X-616-68-197
PREPRINT

NASA TM X- 63241

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JUNE 1968

GSFC

GODDARD SPACE FLIGHT CENTER
GREENBELT, MARYLAND

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Extraterrestrial Physics Branch Preprint Series

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ABSTRACT

Over 1500 hours of data from the satellites IMP 1, 2 and 3 have been used to study the configuration of the magnetic field in the outer magnetosphere between 5 and 18 R_E. Hourly average field vectors were projected in the solar magnetic equatorial plane and in 24 meridian sections corresponding to each hour of local time. The plots show the sweeping back of the field toward the tail and the dawn and dusk transition from compressed dayside field lines to extended night side field lines. Constant B contours in the equatorial plane were constructed and flux conservation was used to establish a quantitative relationship between the equatorial crossing point of an outer magnetosphere field line and the latitude of its earth intersection. A contour diagram in the equatorial plane designating the latitude of field line origin permits the mapping of low altitude phenomena to the equatorial plane and vice versa. Auroral oval field lines are found to come from the region of the magnetopause in the daylight hemisphere but from well within the magnetosphere in the night hemisphere. The outermost closed field line is found to come from approximately 78° throughout the dayside hemisphere.

1. INTRODUCTION

Solar Wind compression of the earth's dipole magnetic field on the sunward side of the earth has been investigated by many spacecraft (e.g., Cahill and Amazeen, 1963; Ness et al., 1964). Sweeping back of the geomagnetic field near the dawn and dusk meridian with accompanying inflation of the magnetosphere (Mead and Cahill, 1967; Fairfield and Ness, 1967; Cahill, 1965; Heppner et al., 1967) and formation of the geomagnetic tail (Ness 1965) have also been observed experimentally. To quantitatively represent these magnetosphere magnetic fields, spherical harmonic analyses of ground magnetic measurements have generally been used as the starting point. Descriptions assuming no current sources outside the earth's surface are adequate out to several earth radii and the use of L shells and invariant latitudes (McIlwain, 1961) in studying trapped particles has been very successful in eliminating the effects due to departures of the geomagnetic field from a simple dipole. These models also allow high altitude equatorial measurements out to several earth radii to be related to low altitude high latitude measurements on the same field lines. Beyond several earth radii, however, external current sources (equivalently described as compression-inflation effects) become important and L coordinates based only on internal sources can no longer be used to relate the foot of a field line to its equatorial plane crossing point.

Theoretical models which include compressional effects (e.g., Mead, 1964; Hones, 1963) have described the sunward magnetosphere quite well, but inadequate understanding of phenomena at the magnetopause has prevented a strictly theoretical description of the night side magnetosphere and geomagnetic tail. Theoretical models have been adjusted to agree with the measurements (Williams and Mead, 1965; Taylor and Hones, 1965) but, clearly experimental results will be of primary importance in understanding magnetospheric fields until there exists a better understanding of the solar wind-geomagnetic field interaction and the dynamic processes of the magnetosphere.

Over 1500 hours of data from the satellites IMP 1, 2 and 3 have been used to derive an improved description of the outer magnetosphere. The data were analyzed in a manner such that the earth intersection point of a high latitude field line may be related to its equatorial crossing point. With this information the position of various field-related phenomena measured at low altitudes and high latitudes can be projected along field lines to the possible location of their source in the equatorial plane. In addition, information from eccentric equatorial satellites can be related to that from polar orbiting low altitude satellites.

2. METHOD OF ANALYSIS

The technique used to establish the equatorial crossing point of a magnetic field line is based on the continuity of magnetic lines of force ($\nabla . \vec{B}=0$). Use is made of the fact that all lines of force crossing through the earth's surface must somewhere cross the equatorial plane before returning to the earth in the opposite hemisphere. Part of the flux from highest latitudes will cross the equatorial plane far downstream in the geomagnetic tail or even by way of interplanetary space and the sun, but lower latitudes lines will cross the equatorial plane within the magnetosphere. Therefore the flux through the earth's surface as a function of latitude may be equated to flux through the equatorial plane as a function of distance in the equatorial plane, yielding the equation

$$\int_{\phi_1}^{\phi_2}\int_{o}^{\theta_L} Z(\theta) \cos \theta \, d \theta \, d \phi = \int_{long} \int_{1}^{R(\phi)} B_n(r) dA \qquad (1)$$

This equation provides a relationship between any latitude θ_L and the equatorial crossing distance of its field line, R. In this equation $\cos \theta d\theta d\phi$ is an element of an area on the earth's surface (r=1) with latitude θ and longitude ϕ; $Z(\theta)$ is the field through the earth's surface which, assuming a dipole, equals $2B_o \sin\theta$ with B_o= .31 gauss = 31000 (Cain and Hendricks, 1968); B_n is the field through the equatorial plane as a function of radial distance; and dA is an area element in the equatorial plane. The longitude interval at the earth's surface must be associated with the longitude region in the equatorial plane through which the field lines pass. Lines of force from different longitudes have different equatorial crossing points due to the asymmetrical distortion of the solar wind and it is necessary to apply equation (1) independently to different longitude intervals. Knowledge of what longitude at the earth's surface is related to what longitude in the equatorial plane has been obtained from the data of the satellites IMP 1, 2 and 3.

The procedure involved the use of hourly average field values which were rotated to solar magnetic coordinates (Fairfield and Ness, 1967) (Z axis along the dipole axis, X axis in the Z-earth sun line plane and Y completing a right handed orthogonal system). The vector projections were then plotted in the XY plane. Southern hemisphere data are shown in Figure 1. All data have been plotted in the daylight hemisphere but only alternate hours have been plotted in the night hemisphere. Additional data have been eliminated in three small, unusually crowded regions. The outstanding feature of this data set is its relatively consistent behavior within any one region of the equatorial plane. This is true despite the facts that: (1) the data were taken by three different satellites during the time intervals November 1963 - May 1964 (IMP-1), October 1964 - April 1965 (IMP-2), and May 1965 - May 1967 (IMP-3), (2) all data was used with no allowances for different solar wind conditions or different levels of geomagnetic activity; and (3) the latitude of the measurements ranged from the predominantly equatorial measurements of IMP-2 to quite high latitude measurements (70^{o}) of IMP-3 late in its lifetime.

From Figure 1 it can be concluded that, at least to a first approximation, the field lines from a given longitude region on the earth are swept back toward the tail with the field lines from different latitudes tending to remain in the same longitude section. (Exceptions to this statement such as the vectors near $X = 2.5\ R_e$, $Y = -5R_e$ are almost all very high latitude IMP-3 measurements where the field lines are going back over the south pole into the geomagnetic tail). Figure 1 shows twenty-four of these longitude sections which have been sketched in with these data and the similar northern hemisphere vectors as a guide. The sections were constructed for the dawn hemisphere and have been reproduced symmetrically in the dusk hemisphere to help illustrate to what extent the field configuration is symmetrical in the two hemispheres. Although there is accumulating evidence for a dawn dusk asymmetry in magnetospheric phenomena, such effects in the average field configuration are not evident in Figure 1. Equation 1 was applied to each one of these sections in the dawn hemisphere with the areas shown in Figure 1 being the areas associated with corresponding 15° longitude intervals at the earth's surface.

The high concentration of data in the dawn hemisphere of Figure 1 is due to the fact that IMP-1 and 2 with 6-month lifetimes made measurements primarily in the dawn hemisphere. IMP-3 with a two-year lifetime made two circuits of the earth and contributed all the measurements in the dusk hemisphere. Since fields are often above the 40γ saturation level of the fluxgate magnetometers (Ness et al., 1964; Fairfield and Ness, 1967) flown on these spacecraft, there is a paucity of measurements in the sunlit hemisphere. The few existing measurements near the subsolar point are mainly from IMP-3 near the weak field region at high latitudes where field lines turn back over the pole. Advantageous field orientation allowed measurement of fields greater than 40γ at many of these times.

Values of B_n for use in equation 1 were obtained from IMP-2 which, with a relatively low apogee of 15.9 R_E, was the only one of the three spacecraft making measurements near the equatorial plane within 18 R_E of the earth. Data plots in solar magnetic coordinates were scanned for times of equatorial crossing which generally took place near the solar magnetic equatorial plane and were readily detectable from the change in field orientation. Values of B were determined at these times and plotted on an equatorial plane diagram. Times when an unusually distant or close-in magnetopause created an unusually weak or strong field were either omitted or appropriately adjusted. Explorer XII data (Hyde and Cahill, 1967) were used to help fill in the subsolar region where fields were too strong to be measured by IMP-2. An observed 25γ noon-midnight asymmetry at 6.6 R_e (Coleman and Cummings, 1967) was also incorporated in the data. The measurements formed a consistent picture and contours of constant B were drawn and are shown in Figure 2. This figure then supplied the values of B_n for equation 1. The magnetopause boundary in Figures 1 and 2 was drawn using boundary crossings from three IMP satellites plus OGO-A (Heppner et. al., 1967).

A dipole magnetic field was assumed inside 5 R_E where the IMP spacecraft do not provide measurements. Cahill (1966) indicates that departures from a dipole field near 5 R_e are of the order of 20γ except during disturbed periods and during times with storm time ring currents. Consequently a 248γ dipole field at 5 R_E connecting to $63^o26'$ latitude was assumed at the inner edge of the region studied in this paper. The integration of equation (1) was carried out analytically at the earth's surface and graphically in the equatorial plane to obtain the relation between latitude and equatoral crossing point in each of 13 longitude regions in the dawn hemisphere at latitudes above $63^o26'$. Results are presented in section 3 and possible errors and uncertainties are discussed in the Appendix.

RESULTS

Results relating the latitude of a field line to its equatorial crossing point are presented in Figure 3. This figure shows a view in the magnetic equatorial plane where solid lines are contours designating the latitude of origin of the field lines through that location. The dashed lines designate the meridian sections of Figure 1 indicating the local time of the foot of the field line. Solid and dashed lines are also lines of constant α and β respectively in the geomagnetic Euler potential system (Stern, 1967). Field lines near the magnetopause can be seen to connect to approximately 78^{o} latitude in the local times 0600-1200. Field lines above this latitude are either swept back over the pole into the geomagnetic tail or else they may connect to interplanetary lines. The tendency of the contours to move away from the earth with increasing angle from the sun direction is due to the weakening of the field strength which requires the field lines to extend further from the earth. The approximately constant latitude of fields near the boundary in the 0600-1200 local time regions means that the increasing area of the sections further away from the sun direction is balanced by the decreasing magnitude of the field strength so that the flux within these sections is constant.

Using Figure 3, several high latitude low altitude phenomena have been mapped along field lines into the equatorial plane and are shown in Figure 4. The shaded regions in this figure designate the auroral oval of Feldstein (1963) representing the location of regions of high probability of occurrence of aurora. This auroral oval is thought to correspond to the region of the auroral electrojet (Akasofu, 1966). The oval corresponds better to the region of instantaneous occurrence of aurora than the classical auroral zone which indicates occurrance averaged over all local time hours and heavily weighted with nighttime data. Feldstein's oval was determined from IGY data, whereas recent work (Feldstein and Starkov, 1968) suggests that this statistically determined oval should be shifted one or two degrees towards higher latitudes during more quiet years. Since the average magnetosphere constructed in this paper is appropriate for more quiet conditions, the mapped oval of Figure 4 might better be imagined as displaced outward by one or two degrees.

Also shown in Figure 4 is the 10^4 intensity contour of 40 Kev electrons determined by Frank et al., (1964) from low altitude Injun 3 data. This relatively low intensity contour roughly corresponds to the high latitude cutoff of 40 Kev electrons found by Armstrong (1965) so the Figure 4 contour can be taken as the average outer limit to intense 40 Kev electron fluxes in the equatorial plane. The crosses in Figure 4 are the projected points of Zmuda et al., (1967) which span the region of magnetic fluctuations determined on the low altitude orbiting satellite 1963 38C.

Figure 4 indicates that the auroral oval corresponds to the magnetopause from 0800-1200 local time. To the extent that the oval and the field configuration are symmetrical about the noon midnight meridian plane, this will also be true in the 1200-0400 region. This suggests that both dayside aurora and the satellite-observed magnetic fluctuations have their origin at the magnetopause. At earlier local times, the auroral oval is contained well within the magnetosphere and most quiet time aurora, particularly away from the midnight meridian, occur on closed field lines. Along with the auroral oval projection of Figure 4 it is of interest to refer back to the contours of constant B in Figure 2. Magnetosphere particles that mirror very near the equatorial plane drift around the earth on contours of constant B if they are not strongly influenced by electric fields. Figure 2 indicates that magnetosheath particles which manage to penetrate the magnetopause (Stevenson and Comstock, 1968) and have large pitch angles will drift to the nightside of the earth and be focused in the 6-9 R_E equatorial region by the converging contours of constant B. This would provide an explanation for the high plasma and particle densities (Bame et al., 1967; Anderson, 1965) associated with the weak fields of this region. This plasma may be a source for auroral particles if the pitch angles of individual particles can be drastically changed.

In Figures 5a-5d the hourly average vectors are shown projected in meridian planes. The planes of projection are the longitudinal sections of Figure 1 so the horizontal axis R' is the distance along the curved section rather than

$(X_{SE}^2 + Y_{SE}^2)^{\frac{1}{2}}$. The data have been separated according to the latitude of the sun and only hours when the sun is below the solar magnetic equatorial plane are plotted. Otherwise all magnetosphere data from the three IMP satellites are shown. The four figures are the sections with the feet of the field lines centered on 0500-0800 local times. Solid field lines have been drawn with the aid of the data and knowledge of the equatorial crossing point from Figure 3. Dashed lines represent undistorted dipolar lines from the same latitudes as the distorted lines. The field lines are labeled with their earth crossing latitude. The rather rapid transition from compressed lines at 0800 to the extended tail like fields at 0500 is apparent.

Figure 6 shows lines and vector projections in the noon-midnight meridian plane in the same format as Figure 5. Again data with the sun below the geomagnetic equatorial plane have been used and the field lines drawn accordingly. The outer most closed field lines in the noon meridian comes from 78° latitude, which is slightly lower than the 81° of Taylor and Hones (1965) and the 82° of Williams and Mead (1965). Considerable distortion of the field lines in the midnight sector is apparent inside of 8 R_E.

A further result of the analysis can be obtained from the total flux through the equatorial plane. In performing the integration of equation 1, the flux through the equatorial plane outside 5 R_E and with $X > -15$ R_E and $Y > 0$ was found to be 12370 γ R_E^2. Adding the flux in one quadrant of the geomagnetic tail which may be taken as $\frac{1}{4}\pi\ (19R_E)^2\ 22\gamma = 6240\gamma\ R_E^2$ gives a total of 18610 γ R_E^2 which may be compared to the flux through the earth's surface in the dawn half of the northern hemisphere which is 19480 γ R_E^2. The difference of 870 γ R_E^2 between the flux through the earth's surface and that crossing the equatorial plane or entering the earth's tail might be attributed to field lines reconnecting to interplanetary lines. However, it should be realized that the dimensions and field strengths in the tail are rather uncertain and inaccuracies may exist in the value of the flux crossing the equatorial plane (see Appendix). Consequently this result should be taken as support for, not proof of, the existence of field lines reconnecting to interplanetary lines.

SUMMARY AND CONCLUSIONS

Over 1500 hours of data from the satellites IMP 1, 2 and 3 have been combined to obtain the average magnetic field configuration in the region 5 - 18 R_E. Hourly average magnetic field vectors were rotated to solar magnetic coordinates and projected in the equatorial plane and in 24 curved longitude sections. It was found that the field lines from different latitudes at the same longitude tend to remain in the same curved longitude section permitting effective plotting of the field vectors in the curved meridian sections.

The transition from the compressed dayside field lines to the weakened field strengths and extended field lines of the geomagnetic tail has been investigated. The position of the region of weakening fields is in good agreement with the edges of the plasma sheet determined by Vasyliunas (1967). Average field strength contours in the equatorial plane were constructed and flux conservation was used to establish a quantitative relationship between the equatorial crossing point of a field line in the outer magnetosphere and the latitude of its earth intersection. Contours in the equatorial were determined indicating the latitude and local time of the foot of the field line crossing the equatorial plane at various points. These contours permit the mapping of phenomena along field lines between the equatorial plane and the polar ionosphere in the high latitude region where L shells are of little use.

The auroral oval and the high latitude cutoff of 40 Kev electrons have been mapped to the equatorial plane. The auroral oval corresponds to the region of the magnetopause in the sunward hemisphere but the locus of the oval moves rapidly towards the earth near the dawn meridian until the inner edge near midnight is as close as 6 R_E. This average picture of the magnetosphere shows that quiet time aurora below 68^o occur on field lines which close within 10 R_E of the earth. The outermost field line at the subsolar point goes to 78^o latitude which is several degrees lower than that given by existing model fields.

The combined magnetic flux through the equatorial plane and that of the tail is slightly less than that crossing the earth's surface. It is suggested that this flux difference may be due to flux which connects to interplanetary space, but this is a tentative result subject to uncertainties in the numbers used.

APPENDIX

In presenting a comprehensive average picture of the outer magnetosphere it is important to realize the limitations of the work and possible uncertainties of the results. This section attempts to point out the causes and magnitudes of such uncertainties.

Possible errors in the equatorial B contours of Figure 2 are rather hard to evaluate. Time variations are particularly important in the night hemisphere and variations by a factor of 2 are probably common in the $B < 10\ \gamma$ region. Because of the importance of these time variations, the results of Figure 3 can better be applied to other statistical results than to instantaneous measurements. The average B_n's are probably accurate within a few gammas, but B_n's only a few gammas too low multiplied by the 371 R_E^2 area of the dawn portion of the equatorial plane ($X>-15, R>5R_E$) could explain the 870 γR_E^2 difference in flux in section 3 which was tentatively attributed to reconnection with the interplanetary field. An error of $\frac{1}{2}R_E$ in the average position of the magnetopause changes the area by 16 R_E^2. Multiplying this by an average boundary flux of 30γ gives a flux of 480γR_E^2. This is probably a less significant source of error in the calculation of total flux through the equatorial plane. Fields within 5 R_E deviating from a dipole by 5γ would give a total flux error of 170γR_E^2 in the dawn hemisphere which is also relatively insignificant.

Errors in the tail flux will be on the order of the average tail field (22γ) times an area uncertainty resulting from a 1 R_E.

error in the radius. This uncertainty is $670\gamma R_E^2$. An error of a few gammas times the 280 R_E^2 area of one quarter of the tail could also be important.

Once the magnetopause and the B contours of Figure 2 are chosen the flux through the equatorial plane is fixed. The longitudinal dependence of the latitude-radial distance relationship presented in Section 2, however depends on how the sections are drawn. Using sections swept back more toward the tail increases the area of the sunward sections, thereby enlarging the flux in these sections, which in turn increases the latitude of the outermost line of force. Since the total flux is fixed, this process reduces the flux in a night side sector and results in more extended lines of force. Although the sections drawn in Figure 2 are rather well-defined by the data, uncertainties exist in the region 5-8 R_E and this is probably the most important source of error in Figure 4. The largest errors in figure 3 occur near the subsolar point and are probably less than a few degrees.

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FIGURE CAPTIONS

Figure 1. Southern hemisphere hourly average field vectors projected in the solar magnetic equatorial plane. Solid lines denote the average magnetopause and 24 longitidual sections which have been drawn with the data as a guide.

Figure 2. Contours of constant field magnitude in the equatorial plane.

Figure 3. Contours in the equatorial plane designating the latitude and local time of the earth intersection point of the field line.

Figure 4. Auroral oval and associated phenomena have been projected along field lines to the equatorial plane using the information of Figure 3.

Figure 5a-d Vectors projected in the curved meridian sections of Figure 1 in the 0800-0500 local time regions for hours when the sun is south of the solar magmetic equatorial plane. Solid lines represent distorted field lines which have been drawn with the data and the information of Figure 3 as a guide. Dashed lines represent undistorted dipole field lines corresponding to each distorted line. The lines are labeled with their earth intersection latitudes.

Figure 6. Distorted and dipole lines of the noon-midnight meridian plane. The lines are labeled with their earth intersection latitudes.

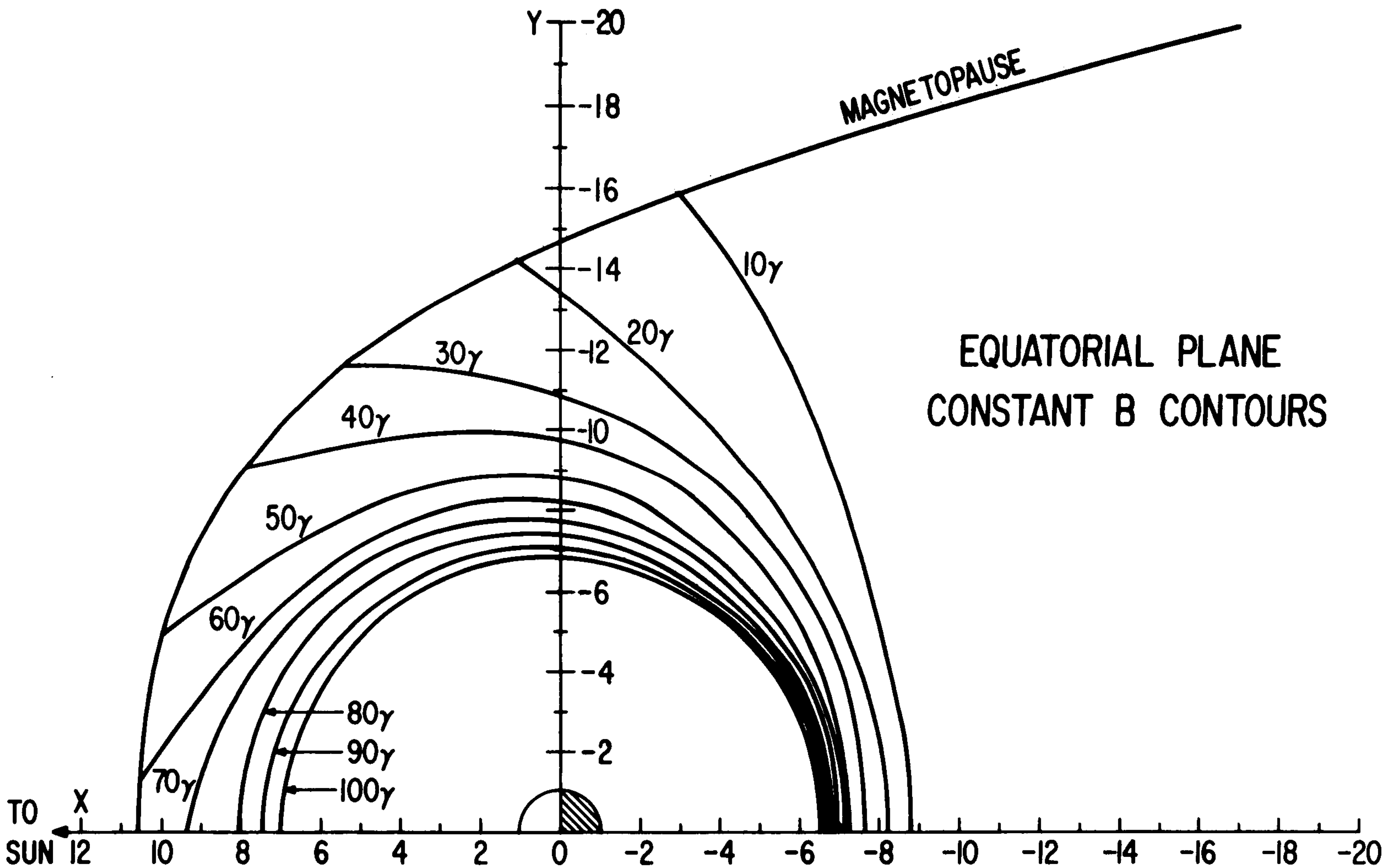

EQUATORIAL PLANE
CONSTANT B CONTOURS
MAGNETOPAUSE
Y
-20
-18
-16
-14
-12
-10
-6
-4
-2
X
TO SUN
12
10
8
6
4
2
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
10γ
20γ
30γ
40γ
50γ
60γ
70γ
80γ
90γ
100γ

FIGURE 2

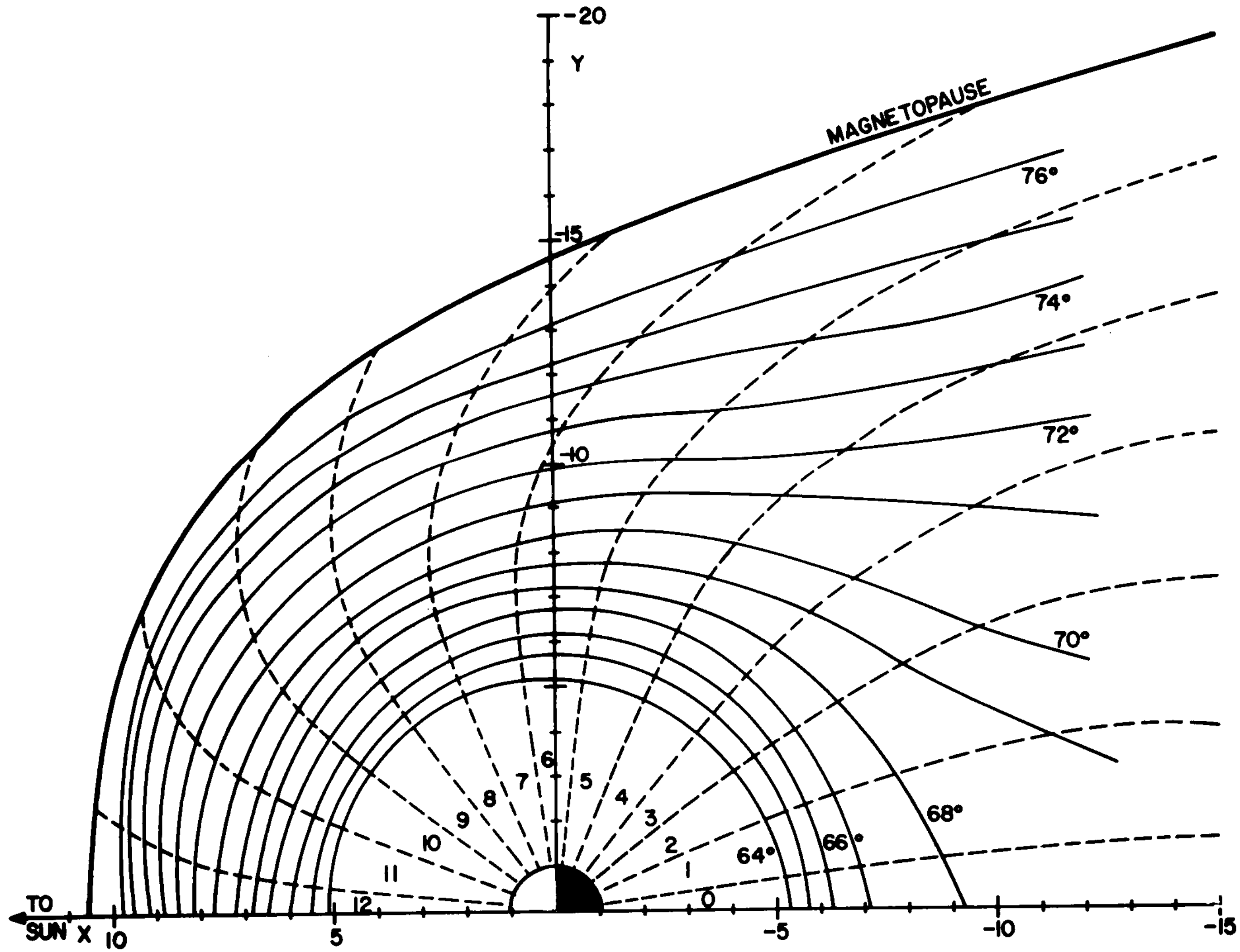

-20
Y
-15
-10
MAGNETOPAUSE
76°
74°
72°
70°
68°
66°
64°
0
1
2
3
4
5
6
7
8
9
10
11
12
TO
SUN
X
10
5
-5
-10
-15

FIGURE 3

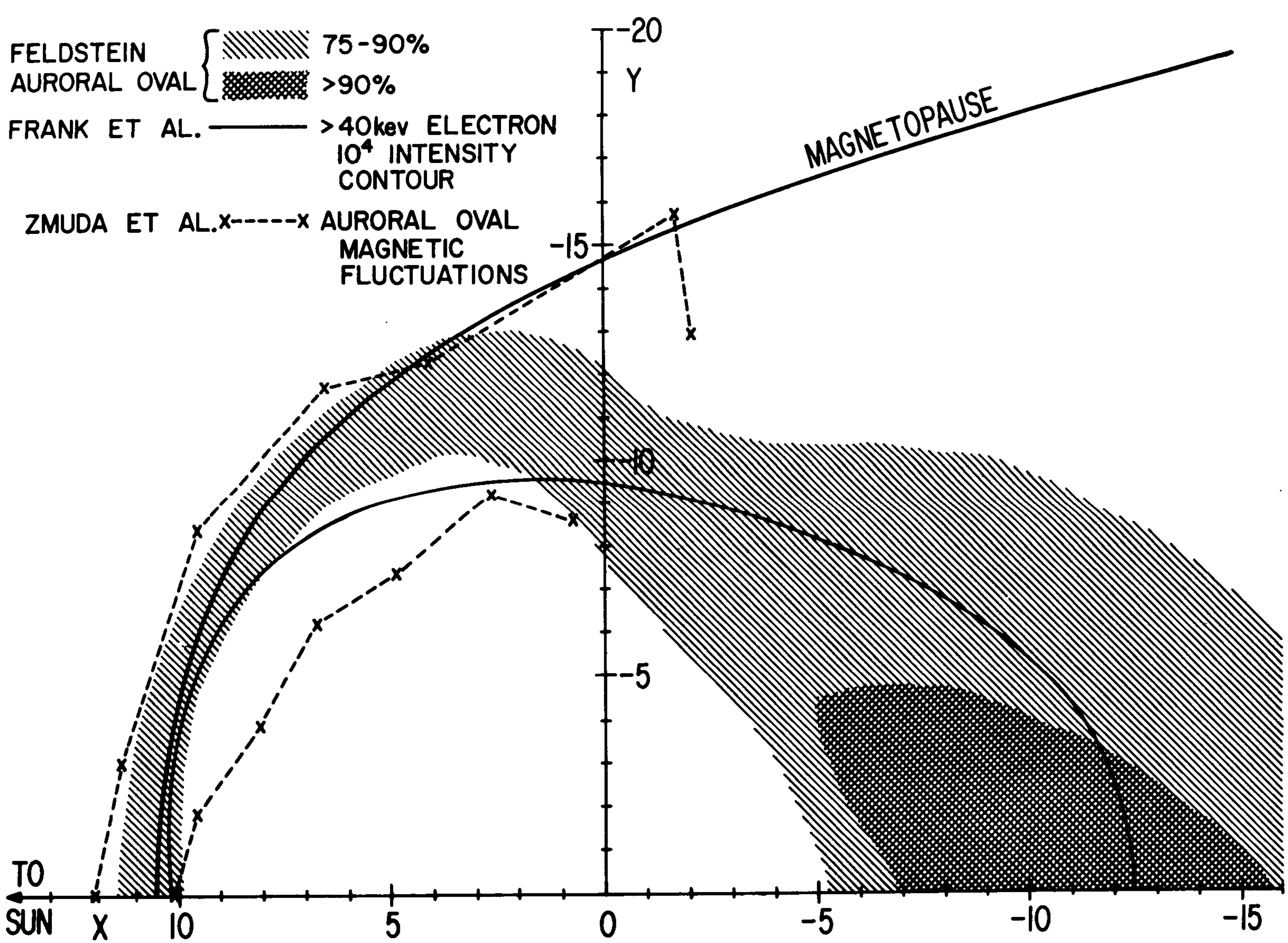

FELDSTEIN
AURORAL OVAL
75-90%
>90%
FRANK ET AL.
>40kev ELECTRON
10⁴ INTENSITY
CONTOUR
ZMUDA ET AL.
AURORAL OVAL
MAGNETIC
FLUCTUATIONS
MAGNETOPAUSE
-20
Y
-15
-10
-5
TO
SUN
X
10
5
0
-5
-10
-15

FIGURE 4

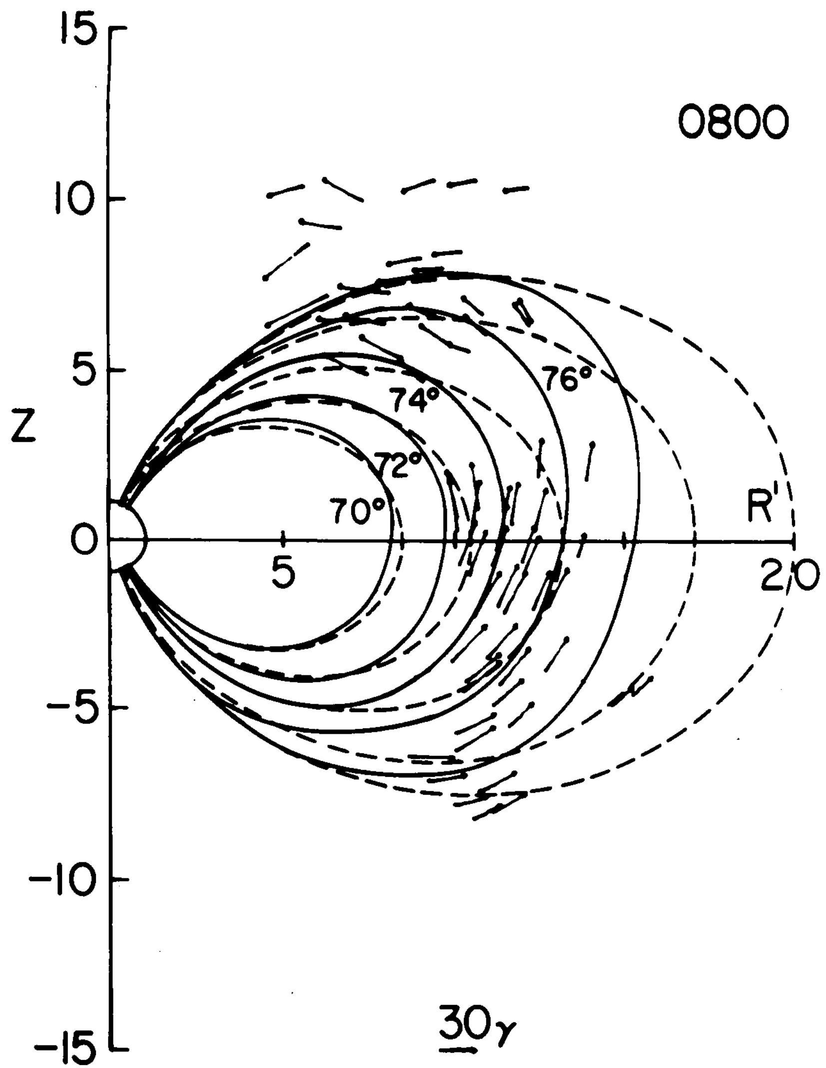


FIGURE 5a

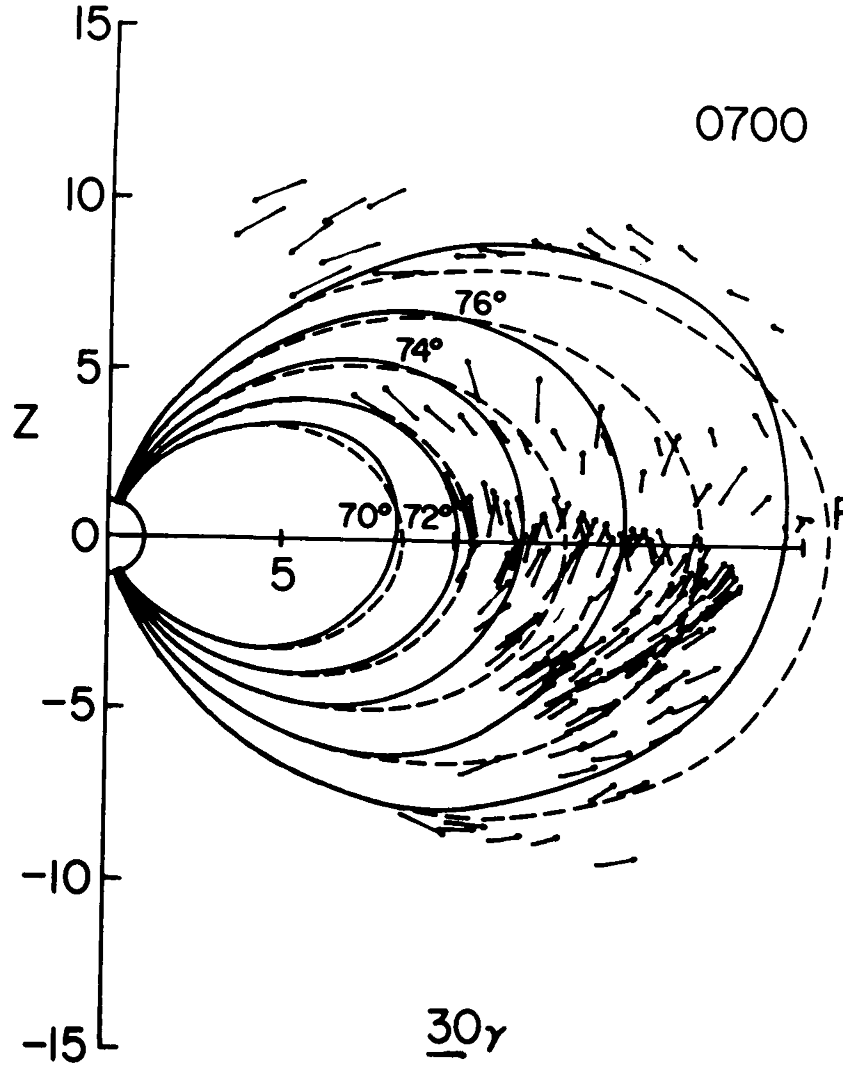


FIGURE 5b

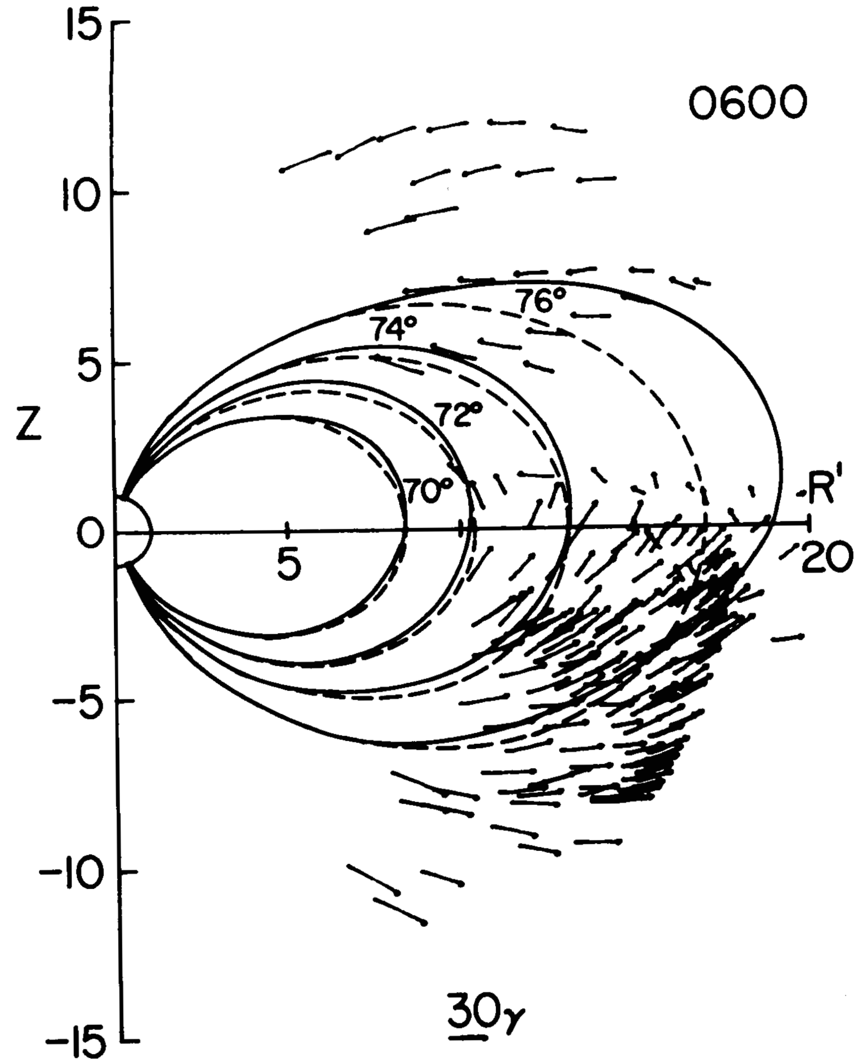


FIGURE 5c

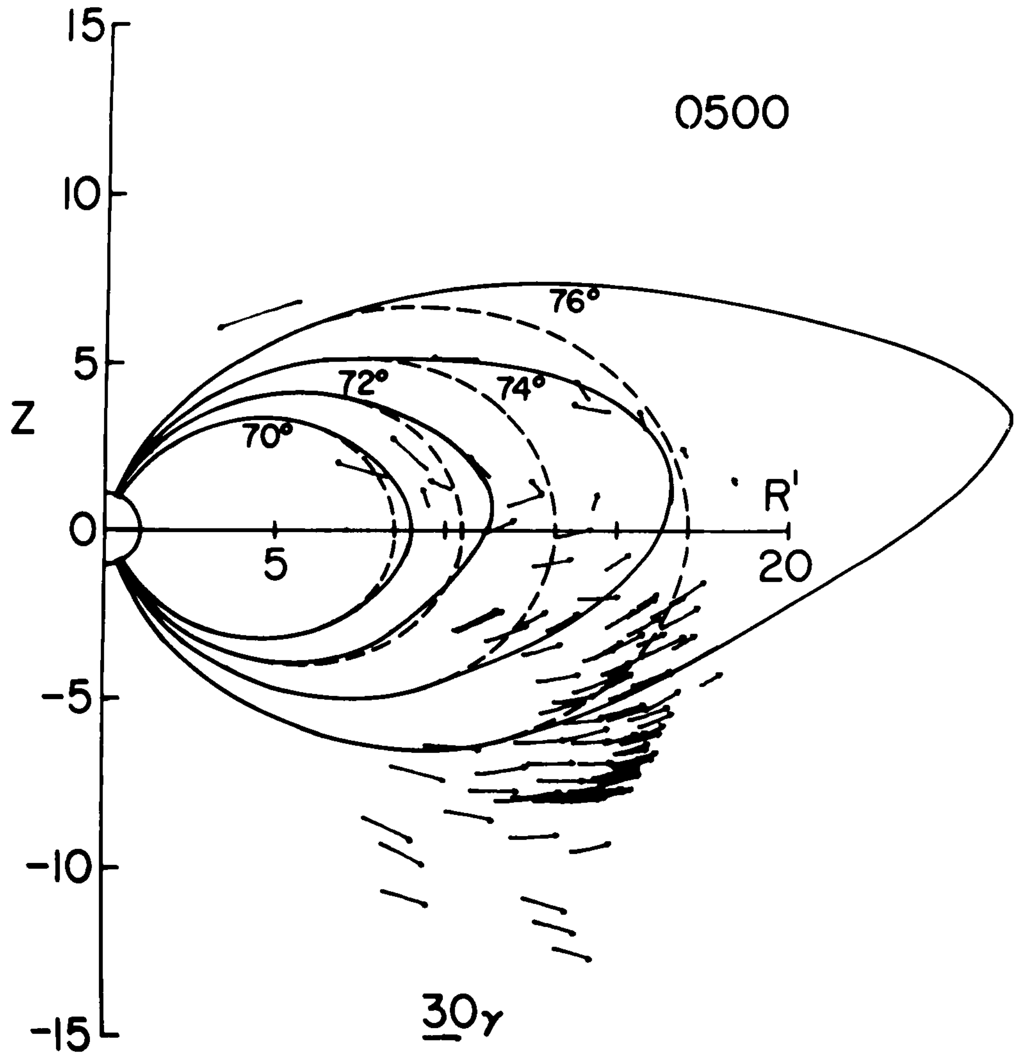
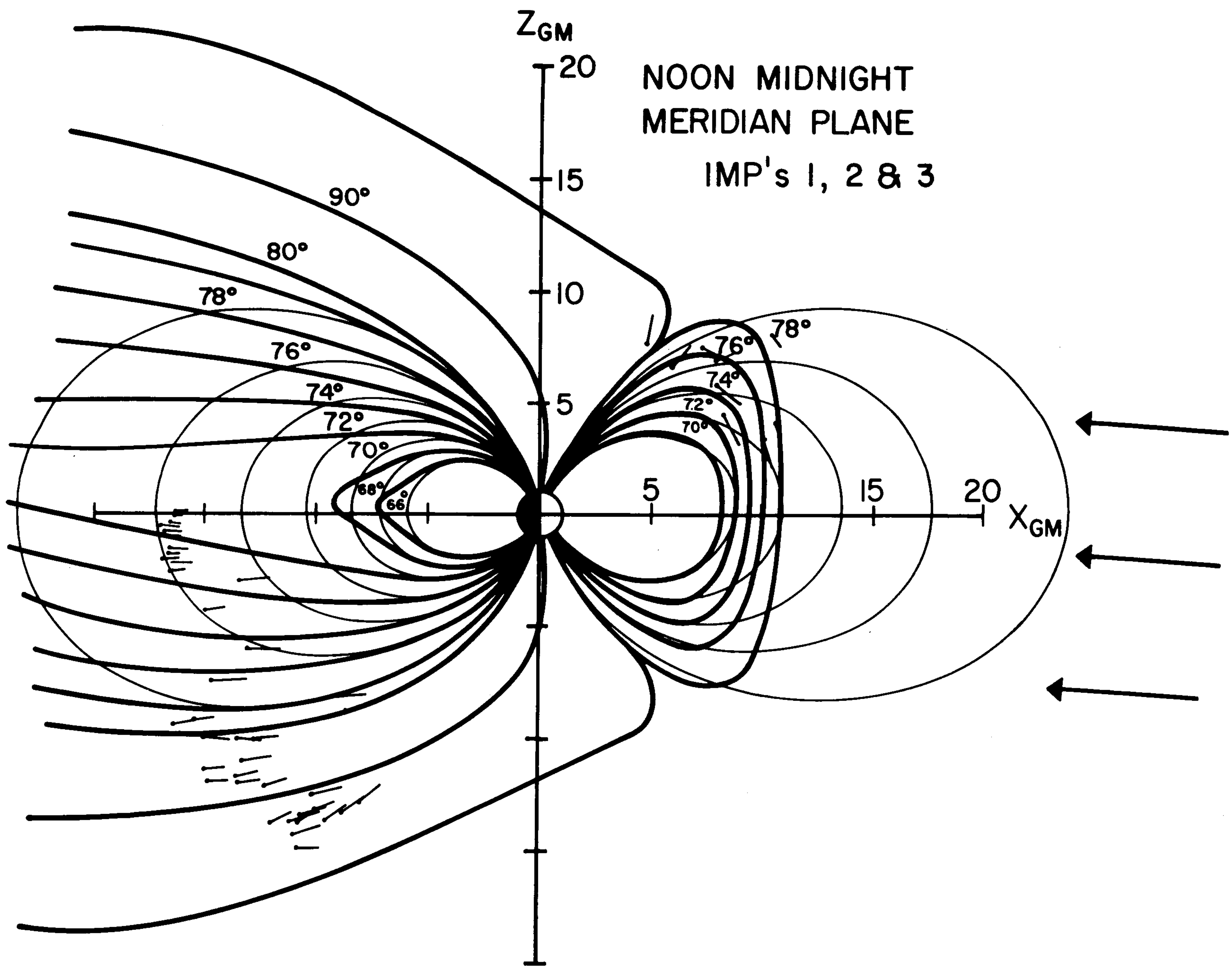


FIGURE 5d



NOON MIDNIGHT
MERIDIAN PLANE
IMP's 1, 2 & 3
Z_{GM}
20
15
10
5
X_{GM}
5
15
20
90°
80°
78°
76°
74°
72°
70°
68°
66°
78°
76°
74°
72°
70°

FIGURE 6