N 67 12274
X-640-66-527

NASA TM X- 55622

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# MEASUREMENTS OF THE DISTORTION OF THE GEOMAGNETIC FIELD BY THE SOLAR WIND

BY

GILBERT D. MEAD
LAURENCE J. CAHILL, JR.

NOVEMBER 1966

NASA

GODDARD SPACE FLIGHT CENTER
GREENBELT, MARYLAND

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# EXPLORER 12 MEASUREMENTS OF THE DISTORTION OF THE GEOMAGNETIC FIELD BY THE SOLAR WIND

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Gilbert D. Mead

NASA-Goddard Space Flight Center

Greenbelt, Maryland

and

Laurence J. Cahill, Jr.

Physics Department

University of New Hampshire

Durham, New Hampshire


November 1966


Goddard Space Flight Center
Greenbelt, Maryland


*Submitted to the Journal Geophysical Research

## ABSTRACT

Magnetometer data from 7 passes of Explorer 12 during quiet times have been compared with theoretical magnetosphere models. The data cover the region from 3-1/2 to 13 earth radii and are expressed in terms of the deviation in field magnitude from a Jensen and Cain reference field, plus inclination and declination angles measured with respect to the dipole axis. Near the noon meridian and from 6-7 earth radii out to the magnetopause, the magnitude and direction of the observed field seem to agree quite well with those predicted by the distorted magnetosphere model of Mead and Beard. Near the dawn meridian, a significant twisting of the field lines out of the dipole magnetic meridian plane is observed, corresponding to the tendency of the field to point in the antisolar direction in the southern hemisphere. From 3-1/2 to 7 $R_E$ there is strong evidence of quiet-time plasma currents tending to inflate the field. In particular, the field magnitude dips well below the Jensen and Cain values at around 3-1/2 $R_E$ close to the geomagnetic equator.

## I. Introduction

Measurements of the magnetic field in the distant magnetosphere have been carried out on a number of satellites and space probes, including Pioneer I (Sonett et al., 1960a), Pioneer 5 (Coleman et al., 1960; Coleman, 1964), Explorer 6 (Sonett et al., 1960b; Smith et al., 1964), Explorer 10 (Heppner et al., 1963), Explorer 12 (Cahill and Amazeen, 1963; Cahill and Bailey, 1967), Explorer 14 (Cahill, 1966a), Imp-1 (Ness et al., 1964; Ness, 1965), Ego-1 (Heppner, 1965), Explorer 26 (Cahill, 1966b), and Electron 2 (Yeroshenko, 1966).

Of these, the Explorer 12 satellite was perhaps the most ideally suited to observe the day-side distortion of the geomagnetic field by the solar wind. With an apogee of 13.1 $R_E$ and a period of 26.5 hours, it made almost two passes a day through the region of maximum distortion. Full vector measurements were obtained with three orthogonal flux-gate magnetometers, and field magnitudes up to 1000 gammas could be measured, permitting observations from 3-1/2 $R_E$ out to apogee.

For this study, data from seven passes of Explorer 12 were analyzed and compared with theoretical magnetosphere models. In order to simplify the interpretation of the data, passes were chosen for which the earth's magnetic dipole axis was nearly perpendicular to the solar wind direction as the satellite traversed the distant magnetosphere. This was done in order to remove one of the many variables which can complicate comparisons with theory, namely the seasonal variation. A large north-south asymmetry could be present during winter and summer, when the angle of attack of the solar wind upon the earth's dipole is either much greater or much less than 90°. Near the fall equinox, when these passes ocurred, the angle is near 90°, and one expects near symmetry from theoretical considerations. All data presented were taken during periods of generally low magnetic activity.

The data are presented in terms of the magnitude of the field plus two angles indicating field direction, one of which, as will be shown, is a measure of the compression or elongation of the field lines, and the other of which is a measure of the twisting of the field lines out of their magnetic meridian. The results are compared both with the Jensen and Cain (1962) field model, representing internal sources only, and also the distorted field model of Mead (1964), which assumes that the solar wind is perpendicular to the dipole axis. The latter model includes the effect of compression of the earth's field on the day side by the solar wind, but, as will be seen, it does not adequately include the effect of the earth's magnetic tail, where the lines of force are observed to stretch out in the anti-solar direction. Explorer 12 explored the region between the noon and dawn meridians, where the effect of the boundary is most prevalent, and never received data from the tail region.

We find that on the day side, not too far from the noon meridian, the measured distortions seem to match quite well the predictions of the Mead model. However, as one moves toward the dawn meridian, there is somewhat less compression than predicted, and there is a significant twisting of the field lines out of their magnetic meridian. And finally, in the region from 3 to 6 or 7 $R_E$, effects of local quiet-time plasma currents are seen, particularly in the region near the geomagnetic equator, where the depression of the field magnitude due to what might be termed a quiet-time ring current is quite significant.

## II. Satellite Considerations and Data Analysis

Explorer 12 was launched on August 16, 1961, and transmitted data until December 6, 1961 (Cahill and Amazeen, 1963). Initial apogee at 83,714 km geocentric was approximately 3.5° east, i.e., on the dusk side, of the noon meridian, and 14° below the equatorial plane. Due to the apparent motion of the sun, by December 6 apogee was 103° west of the noon meridian, i.e., approximately 0500 hours local time. Inclination of the orbit to the earth's equatorial plane was 33.4°. Together with the tilt of the dipole, this means that southern geomagnetic latitudes of up to 44° in the distant magnetosphere were explored.

Initial processing of the data from the spacecraft gives the field magnitude plus two spacecraft angles, $\alpha$ and $\psi$ (Cahill and Amazeen, 1963), which are measured with respect to the satellite spin axis. In order to convert to a system independent of the spacecraft, the direction of the spin axis must be accurately known. Unfortunately, the precise direction of the Explorer 12 spin axis has never been determined with complete certainty. The value used in the present analysis (47° right ascension, -27.5° declination) may be in error by up to five or ten degrees of arc. Only a sun sensor was used to determine spacecraft attitude (the Imp satellites, for example, use in addition an earth sensor), and it has not been possible to determine whether and to what extent the spin axis drifted with time. The value used is the best determination of the average direction over the four-month period of data reception. In addition, although the spacecraft spin made it possible to continuously determine the zero levels of the magnetometers measuring the x and y components perpendicular to the spin axis, residual spacecraft fields produced uncertainties in the z component (parallel to the spin axis) of up to ±10 gammas. This produces a corresponding uncertainty in the spacecraft angle $\alpha$, which is greatest when the measured field is weak. Both of these factors introduce uncertainties into the transformed angles I and D (defined in the next section), particularly at large distances from the earth. Therefore, although changes in these angles with time are quite reliable, their absolute values are uncertain to perhaps 10 or 15 degrees near the magnetopause, and somewhat less than this near the earth.

Complete readouts of the three magnetometer sensors were received from the spacecraft at the rate of approximately 3 per second. B, $\alpha$, and $\psi$ were calculated for each readout, and the values from 32 successive readouts were averaged together to obtain one point. Thus each point represents approximately a 10-second average. Only a small portion of the data actually received is represented on the graphs, however, since adjacent points to be plotted were selected from the data so as to make $\Delta r = 500$ km. Using a typical satellite radial velocity at 8 $R_E$ of 2.2 km/sec, one finds that the interval between each 10-second average in this region is about 230 seconds.

## III. Coordinate System

A number of coordinate systems have been used in the past to indicate the directional character of the distant magnetic field, including spacecraft (Cahill and Amazeen, 1963), solar ecliptic (Heppner et al., 1963), and solar magnetospheric coordinates (Ness, 1965). Near the earth, of course, the dipole field predominates. Only at large distances does the solar wind begin to exert a strong effect. Recent data taken in the tail of the magnetosphere (Ness, 1965; Cahill, 1966a; Singer et al., 1966; Speiser and Ness, 1966) indicate that the symmetry of the magnetosphere is determined primarily by the geomagnetic dipole equator out to distances of about 10 $R_E$. Beyond this distance the magnetic field lines and the neutral sheet in the tail tend to be aligned with the solar wind velocity vector, rather than the dipole equator. This implies that a coordinate system with the primary axis parallel to the earth's dipole is preferable near the earth. At large distances, however, solar magnetospheric coordinates (Ness, 1965) based on the sun's direction, are preferable.

The Explorer 12 data analyzed here were obtained in regions (3-1/2 to 13 $R_E$) where the earth's dipole field predominates. We therefore have chosen a coordinate system which emphasizes the small perturbations from this dipole field. For each pass we show the difference in field magnitude from a reference field (Jensen and Cain, 1962) plus two angles showing inclination (I) and dipole declination (D), defined as follows:

$$\Delta B = B - B_{\text{Jensen and Cain}} \tag{1}$$

$$\sin I = -\frac{B_r}{B} \tag{2}$$

$$\sin D = \frac{B_\phi}{H} \tag{3}$$

$$\cos D = -\frac{B_\theta}{H} \tag{4}$$

$$H = \sqrt{B_\theta^2 + B_\phi^2} \tag{5}$$

$$-90° < I < 90°$$

$$-180° < D < 180°$$

where $B_r$, $B_\theta$ and $B_\phi$ are the outward radial, southward, and eastward components respectively and $B_\theta$ and $B_\phi$ are measured with respect to the dipole axis.

The inclination or dip angle I is the customary angle used in studies of geomagnetism, and is illustrated in Fig. 1 for a dipole field. It is the angle between the field direction and the local horizontal. It is normally positive in northern magnetic latitudes and negative in southern latitudes. In an undistorted dipole field there is a relation between I and magnetic latitude $\lambda_m$:

$$\tan I = 2 \tan \lambda_m \tag{6}$$

If the field lines are compressed by the solar wind, as one would expect on the day side of the magnetosphere, the magnitude of the inclination is reduced from that predicted by (6), as is shown in Fig. 1. Likewise, if the field lines are elongated or inflated as one might expect in the geomagnetic tail, the magnitude of I is increased. Thus the observed inclination angle is a measure of the compression or inflation of the geomagnetic field. The expected relation between I and $\lambda_m$ for these different situations is shown in Fig. 2. At the magnetic

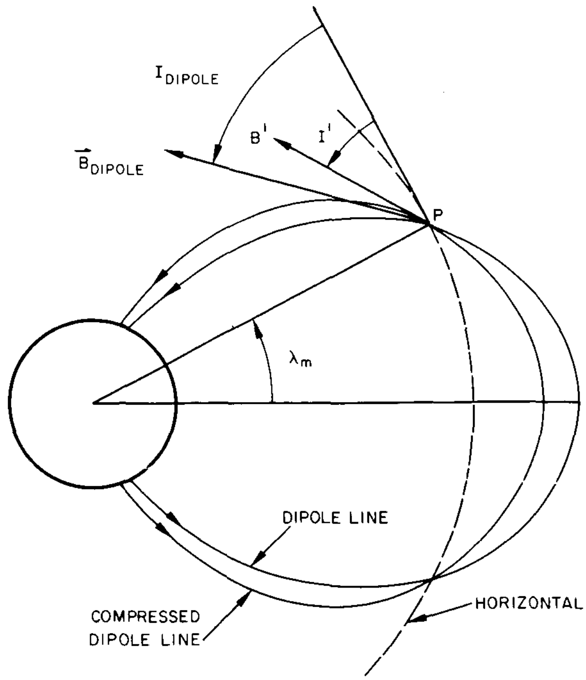



Figure 1—Inclination or dip angle (I), defined as the angle between the field vector and the local horizontal, positive if directed downwards. $\lambda_m$ is the geomagnetic latitude. If at a point P in space one compares two symmetric field lines, one a dipole line and the other a compressed dipole line, the magnitude of the inclination angle for the compressed dipole (I') will always be less, both in the northern and southern hemispheres. If the field line is elongated, the magnitude of I will be increased over the dipole value.

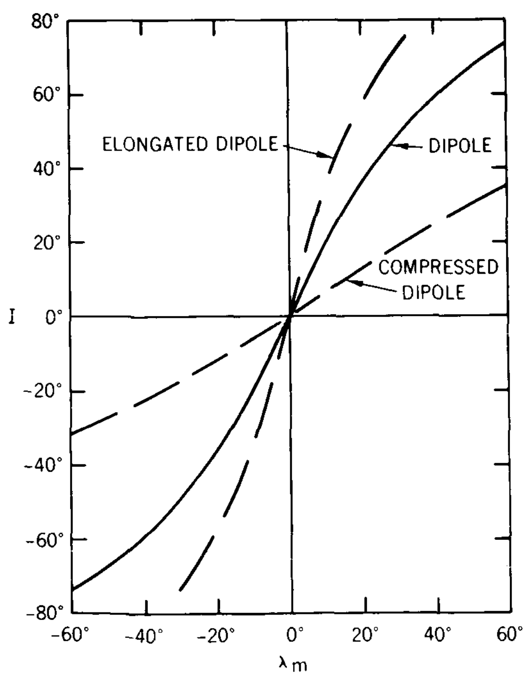



Figure 2—Expected relation between I and $\lambda_m$ for a pure dipole field, a compressed dipole, and an elongated dipole. See Equation 6 and subsequent discussion.

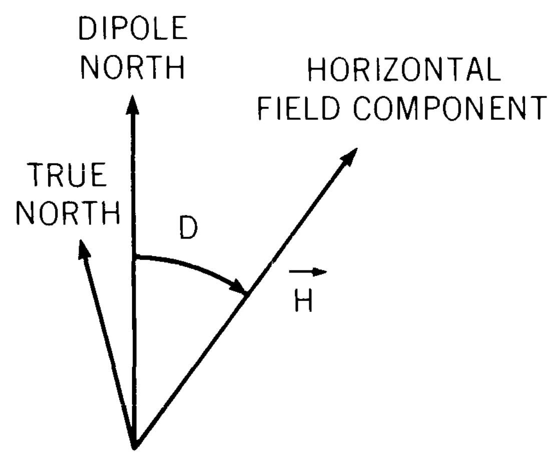



Figure 3—Dipole declination angle (D), defined as the angle between the horizonal field component and the north dipole direction, positive when directed east. D = 0 everywhere for a pure dipole field.

equator, if the magnetosphere is completely symmetric, as one might expect if the solar wind were perpendicular to the dipole axis, the inclination should be everywhere zero. The observed deviation from the dipole value is expected to be greatest at high latitudes.

The other angle used is dipole declination, D. Its definition is illustrated in Fig. 3. It differs from the usual geomagnetic declination in that it is measured with respect to the dipole north pole instead of the geographic pole. In a pure dipole field the dipole declination is everywhere zero. The deviation from zero is a measure of the twisting of field lines out of their meridian plane. In a symmetric magnetosphere distorted by the solar wind, in regions near the boundary on the dawn side, the declination angle is expected to be slightly positive in northern geomagnetic latitudes and negative in southern latitudes (Mead, 1964). These relations would be reversed on the dusk side of the earth. The declination would be zero everywhere at the equator and on the noon and midnight meridians. One can visualize this twisting of the field lines by considering the effect of the pressure exerted by the solar wind along the sides of the magnetopause. The plasma pressure will force that portion of a line of force near the equator, where the field strength is at a minimum, back towards the tail. The field line will no longer be confined to a meridian plane, and non-zero declinations result. As the effect increases, the field tends to point in the anti-solar direction in the southern hemisphere and the solar direction in the northern hemisphere, as has been observed in the distant tail regions (Ness, 1965).

## IV. Results

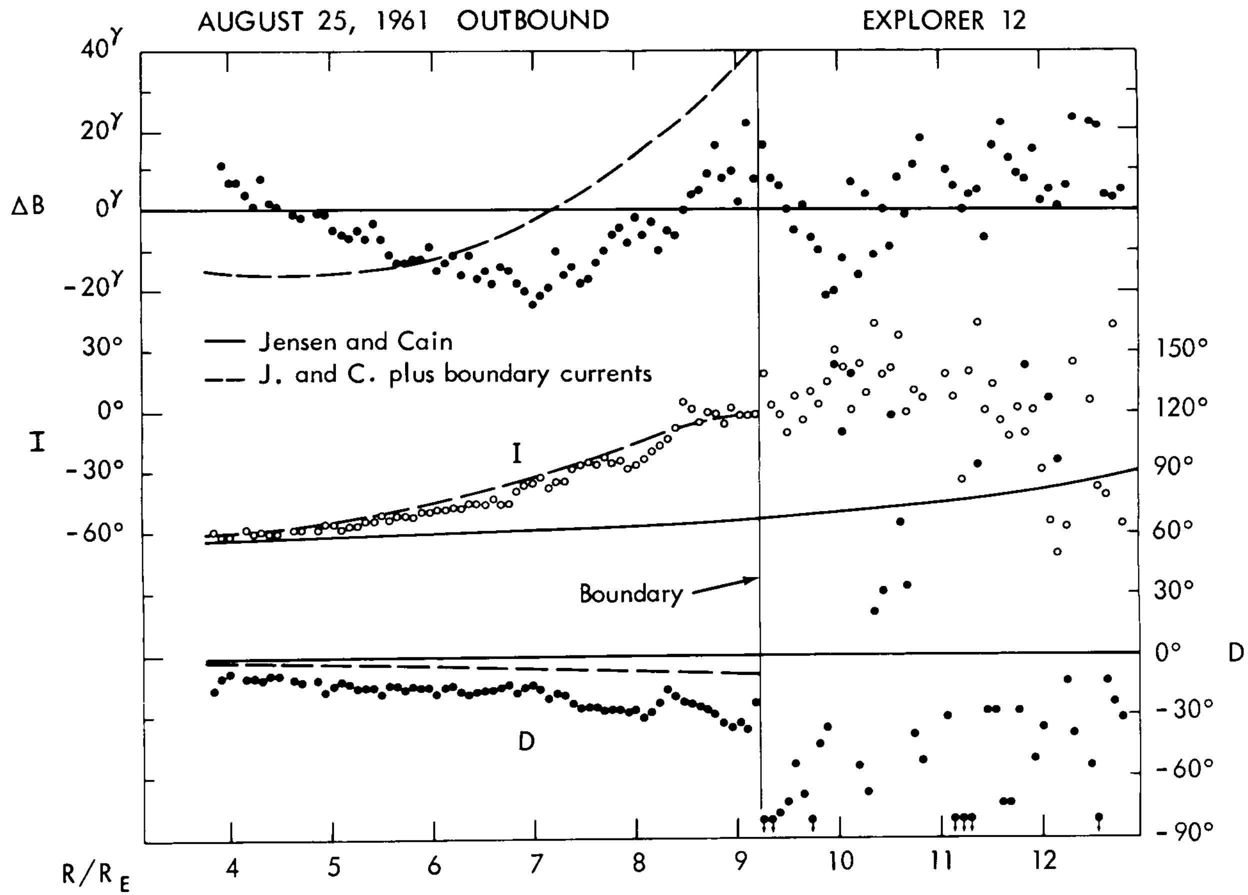
As mentioned earlier, data for the seven passes presented here were taken during periods of generally low magnetic activity, while the solar wind was nearly perpendicular to the dipole axis. The average values of the planetary index Kp and of the magnetic storm index Dst during each interval are shown in Table 1.

Table 1.

Average values of Kp and Dst over the intervals encompassed by the seven passes. Dst values were taken from Sugiura and Hendricks (1966). A Dst in excess of $-100\gamma$ indicates a storm with a significant main phase decrease.

| Date | U. T. | Ave. Kp | Ave. Dst |
|---|---|---|---|
| 25 Aug 1961 | 0100-0500 | 2 | $15\gamma$ |
| 28 Aug 1961 | 0000-0600 | 2 | 2 |
| 20 Sept 1961 | 0800-1300 | 2- | -5 |
| 21 Sept 1961 | 1700-2400 | 1- | 10 |
| 20 Oct 1961 | 1200-2000 | 1- | -27 |
| 21 Oct 1961 | 1400-2200 | 2+ | -21 |
| 24 Oct 1961 | 1200-2000 | 1- | -6 |

Fig. 4 shows the data from the August 25, 1961, outbound pass. Plotted as a function of geocentric distance in earth radii are the difference in measured field magnitude from the Jensen and Cain (1962) reference field, plus the measured inclination and dipole declination, as defined earlier. Solid lines give the




| | | | | | |
|---|---|---|---|---|---|
| $\lambda_m$ | -44° | -40° | -36° | -31° | -21° |
| ∠ SEP | 71° | 56° | 47° | 40° | 32° |
| ∠ SED | 87° | 89° | 90° | 90° | 85° |
| L.T. | 8:00 | 9:10 | 9:50 | 10:15 | 10:40 |
| U.T. | 1:20 | 2:25 | 3:45 | 5:40 | 8:35 |
| $B_{J.\&C.}$ | $770^{\gamma}$ | $220^{\gamma}$ | $90^{\gamma}$ | $42^{\gamma}$ | $21^{\gamma}$ |

Figure 4–August 25, 1961, outbound pass. See text for definition of orbital parameters. Note decrease in magnitude around 5-8 $R_E$, characteristic of high latitudes. Observed field direction is distorted by ~60° near boundary.

calculated Jensen and Cain reference field, and dashed lines give the magnitude difference and two angles as predicted by the distorted model of Mead (1964). Shown also at the bottom of the figure are additional satellite data as calculated from the orbital parameters. $\lambda_m$ is the geomagnetic latitude of the satellite, LSEP is the sun-earth-probe angle and LSED is the sun-earth-dipole angle, which is 90° when the solar wind is perpendicular to the dipole axis (neglecting aberration). It will be seen that this angle rarely deviates more than a few degrees from 90° for the passes chosen. L. T. is local time, or the azimuthal angle as measured from the midnight meridian, and U. T. is universal time. $B_{J\&C}$ is the total field magnitude calculated from the Jensen and Cain field model, which does not exceed $800\gamma$ for the portion of the passes plotted. Note the distinction between LSEP, which can never exceed 180°, and local time, with a range of 24h or 360°. Local time is a measure of the projection of LSEP upon the equatorial plane. LSEP alone cannot distinguish between the dawn and dusk sides of the magnetosphere.

This pass is an example of a typical high-latitude pass in regions not too far from the noon meridian. The magnetosphere boundary is well defined, seen primarily as a sudden change in direction, along with increased fluctuations in the direction angles. At these high latitudes, the angles, particularly the inclination angle, are highly distorted, although they converge to the reference field, as expected, near the earth. Near the boundary the measured field direction is distorted by approximately 60°, seen mainly as a compression of the field lines. The change in inclination matches rather closely the predictions of the distorted field model. The changes in declination are somewhat greater than predicted, indicating a significant twisting of the field line out of its local meridian. Between 4-1/2 and 8 $R_E$, the field magnitude at these high latitudes is actually decreased from the reference field, instead of showing the usual enhancement characteristic of low latitudes. This high-latitude field decrease is a characteristic prediction of closed magnetosphere models. The measured field magnitude does not follow well the prediction of the distorted field model in detail, however. This may very likely be the result of plasma currents within the magnetosphere.

The August 28 inbound pass, shown in Fig. 5, is an example of a low-latitude pass near the noon meridian. Near the boundary the field magnitude is enhanced by a factor of 2 or more over the reference field, as expected. A significant decrease in magnitude is observed at the boundary, accompanied by the usual abrupt change in direction. Note that the magnitude change is not nearly so abrupt as the change in direction. Inside 4 earth radii the measured field magnitude begins to dip well below the reference field. This is most likely due to the presence of quiet-time plasma currents in this region of space. Decreases of this type are typically observed when the satellite is within 4 earth radii and close to the geomagnetic equator (in this case the geomagnetic latitude is about 5°). Further observations of the inflation of the geomagnetic field in this region of space, particularly during magnetic storms, have been reported by Cahill (1966b) and by Cahill and Bailey (1967). Note that the measured inclination remains positive and is about 10-15° greater than that predicted by the distorted model throughout the pass. This may be at least partly due to the experimental uncertainties in the direction. The declination remains close to 0°.

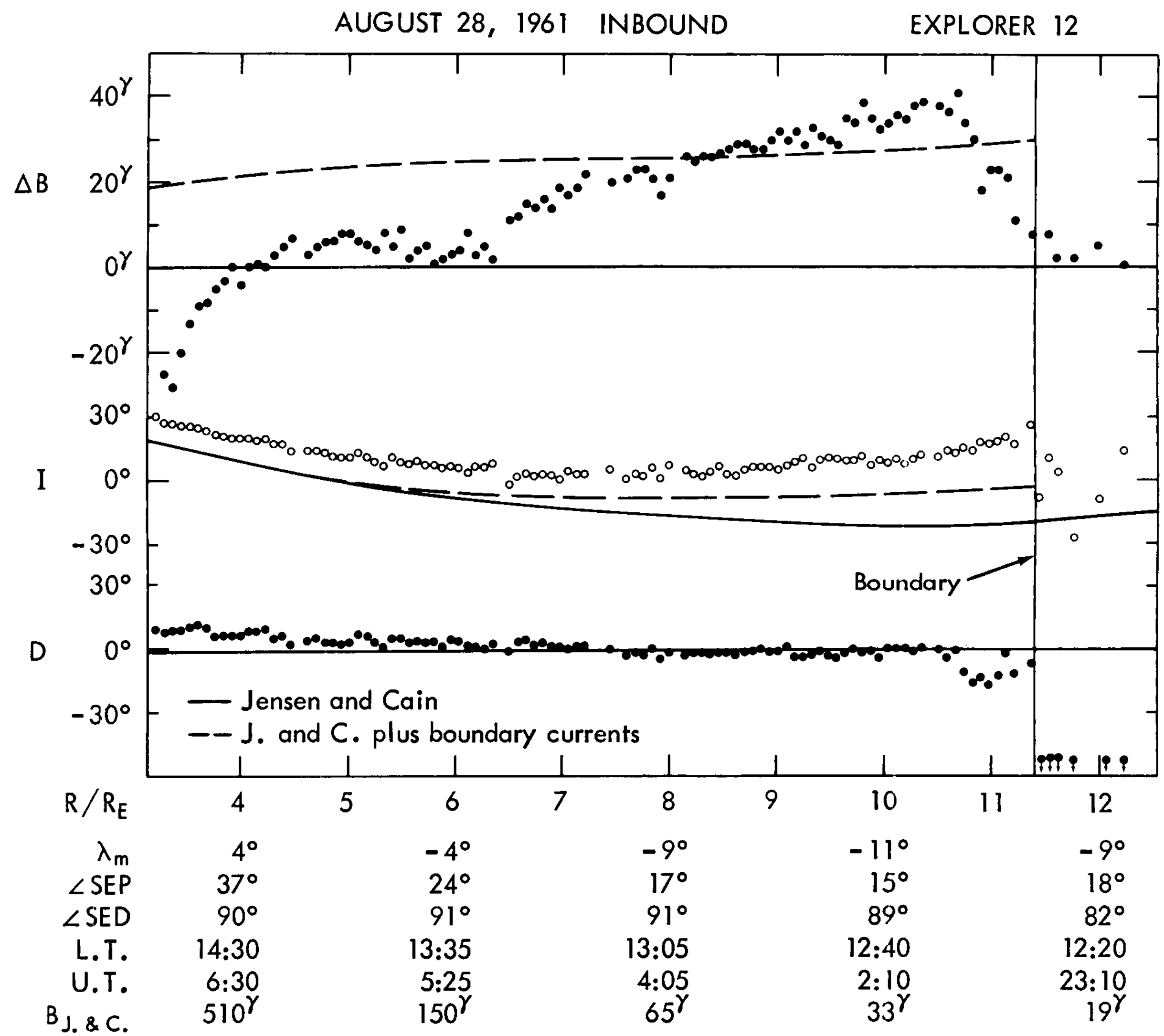
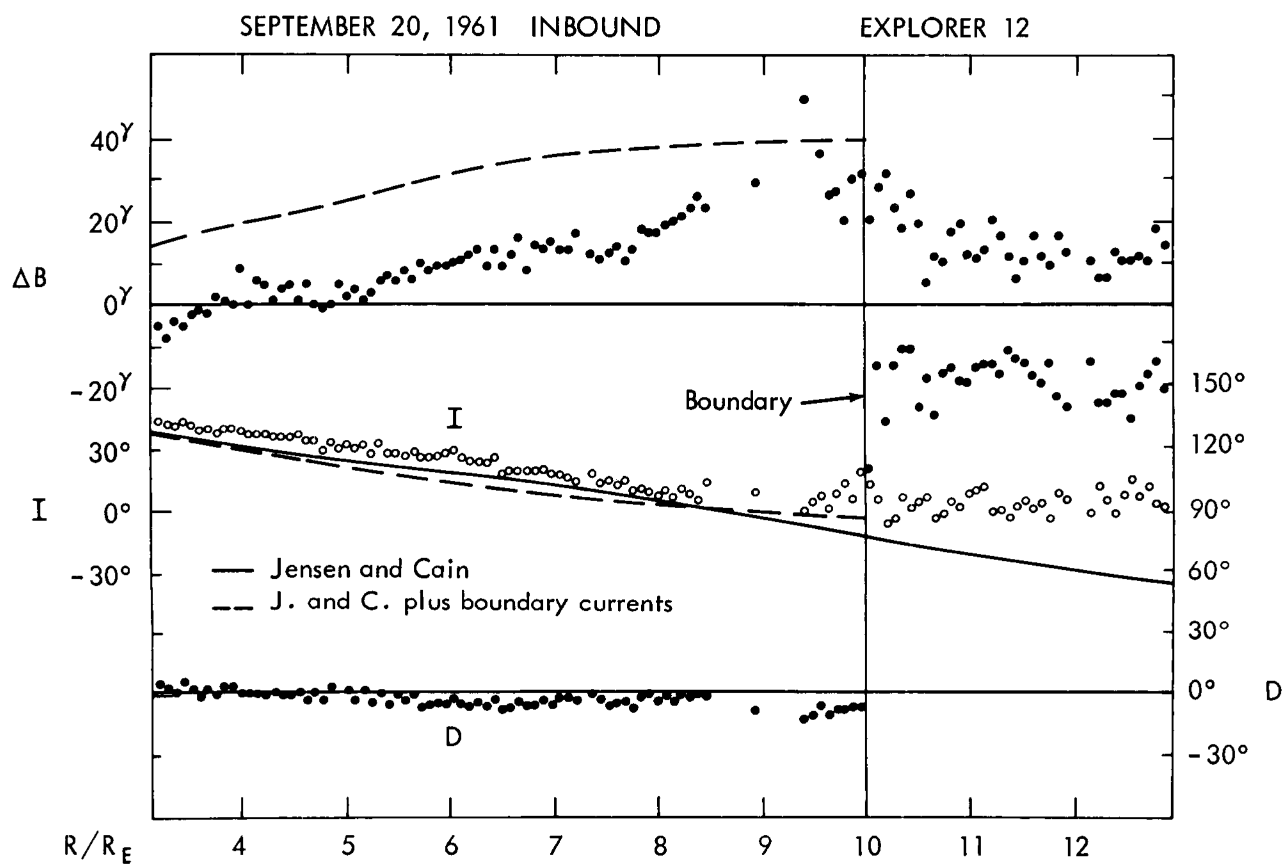



Figure 5–August 28, 1961, inbound pass. Note typical low-latitude enhancement of field magnitude near boundary, but decrease inside 4 $R_E$, indicating some quite-time inflation.

Another inbound pass, one month later, is shown in Fig. 6 (September 20). In this case the satellite traversed the boundary at 10 $R_E$, very close to the subsolar point (L. T. 11:15, LSEP = 12°). This pass is unusual in that although the field direction changes abruptly at the boundary, it is unusually stable in the magnetosheath. The direction changes from almost due north (D = 0°, I = 0°) inside the boundary, to approximately south-southeast (D = 150°, I = 0°) outside. The inclination remains near zero, as one would expect near the subsolar point if the field is tangential to the boundary both inside and outside. Theoretical studies have shown that the boundary should be approximately spherical here, and therefore the inclination should be zero, since a non-zero inclination indicates the presence of a radial component of the field (see equation 2).

Since this is a low-latitude pass, both the predicted and the measured angular distortions from the dipole field are small. The measured inclination is slightly larger than predicted, which, if real, would indicate some inflation between 4 and 8 earth radii. The increase in field magnitude in this region is also not as large as predicted. These effects may be related to the fact that Dst was recovering from a small depression on 16-17 September. The field decrease near the earth is again seen, though not as clearly as in the last example ($\lambda_m$ = 19°, somewhat larger than previously).

Fig. 7 shows a mid-latitude outbound pass, on September 21, between the noon and dawn meridians (L. T. = 0800 - 0900). It is evident that the field compression is not as large as that calculated in the distorted model. The field magnitude around 9 $R_E$ is close to the Jensen and Cain value and the change in inclination is not as large as predicted. This may be related to the fact that the




| | | | | | |
|---|---|---|---|---|---|
| $\lambda_m$ | 19° | 11° | 3° | -6° | -15° |
| ∠ SEP | 25° | 10° | 5° | 12° | 20° |
| ∠ SED | 84° | 87° | 91° | 96° | 100° |
| L.T. | 13:25 | 12:25 | 11:45 | 11:15 | 10:45 |
| U.T. | 12:20 | 11:15 | 9:50 | 8:00 | 5:00 |
| $B_{J.\&C.}$ | $535^{\gamma}$ | $147^{\gamma}$ | $60^{\gamma}$ | $31^{\gamma}$ | $20^{\gamma}$ |

Figure 6—September 20, 1961, inbound pass. Boundary crossing occurs very near subsolar point. Field direction is relatively stable in magnetosheath, and essentially parallel to the magnetopause on both sides of it.

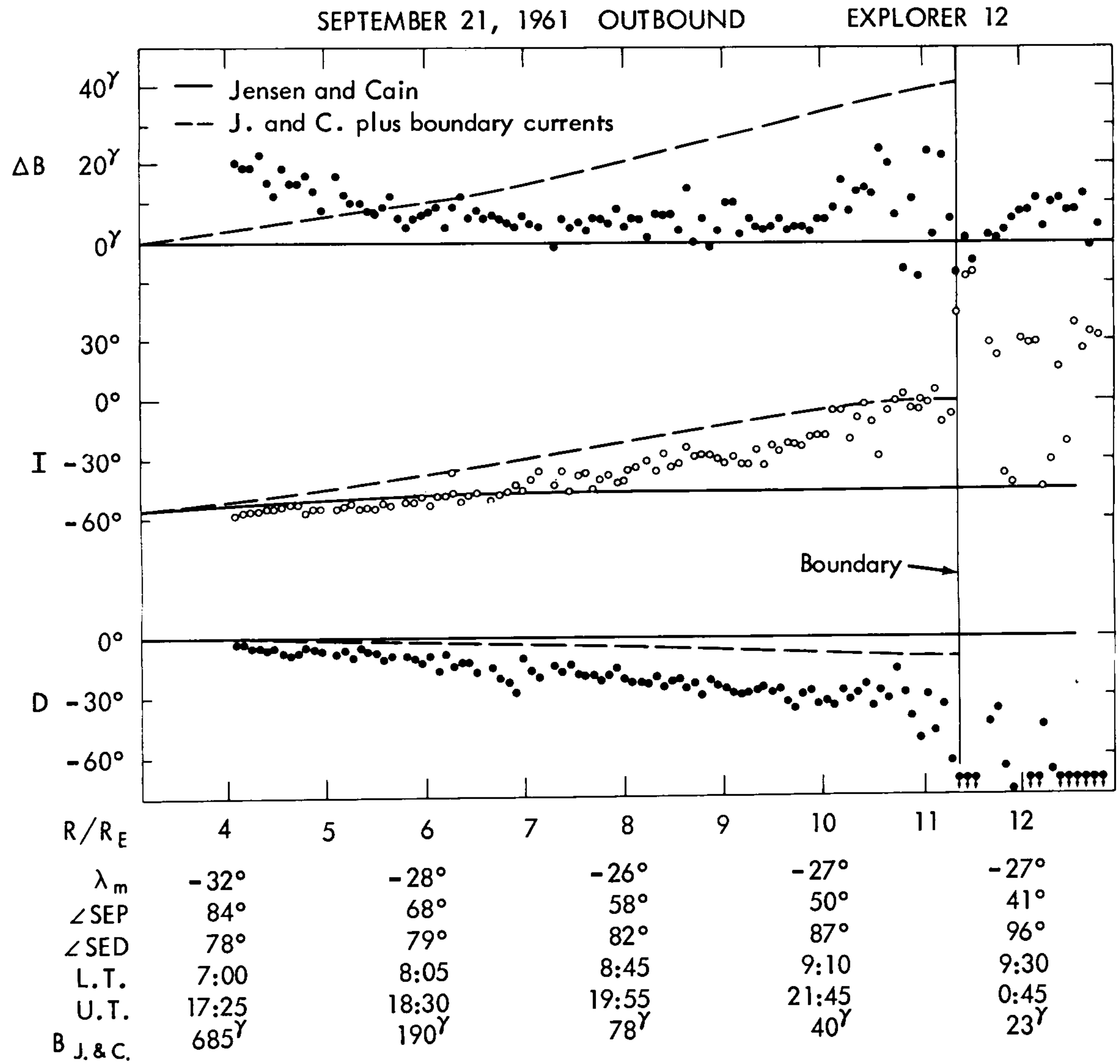



Figure 7—September 21, 1961, outbound pass. Enhancement of field magnitude near boundary is not as large as predicted, and the negative declination indicates a twisting of the field lines out of their meridian plane.

observed magnetopause flares out on the sides somewhat more than theory predicted (Ness, 1965), and thus the compression of the field along the sides may not be as large as that expected from theory. However, the observed change in declination angle is significantly greater than predicted, which indicates that the twisting of field lines is a major effect.

This process is enhanced in the next two outbound passes, shown in Figs. 8 and 9 (October 20 and 21), when the satellite was near the dawn meridian. In both cases the angle of declination was between -30° and -60° near the magnetopause (on October 20 the boundary was beyond apogee), compared with about -10° as calculated from the Mead model. In addition, the magnitude of I is larger than the dipole value, rather than smaller, indicating an extension, rather than a compression of the field. Analysis of the Dst records indicates that a small, possibly M-region magnetic storm was in progress October 20-22, and this field line extension may be partially associated with storm-time magnetosphere inflation. In addition, the effects of an extended geomagnetic tail may begin to appear near the dawn meridian. The observed distortions in D and I are what one would expect from the tendency of the field to point away from the sun in the southern hemisphere.

Finally, Fig. 10 shows the inbound pass of October 24, approximately midway between the noon and dawn meridians. This pass is unusual in that the twisting of the field lines, as evident from the declination value of about -30° near apogee, is in the opposite sense from what one would expect. This pass is above the geomagnetic equator ($\lambda_m$ = 10° to 20°) on the dawn side, where one would expect any distortion to produce a small eastward component, and thus positive

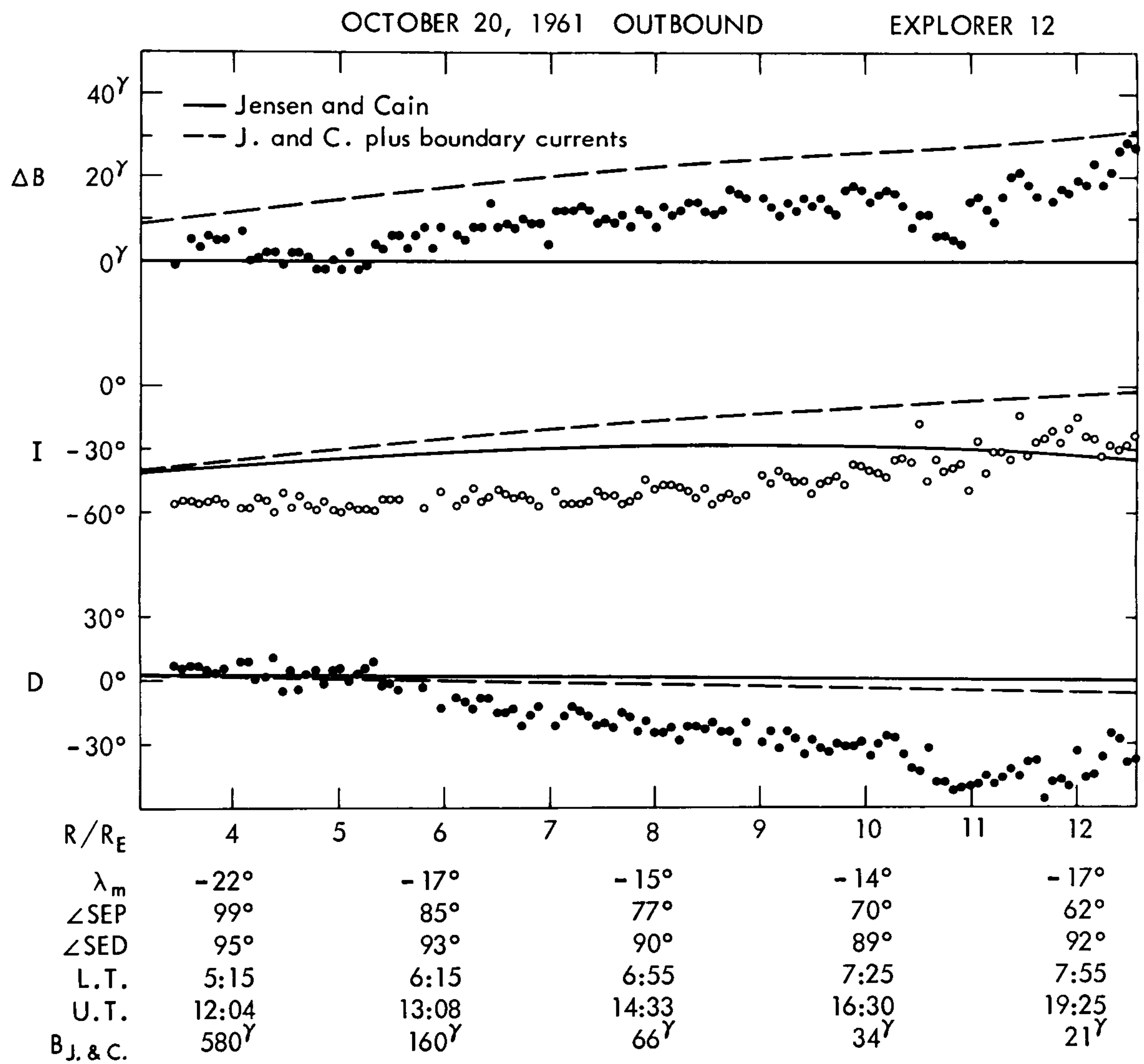



Figure 8–October 20, 1961, outbound pass. Boundary is beyond apogee. Field line is twisted 30–60° near apogee. The large magnitude of I indicates extension of the field lines.

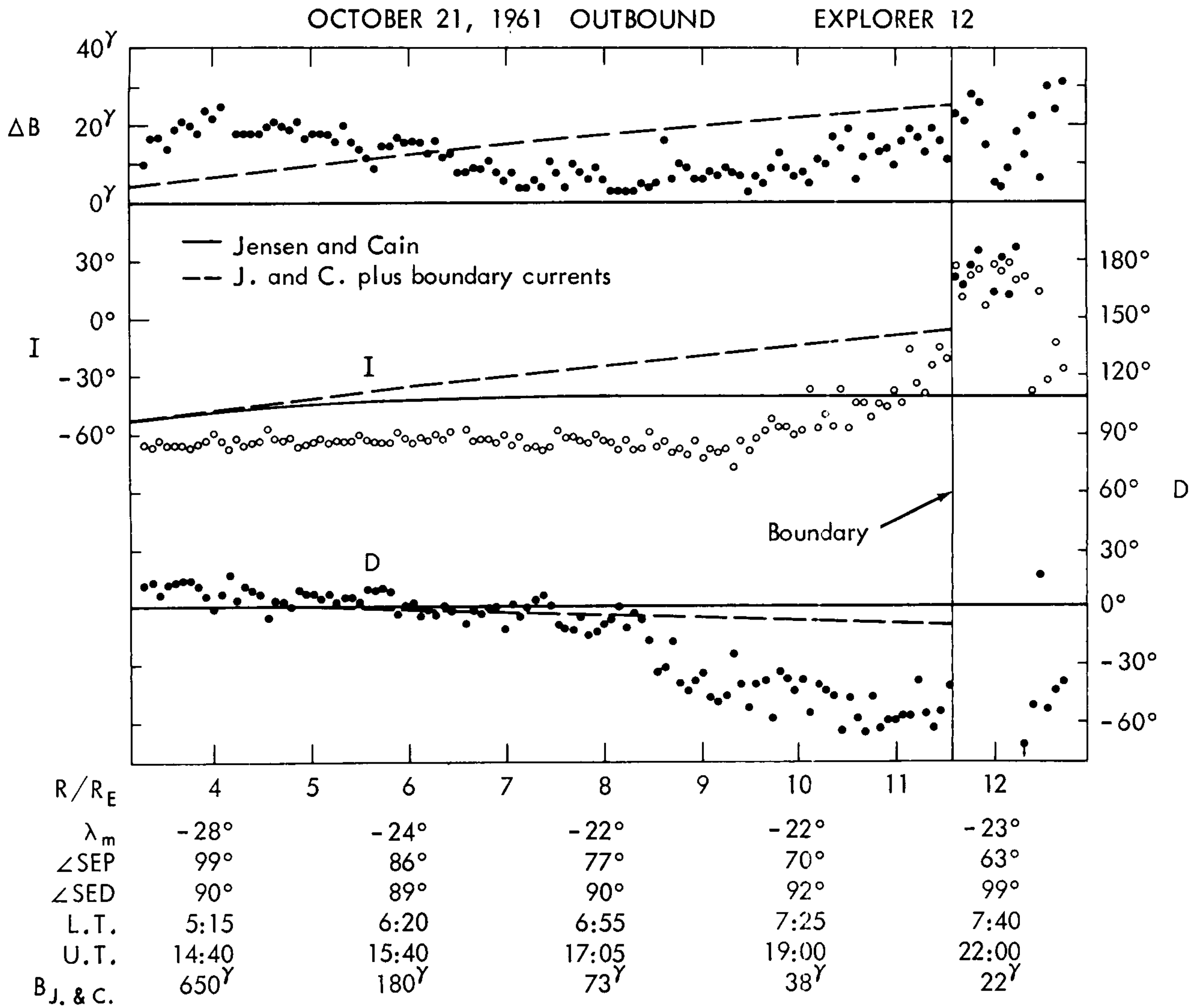



Figure 9—October 21, 1961, outbound pass. Note large decrease in D near boundary.

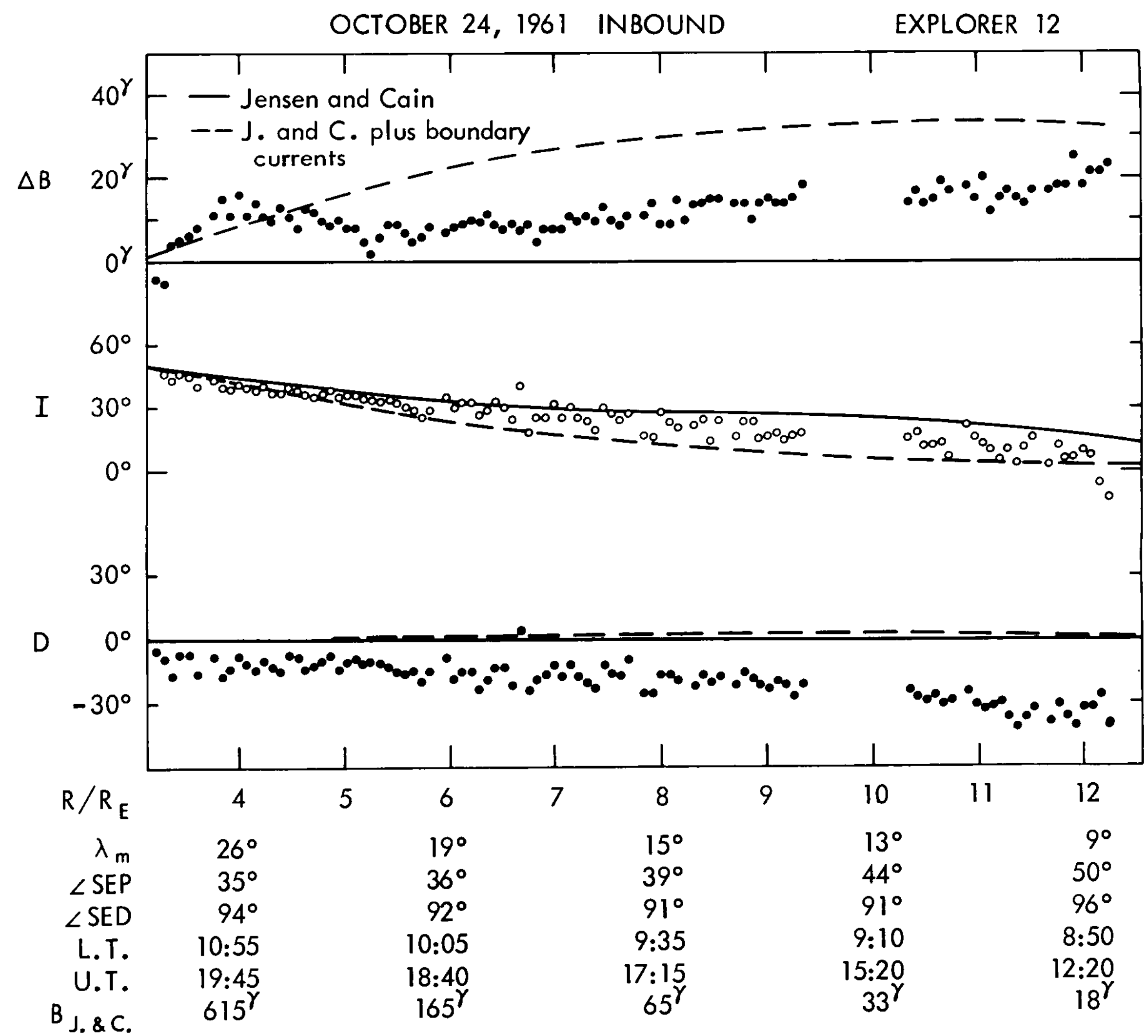



Figure 10–October 24, 1961, inbound pass. Boundary is beyond apogee. Although satellite was at positive geomagnetic latitudes, angle D is still negative, contrary to expectations, indicating possible north-south asymmetries in the magnetosphere.

declinations (see equation 3). The existence of a distortion in the opposite direction from that expected is difficult to understand. It is doubtful that the uncertainties in the field direction, discussed in Section II above, could lead to an error this large. If the effect is real, it implies a breakdown in the north-soutn symmetry expected from theoretical considerations. Current systems are present which give rise to a significant westward component in both the northern <u>and</u> the southern hemispheres. This also implies a significant longitudinal shift in conjugacy between the two points at the ends of these field lines. The northern conjugate point would be shifted westward from the calculated position during early morning local times. It is not obvious what current systems could produce these westward components in northern latitudes. An alternate explanation for this asymmetry, namely that the solar wind velocity vector was directed 20-30° north of the ecliptic plane during this period, does not seem reasonable in light of recent satellite and space probe measurements of the directionality of the solar wind.

## V. Conclusions

Several conclusions may be drawn from this study.

1. Near the noon meridian and from 6 or 7 $R_E$ out to the boundary, the observed field seems to agree quite well with the distorted field model of Mead (1964). The observed increases in field magnitude at low latitudes, the decrease in magnitude at high latitudes, and the changes in field direction are all in reasonable accord with the theory. The observed angular distortions from a dipole field inside the magnetosphere are sometimes as large as 60°, well in excess of any possible error due to experimental uncertainties.

2. As one moves away from the solar direction towards the dawn meridian, the boundary currents seem to have less effect than predicted. The magnitude of the field is not as large as predicted, and the field lines are not so highly compressed. There begins to be a strong twisting of the field lines out of their meridian plane, corresponding to the tendency of the field to point in the anti-solar direction south of the magnetic equator. On one pass north of the equator, (see discussion of Fig. 10) this twisting is in the opposite sense from that expected, indicating that there may possibly exist large north-south magnetosphere asymmetries even when the solar wind should be nearly perpendicular to the dipole axis. Asymmetries of this type are not predicted by any of the current theories.

3. There is evidence, even during quiet times, of plasma currents deep in the magnetosphere which change both the magnitude and direction of the observed field. From 3-1/2 to 7 $R_E$ the increase in field magnitude is normally not as large as predicted by the distorted field model, and the magnitude of the inclination angle tends to be larger than predicted, indicating some inflation of

the field. The change in field direction is often as much as 20 or 30 degrees in this region. However, experimental uncertainties, particularly in the assumed direction of the spin axis, may account for part of this change. The field magnitude often shows a sharp decrease inside 4 $R_E$, particularly when the satellite is very near the geomagnetic equator.

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