PROPAGATION OF THE SUDDEN COMMENCEMENT OF 8 JULY 1966 TO THE MAGNETOTAIL*

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ABSTRACT

The solar flare of 7 July 1966 produced a sudden commencement on the earth at 2102 UT on 8 July. The OGO-3 satellite observed a sudden increase in the magnetic field in the magnetotail following the sudden commencement. Using the IMP-3 and Explorer 33 observations by Ness and Taylor of the interplanetary shock that caused the sudden commencement, the propagation of the field increase from the front side of the magnetosphere to the tail is discussed. It is shown that the magnetospheric propagation of this perturbation toward the tail is faster than the propagation of the interplanetary shock just outside the bow shock. Based on the observations by OGO-3, the ground observations, and those made in interplanetary space by IMP-3 and Explorer 33, we estimate the interplanetary shock speed to be approximately 500 km/sec, with an Alfvén Mach number for the shock about 1.2. This speed is considerably lower than that deduced by Lazarus and Binsack from their plasma measurements on Explorer 33, namely, 700 km/sec. Conclusions drawn from the present study are: (i) that the observed magnetic field increase in the tail is unlikely to be due to an increased lateral pressure of the post-shock solar wind gas from the side of the tail, and (ii) that the transfer of additional polar magnetic flux to the tail due to the increase in the solar wind pressure on the front side of the magnetosphere can account for the observed tail field increase.

INTRODUCTION

Various effects caused by the class 2 solar flare of 7 July 1966 have been discussed extensively. Van Allen and Ness (1967), Ness and Taylor (1967), and Lazarus and Binsack (1967) have reported their observations of an interplanetary shock generated by the flare gas. With the magnetic observations made by the IMP-3 and Explorer 33 satellites just outside the earth's bow shock Ness and Taylor (1967) were able to determine the orientation of the shock normal in interplanetary space near the earth. The impact of the flare gas on the magnetosphere resulted in the sudden commencement (SC) of 8 July followed by a magnetic storm of moderate intensity. The present paper presents the OGO-3 magnetometer observation of a sudden magnetic field change in the magnetotail associated with the above SC, and discusses the gross feature of the propagation of the magnetic perturbation of this SC from the front side of the magnetosphere to the magnetotail.

OGO-3 OBSERVATION

The magnetic field instrumentation for OGO-3 consists of a duplicate set of the magnetometers flown on OGO-1, namely a rubidium vapor magnetometer and a fluxgate magnetometer (Heppner et al., 1967). The triaxial, dual range fluxgate magnetometer measures vector field over the ranges of 0 to $\pm$ 30 γ and 0 to $\pm$ 500 γ. The four-cell rubidium vapor magnetometer measures the scalar field over the range of 3 to 14,000γ with a programmed bias field added for vector measurements in weak magnetic fields. The vector measurements with the rubidium vapor magnetometer are used to make in-flight calibration of the fluxgate magnetometer.

Figure 1 shows the magnitude B of the magnetic field intensity as observed by the OGO-3 magnetometers during a ten hour period including the effect of the SC, namely, a sudden increase by approximately 15γ in B commencing at about $21^h02^m40^s$ on 8 July 1966. For most of the period covered in Figure 1, from 15^h00^m to 22^h36^m, points represent 2-minute averages of the rubidium vapor magnetometer readings, and for the remaining period B was calculated from the 30 second averages of the 3-component flux-gate magnetometer data. For several hours prior to the sudden increase the satellite was in a steady magnetotail field of 40γ. At the time of the onset of the field increase the solar ecliptic coordinates, X, Y, and Z of the position of OGO-3 were -10.10, 10.27, and 11.55 earth-radii (R_e), respectively; here the X axis is directed toward the sun, the Z axis perpendicular to the ecliptic plane and toward the north, and the Y axis is oriented so that the X, Y, and Z axes form a right-handed orthogonal system. (The positions of the satellites projected onto the solar ecliptic plane will be shown later in Figure 4.)

The rise time of the sudden change was approximately 4 minutes. Though the change appears to be abrupt in a plot on a condensed time scale like in Figure 1, the field change is found to be gradual and smooth when the raw data, taken at higher sampling rates, are plotted on an expanded time scale. In such plots the onset time of the field change cannot be precisely assigned because of the slowness of the rise. The time given above, i.e., $21^h02^m40^s$, should be understood in this context; while the rise time of 4 minutes describes the gross feature of the change quite well. Figure 2 showing B and the field direction in solar ecliptic coordinates is presented to illustrate the smoothness of the variation and the smallness in the direction change. Immediately before the SC change the direction of the magnetic field vector can be expressed, in terms of solar ecliptic latitude θ and longitude ϕ, by: $\theta \approx -5^\circ$ (minus sign for south of the solar ecliptic plane) and $\phi \approx -25^\circ$ (minus sign for west of the sun). Figure 3 shows a section of the data taken at the rate of 6.94 samples per second. The small scatter in data points is mainly due to the noise from the spacecraft. No high frequency fluctuations such as those often observed near the bow shock (Heppner et al., 1967) are found in the SC field increase even when the data taken at the sampling rate of 111.1 times per second are examined.

OTHER OBSERVATIONS

(1) The results obtained by Ness and Taylor (1967) from their magnetometer observations on the satellites IMP-3 and Explorer 33 play an important role in the subsequent discussions. Hence their results pertinent to our study are summarized below.

According to Ness and Taylor (private communication) the times of encounter of the flare-generated shock with IMP-3 and Explorer 33 and the positions of these satellites at the time of the encounter in solar ecliptic coordinates (X, Y, and Z) are as follows:

IMP-3: (2.57, 36.74, -5.66), $21^h05^m39^s \pm 20^s$ UT

Explorer 33: (-29.2, -60.0, -2.3), $21^h05^m42^s \pm 6^s$ UT

where X, Y, and Z are given in units of earth-radii (R_e).

From the condition that the component of the magnetic induction $\underline{B}$ normal to the discontinuity surface is continuous across this surface Ness and Taylor (1967) calculated the direction of the surface normal. The results are: from IMP-3, $\theta = 16^\circ$, $\phi = 160^\circ$; from Explorer 33, $\theta = 47^\circ$, $\phi = 163^\circ$. When the coplanarity theorem for an ideal shock is applied the results differ from these values, appreciably for Explorer 33. Ness and Taylor noted that the difference for Explorer 33 might have been due to the presence of the moon in front of the satellite.

(2) The time of the onset of the SC as observed on the earth's surface has been determined to be $21^h02^m15^s$ on 8 July with an uncertainty of about $\pm$ 5 seconds due mainly to the slowness of the initial rise. This determination is based on an inspection of the rapid-run magnetograms from Honolulu, College, Tucson, and Fredericksburg. Standard magnetograms from different parts of the world indicate a world-wide nature of the event, but their time resolutions are not adequate to provide accurate data on the onset time. The accuracy of the onset time adopted here is adequate for the following discussions.

INTERPRETATION

For the present purpose the times of encounters of the shock with IMP-3 and Explorer 33 as indicated in the preceding Section are close enough to be regarded as being simultaneous. We take the common time of encounter to be $21^h05^m40^s$ for the sake of simplicity. Note that the differences between this time and those given in the preceding Section are within the uncertainties prescribed by Ness and Taylor. Later we will show that these uncertainties will not affect the main line of argument in the present paper. Since the satellite velocities are small, being on the order of 1 km/sec, the uncertainties in the positions of the satellites arising from those in time are completely negligible.

We assume that the shock surface can be considered as being approximately a plane moving with a uniform velocity in the direction normal to its front surface over dimensions of the order of 100 R_e, roughly the distance between IMP-3 and Explorer 33 at the time of the passage of the shock. As was depicted by Ness and Taylor in Figure 6b in their paper (1967) the shock front must have had a curved surface when viewed on a large, interplanetary scale. However, over such small dimensions as are considered here the assumption indicated above seems to be reasonable.

Having made this assumption and another regarding the simultaneous encounters of the shock with IMP-3 and Explorer 33, the direction of the normal to the shock surface can readily be determined. The angle ϕ for the normal so obtained is 161.8°. For simplicity and clarity of argument we only consider a two-dimensional problem on the solar ecliptic plane by following the motion of the intersection of the shock and this plane; and the satellite positions are all projected onto the same plane. We define mutually orthogonal ξ, η axes with their origin at the earth's center and let the positive ξ axis be directed parallel to the shock normal as shown in Figure 4. Figure 4 is intended to show the direction of propagation of the interplanetary shock and relevant geometrical relations between the three satellites, the earth, the magnetopause, and the bow shock.

According to Lazarus and Binsack (1967) the density, n, and the velocity, v, of the solar wind observed by the MIT plasma instruments on Explorer 33 were: $n = 3\ cm^{-3}$ and $v = 350$ km/sec before the arrival of the shock. The distance of the magnetopause from the earth's center at the subsolar point for these plasma parameters is estimated at 11 R_e. The magnitude, B, of the magnetic induction in interplanetary space was about 10γ prior to the arrival of the shock (Ness and Taylor, 1967).

With the density of 3 protons cm^{-3} the Alfvén velocity is 126 km/sec and the Alfvén Mach number M_A for the solar wind is 2.8. Using the results of the work of Spreiter et al. (1966), the stand-off distance for the bow shock is approximately 5 R_e. Thus the position of the bow shock at the subsolar point is estimated to be near 16 R_e before the arrival of the shock from the flare.

By taking projections of the positions of the three satellites onto the ξ-axis we can now represent the series of events associated with the shock one-dimensionally. Referring to Figure 4, an overall picture is as follows: well within 30 seconds of the onset of the SC at the earth the front of the perturbation was propagating into the magnetotail passing OGO-3; while it took more than 3 minutes for the interplanetary shock to reach IMP-3 and Explorer 33, though the coordinates ξ for these satellites were less than ξ for OGO-3. This suggests that the propagation of the SC perturbation in this event, and very likely in many other cases, is faster inside the magnetopause than in interplanetary space.

Figure 5 shows the propagation of the perturbation front by plotting events in a ξ-time coordinate system. In such a diagram the trajectory of an object, whether a wave front or a satellite, could be represented by a curve, and its local velocity by the local slope of the curve. Because of their very low velocities the satellites are virtually stationary over the time intervals relevant here.

From the continuity of mass flow across the shock Lazarus and Binsack (1967) estimated the shock speed to be about 750 km/sec assuming the shock normal to lie in the ecliptic and along a radial direction from the sun (i.e., $\phi = 180^\circ$); if the normal is taken to be in the ecliptic but with $\phi = 160^\circ$, the shock speed becomes 700 km/sec, as these authors indicate. In Figure 5 a straight line is drawn through the point representing IMP-3 and Explorer 33 to show the shock propagation with the speed of 700 km/sec.

The time required for a hydromagnetic wave to travel from the magnetopause to the earth has been estimated by several authors (e.g., Dessler, 1958; Francis et al., 1959; Sugiura, 1965). A similar estimate is repeated in the present paper incorporating recent observational results on plasma density and a magnetic field model that includes the presence of a sheet current across the magnetotail, using the Williams-Mead model (Williams and Mead, 1965). For the fast mode of hydromagnetic wave, a ray can be traced by integrating certain canonical equations (Stegelmann and von Kenschitzki, 1964; Sugiura, 1965). Although the ray theory is, strictly speaking, valid only for small amplitude waves, estimates of transit times based on this method probably give values that are correct in order of magnitude, and should be useful until exact solutions are found.

The time of transit radially inward from the subsolar point on the magnetopause to the ionosphere at 300 km level is approximately 80 seconds for the model used. Considering the varying conditions in the magnetosphere a transit time of 60 to 90 seconds would be a reasonably reliable estimate. Taking these values as the limits, a range for the average speed of propagation from the magnetopause to the earth is indicated in Figure 5 by the two broken lines extending from the earth toward a shaded area representing the regions on the magnetopause from which the first effect of the SC propagated to the earth. The actual path of a ray would not be a straight line since the Alfvén velocity varies considerably during its transit. An example of a ray that propagates radially inward is shown by a curve in Figure 5.

As has already been mentioned, the magnetic field in the pre-shock solar wind was about 10γ (Ness and Taylor, 1967). There are no observations of the magnetic field or the plasma in the magnetosheath near the subsolar point at the time of our present interest. We arbitrarily set the lower limit to the average Alfvén velocity in this region to be 3 times the Alfvén velocity in the pre-shock solar wind; this value is then found to be roughly the pre-shock solar wind velocity. On the other hand, the average Alfvén velocity in the magnetosheath near the subsolar point is probably less than that immediately inside the magnetopause, and the upper limit to this velocity may be set at 1000 km/sec. Exact values for these limits are not critical in the discussions that follow. The propagation in the magnetosheath is illustrated in Figure 5 between the two shaded areas. The shaded area in the lower left represents the region of the bow shock that had the initial contact with the interplanetary shock.

In the outer region of the magnetosphere the Alfvén velocity, V_A, could be quite high. If $B = 40\gamma$ and $n = 1\ cm^{-3}$, $V_A = 870$ km/sec, a value already greater than the shock speed in interplanetary space. This applies also to the magnetotail. In the pre-SC condition B in the tail was 40γ (see Figure 1); thus, if the ion density was less than 1 cm^{-3}, the Alfvén velocity in the magnetotail, at this latitude outside the plasma sheet, could have been in excess of 1000 km/sec. In Figure 5 the local Alfvén velocity in the vicinity of OGO-3 is illustrated by showing two velocities corresponding to $n = 1\ cm^{-3}$ and $n = 0.1\ cm^{-3}$.

With these considerations there does not seem to be any difficulty in accepting that the SC perturbation propagated faster inside the magnetopause than in interplanetary space. It is noted here that we have not had any extraordinary conditions in this particular event; the magnetic field in the magnetotail may be somewhat stronger than usual, but certainly not much. Thus the above circumstance must occur frequently.

Having placed the observations at the earth and at the position of OGO-3 in proper order, we suggest, on the basis of Figure 5, that the shock speed in near-earth interplanetary space was about 500 km/sec. Even when effects of various uncertainties, such as those discussed below, are assessed the shock speed of 700 km/sec suggested by Lazarus and Binsack (1967) seems to be too high to be compatible with other observations unless the shock front had considerable curvature over a dimension of 100 R_e near the earth.

From the continuity of mass flow across the shock the shock velocity V can be expressed as

$$V = (\alpha\ v_2 - v_1)/(\alpha - 1)$$

where v_1 and v_2 are the plasma velocities in the pre-shock and the post-shock gas and $\alpha = n_2/n_1$, i.e., the ratio of the plasma densities. Taking $V = 500$ km/sec, $\alpha = 2$ (using $n_1 = 3\ cm^{-3}$, $n_2 = 6\ cm^{-3}$) and $v_1 = 350$ km/sec, v_2 must be 425 km/sec. This value depends on the ratio of n_2 to n_1 only, and so long as this ratio is about 2, v_2 cannot be very much different from the above value. For V = 500 km/sec the Alfvén Mach number for the shock (relative to the pre-shock gas) is 1.2, indicating that this is a weak shock.

As has been indicated earlier the times of encounter of the shock with IMP-3 and Explorer 33 have uncertainties of ± 20 seconds and ± 6 seconds, respectively. These uncertainties will reflect on the determination of ϕ. Let us take two extreme cases, namely: (i) a case in which the time correction for IMP-3 is +20 seconds and that for Explorer 33 is -6 seconds, and (ii) another case in which the former is -20 seconds and the latter is +6 seconds. Corresponding to these two extreme cases ϕ is 160.1° and 163.5°, respectively. Coordinates ξ and η will change accordingly. The positions of the satellites for these two cases are shown in Figure 5 with marks A and B. It is clear that the arguments presented above are not affected by the uncertainties in time.

DISCUSSIONS

(1) Except in the plasma sheet across the middle of the magnetotail the magnetic field energy density must dominate over the plasma kinetic energy density for a considerable distance from the earth. This is inferred from the remarkable steadiness of the tail field outside the plasma sheet. At the surface of the magnetotail the magnetic pressure inside is balanced, in an equilibrium state, by the plasma pressure plus the magnetic pressure in the magnetosheath. The arguments presented in the preceding Section clearly indicate that the increase in the magnetic field in the tail as observed by OGO-3 is not due to an increase in the lateral pressure from the solar wind gas immediately outside the magnetotail, since the front

surface of the high velocity, high density gas has not reached that distance in interplanetary space.

A more plausible explanation is to interpret the increase in the tail field to be due to a transfer of magnetic flux from the front side of the magnetosphere to the tail as a result of the compression of the magnetosphere. A rough estimate of the amount of flux transferred to the tail due to a compression can be made as follows. We first make a simple assumption that the magnetic flux crossing the earth's surface within a circle of colatitude θ, is all drawn back to the tail when the geocentric distance of the magnetopause along the sun-earth line is r_{b1}. Then we ask: (a) where this dividing colatitude circle goes when the magnetopause is compressed to r_{b2}, and (b) how much more flux will be pushed back to the tail when the additional compression alone is taken into account.

For a pure dipole, the magnetic flux Ψ that crosses the earth's surface within the circle of colatitude θ is given by

$$\begin{aligned} \Psi &= R_e^2 \int_0^{2\pi} d\phi \int_0^{\theta} B_r \sin\theta d\theta \\ &= 2B_o \pi R_e^2 \sin^2\theta \end{aligned} \tag{1}$$

where B_r is the radial component of $\underline{B}$, ϕ longitude, and B_o the magnetic induction at the equator on the earth's surface. We assume that the cross section of the tail has an area k^2 times that of the earth, i.e., $k^2 \pi R_e{}^2$, and that the tail field is uniform in magnitude but is directed toward the earth in one-half the cross sectional area and away from the earth in the remaining half. No assumption is made at this stage on the shape of the tail. The tail field magnitude B_t, is then given by

$$B_t = (4\ B_o/k^2)\ \sin^2\theta \qquad (2)$$

Thus, if k remains the same after the SC, we have

$$B_{t2}/B_{t1} = \sin^2\theta_2/\sin^2\theta_1 \qquad (3)$$

We now attempt to determine the right-hand side of Eq. (3) from the magnetosphere compression on the front side, using a property of the Mead-Beard magnetosphere model (Mead and Beard, 1964; Mead, 1964), namely that their model magnetosphere can be scaled to different solar wind conditions, as represented by the subsolar magnetopause distance r_b, by adjusting the radius of the earth. We make a hypothesis that the same method can be applied to our field configuration that includes the magnetotail. Then, once we postulate the position of the dividing colatitude θ_1 when the magnetopause is at r_{b1}, the dividing colatitude θ_2 when $r_b = r_{b2}$ can be approximately determined by taking an undisturbed dipole field line that intersects the earth's surface at θ_1 in the initial state, and by finding the colatitude θ_2 at which the same field line intersects the spherical surface representing the earth's surface in the final state. This can be done by taking the radius of the earth in the latter state to be r_{b1}/r_{b2} times the initial radius. The approximation lies in the use of an undistorted dipole field line rather than the actual distorted field line that represents the dividing line in the Mead-Beard model; this approximation is justified in the vicinity of the earth. Using the equation for the dipole line of force, we have

$$\sin^2\theta_2/\sin^2\theta_1 = r_{b1}/r_{b2} \qquad (4)$$

From Eqs. (3) and (4) the ratio B_{t2}/B_{t1} reduces to

$$B_{t2}/B_{t1} = r_{b1}/r_{b2} \tag{5}$$

Hence this ratio is independent of k^2; all that is required is that k^2 remains constant. The increase $\Delta B_t (\equiv B_{t2} - B_{t1})$ is given by

$$\Delta B_t = B_{t1} \; [(r_{b1}/r_{b2}) - 1] \tag{6}$$

According to Mead (1964) the distance r_b of the magnetopause at the subsolar point is given by

$$r_b = 1.068 \; (M^2/4\pi \; nmv^2)^{1/6} \tag{7}$$

where M is the earth's dipole moment, n and v the density and the velocity of the solar wind, respectively, and m the proton mass. Using the solar wind parameters quoted in the preceding Section r_{b1} and r_{b2} are found to be 11.1 R_e and 8.5 R_e respectively. However, it is the ratio r_{b1}/r_{b2} that is of our present interest. This ratio reduces to

$$r_{b1}/r_{b2} = [(n_2/n_1)(v_2/v_1)^2]^{1/6} \tag{8}$$

which implies that r_{b1}/r_{b2} depends only on the ratios n_2/n_1 and v_2/v_1. In our present case r_{b1}/r_{b2} is found to be 1.305. Substituting this value in Eq. (6) the tail field increase ΔB_t becomes 12γ, which is roughly the observed level change in the tail field. The peak of the initial rise (Fig. 1) is several gammas higher than the above value, but this may be due to a hydromagnetic impact effect rather than due to a quasi-stationary level change that is being considered here.

So far no assumptions have been made concerning the shape or the size of the tail. To determine values of θ_1 and θ_2 we must specify k^2, i.e., the cross sectional area of the tail in units of the earth's cross section. In particular, if we take the tail to be cylindrical, k becomes the radius of the cylinder in units of earth-radii. Taking the radius of the cylindrical tail to be 15 R_e, $\theta_1 = 74.4^\circ$ and $\theta_2 = 72.1^\circ$.

In the course of the compression of the magnetosphere the transfer of magnetic flux to the tail proceeds hydromagnetically. Displacements of lines of force caused by a sudden increase in the solar wind pressure have been discussed by Sugiura (1965) using the Mead-Beard model without including the tail.

(2) There is another important aspect in the present observation that is not directly related to the propagation of the sudden commencement change. The magnetograms from several high latitude observatories in the Scandinavian sector indicate that the SC triggered a large change in the already existing disturbed conditions. Such an example has previously been shown by Heppner (1968). The important aspect to be noted is that the change in the polar disturbance triggered by the SC was not preceded by a change in the magnetotail. This gives an additional support to our thesis (Heppner et al., 1967) that the immediate source of polar disturbances does not lie deep in the magnetotail and that instead the distant magnetotail simply reacts to changes in the fields and plasmas within closed magnetospheric shells in the "near tail" region. The response of the magnetic field in the tail to an auroral zone negative bay is generally characterized by a collapse of the tail field configuration and a return

toward the dipole configuration in the tail sector located near the meridian plane of the bay onset. Two examples of this nature are shown in Figure 6a which depicts the magnetic field behavior at large distances during the storm that followed the SC under discussion. In Figure 6a the two hatched epochs represent polar disturbances as deduced from the ground observations, part of which are shown in Figure 6b. It is evident, particularly from the inclination angle, that following each of the two principal magnetic bay onsets occurring near the satellite meridian plane the field deviates such as to approach the theoretical field, represented by the continuous curve.

(3) Finally, a brief remark is made on a main phase storm effect seen in Figure 6a, namely the large deviation of the observed field from the theoretical reference field inside 7 R_e. This field decrease is due to the diamagnetic effect of a high energy plasma that existed during the main phase of the storm. Frank (1967) has reported on measurements from the same satellite of electrons and protons in the energy range 0.2 to 50 kev in this region. Problems concerning large magnetic storm effects in the magnetosphere will be discussed in a separate paper.

CONCLUSIONS

A sudden magnetic field increase was observed in the magnetotail within about 30 seconds of the onset at the earth of the sudden commencement on 8 July 1966. Using the IMP-3 and Explorer 33 magnetic observations by Ness and Taylor (1967) of the interplanetary shock that caused the sudden commencement, it is concluded that the observed tail field increase is not likely to be the result of an increased solar wind pressure from the sides of the tail. With an idealized model we have shown that the increase in the tail field is due mainly to a transfer of magnetic flux to the tail by the increased solar wind pressure exerted on the front and the sides of the magnetosphere.

To be consistent with the observations on the earth's surface and by OGO-3 in the magnetotail the velocity of the shock in near-earth interplanetary space must have been approximately 500 km/sec with an Alfvén Mach number of 1.2. This velocity is appreciably lower than the value of 700 km/sec deduced by Lazarus and Binsack (1967).

Alfvén velocities in the magnetosphere including the tail outside the plasma sheet are generally greater than either the Alfvén velocity in the solar wind or the solar wind velocity itself. Thus the hydromagnetic perturbation produced by an impact of an interplanetary discontinuity on the solar side of the magnetosphere would normally propagate inside the magnetosphere and into the tail ahead of the front of the discontinuity in interplanetary space. Therefore the interpretation presented above must be of a quite general nature rather than an account unique to the particular event treated.

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References

Dessler, A. J., The propagation velocity of world-wide sudden commencements of magnetic storms, J. Geophys. Res., 63, 405-408, 1958.

Francis, W. E., M. I. Green, and A. J. Dessler, Hydromagnetic propagation of sudden commencements of magnetic storms, J. Geophys. Res., 64, 1643-1645, 1959.

Frank, L. A., On the extraterrestrial ring current during magnetic storms, J. Geophys. Res., 72, 3753-3767, 1967.

Heppner, J. P., Correlations between magnetospheric magnetic field variations and auroral electrojet activity, Ann. Geophys., 1968 (in press).

Heppner, J. P., M. Sugiura, T. L. Skillman, B. G. Ledley, and M. Campbell, OGO-A magnetic field observations, J. Geophys. Res., 72, 5417-5471, 1967.

Lazarus, A. J., and J. H. Binsack, Observations of the interplanetary plasma (associated with the July 7, 1966 flare), to be published in IQSY Annuals; MIT, Lab. for Nuclear Sci. Preprint 1967.

Mead, G. D., Deformation of the geomagnetic field by the solar wind, J. Geophys. Res., 69, 1181-1195, 1964.

Mead, G. D., and D. B. Beard, Shape of the geomagnetic field solar wind boundary, J. Geophys. Res., 69, 1169-1179, 1964.

Ness, N. F., and H. E. Taylor, Observations of the interplanetary magnetic field July 4-12, 1966, Goddard Space Flight Center Report X-612-67-345, 1967.

Spreiter, J. R., A. L. Summers, and A. Y. Alksne, Hydromagnetic flow around the magnetosphere, Planet. Space Sci., 14, 223-253, 1966.

Stegelmann, E. J., and C. H. von Kenschitzki, On the interpretation of the sudden commencement of magnetic storms, J. Geophys. Res., 69, 139-155, 1964.

Sugiura, M., Propagation of hydromagnetic waves in the magnetosphere, Radio Sci., 69D, 1133-1147, 1965.

Sugiura, M., A sudden change in the solar wind pressure and the outer region of the magnetosphere, J. Geophys. Res., 70, 4151-4158, 1965.

Van Allen, J. A., and N. F. Ness, Observed particle effects of an interplanetary shock wave on July 8, 1966, J. Geophys. Res., 72, 935-942, 1967.

Williams, D. J., and G. D. Mead, Nightside magnetosphere configuration as obtained from trapped electrons at 1100 kilometers, J. Geophys. Res., 70, 3017-3029, 1965.

Figure Captions

Figure 1. The sudden commencement in the magnitude B of the magnetic field observed by OGO-3.

Figure 2. The magnitude (B) and direction (solar ecliptic latitude θ and longitude ϕ) of the magnetic field. B from the Rb magnetometer; θ and ϕ calculated from three components, two of which are direct readings from the sensitive fluxgate magnetometer; the third component, being saturated on the sensitive scale, was calculated from B and the remaining two components; thus when bias coil calibrations are made on the Rb magnetometer these appear in θ and ϕ through the computed third component.

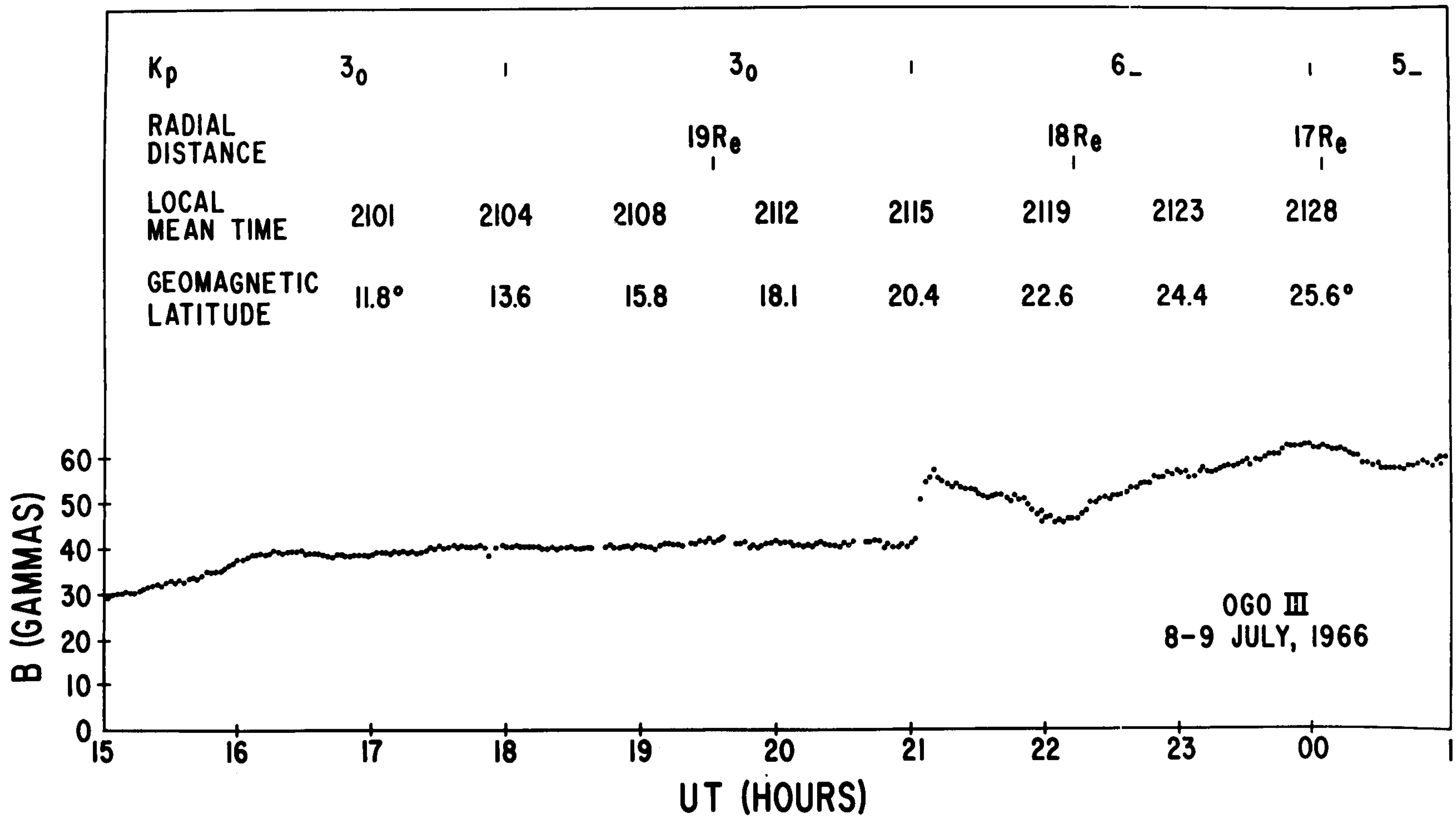
Figure 3. The magnitude of the magnetic field observed at the rate of 6.94 samples per second to illustrate the smoothness of the variation; the small scatter is due to spacecraft noise.

Figure 4. Projection of the satellite positions onto the solar ecliptic plane and the definition of the ξ, η axes.

Figure 5. The ξ-time representation of the propagation of the interplanetary shock and the magnetospheric disturbance (i.e., the sudden commencement).

Figure 6a. OGO-3 magnetic observations during the storm following the July 8 sudden commencement, illustrating variations in the magnetic field approaching the theoretical dipole field (shown by the continuous curve) following negative bay onsets. Two hatched areas represent the principal negative bays occurring near the local time zone of the satellite.

Figure 6b. Ground observations at high latitudes during the July 8 storm. Negative bay onset times are indicated. The letter "S" with an arrow, shown once for each observatory, indicates the time at which the satellite passed through that observatory's meridian plane.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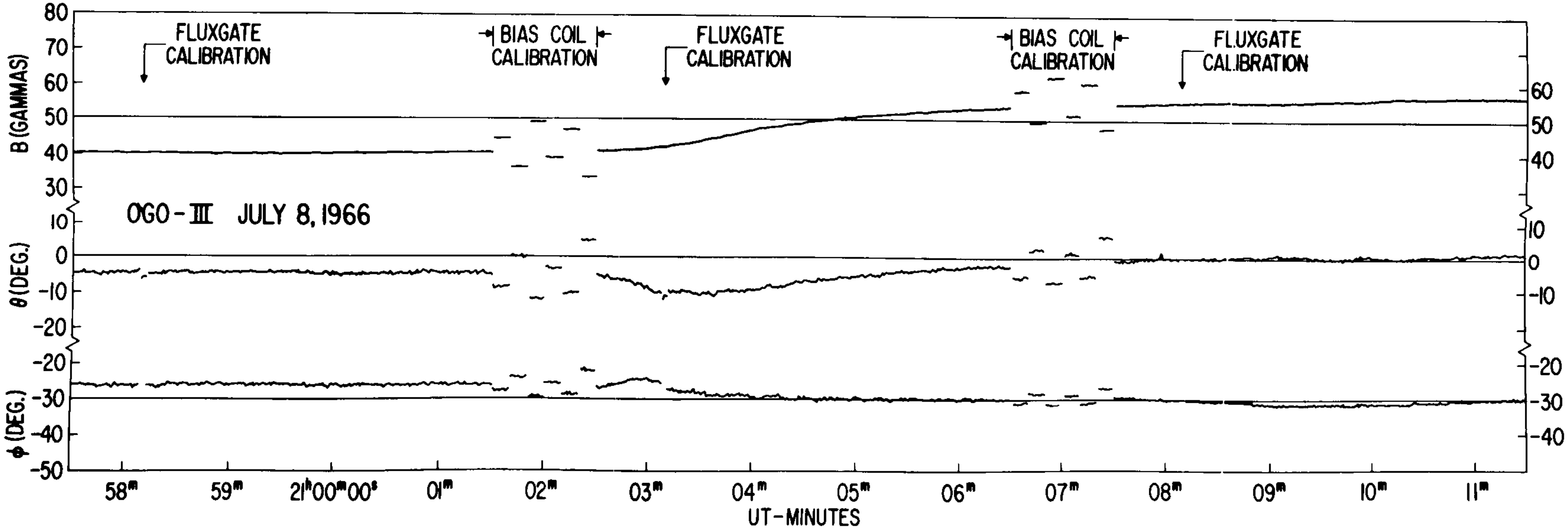
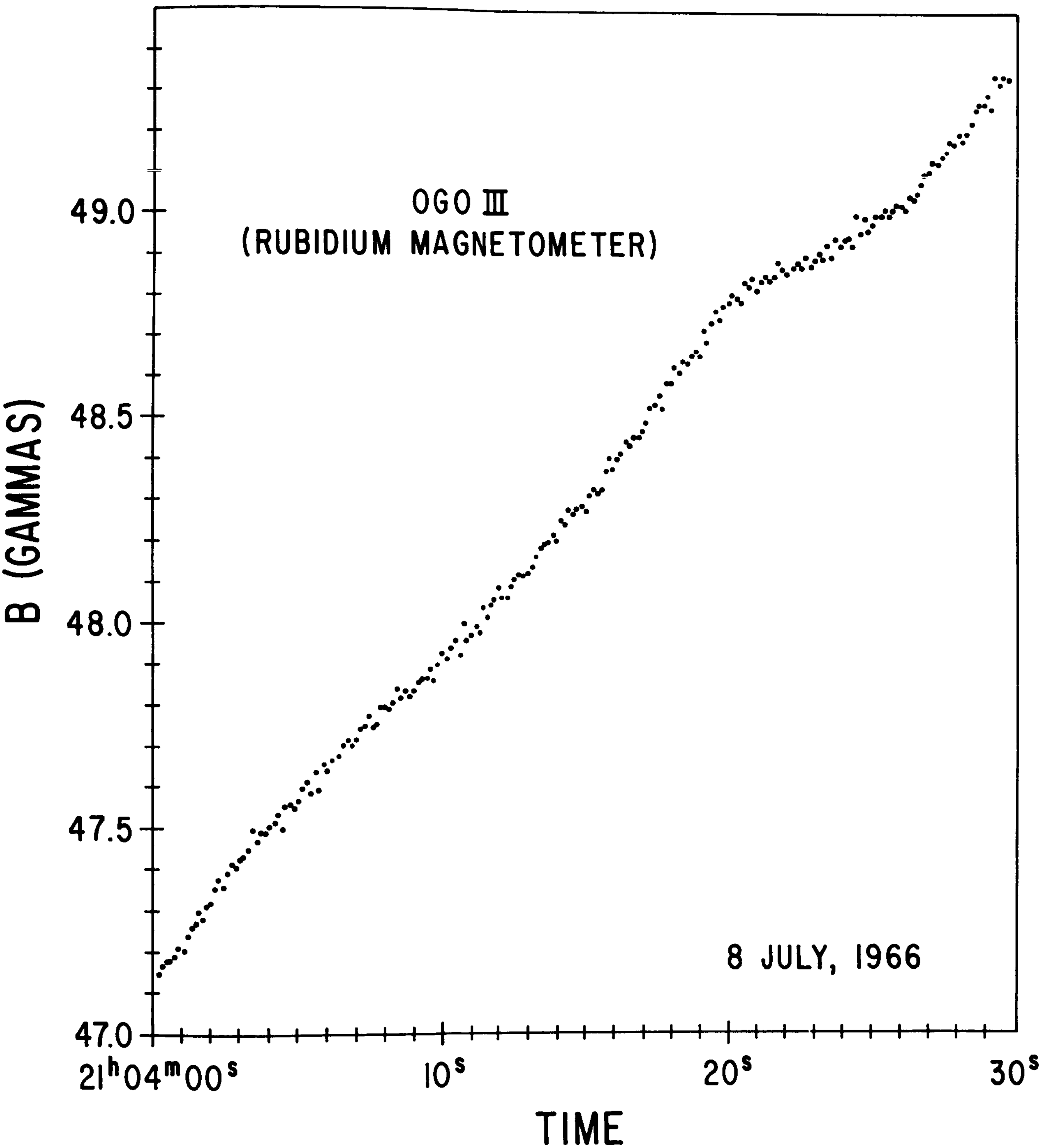
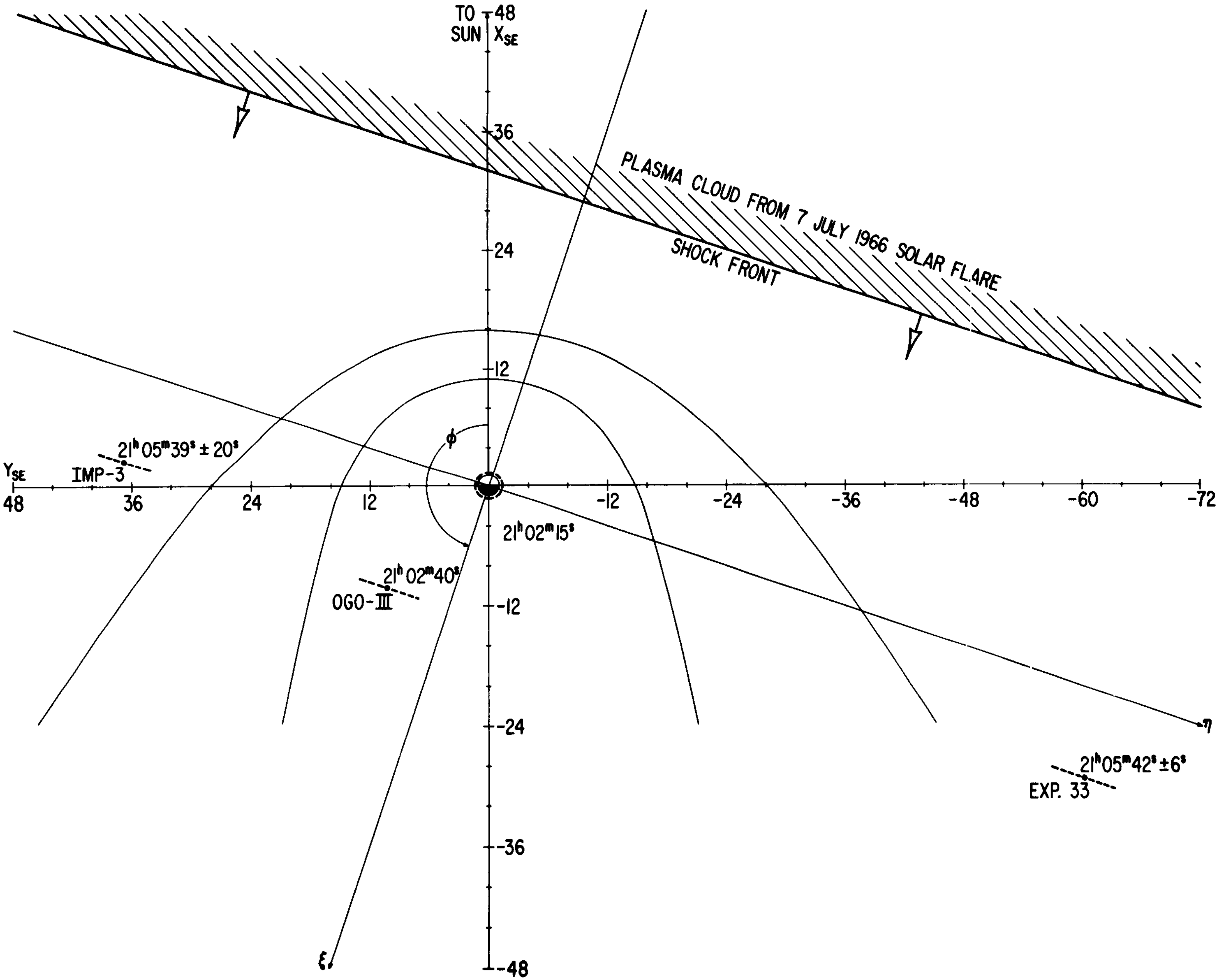
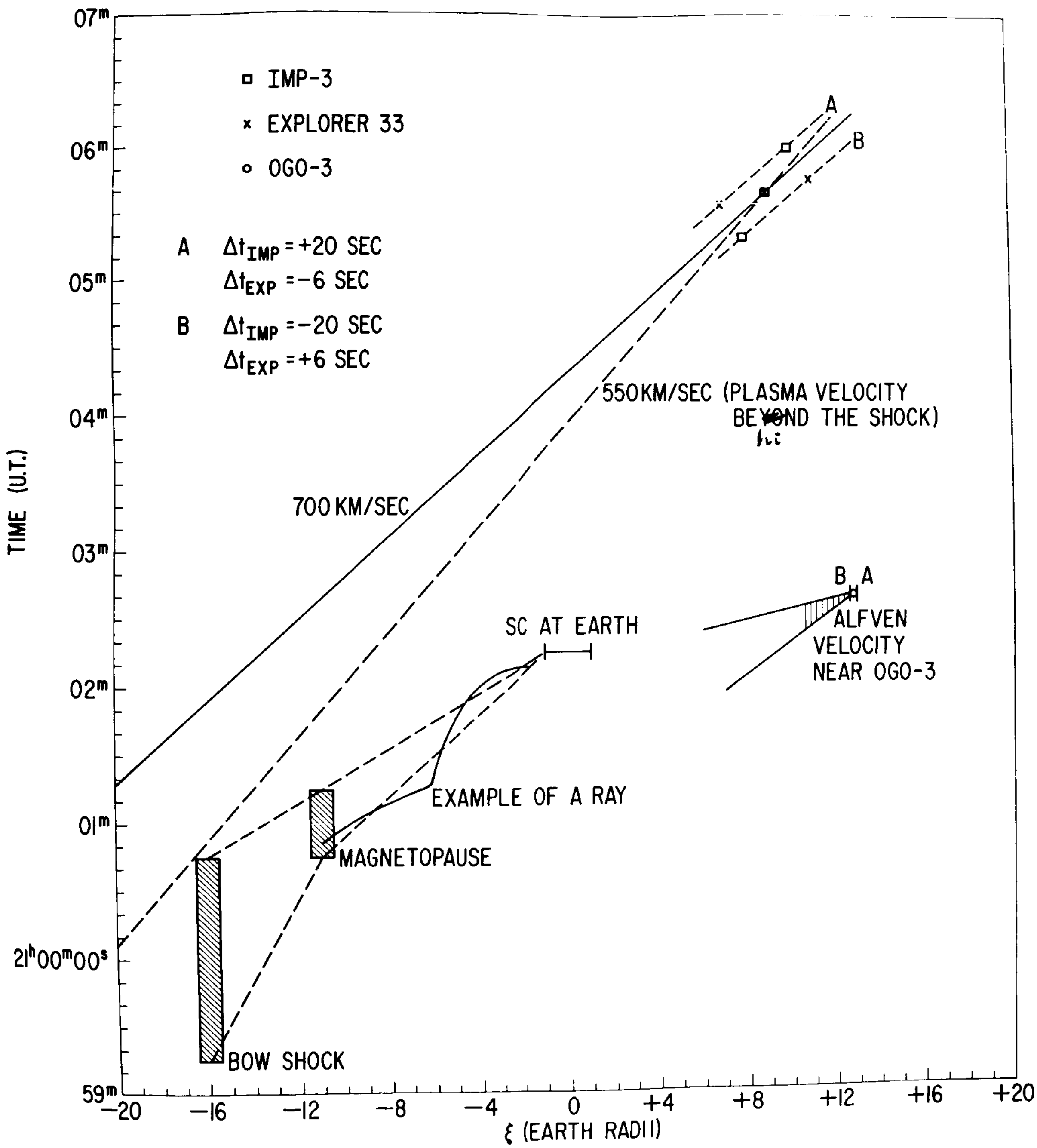
OGO III
8-9 JULY, 1966


OGO-III JULY 8, 1966
FLUXGATE CALIBRATION
BIAS COIL CALIBRATION
FLUXGATE CALIBRATION
BIAS COIL CALIBRATION
FLUXGATE CALIBRATION
B (GAMMAS)
θ (DEG.)
φ (DEG.)
58m
59m
21h00m00s
01m
02m
03m
04m
05m
06m
07m
08m
09m
10m
11m
UT-MINUTES

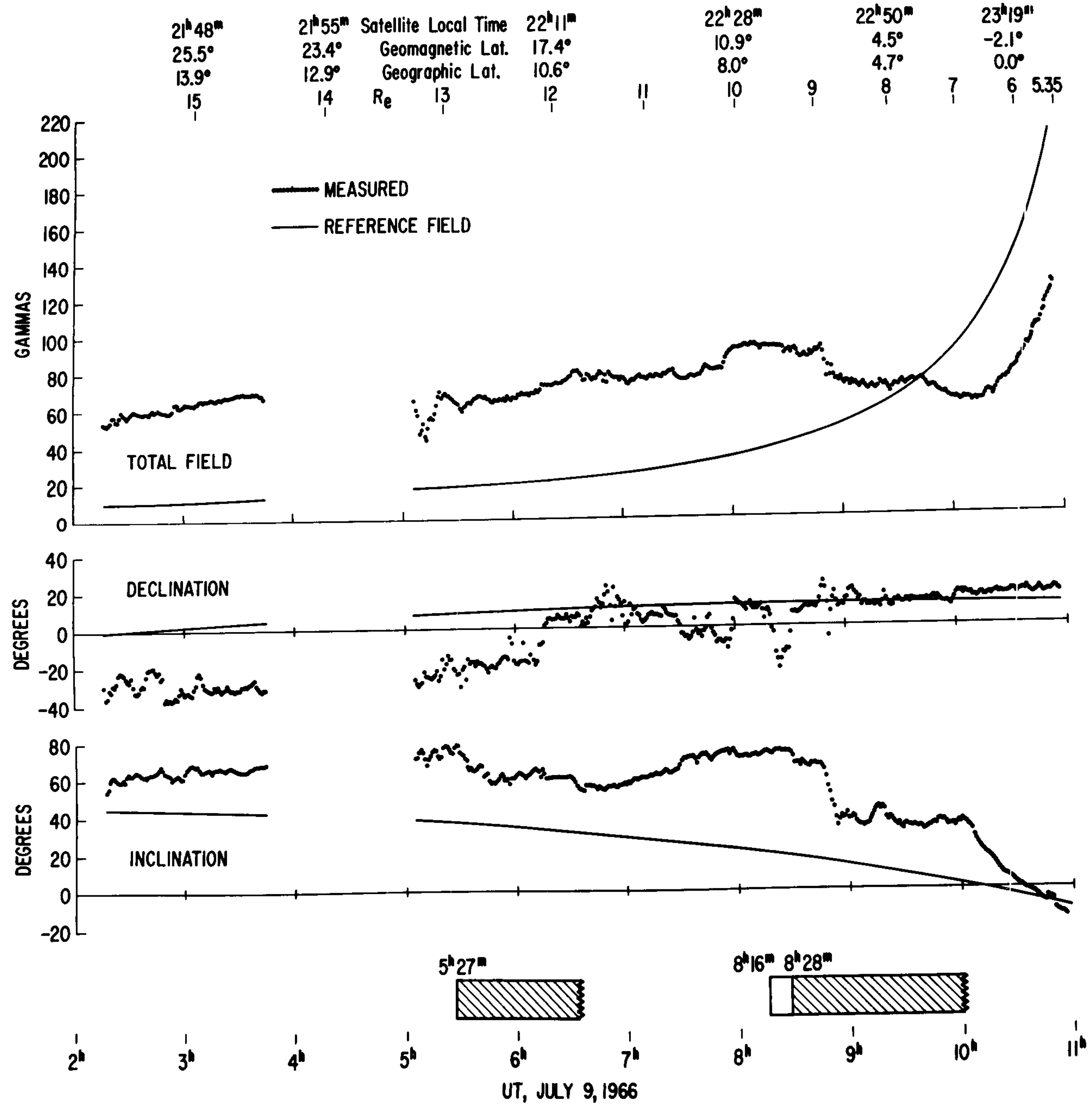


OGO III
(RUBIDIUM MAGNETOMETER)
8 JULY, 1966
B (GAMMAS)
49.0
48.5
48.0
47.5
47.0
$21^h04^m00^s$
10^s
20^s
30^s
TIME

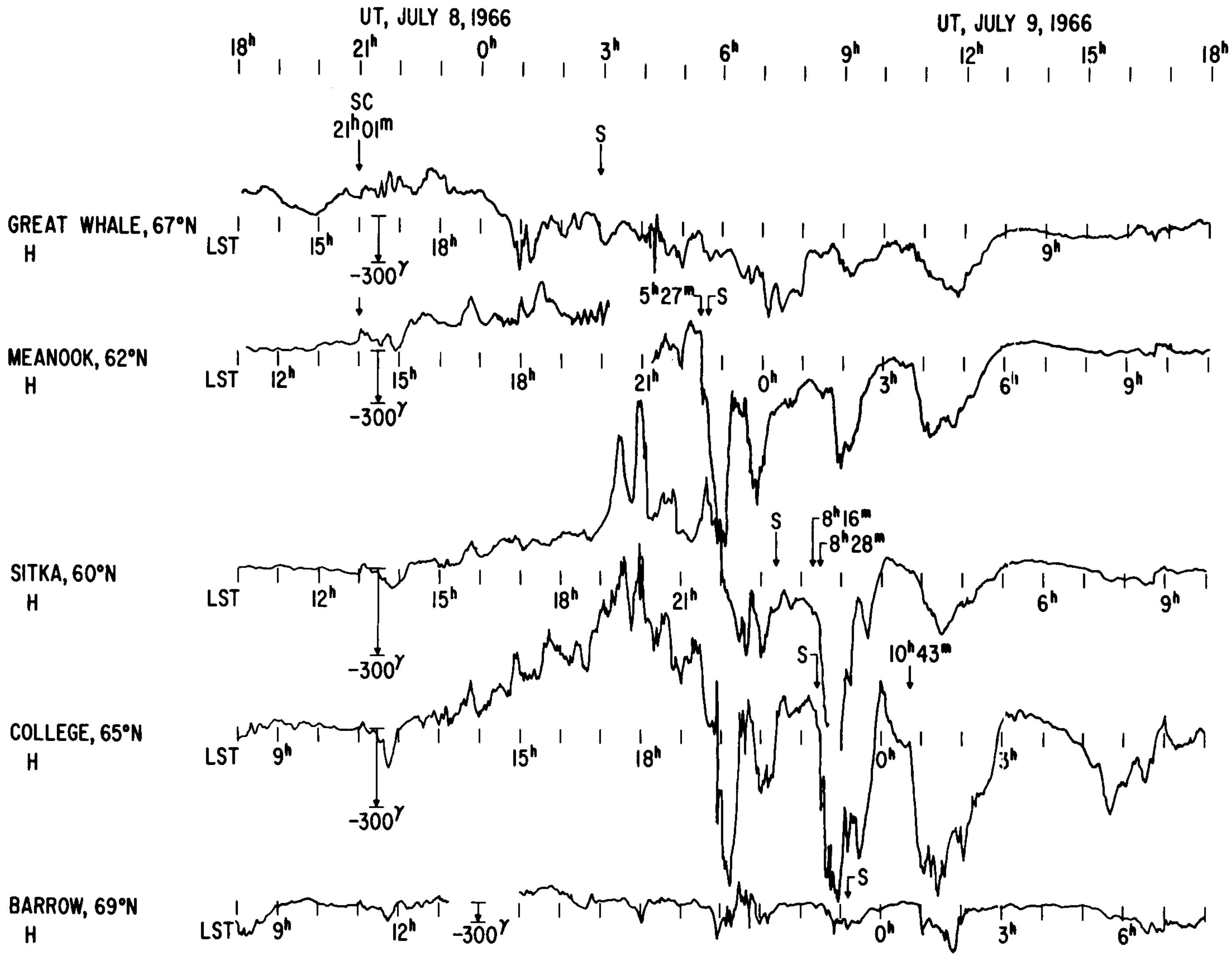

TO SUN
X_{SE}
Y_{SE}
PLASMA CLOUD FROM 7 JULY 1966 SOLAR FLARE
SHOCK FRONT
ϕ
$21^h 05^m 39^s \pm 20^s$
IMP-3
$21^h 02^m 40^s$
OGO-III
$21^h 02^m 15^s$
$21^h 05^m 42^s \pm 6^s$
EXP. 33
η
ξ
48
36
24
12
-12
-24
-36
-48
-60
-72



IMP-3
EXPLORER 33
OGO-3
A Δt IMP = +20 SEC
Δt EXP = −6 SEC
B Δt IMP = −20 SEC
Δt EXP = +6 SEC
550 KM/SEC (PLASMA VELOCITY BEYOND THE SHOCK)
700 KM/SEC
SC AT EARTH
ALFVEN VELOCITY NEAR OGO-3
EXAMPLE OF A RAY
MAGNETOPAUSE
BOW SHOCK
TIME (U.T.)
07m
06m
05m
04m
03m
02m
01m
21h00m00s
59m
ξ (EARTH RADII)
−20
−16
−12
−8
−4
0
+4
+8
+12
+16
+20
A
B



21h48m
25.5°
13.9°
15
21h55m
23.4°
12.9°
14
Satellite Local Time
Geomagnetic Lat.
Geographic Lat.
Re
13
22h11m
17.4°
10.6°
12
11
22h28m
10.9°
8.0°
10
9
22h50m
4.5°
4.7°
8
7
23h19m
-2.1°
0.0°
6
5.35
MEASURED
REFERENCE FIELD
GAMMAS
TOTAL FIELD
DECLINATION
DEGREES
INCLINATION
DEGREES
5h27m
8h16m 8h28m
2h
3h
4h
5h
6h
7h
8h
9h
10h
11h
UT, JULY 9, 1966


UT, JULY 8, 1966
UT, JULY 9, 1966
18h 21h 0h 3h 6h 9h 12h 15h 18h
SC
21h01m
S
GREAT WHALE, 67°N
H
LST 15h 18h 9h
-300γ
5h27m S
MEANOOK, 62°N
H
LST 12h 15h 18h 21h 0h 3h 6h 9h
-300γ
S
8h16m
8h28m
SITKA, 60°N
H
LST 12h 15h 18h 21h 6h 9h
-300γ
S
10h43m
COLLEGE, 65°N
H
LST 9h 15h 18h 0h 3h
-300γ
S
BARROW, 69°N
H
LST 9h 12h 0h 3h 6h
-300γ