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NORMAN F. NESS

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REVIEW OF MAGNETIC FIELD OBSERVATIONS

Norman F. Ness
Laboratory for Extraterrestrial Physics
NASA-Goddard Space Flight Center
Greenbelt, Maryland 20771

Abstract

Detailed magnetic field observations are now routinely conducted on satellites mapping the magnetosphere and its boundaries. Sufficiently comprehensive spatial, temporal and high time resolution observations have improved the morphological description of the structure of and fluctuations in the magnetosphere, magnetosheath, plasma sheet and bow shock. Large scale distortion of the magnetosphere structure is detectable in the magnetic field data during and following major geomagnetic and substorm disturbances. Recent observations in previously unexplored regions of the magnetosphere, particularly the polar cusp region, compliment and reinforce emphasis on particle access to the plasma sheet via the polar neutral points. Significant distortions of the geomagnetic field in the polar cusp region suggest field aligned currents at large geocentric distances which can be related to low altitude polar cap phenomena. Studies of the microstructure of the field reversal region of the plasma sheet imbedded in the geomagnetic tail suggest a periodic structure of more complexity then earlier assumed simplified single neutral-line models. No significant solar cycle variation of magnetospheric structure has been detected. This review highlights the salient features of the more recent observations of the magnetic fields in the magnetosphere and identifies critical experiment and data areas for further study and theoretical analysis and interpretation.

Introduction

Accurate and rapid measurements of magnetic fields in space are now routinely conducted on satellites exploring the inner and outer magnetosphere, distant geomagnetic tail, and the boundaries of the magnetosphere and magnetosheath, the magnetopause and bow shock respectively. Recent reviews of these observations have been published by Heppner (1966a,b), Ness (1967, 1969), Fairfield, (1967), Cain (1971) Sugiura (1971) and the overall geometry and characteristics are now well established describing the earth's plasma-field environment in space. It is not the purpose of this review to summarize the well-established facts discussed by these earlier authors. Instead this review will concentrate on those recent results of specific interest to:

(1) Quantitative studies of the solar wind interaction with the earth's magnetic field,

(2) New regions of measurements near the earth's equator at $R=2-8\ R_E$,

(3) The polar cusp region of the geomagnetosphere, and

(4) New model of the detailed structure of the neutral sheet region in the geomagnetic tail.

1.0 Observations and Interpretation of Bow Shock and Magnetopause Positions

An extensive set of observations of the earth's bow shock and magnetopause have been obtained by the IMP series of spacecraft since 1963. Fairfield (1971) has summarized these observations and derived a quantitative best fit ellipse and hyperbola to the magnetopause and bow shock on the sunlight hemisphere of the earth. The observations and derived best fit curves are shown in Figures 1 and 2. The data points have been rotated by 4° about the Z_{se} axis to remove the effects of aberration due to the heliocentric motion of the earth. Average geocentric distances to the magnetopause and bow shock at the subsolar point are 11.0 and 14.6 R_E. In the dawn meridian these distances increase to 15.1 and 22.8 R_E while in the dusk meridian they increase further to 15.8 and 27.6 R_E.

The dawn-dusk asymmetry is in a direction consistent with that expected when aberration of a radial solar wind flow is considered. The magnetopause observations agree well with theoretical predictions based upon the measured momentum flux of the solar wind near the noon meridian plane but increase to greater distances than the theoretical boundaries in the dawn and dusk meridian plane. All of the observations to date demonstrate that the position of the bow shock (and magnetopause) is time dependent and so the observations reported by Fairfield (1971), as shown in Figure 1 and 2, represent the average position on each orbital pass.

There is no evidence yet available to demonstrate a long term secular variation of the average position of the bow shock and magnetopause. Substantial evidence does exist for short term variations, indicating that the momentum flux and to a lesser degree the sense of the north-south component of the interplanetary magnetic field is important in determining the positions of these two boundaries. Figure 3 presents a study of the variation of the position of the magnetopause observed as compared with that predicted on the basis of simple fluid dynamic models in which the momentum flux of the solar wind (unaffected by the earth's bow shock) is balanced by the pressure of the geomagnetic field. The average distance to the magnetopause for the observations would be predicted as 10.3 R_E which is to be compared with the observed position of 10.9 R_E. The discrepancy can easily be accounted for by modification of the measured solar wind number density and is within the experimental accuracy of observations to date.

The very favorable comparison of the frequency distribution shown in Figure 3 has been further investigated by studying explicit time variations on the IMP 4 satellite. It now appears possible to predict the average bow shock and magnetopause position to within 0.5 R_E at least 1/2 of the time and to within 1 R_E at least 80% of the time.

An investigation of an effect of the north south component of the interplanetary magnetic field has shown that when the field is directed northward the average geocentric distance to the magnetopause at the subsolar point is 10.5 R_E while it increases to 11.6 R_E when the field points to the south. Future studies of the bow shock and magnetopause positions may refine these conclusions but it is not expected that a significant departure from them will arise since the data on which the conclusions are based extends over a substantial time interval under a variety of interplanetary and terrestrial conditions.

It should be noted, however, that on rare occasions the earth's bow shock is observed at extremely distant positions (see Figure 1). Investigation of solar wind conditions upstream at this time suggest the possibility that the solar wind flow may not be super-Alfvenic but occasionally sub-Alfvenic so that a Laminar flow pattern develops. Thus far, great success has been achieved in the comparison of continuum fluid models of the collisionless solar wind plasma flow past the geomagnetic field with slight modifications to classical parameters used in continuum approximations.

2.0 Inflation of the Inner Magnetosphere

The majority of eccentric orbiting satellites have failed to provide measurements insitu of the field and plasma characteristics at low geomagnetic latidues but at moderate distances from the earth, that is geomagnetic latitudes less than 20^{o} and geocentric distances between 2 to 8 R_E. Recent observations by the ATS-1 and OGO's 3 and 5 satellites, however, have contributed significantly to these studies. Sugiura et al. (1971) have recently summarized their OGO 3 and 5 magnetic field observations obtained with a rubidium vapor magnetometer of high accuracy. For interpretation of data they have utilized the parameter

$$\Delta B = |\vec{B}_{obs}| - |\vec{B}_{theory}|$$

which represents the magnitude difference between observations and theory. Figures 4 and 5 summarize these results for four quadrants of the magnetosphere, according to local magnetic time and for two conditions of magnetic activity: quiet (Kp = 0-1) and moderately disturbed (Kp = 2-3).

Two important results from these observations relate to the classical ring current problem and the recent observations obtained by ATS 1. Computation of the magnetic fields to be expected from ring currents typified by particles observed by Frank and his colleagues (Frank, 1967; 1970; 1971 and Frank and Owens, 1970) strongly suggest that the main source of particles responsible for inflation in the magnetosphere has not been measured. The basis for this conclusion by Sugiura et al. (1971) is the geometry of the field perturbations observed by OGO's 3 and 5 when compared with that obtained from theoretically computed perturbations associated with observed particle flux measurements. Generally, the particle flux measurements have been made at higher geomagnetic latitudes than those required to detect a localized low energy plasma distribution limited near the earth's equator which seems to best fit the disc like magnetic field anomaly. This currently represents one of the more critical discrepancies in the magnetosphere regarding a need for reconcilation of plasma and magnetic field observations.

It should be noted that the use of a slightly different dipole coefficient for the geomagnetic field will not significantly alter the location of observed magnitude anomaly since the maximum modification (50γ at earth's surface) scales to less than 1γ at the distances of interest (near 5 R_E).

Another result of this mapping of the inner magnetosphere's magnetic field is summarized in Table 1 below. Here the average magnitude of the magnetic field in the noon-midnight meridian plane at the equator ($R=6.6\ R_E$) is shown for both quiet and moderately disturbed geomagnetic conditions. These values are compared with those derived from ATS 1 observations (Cummings et al., 1968; Coleman and Cummings, 1967).

TABLE 1

	OGO 3 and 5 Kp = 0-1	2-3	ATS
Noon	120	120	135
Midnight	85	75	105
Diurnal	35	45	30-40

The difference between the average fields observed is significant and is no doubt due to an incorrect zero level assumed for the ATS 1 spacecraft magnetic field component parallel to the spin axis (which represents the local horizontal component in the ATS 1 nomenclature). Better models of the distorted magnetosphere are necessary for quantitative comparison with these observations and future work in this area will require substantial improvement and increased sophistication of models used for theoretical studies.

3. Magnetic Field Observations in High Latitude Outer Magnetosphere

Early studies of the problem of solar wind interaction with the geomagnetic field lead to the concept of two neutral points in the polar regions of the magnetosphere which separated field lines which closed on the dayside from those field lines which were stretched back to form the geomagnetic tail. The first good opportunity to make high latitude high altitude measurements began with the IMP 5 satellite in 1969. Early measurements on the plasma flux in the cusp region by Frank (1970) were interpreted in terms of the injection of solar wind plasma from the magnetosheath into the magnetosphere. Corresponding magnetic field measurements have been reported upon by Fairfield and Ness (1971).

Measurements of the magnetic field in the cusp region show a very broad depressed field region in which field strengths are less than 50% to 70% that of the undistorted dipolar field. No well-defined magnetopause boundary is observed between the magnetosheath and polar cusp regions. The change from the magnetosheath to the polar cusp is characterized by large amplitude fluctuations of the magnetic field with magnitudes up to 45γ and in directions which are approximately perpendicular to the average field. These magnetic field perturbations are suggestive of field aligned currents such as have been reported from low altitude polar orbiting spacecraft by Zmuda and colleagues.

The general character of the magnetic field in the region of the polar cusp is in good agreement with earlier measurements at low geomagnetic latitudes and theoretical predictions. The orientation of the magnetic field in the polar cusp is suggestive of direct connection with interplanetary magnetic field lines. However, this conclusion is not unique because there exists no well-defined boundary to the magnetosheath in this region of space. But no other reasonable alternative tothe topology of the magnetic field consistent with the observations has yet to be offered.

4. Microstructure of the Geomagnetic Neutral Sheet

For sometime, the existence of a geomagnetic tail with small magnetic flux crossing the field reversal region has been an accepted characteristic of the deformed magnetosphere. Experimental observations have not been in perfect agreement, however, on the possible position of a neutral line in the geomagnetic tail since observations of the north south component have not always revealed a north component only. In an attempt to study the detailed structure of the neutral sheet in the field reversal region, a statistical approach is necessary since it is not possible to uniquely separate space and time variations from each other in observations obtained from a single satellite traversing the field reversal region.

In a study of the detailed observations of the field obtained from IMP 5 by Schindler and Ness (1971), a new configuration for the microstructure was suggested to be consistent with the field reversal region. This new structure consists of a series of neutral lines in the geomagnetic tail and is motivated by theoretical considerations which have been discussed recently by Schindler (1971).

Observations show that for north-south components greater than one gamma the frequency of northward occurring fields is 6 times that of southward occurring fields. If consideration of field components greater than 5γ is made, the ratio increases to 20 to 1. The fact that the ratio is magnitude dependent suggests strongly a more detailed structure than the simple one dimensional field reversal regions utilizing a single neutral line. The motivation for a statistical study was that relative motion of a relatively fixed spatial structure past the satellite should, providing a sufficiently large number of data are employed, yield statistical characteristics of the field which reflect the spatial structure only and from which the time variations have been removed. Table 2 below summarizes the statistical distribution of the average north-south component of the field in solar magnetospheric coordinates as a function of field magnitude and the percentage of the time that the north south component is directed southward.

TABLE 2

Magnitude Range	Average Field North(+) South (-)	% Southward Field
0 - 1.25	-0.03	55
1.25 - 1.875	0.26	39
1.875-2.625	0.81	27
2.625-3.375	1.13	22
3.375-4.125	1.51	18
4.125-5.25	1.83	16
5.25-6.750	2.11	13
6.750-1.50	2.03	17
8.50-10.5	2.26	17

The nature of this distribution is such that it favors multiple neutral lines over the rather implausible situation of a single netural line moving rapidly back and forth past the satellite i.e., towards and away from the earth. Arguments for the choice of interpretation of multiple neutral lines have been presented by Schindler and Ness (1971).

Figure 6 presents a schematic diagram of the field topology in the midnight meridian plane showing the presence of both multiple X type neutral points in the geomagnetic neutral sheet on a fine spatial scale.

The merits of this suggestion must be tested by additional studies of satellite measurements at different distances in the geomagnetic tail and an evaluation of the associated theoretical model.

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FIGURE CAPTIONS

Figure 1 Projections on ecliptic plane of bow shock observations by IMP spacecraft from 1963 to 1968. Solid line is a best fit hyperbola to those points for which $|Z_{se}|$ less than 7 R_E. Line segments beyond average shock position represents observations of unusually distant bow shock locations. (Fairfield, 1971).

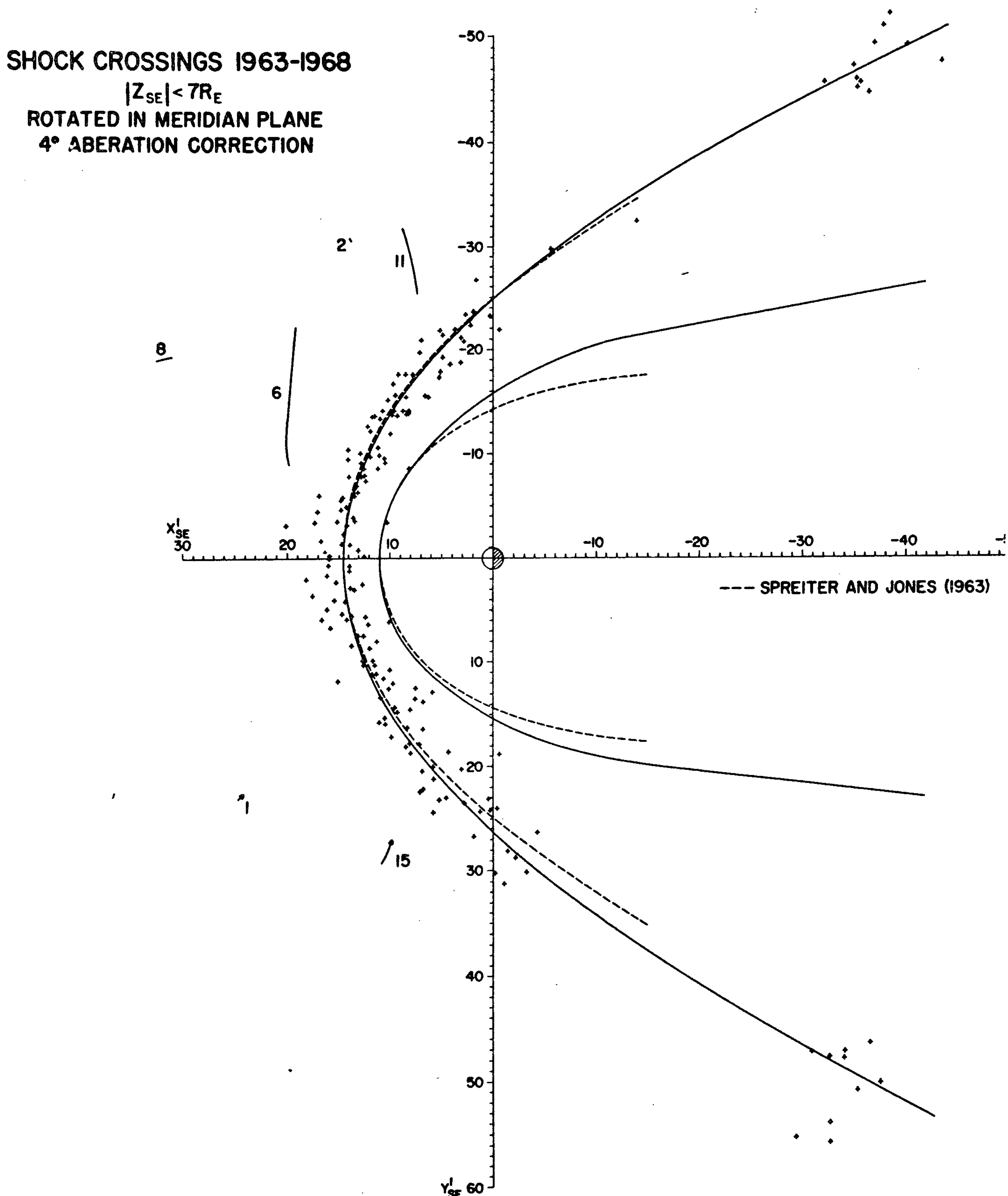
Figure 2 Projection on ecliptic plane of observations of magnetopause as observed by IMP spacecraft from 1963 to 1968. Solid line ellipse represents the best fit curve to those points for which $|Z_{se}|$ less than 7 R_E. (Fairfield, 1971).

Figure 3 Frequency distribution of observed (IMP 4: 1967 -1968), and predicted subsolar magnetopause positions. Note that theoretical positions have been adjusted so they are centered on the observed average position at 10.9 R_E. (Fairfield, 1971).

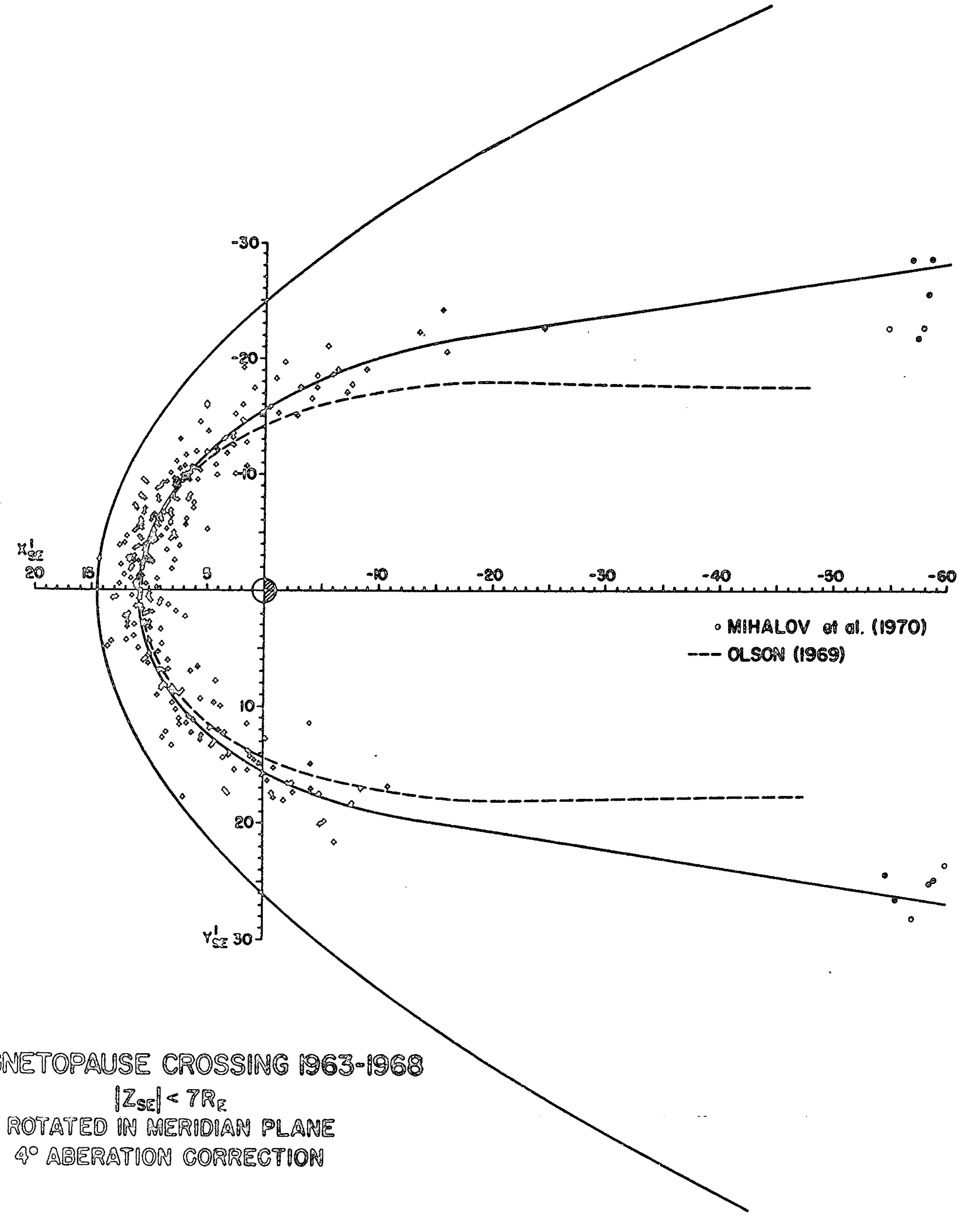
Figure 4 Contours of isointensity magnetic field magnitude anomaly ΔB in the geomagnetic noon midnight meridian plane (top) and in the geomagnetic dawn-dusk meridian plane for quiet conditions (Kp = 0) in units of gammas (Sugiura et al., 1971).

Figure 5 Contours of isointensity magnetic field magnitude anomaly ΔB in the geomagnetic noon midnight meridian plane (top) and in the geomagnetic dawn-dusk meridian plane for slightly disturbed conditions, Kp = 2-3 in units of gammas (Sugiura et al., 1971).

Figure 6 Topology of magnetic field in model neutral sheet with multiple neutral lines. The two-dimensional structure is replicated along the neutral sheet (Schindler and Ness, 1971).



SHOCK CROSSINGS 1963-1968
|Z_SE| < 7R_E
ROTATED IN MERIDIAN PLANE
4° ABERATION CORRECTION
--- SPREITER AND JONES (1963)
X'_SE
Y'_SE
2
11
8
6
1
15
30
20
10
-10
-20
-30
-40
-50
40
50
60



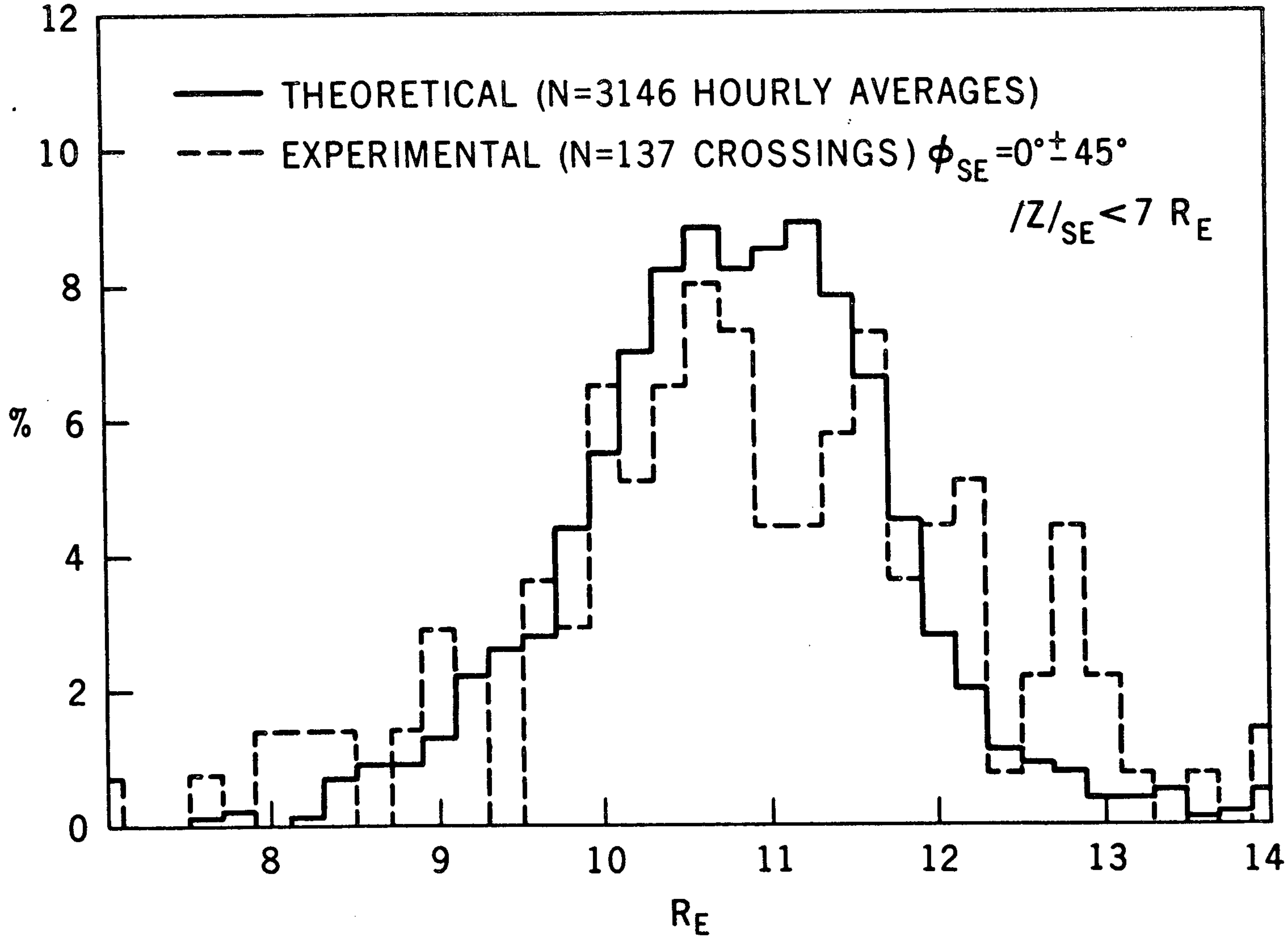
MAGNETOPAUSE CROSSING 1963-1968

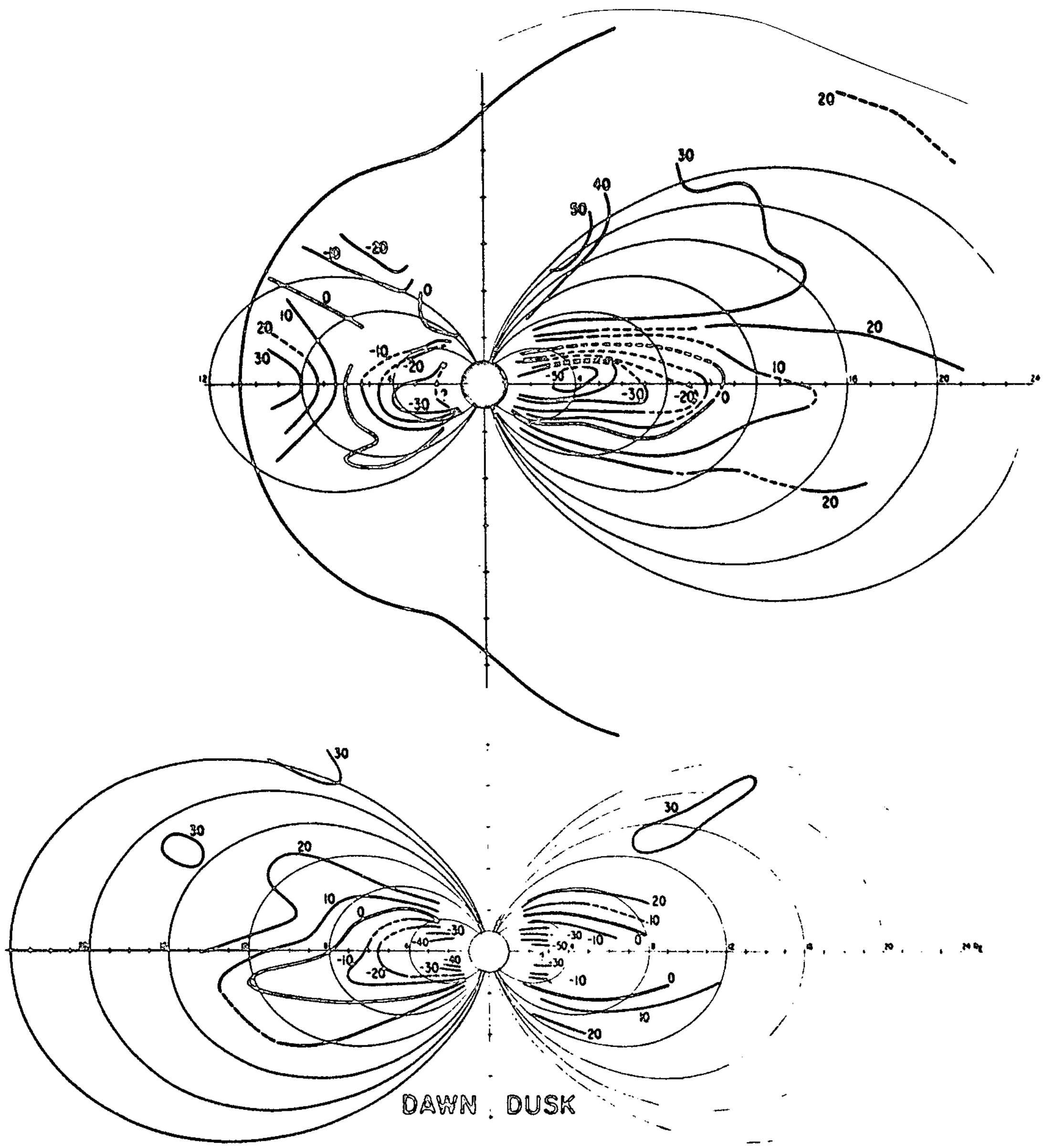
$|Z_{SE}| < 7R_E$

ROTATED IN MERIDIAN PLANE

4° ABERATION CORRECTION

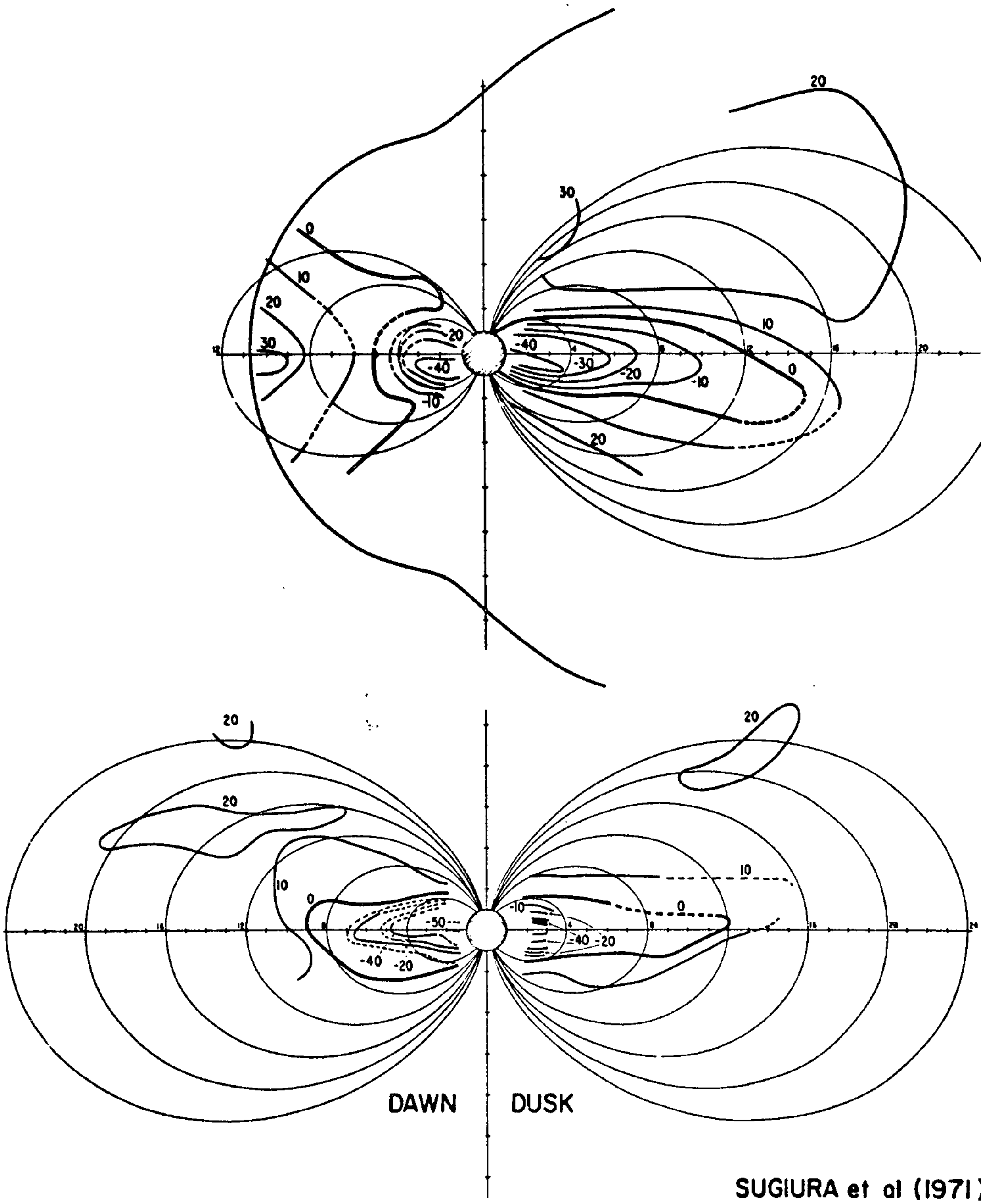
SUBSOLAR MAGNETOPAUSE POSITIONS



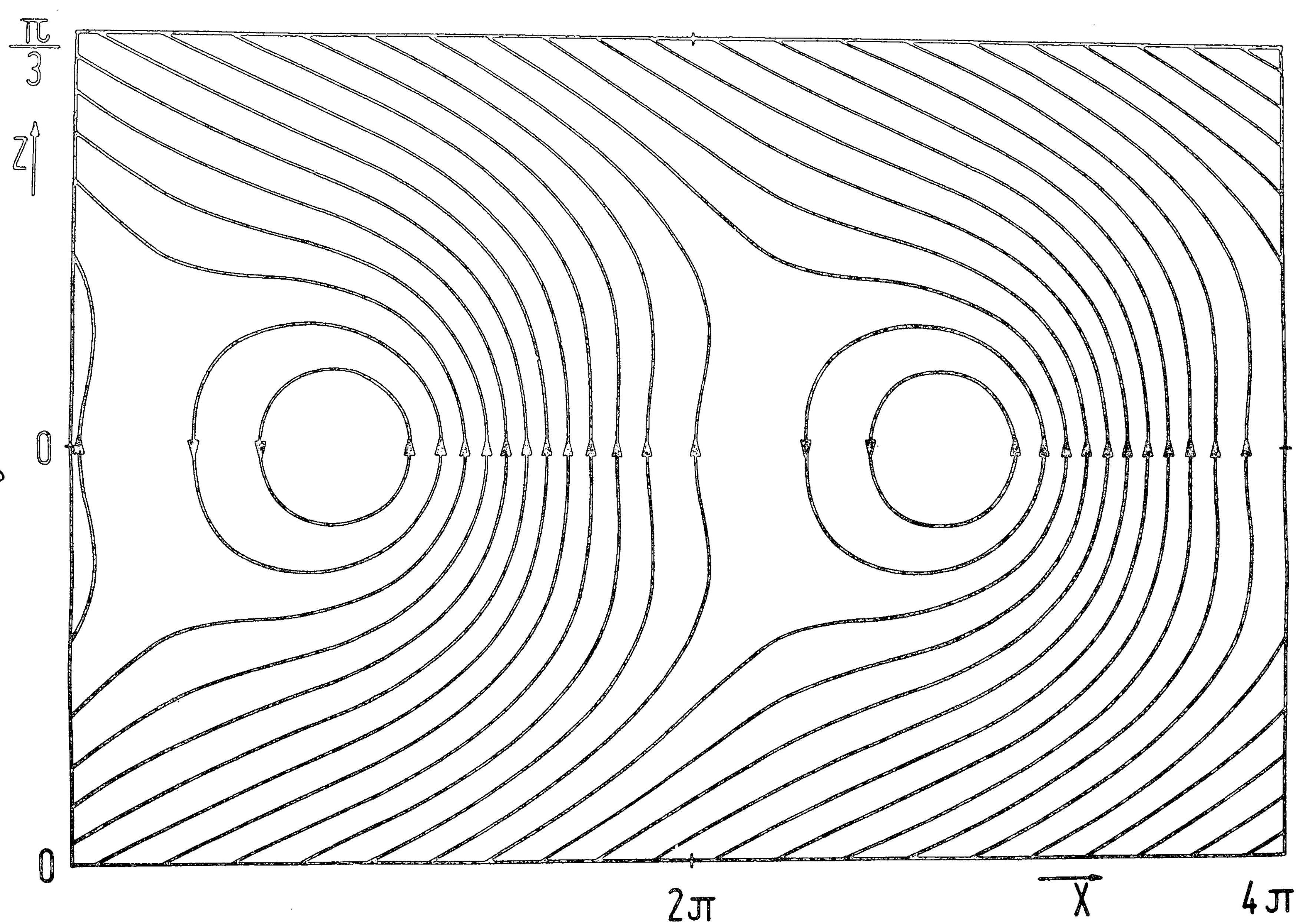


SUGIURA et al (1971)

ΔB OGO 3&5
Kp=0-1



ΔB OGO 3&5
Kp = 2-3



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