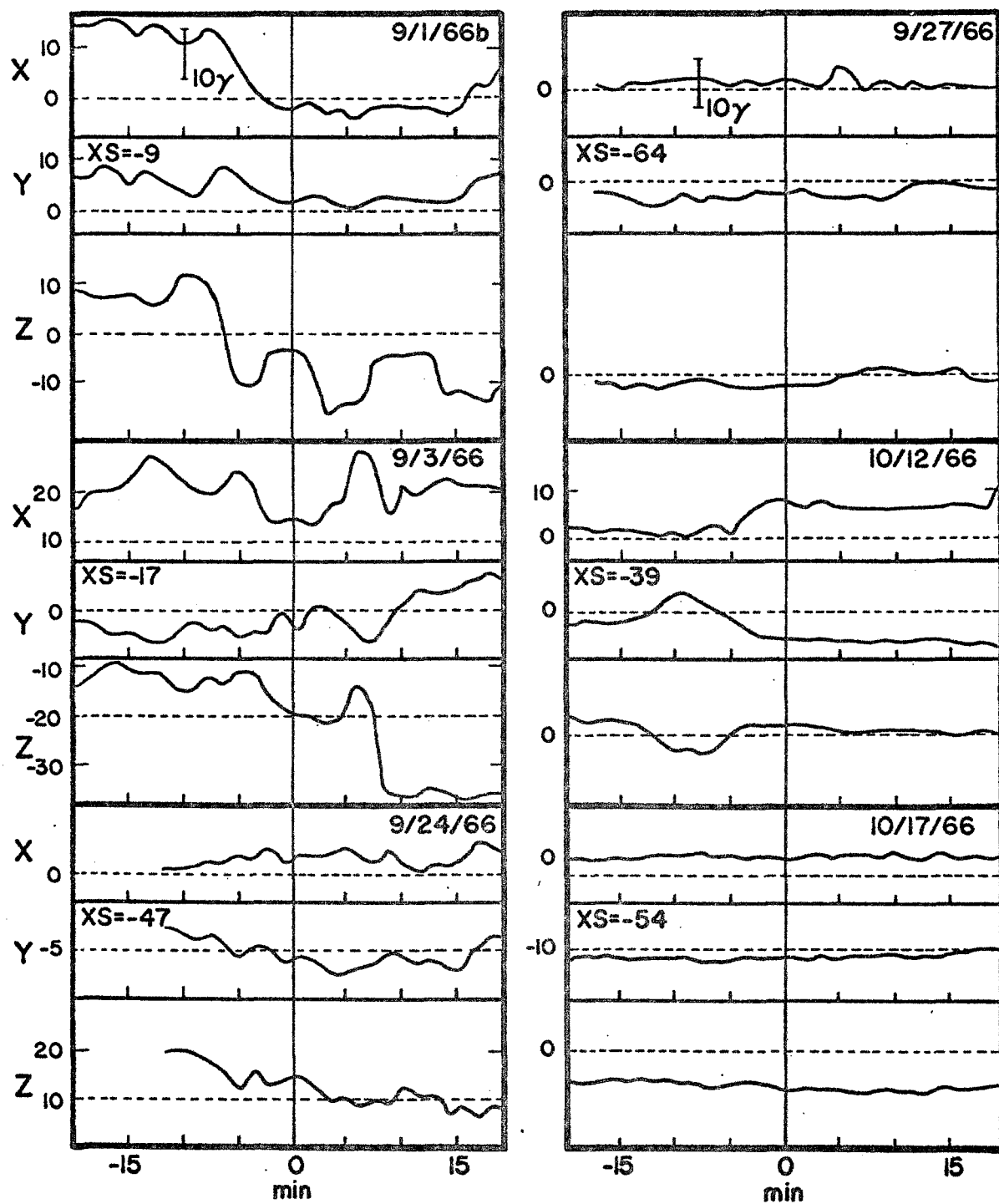


Fig. 5b