N87-20065

PREDICTING THE MAGNETOSPHERIC PLASMA OF WEATHER

by

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I. INTRODUCTION

When I was asked to talk on plasma technology for the space station I had a little trouble deciding just what to talk about. Being basically a plasma physicist and not really an expert on the space station, I knew there were potentially a large number of technological applications; the subject of plasma physics is very broad and its technological applications are expanding every day. Probably the most important applications to the space station have not yet been thought of. Some topics which I considered but rejected were the following.

A. Applications of Fusion to the Space Station

Fusion research has made substantial gains in the last few years. Fusion as a power source for a space station would have many advantages. However, I do not expect that a fusion power source, particularly one that can be employed on the space station, will be available by the year 2000. But I do think this is something people who are interested in plasma technology for space should keep their eyes on.

I might interject at this stage that it recently has been realized that the lunar soil contains a large amount of ^{3}He; a very good and particularly clean fusion fuel. It appears that it is economical to mine it from the lunar soil and return it to Earth.

Finally towards the end of this talk I will mention one possible application of fusion technology which I think might find some interesting and useful immediate applications.

B. Building of Very Powerful Plasma Thrusters (100's of Kg thrust)

There seems to me to be some rather interesting possibilities here. However, I believe this application may find more use in things like manned Mars missions or sending large payloads on deep space missions, than on the space station.

C. Plasma Materials Processing

One might do something here, but plasma processes tend to be energy intensive and it is not clear that there is something that can be done on the space station that cannot be done better on Earth. However, there are probably important applications in fabricating space station components on Earth.

D. Investigations in Plasma Science

I think this will clearly be an important aspect of the space station. It will be flying in a interesting plasma supplied free by nature. We clearly will want to learn more about this plasma and it will offer unique opportunities for experiments. We may also want to create our own plasmas to experiment on in space. I regard this as an important activity of the space station but did not feel that it quite was in the spirit of technological applications of plasma to the space station.

II. PREDICTING THE PLASMA WEATHER FOR THE SPACE STATION

The subject I did decide to talk on, "Developing a Predictive Capability for the Plasma Condition at the Space Station", may seem rather theoretical, but I believe it truly comes under the heading of a plasma technological development of importance to the space station. What I am concerned with is predicting the plasma environment in time, the plasma weather, if you will. I know the space station will be operating in a relatively low orbit near to the equator where it is largely protected from larger variations produced by solar activity. It will be in a sheltered cove, so to speak. Nevertheless, we know that from time to time there are large magnetic storms that have produced aurora's as far south as Mexico City. It will be important to be able to predict when and what precautions to take both for the people on board and probably for such things as sensitive control (computer) equipment. We will also want to start establishing both a set of plasma weather records and records of our ability to predict similar to what has been accumulated for the Earth's weather over the last hundred years or so.

A successful forecasting system will require:

1. A set of satellite weather stations to provide data from which predictions can be made. It will be particularly important to have stations between the Earth and Sun so that data on the incoming solar wind can be obtained. One may want solar observations that can see regions of the sun not visible from Earth. The development of a capability for remotely sensing the conditions of the magnetosphere and solar wind plasmas would be very desirable.

2. A set of plasma weather codes capable of accurately forecasting the status of the Earth's magnetosphere in sufficient detail when provided with the data.

I will return to the data gathering shortly and start by discussing the problems of obtaining a predictive capability.

One of the efforts at UCLA has been in numerical modeling of the magnetosphere. These efforts have been aimed at using MHD fluid models to attempt to simulate the large scale behavior of the magnetosphere. With these models we have tried to reproduce many of the effects observed in the magnetosphere. We have had some success, but these efforts are still far from having a predictive capability. Nevertheless, they are sufficiently encouraging that over the next twenty years or so I believe it is possible to develop a predictive capability if the effort is put into it.

Let me start by giving a quick review of some of the findings. The basic model is shown in Figure 1. The earth is represented as a simple dipole embedded in the solar wind flow. Simple MHD fluid equations are used to model the dynamics of this system; these are:

$$\rho \left(\frac{\partial \underset{\sim}{v}}{\partial t} + \underset{\sim}{v} \cdot \underset{\sim}{\nabla}\underset{\sim}{v}\right) = \frac{\underset{\sim}{j} \times \underset{\sim}{B}}{c} - \underset{\sim}{\nabla}p + \underset{\sim}{g}\rho + \mu\nabla^2\underset{\sim}{v} \tag{1}$$

$$\frac{\partial \rho}{\partial t} + \underset{\sim}{\nabla} \cdot (\rho\underset{\sim}{v}) = D\nabla^2\rho \tag{2}$$

$$\frac{\partial P}{\partial t} + \underset{\sim}{v} \cdot \underset{\sim}{\nabla}P = -\gamma P\underset{\sim}{\nabla}\cdot\underset{\sim}{v} + D_p\nabla^2 P \tag{3}$$

$$\frac{\partial \underset{\sim}{B}}{\partial t} = \underset{\sim}{\nabla} \times (\underset{\sim}{V} \times \underset{\sim}{B}) - \eta\nabla^2\underset{\sim}{B} \tag{4}$$

$$j = \nabla \times \left(\underset{\sim}{B} - \underset{\sim}{B}_{dipole}\right) = \underset{\sim}{\nabla} \times \underset{\sim}{B} \tag{5}$$

$$\gamma = 5/3\ , \qquad N = N_o\ (T/T_o)^{-3/2}$$

Reynolds Numbers Run, $S = 100\text{–}1000$

The solar wind (containing its own magnetic field) flows in from the left and out at the right; the boundary conditions along the sides are such as to have only outgoing disturbances there. Typical parameters used in the model are the following:

Grid 48×48×24 (North–South Mirror Symmetry)

$\Delta x = \Delta y = \Delta z = 1\ R_e$

$N_{SW} = 5/cm^3$, $V_{SW} = 300$ km/sec

$T_{SW} = 2\times10^{50}$ K

$\underset{\sim}{B}_{IMF} = (0,\ B_{IMF}\cos\theta,\ B_{IMF}\sin\theta)$

$|B_{IMF}| = 5$ nT

We have used this model to model the flow in the magnetosphere, the currents flowing into and out of the auroral regions, the magnetopause, the bow shock location and the magnetotail of the earth. Most of these, of course, would only indirectly effect the plasma weather at the Space Station.

Let me show you some general features of the flow that this model gives. There is, of course, the bow shock, magnetopause and plasma sheath in the tail. There are also large convective or vortex-like motions set up just as there are in the flow of fluid around an object. Figure 2 shows a sketch of such flows. Such vortexes can act as huge MHD generators that drive currents into and out of the auroral regions. The results of such 3-dimensional calculations can be very complex as shown by the so-called spider diagram for the magnetic field shown in Figure 3. We need some simpler ways to analyze and interpret what is going on.

One way to analyze the results of such calculations is by projecting the quantities of interest along the magnetic field line onto the polar regions of the earth. Such projections are shown in Figure 4.

In this figure we see the plasma pressure, the field aligned current, the vorticity and the plasma flow parallel to B projections. You see that these are quite complicated patterns looking much like conventional weather maps. One of the successes of the simulation was the prediction of the θ aurora; this was almost simultaneously discovered by satellite and in the simulation. Fig. 5 shows observations of the θ aurora; it occurs only when there is a northward IMF. I believe the observations preceded the calculation by a few months but the calculations were already being carried out and were not influenced by the observations.

In the computations, such a configuration was obtained by introducing a solar wind magnetic field in the northward direction. The resulting polar projections are shown in Figure 6.

One can see the currents flowing into and out of the ionosphere now form a θ pattern. As one goes down the figure one sees what happens as one rotates the solar wind magnetic field in the west/east direction; the pattern shifts east and west. At the bottom are shown results for a southward solar wind field.

We have also compared observed currents into the polar regions with our computations. The agreement that is obtained is shown in Figs. 7, 8 and 9.

We see regions where the current flows in and out as observed and as predicted; the agreement is fairly good.

These results give us some confidence that the models are predicting real effects; what needs to be done? There are many unrealistic aspects of the models. Below I have a list of some of the shortcomings of the present models:

1. The grid is much too coarse to give real details of what is happening near the earth. Grid size at least 1 R_e; projection patterns look good because of the convergence of the field lines.

2. There is no accurate treatment of the ionospheric or magnetospheric coupling. The physics of the ionosphere must be put in. Such physical processes including a saturation current (electron flow velocity) along the field lines and kinetic effects as magnetic mirroring of the electron need to be included.

3. The models are simple MHD ones and subtle physics of more realistic models is not contained in them. Relative slips between electrons and ions across B [the Hall effect]; individual electron and ion pressure effects, multicomponent plasmas [H, N, O, He, etc.], Vlasov [kinetic effects], the effects of microturbulence, ... The importance of all these effects is not yet known.

4. Lack of sufficient data so that something like a detailed prediction based on it can be made and compaired with observations.

The last of these points is quite a serious one, I believe, if we expect any kind of accurate predictions. We do have quite a number of satellites and spacecraft out observing the plasma conditions in the magnetosphere and in the solar wind, but these make measurements only at points along their orbits. We also have observations of the sun and we know something about what the occurrence of flares of a certain magnitude will do but I think it is safe to say we are a long way from a real predictive capability.

As far as the space station goes, it could launch a large number of observational satellites which it could monitor from its vantage point. It should also be able to make much better observations of the sun as has already been shown with sky lab and other satellites. However, I expect that all of these will not give the amount and quality of data we would want for a predictive capability.

Remote sensing of plasma conditions by scattering of electromagnetic waves from the plasma is used all the time in diagnosing fusion and laboratory plasma. It would be worthwhile to explore this possibility in some detail for the magnetospheric and solar wind plasmas, as illustrated in Fig. 10. A wide range of frequencies can be used. Also the scattered radiation could be measured by satellites at various places as well as by the space station. A second thing that can be done is to measure refraction and phase shifts of satellite signals which has to do with their passage through intervening plasma on the way to the space station.

Finally I would like to mention one more technique for monitoring the magnetosphere. This is to inject positrons into flux tubes, as illustrated in Fig. 11. These will follow the field lines and move with the $E \times B/B^2$ velocity. They are easily detected when they annihilate with electrons and the detection techniques are highly developed for medical PET scans, illustrated in Fig. 12. Relatively few positrons are required, I believe, because the background should be very low. I think $\sim 10^{-3}$ to 10^{-6} positrons per cubic meter will be enough. Nevertheless, a large number will be needed because of the large volume.

Positrons generally require a large amount of energy to create; typically ~10-20 Gev per positron and energy is a premium commodity on the space station. Here is where fusion technology might make a direct contribution.

The simplest way to make positrons is to create positron emitters by bombarding suitable isotopes with energetic protons; Table 1 lists some possibilities with thresholds' energies and half-lives. Generally the positron emitters are made by bombarding the isotopes with 10 MeV protons from a cyclotron. Typically these produce 100 μ A of 10 MeV protons and can generate 100 n A of positrons. This is much too small.

Fusion technology may help us. If we use the D-^{3}He reaction it makes a 14.7 Mev proton suitable for producing the (pn) reactions needed. Very powerful neutral D beams have been produced (10's to 100's of A) at about 100 Kev which are suitable for producing D-^{3}He reactions. These should be able to produce maybe $\sim 10^{-2}$ to $\sim 10^{-1}$ A of 14.7 Mev protons. It appears that by properly seeding the fusion plasma with the right fertile isotopes 10^{-3} of these protons can be converted to positron emitters so we might get 10^{-5} to 10^{-4} A of positrons. This is 2 to 3 orders of magnitude more positrons than from a cyclotron and would give us the number of positrons we need ($\sim 10^{14}$ -10^{17}) in (~1-3 hours); this is enough to be interesting.

TABLE 1. Some (pn) Reactions for Positron Production

$D + {}^3He \rightarrow {}^4He + p$ (14.7 MeV)

1. $p + {}^{11}B \rightarrow {}^{11}C + n$ (E_T = 2.76 MeV)
   ${}^{11}C \rightarrow {}^{11}B + {}^+\beta$ ($\tau_{1/2}$ = 20 min.)

2. $p + {}^{13}C \rightarrow {}^{13}N + n$ (E_T = 3 MeV)
   ${}^{13}N \rightarrow {}^{13}C + {}^+\beta$ ($\tau_{1/2}$ = 10 min.)

3. $p + {}^{15}N \rightarrow {}^{15}O + n$ (E_T = 3.53 MeV)
   ${}^{15}O \rightarrow {}^{15}N + e^+$ ($\tau_{1/2}$ = 2.03 min.)

$\sigma \approx 200$ mb

4. $p + {}^{17}O \rightarrow {}^{17}F + n$ (E_T = 3.55 MeV)
   ${}^{17}F \rightarrow {}^{17}O + {}^+e$ (τ_{V_2} = 66 sec.)

5. $p + {}^{18}O \rightarrow {}^{18}F + n$ (E_T = 2.45 MeV)
   ${}^{18}F \rightarrow {}^{18}O + {}^+e$ ($\tau_{1/2}$ = 1.87 hr.)

6. $p + {}^{19}F \rightarrow {}^{19}Ne + n$ (E_T = 4.03 MeV)
   ${}^{19}Ne \rightarrow {}^{19}F + {}^+e$ ($\tau_{1/2}$ = 18 sec.)

7. $p + {}^{26}Mg \rightarrow {}^{26}Al + n$ (E_T = 5.01 MeV)
   ${}^{26}Al \rightarrow {}^{26}Mg + {}^+e$ ($\tau_{1/2}$ = 6.5 sec.)

Acknowledgements

I wish to acknowledge valuable interactions with R.J. Walker, T. Ogino, M. Ashour-Abdalla and P. Pritchett on these research topics. This work was partially supported by NSF Contract No. ATM 85-21125.

FIGURE CAPTIONS

Fig. 1 Model of the Magnetosphere and Solar Wind.

Fig. 2 Vortex Flow Pattern from MHD Model of Ogino.

Fig. 3 Spider Diagram for the Magnetic Field Around the Earth from Ogino's MHD Calculation.

Fig. 4 Projection of Various Quantities Along B Lines onto the Polar Region - Taken from MHD Simulation of the Magnetosphere.

Fig. 5 Satellite Observations of θ Aurora.

Fig. 6 Polar Projections of the Vorticity, the Field-Aligned Current and the Open Field Region for Various Orientations of the Solar Wind Magnetic Field. 90° is northward, 270° is southward.

Fig. 7 Field Aligned Currents: Model and Observations (θ=105°, θ=150°).

Fig. 8 Field Aligned Currents: Model and Observations (θ=90°, θ=105°, θ=150°).

Fig. 9 Field Aligned Currents: Model and Observations (θ=180°, θ=210°).

Fig. 10 Schematic for Remote Sensing of Magnetospheric Plasma Conditions.

Fig. 11 Magnetosphere of Earth with Positron Sampling a Flux Region.

Fig. 12 Schematic of a Positron Detector.

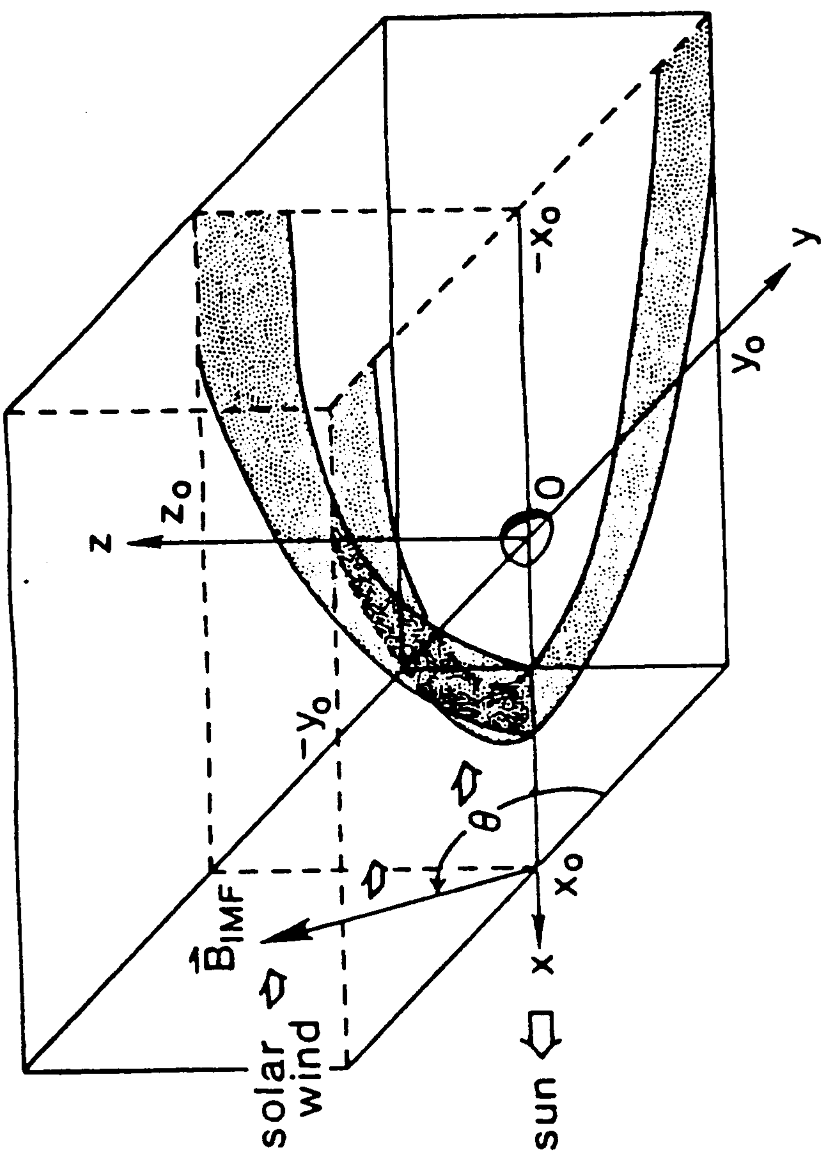


Fig. 1

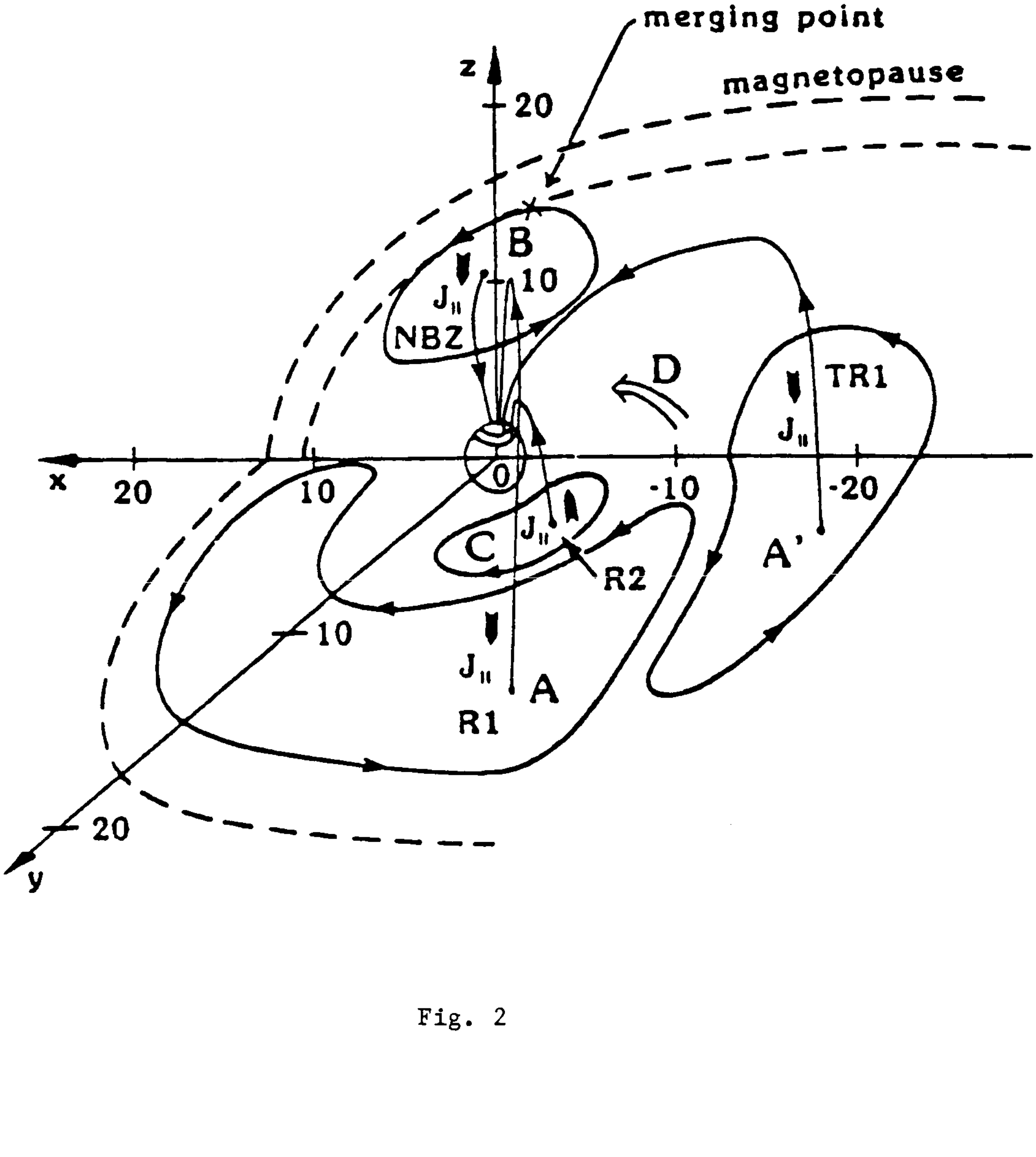

merging point
magnetopause
z
20
B
10
$J_{\parallel}$
NBZ
D
TR1
$J_{\parallel}$
x
20
10
0
-10
-20
$J_{\parallel}$
C
R2
A'
10
$J_{\parallel}$
A
R1
20
y

Fig. 2

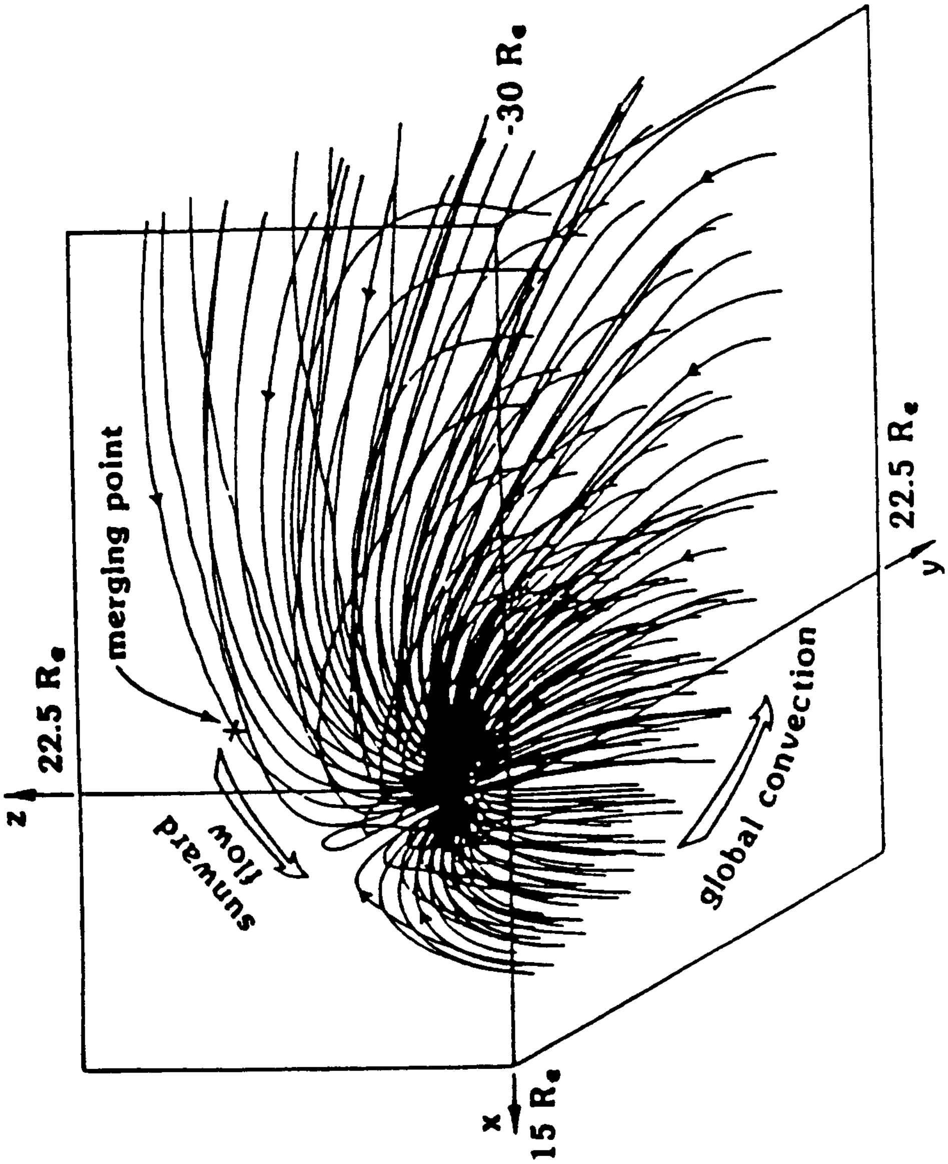

z
22.5 Re
merging point
sunward flow
global convection
-30 Re
22.5 Re
y
x
15 Re

Fig. 3

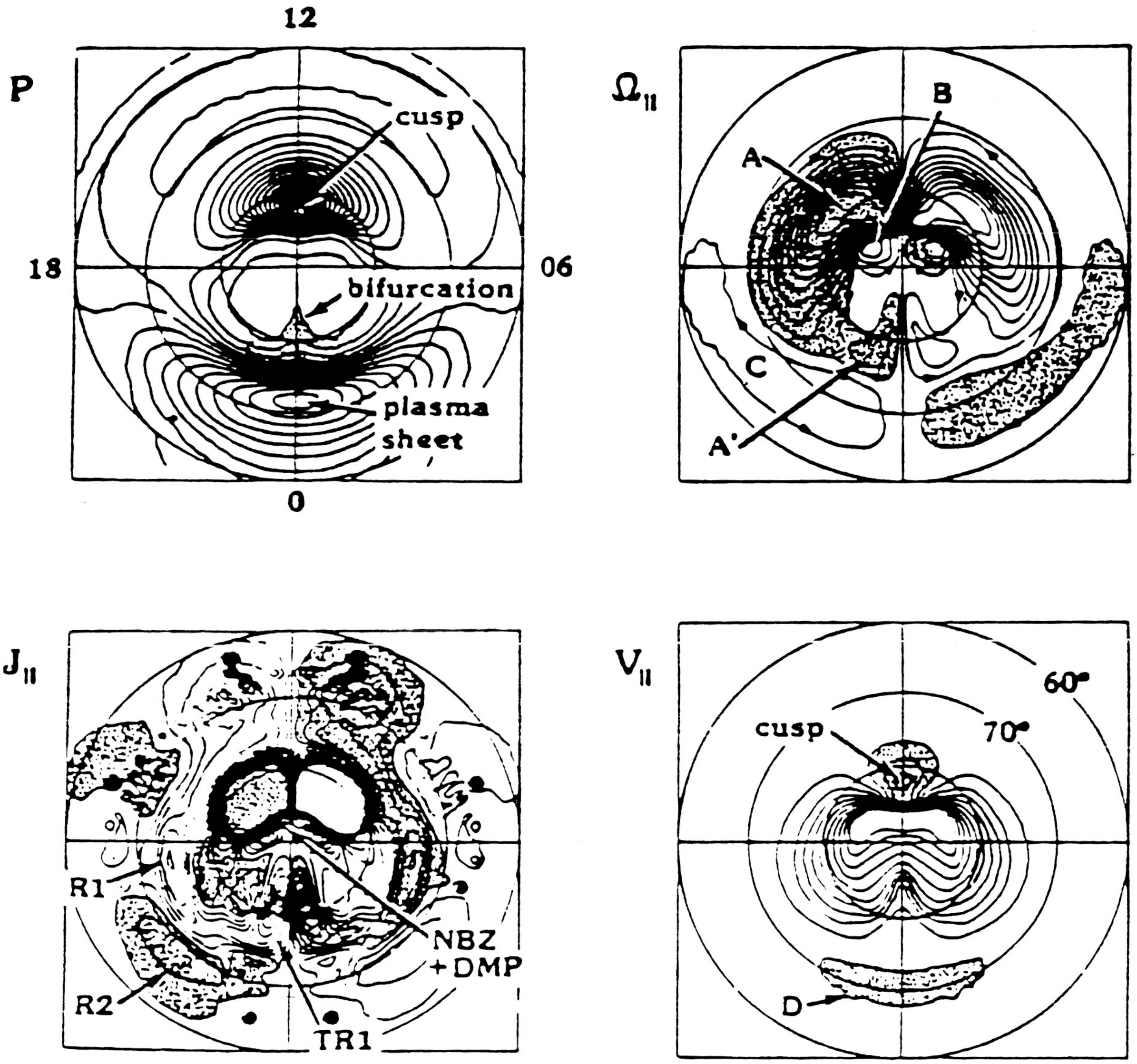

12
P
cusp
18
06
bifurcation
plasma
sheet
0
$\Omega_{\|}$
B
A
C
A'
$J_{\|}$
R1
R2
NBZ
+DMP
TR1
$V_{\|}$
60°
70°
cusp
D

Fig. 4

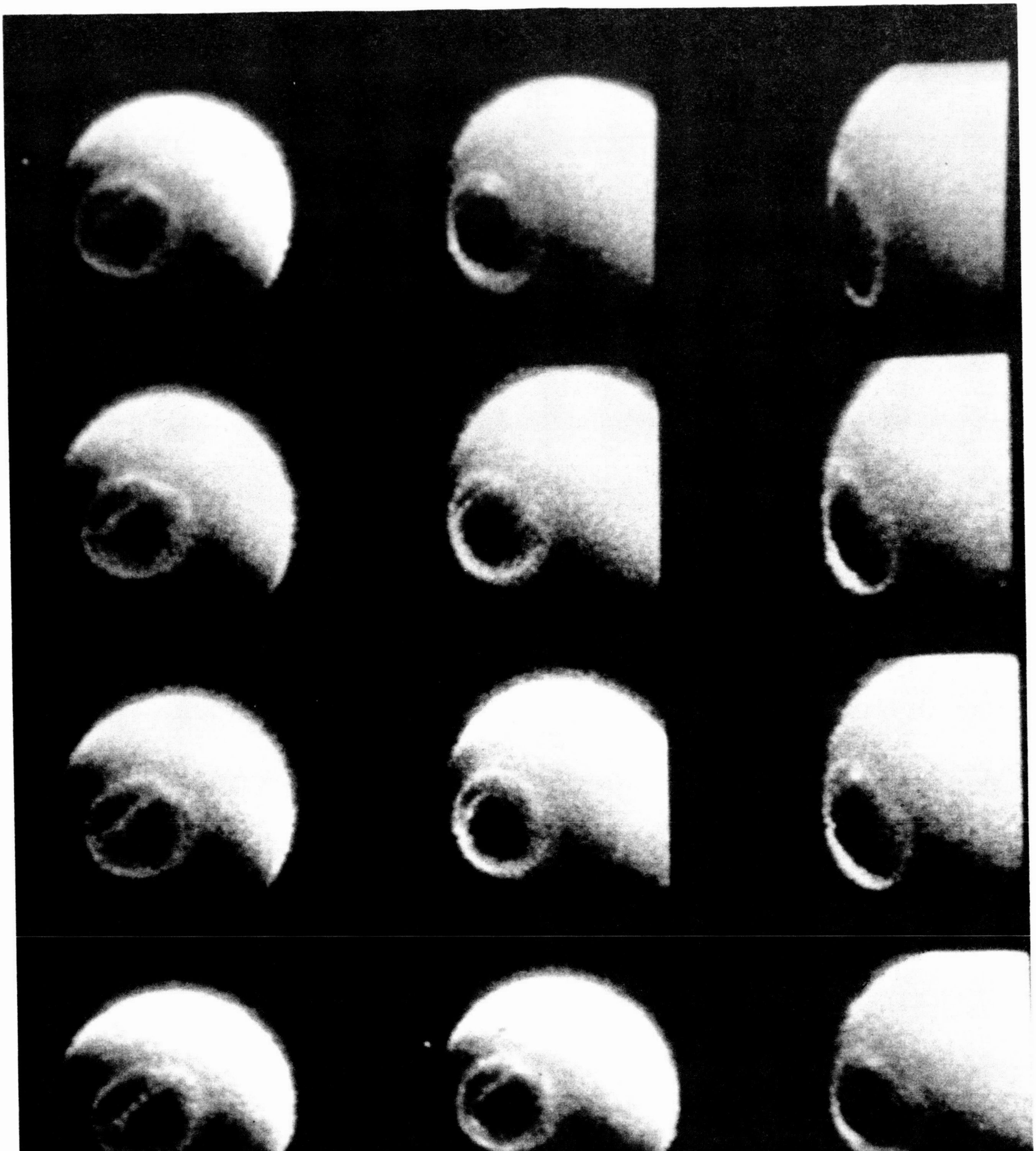
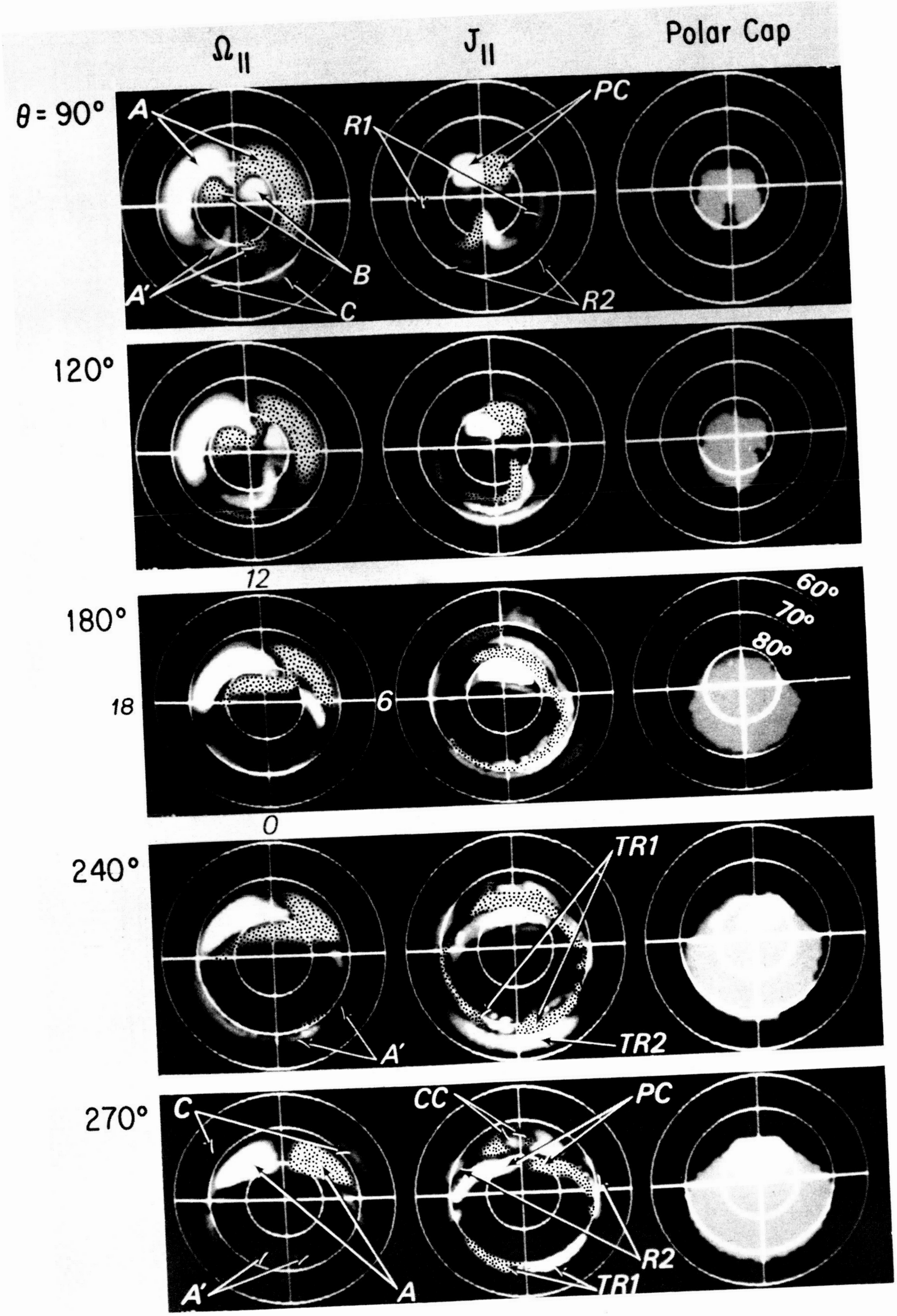


Fig. 5



Ω∥
J∥
Polar Cap
θ = 90°
A
PC
R1
B
A′
C
R2
120°
12
180°
60°
70°
80°
18
6
0
240°
TR1
A′
TR2
270°
C
CC
PC
R2
TR1
A′
A

Fig. 6

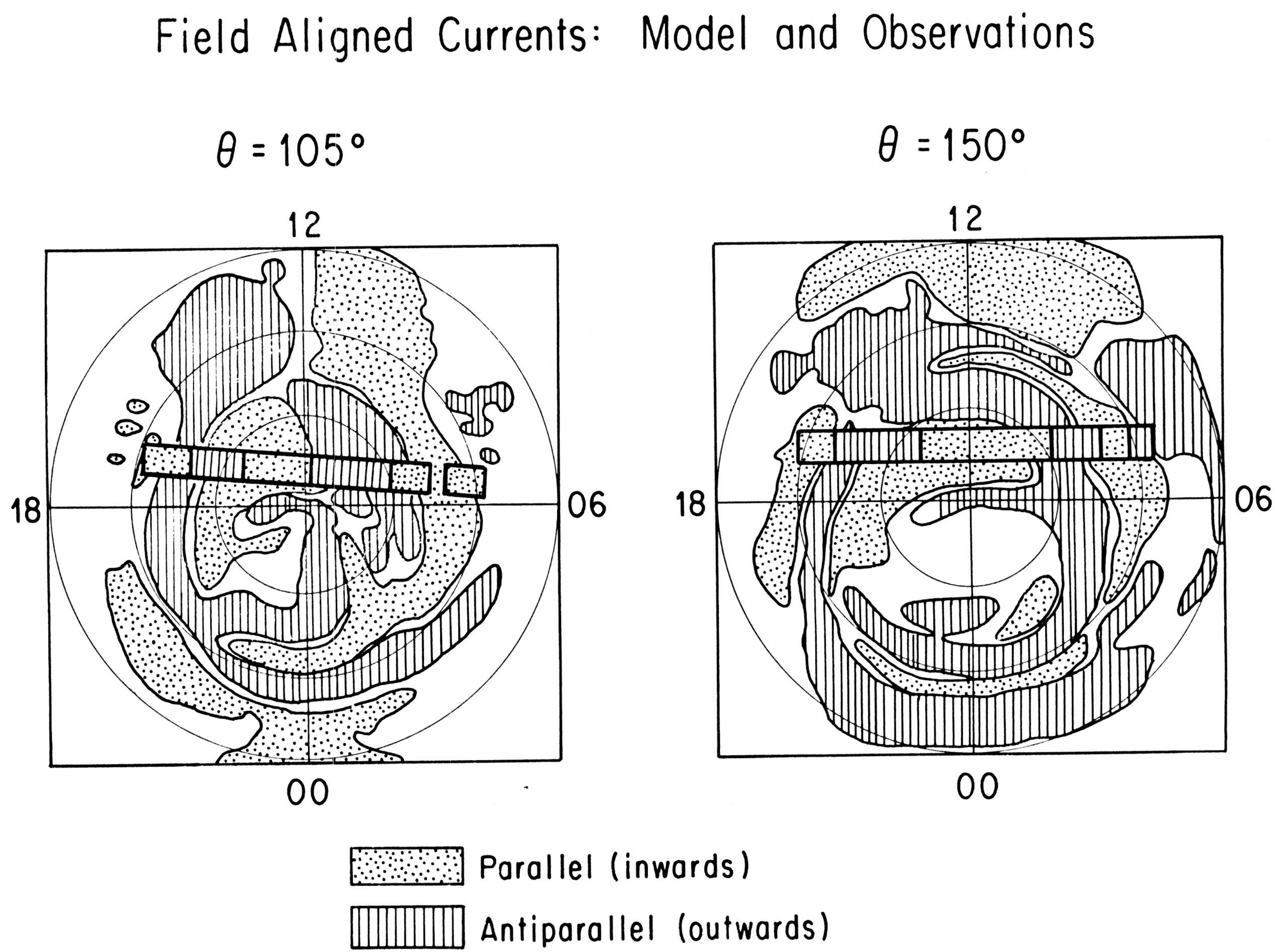
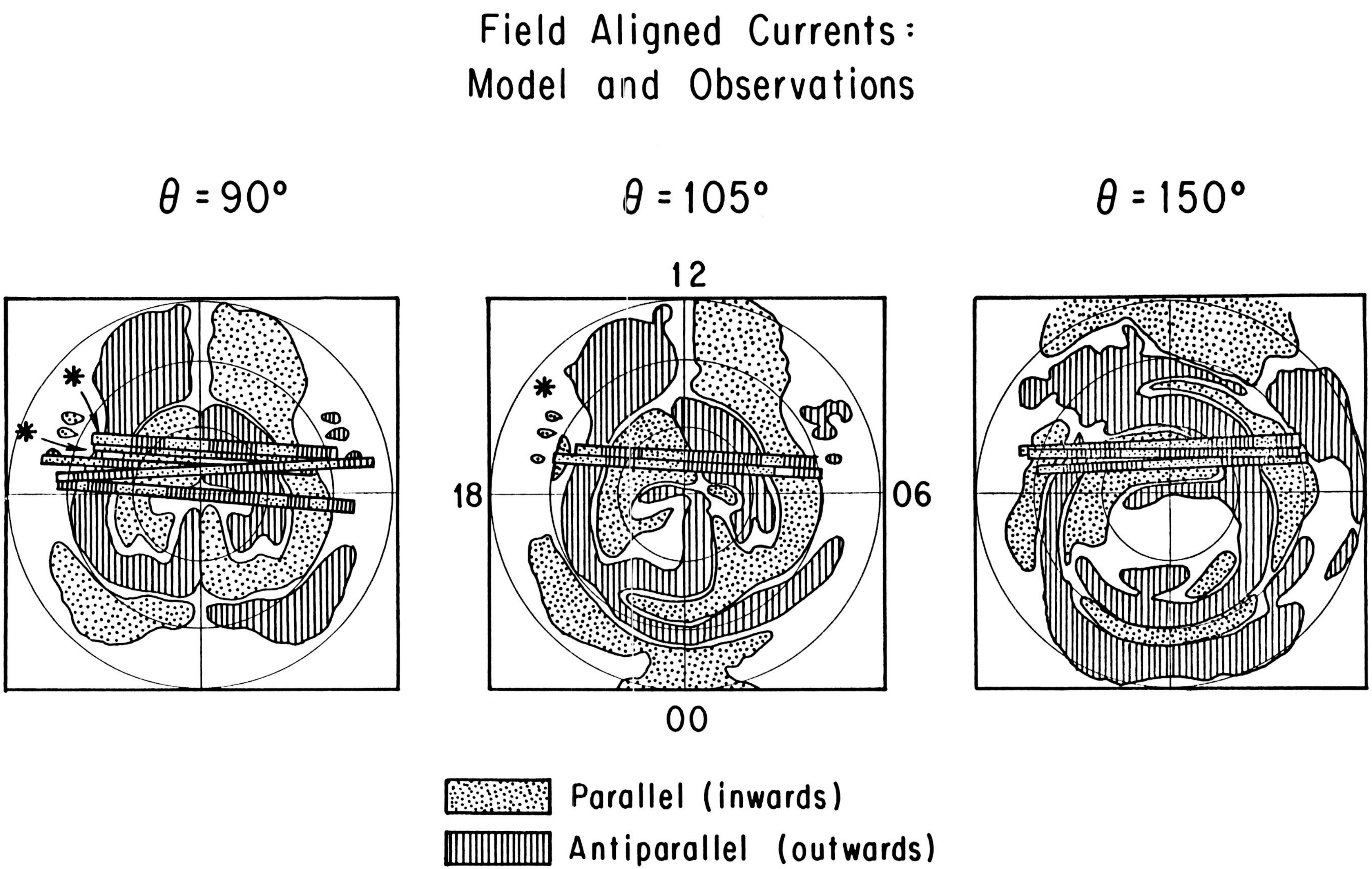

Field Aligned Currents: Model and Observations
$\theta = 105°$
$\theta = 150°$
12
18
06
00
12
18
06
00
Parallel (inwards)
Antiparallel (outwards)

Fig. 7


Field Aligned Currents:
Model and Observations
$\theta = 90°$
$\theta = 105°$
$\theta = 150°$
12
18
06
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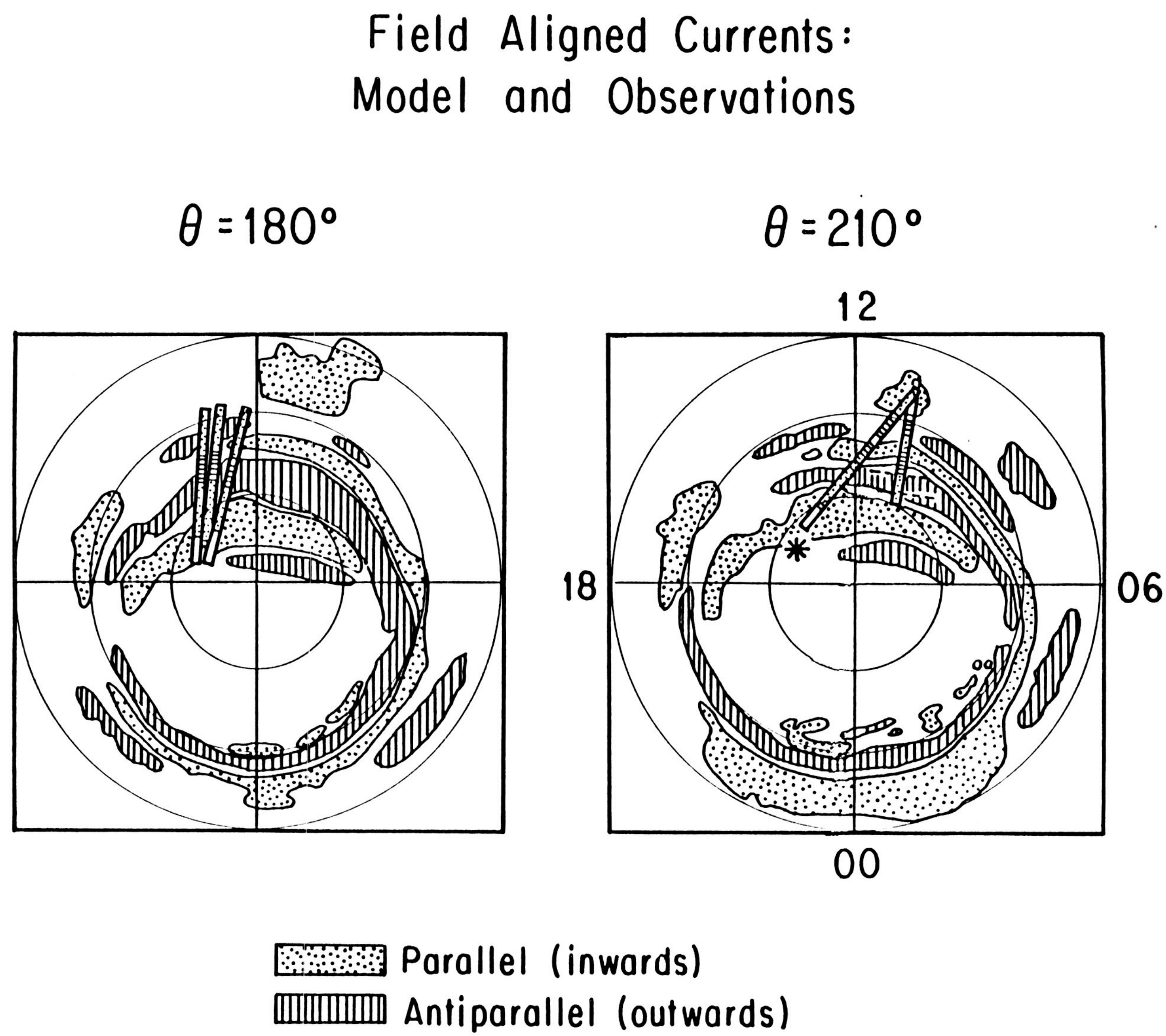
Parallel (inwards)
Antiparallel (outwards)

Fig. 8



Field Aligned Currents:
Model and Observations
$\theta = 180°$
$\theta = 210°$
12
18
06
00
Parallel (inwards)
Antiparallel (outwards)

Fig. 9

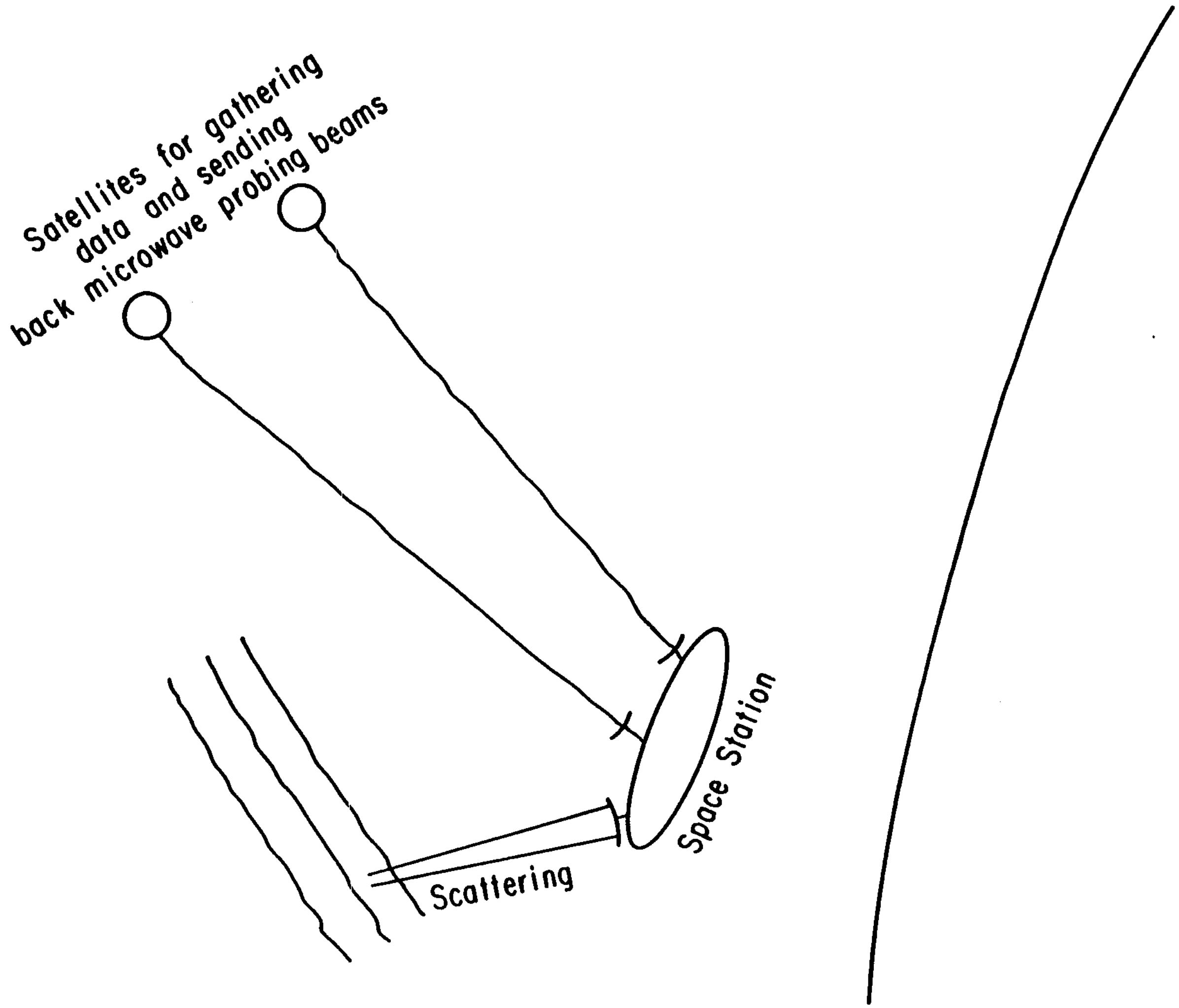

Satellites for gathering
data and sending
back microwave probing beams
Space Station
Scattering

Fig. 10

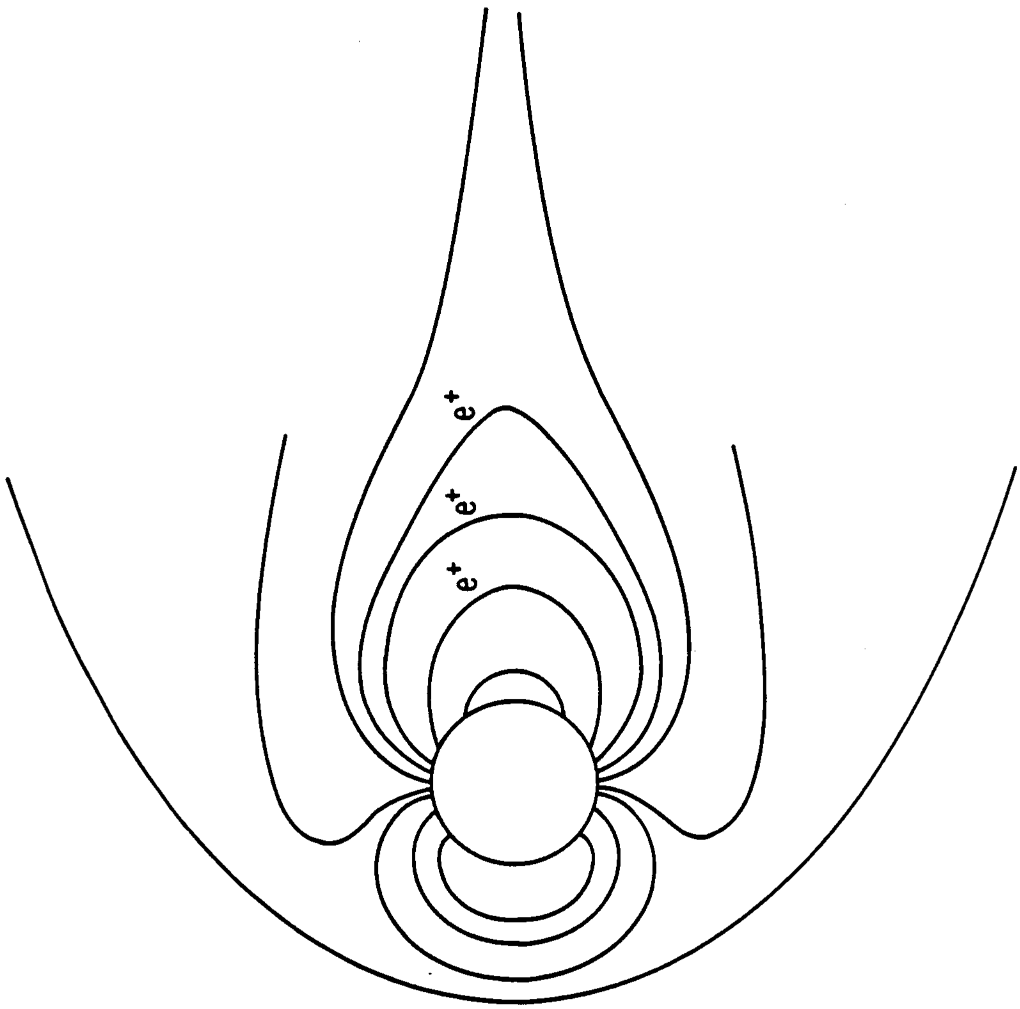


Fig. 11

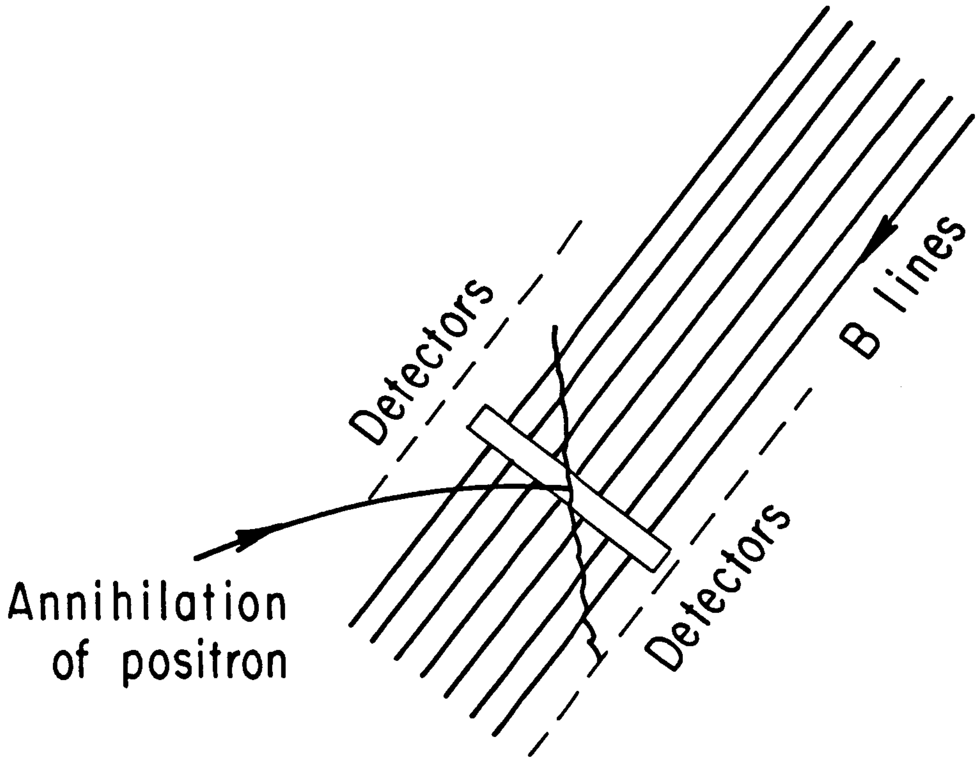


Fig. 12