THE SOLAR WIND AND ITS INTERACTION WITH THE MAGNETOSPHERE

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ABSTRACT

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A short summary of the properties of the solar wind as they apply to the interaction process with the earth's magnetosphere is given. Necessary conditions on the bow shock are discussed and are compared to experimental evidence from several space probes. The importance of the downstream or post-shock flow is emphasized. Power spectra and details of the turbulence in this region are reviewed. Limitations due to the very preliminary status of IMP data analysis are emphasized.

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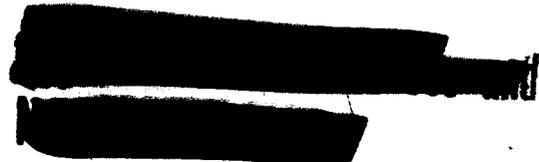
1. Introduction

This paper summarizes some of the properties of the solar wind as they are known from space probe data and attendant physical processes as they may be regarded in light of our generally rudimentary knowledge of collision-free plasmas. A pervasive aspect of the solar wind is its interaction with the magnetosphere of the earth and the subsequent generation of geophysical processes which are noted on the surface of our planet.

It is understood that the solar wind flows nearly continuously and that the outward flow carries along the solar magnetic field. The rotation of the sun results in the field's being drawn out in a spiral pattern whose angle depends upon the velocity of the wind. Although the primary source of energy for the interaction of the solar wind with the magnetosphere comes from the convective energy of the wind, a small additional increment may be found from the rotation of the earth through a drag interaction, such as that proposed by Axford and Hines [1961].

The simplest view of the total phenomenon is that the magnetosphere presents an obstacle to the passage of the solar wind in the manner of a blunt body in aerodynamic flow. The interruption of flow results in a shock wave followed by a shocked gas region and boundary layer of subsonic flow around the magnetosphere with the free surface of the magnetosphere itself determining the detailed flow properties near the boundary.

The validity of this aerodynamic point of view is based primarily upon two factors. First, though entirely collision-free over a scale determined by the magnetosphere, the solar wind carries along a magnetic field which is thought to organize the gas into collective motion, i.e., to propagate linear and angular momenta from particle to particle. Secondly, the field appears to have an energy density comparable to the thermal energy of the solar wind gas, but entirely ignorable compared to the energy of bulk convective flow. Thus the flow against the magnetosphere is often regarded as a high Mach number instance of aerodynamic flow with the electrodynamic conditions being subsidiary. Though the interaction is magnetohydrodynamic, the flow properties are taken in this view to be essentially aerodynamic.

2. The Solar Wind.

Mariner data are the most complete available in regard to the properties of the solar wind. From these data typical gas parameters indicate a volume density of ~ 10 per cm^3, a temperature of $\sim 10^5$ $^{\circ}K$, a magnetic field of 5 gamma, and a streaming velocity of 400 km/sec as being typical of the wind, though the actual value of these parameters fluctuates markedly from time to time. For example, in the experiment of Snyder and Neugebauer [1964] the velocity ranged from 300 to 800 km/sec for 90 percent of the data, the temperature reached extremes of several hundred thousand degrees Kelvin, while the magnetic field attained values as high as 20 gamma.

From these measurements we calculate a mean-free path ranging
from 1 to 10 AU depending upon the temperature and density values.
The electrical conductivity is some 6×10^{14} esu, 10^{-3} that of copper,
nevertheless, an extreme value over the cosmic dimensions character-
istic of interplanetary space. The absolute viscosity of the solar
wind gas is some 10^{-3} gram/cm sec. The kinematic viscosity is about
10^{20} cm^2/sec, which is to be compared to air at standard temperature
and pressure for which the value of kinematic viscosity is
1.5×10^{-1} cm^2/sec. Since the kinematic viscosity measures the ratio
of viscous to inertial forces, it is seen that the viscosity is
extremely high and that the solar wind is indeed a very sticky gas,
even though the absolute viscosity is low. Another way to regard
the kinematic viscosity is to understand it in terms of the transport
of momenta, i.e., the diffusion of momentum across a region, this
having an extremely large rate because of the long mean-free path.
Thus one is faced with a somewhat paradoxical situation that the more
rarefied the gas the higher the kinematic viscosity and the greater
the "stickiness." The aerodynamic Reynolds number which is given by
the velocity times a characteristic length divided by the kinematic
viscosity also measures the effective viscosity of the gas. For
the solar wind, the Reynolds number, R_n, is of the order of 10^3 over
a scale size of the magnetosphere. For smaller scale sizes associated
with detailed phenomena in the interaction region, the Reynolds number
is reduced accordingly. For magnetospheric scale size, R_n approaches the
critical number for the onset of ordinary turbulent flow. It is
unfortunately not possible to extrapolate exactly from this because
the magnetic field contained in the solar wind will inhibit the onset
of turbulence, kinematic viscosity being reduced by the decrease

transport across the field lines. It is possible that the inhibition of transport so increases the viscosity that at all times the flow or the solar wind against the magnetosphere is highly viscous.

Transverse velocity spectra can only be inferred from Mariner data. These are usually taken to be the same as the longitudinal, isotropy of the velocity distribution being assumed. (The Mariner probe was pointed at the sun and could not measure transverse velocity directly.) It is also indicated from Mariner that some α particles are present in the solar wind. This conclusion is supported by Explorer 14 plasma data [Wolfe and Silva, 1964] taken during the flight of Mariner II on October 7, 1962. Solar wind electrons have never been detected in deep space, but would be expected to be transported with the same bulk velocity as that of the ions, otherwise large currents which are not observed would exist in interplanetary space. Actually, the velocity distribution for electrons in thermal equilibrium with the ions has a mean value lying between 1.3 and 3.7×10^8 cm/sec, based upon the ion temperatures of the Mariner and a ratio of specific heats of 2. Therefore, the bulk and thermal velocities become co-mingled and their roles tend to be reversed from the ion case. Because of their higher mobility, electrons should be important in transport processes, such as heat conduction and kinematic viscosity.

Properties of the solar wind vary strongly from the base of the corona where it is created out to 1 astronomical unit. At the orbit of earth the Debye length, using the Mariner ion temperature of 10^5 °K and a volume density of 10^5 deg/cm^3, is about seven meters. Although such a distance is large compared to the dimensions of present day spacecraft, this parameter must be referred to the streaming velocity of the wind. Thus random fluctuations taking place within a Debye sphere occur in times of the order of microseconds and are unobservable, lying outside of the passband of present day magnetometers and plasma probes. Mean collision times are perhaps a day for protons. The greater mobility of electrons means that the collision times are more likely on the order of minutes to an hour.

The flow of the solar wind is often taken to be sheet-like in the plane of the ecliptic, though there is no known spacecraft test of this property. Some evidence for a drop-off in solar wind bulk flow with ecliptic latitude comes from comet tails observed out of the plane of the ecliptic, indicating a drop-off in solar wind forces [Beyer, 1953]. The magnetic field entrained in the solar wind is swept into a spiral pattern according to arguments first given by Parker [1958] which involves the solar rotation. For a nonrotating sun, the field lines would be expected to be radially outward from the sun.

The existence of magnetic fields in interplanetary space was suspected long before spacecraft flights. In particular, the 11-year modulation of the galactic component of cosmic rays, Forbush decreases, and 27-day and diurnal variations indicated the existence of a magnetic modulating mechanism sometime before the first spacecraft experiments on Pioneer V. Variations in the intensity and direction of the interplanetary field are now known from the Mariner measurement [Davis, Smith,Coleman,and Sonett, 1964] to show a marked 27-day effect (fig. 1), which reflects a view of the radially outward component of the field; variations of 10 gamma over a 27-day period are seen in this figure. The lower part of the figure displays the standard deviation taken over different sampling intervals up to 1 day. A small-scale variability is seen in the field, indicating fluctuations in direction. In figure 2 is shown the interplanetary field as determined by Mariner II in ecliptic spherical coordinates with β being ecliptic latitude, Λ ecliptic longitude, and the magnitude of the field shown in the lower part of the figure. Here the magnitude displays a 27-day variation, the longitude is plotted against the ideal angle of the magnetic field as determined by the solar wind bulk velocity, and the ecliptic latitude shows large variations in and out of the ecliptic component of the field. The general character of these data indicates that over large scales the field takes on the theoretical spiral angle direction and that over periods of a day or less gross variability in direction is to be seen.

Lastly, it is primarily the magnitude of the field which displays the 27-day variation rather than direction as indicated in the lower part of figure 2. Fluctuations of the type displayed in the Mariner data indicate that the magnetic field is in approximate energy equilibrium with the thermal energy of the solar wind gas, so that in a frame of reference moving with the solar wind, the field and gas display equipartition, the thermal motions of the gas being shared with a disorder of the magnetic field.

That the interplanetary magnetic field is closely associated with events which take place in the atmosphere of the sun has been suggested by Greenstadt [1963] who has shown a close correlation between both the coronal green line integrated index and plage index and the intensity of a model field based upon Pioneer V. An unexplained aspect of these data is a time dependence indicating a 5- to 7-day delay between an increase in solar indices and the corresponding field increase at the spacecraft.

3. The Magnetospheric Boundary

Prior to the introduction of the shock concept of stopping the solar wind by the magnetosphere, most investigations of the termination consisted in solving the problem of free-molecule flow of a solar wind, without a magnetic field, against a plasma-free magnetospheric cavity. A number of investigators have made reasonably exact calculations of the shape of the cavity formed by the pressure of this free molecule flow, and the results of their various techniques are not grossly different. All results display neutral points corresponding to where the polar line of force is matched to the surface field of the boundary. Further, all solutions display the characteristic doubling of the magnetic field due to the termination and the consequent flow of surface currents. Since the model used for these calculations has no field carried in the solar wind, the matching of magnetic boundary conditions is simple except for the surface being a free boundary. Clearly, the surface field must be wholly contained in the boundary and the normal component is zero. Seasonal effects cause the surface to change slightly as pointed out by Spreiter and Summers [1963]. They calculated the boundary shape for the case of a wind flowing obliquely, corresponding to seasonal changes. Such changes, they found, cause small variations in the position of the polar neutral points and in the position of the stagnation point. However, they found the tail of the magnetosphere to lie in the plane of the ecliptic regardless of seasonal change. Such changes cause the position of the polar neutral points and of the stagnation point to change slightly.

Calculations of the type discussed here are important since a precise boundary appears often even though a much more complicated over-all view evolves from current experiments. Indeed even the early results of Pioneer I were not in agreement with the view of a simple smooth Chapman-Ferraro boundary.

4. The Bow Wave

In collision dominated flow, a shock wave will form when the local speed of flow exceeds the sound velocity. Such a wave is a manifestation of the role of the fluid motion in transmitting changes in the fluid rather than by means of sound waves. In this primitive view there is no essential difference between shock waves in free motion and those that occur before an obstacle which is placed within the fluid, except that downstream of the bow wave a region of subsonic flow of great complexity is developed which may expand back to the free-stream supersonic conditions far from the obstacle. This cannot take place, for example, in the one-dimensional shock tube.

The bow wave is greatly complicated by several factors which do not exist in the ordinary collision dominated gas dynamic shock wave. The two issues complicating the physics of this problem are the magnetohydrodynamics and the collisionless property of the gas. Introducing these problems also suggests that shock stability and the modes of propagation of the fluid need to be considered. The energetics of the shock wave are determined primarily by the flow energy of the wind since the thermal and magnetic energies of the gas are so much lower. The bulk flow energy is some 10^{-9} to 10^{-8} ergs/cm^3 which is usually one to two orders greater than that of either the thermal or magnetic energies. Because of this, it is plausible to expect some similarity to aerodynamic flow in the gross sense. Spreiter and Jones [1963] have calculated a model shock based on an aerodynamic theory for a blunt body as developed earlier. Using values for the ratio of specific heats of 5/3 and 2 and restricting their considerations to regions near to the stagnation point, they arrive at shock surfaces which are similar to those in the true aerodynamic case.

Modifying the Spreiter-Jones calculation to the MHD case requires that the interplanetary field be included. Walters [1964] studied the combination of a weak interplanetary field together with the rapid changes in direction. He developed the downstream parameters of the shock from assumptions regarding the upstream or solar wind properties. As expected he found that the downstream properties varied with the free-stream parameters. In his calculation he used the de-Hoffman-Teller [1950] equations together with Spreiter and Jones': gross geometry for the aerodynamic shock. The potential weakness of his calculation lies in the lack of self-consistency since, in the computation, the shock surface position is fixed. In reality the consequences of changes in upstream parameters may be reflected in variations in the position of the shock as well as in the downstream direction of flow of the gas and the direction of the magnetic field.

When the bow wave is considered, it is essential also to take into account the modes of propagation in the solar wind. If an interplanetary field of 10 gamma and a particle density of $10/cm^3$ are assumed, the Alfvén velocity is about 10^7 cm/sec. For a ratio of specific heats of 5/3 and a temperature of 10^5 ^oK the sound velocity becomes 6×10^6 cm/sec. Thus for an ideal field spiral angle of 45°, the slow mode velocity in the direction of flow of the solar wind becomes 1.8×10^6 cm/sec and the fast mode, 3.7×10^7 cm/sec. For a solar wind velocity of 400 km/sec this means that for the fast mode the wind is barely supersonic. Little is known of the detailed properties of the shocks corresponding to these modes, especially regarding their stability. The slow shock is expected to display a decrease in field through the discontinuity, while the Alfvén shock is incompressible and, in effect, a large amplitude linear wave. It seems proper until the stability problems are further clarified to consider that the bow wave is indeed the fast mode shock. Support for this view comes from the calculation of the Mariner Oct. 1962 interplanetary event discussed elsewhere in this paper where the Mach numbers for the flow fit only a fast magnetosonic mode.

An especially important peculiarity of the blunt-body shock is the variation of Mach number over the face of the shock due to the curved geometry. Thus the shock is strongest at the stagnation point where the flow is normal to the surface, and the strength of the shock diminishes on the flanks as the normal component of the flow decreases. The same kind of argument is expected to apply to the blunt body wave with an important added effect due to the presence of the magnetic field. It is easily seen that the presence of the field radically alters the geometry of the shock and makes the problem asymmetric. For example, if we assume the ideal spiral angle of 45° with respect to the earth-sun line for the direction of the interplanetary field, then the fast mode velocity at the face of the shock will vary in a complicated manner. Depending upon the geometry of the surface of the shock, conditions can be anticipated where the normal component of the flow may be along the direction of the field while on the other side of the magnetosphere the normal component of the flow may turn out to be normal to the local field direction. Thus, the sonic speed may vary over wide ranges on the face of the shock and, indeed, where the flow is along the field, one must consider that the details of the shock and the specification of the local Mach number become difficult to define, in view of the collisionless aspect of the flow. The fact that it is not difficult to find a fast mode velocity for typical solar wind parameters means that from time to time the flow may actually become subsonic for this mode. If the diffusion of hot electrons produced in the shocked flow takes

place in the upstream direction, this alone could contribute to the
modified sonic velocity's becoming greater than the flow speed of
the solar wind.

In attempting to obtain an understanding of collision-free shocks
we have studied an especially favorable shock event which took place
in interplanetary space on Oct. 7, 1962. The preliminary results of
this calculation have been reported elsewhere [Sonett, Colburn,
Davis, Smith, and Coleman, 1964] and here we provide only a summary
of the findings. The event noted was a sudden commencement storm
with a degenerate main phase and which was seen at the Mariner space-
craft 4.7 hr earlier than the geomagnetic effects. The spacecraft
events allow the application of the Rankine-Hugoniot equations and
the discontinuity in plasma velocity and magnetic field is treated
as a shock wave in a wall-less environment. The change in the field
is shown in figure 3 which marks the interplanetary onset. The shock
plane appears to be slightly tipped with respect to the earth-sun line,
denoting an oblique shock. This together with the solar wind aberra-
tion required that the most general form of the shock equations be
applied. Temperature effects were important in correcting the density.
The results of this calculation are to be compared with the measure-
ments which were sufficiently redundant to afford a detailed comparison.
Both the measured and computed parameters are given in table 1 which
demonstrates an interesting parallel between the different sets of
numbers. We believe that within the constraints and limitations of
the data available, the results are in reasonable agreement with the
assumption of a shock model. Thus the applicability of the shock
jump equations is suggested for the collision-free domain, provided
the downstream parameters are appropriately averaged before being
entered into the computation.

Electrons have not been seriously considered either in the free-stream solar wind or in the shock flow at the magnetosphere. Yet it is expected that their mean thermal velocity, for the same temperature as the ions, would result in fast diffusion. If, in fact, the thermal conductivity is governed by the diffusion of electrons, it may follow that this may limit the thickness of the shocked region in a manner analogous to gas dynamic shocks where both thermal conductivity and viscosity can play a critical role in determining the minimum thickness of the shocked layer.

In MHD shock theory, cases are cited [Sears, 1960] where the formation of a Mach cone is either inhibited, made asymmetrical, or made to appear pointing into the upstream flow. In order to visualize how this can take place reference is made to the group propagation in the anisotropic plasma of the solar wind. Constructing a Friedrichs diagram for the three modes present in a warm plasma allows the group propagation vectors for a solitary pulse to be constructed. Figure 4 is the familiar plot of phase velocities in the case of the magnetic plasma. Figure 5 shows the construction of the envelope for a pulse propagating along the axis defined by the magnetic field. The diagram shows the surface of constant phase for each of the three modes. The fast mode propagates in a slightly asymmetric manner with cylindrical symmetry about an axis defined by the magnetic field. Thus the diagram can be construed as a body of revolution. The propagation velocity across the field is $(A^2 + C^2)^{1/2}$ where C is the sonic velocity and A, the Alfvén velocity. The speed in the direction

of the magnetic axis is the larger of C and A. For the Alfvén

mode, propagation is restricted to the direction along the magnetic

field, while for the slow mode, the dependence upon direction contains

a cosine factor which goes to zero for the direction normal to the

magnetic field. To develop the group velocity from this diagram we

construct the locus of the normal surfaces taking into account all

directions of propagation. For the Alfvén mode this degenerates to

a point while for the mixed modes more complex patterns unfold. The

group wave front is determined geometrically by the locus generated

by the family of normals to the phase fronts, figure 5 [Sears, 1960].

Inspecting the peculiar group locus one sees directly that for the

slow mode the wave normal direction takes on many values, including

that perpendicular to the magnetic field. However, the velocity

drops to zero in this latter instance. The results of this type of

representation have been shown by Sears [1960] to be directly applicable

to the construction of Mach cones, wakes, and their directions with

respect to the shock. In particular, figure 6 shows several cases for

the flow velocity vector parallel to the magnetic field, with the Mach

cone being symmetric. To develop the Mach cone it is necessary that

the flow be supersonic to the mode in question, and that it be possible

to construct tangent lines from the velocity vector to the group

velocity surface. In figure 6(b) such a construction is impossible

and the development of a Mach cone is forbidden. In figure 6(c) the

flow is subsonic in the sense of the magnitude of the velocity. Yet

a Mach cone can be constructed albeit in the upstream direction. It

is seen immediately upon consideration that the Mach cones become asymmetric when the velocity vector is not colinear to the direction of the magnetic field. Since the Mach cone defines the boundary surface for the shock of infinitesimal strength, it follows that an MHD model for the bow wave flow in front of the earth must be approached with considerable caution. It is hoped that later experiments will allow an examination of the applicability of these properties of MHD waves to the case of the bow shock.

5. The Post-Shock or Downstream Flow

Usually labeled the transition region, this volume is occupied
by the shocked gas generated in the interaction process. The limited
indications of theory are that collision-free shocks are not time
stationary; thus the transition region may, in reality, be an extension
of the initial shock with relaxation taking place over a region much
thicker than the few gyro radii of the first pulse. Indeed the
Mariner calculation suggests this, as a fit was obtained by using
average values of gas and field parameters downstream of the shock.

The downstream flow is an especially interesting problem from
the standpoint of plasma physics since the general development of
turbulence and stochastic acceleration experiments in collision-free
plasmas can be carried out in this region of space. This space is
known to be occupied, at least sometimes, by a highly disordered
field, a sample of which is shown in figure 7. Spectra of the mag-
netic turbulence suggest that two separate processes are present
[Sonett, 1963]. The large pulses seen in figure 7 show a strong low
frequency component while a frequency dependent component appears at
higher frequencies (fig. 8). There is little similarity to either of
the two basic modes of turbulence suggested by Chandrasekhar [1955],
a velocity or magnetic mode depending upon the partition of energy
between field and gas. That this gas is in motion and is sweeping
around the magnetosphere in the usual manner of blunt body flow is
suggested by the experiment of Wolfe and Silva [1964]. Figure 9,
taken from their paper, gives a view of the direction of the plasma
arriving during the events of Oct. 7, 1962 and for the period of time
during those events when the satellite was within the shocked gas of
the transition layer. It is observed that the flow originates from
a region making an angle of about 35° with respect to the sun. The
details of this experiment are reported elsewhere and only the results
are quoted here. Since the spacecraft was on the dawn flank of the
magnetosphere, consideration of the geometry shows that the flow was
from the general direction of the stagnation point and clearly not from
the solar direction. We take this to be evidence of transition-layer
flow of the blunt-body type.

Observation of the turbulence of the magnetic field in the transition layer is made in a number of satellite and space probe experiments, though three-dimensional cross correlation functions needed for a definition of the exact properties cannot be made because of limitations either in experiments or in the manner of reading out the data. At the present stage of understanding together with the restricted satellite data available it becomes unfeasible to attempt to separate wave motions from stationary or pseudo-stationary variations in downstream plasma properties. Thus such matters as correlation tensors between the pertinent plasma parameters must be regarded as quantities which are mixed with time-variant wave-like motions as well as the streaming properties of the gas.

Since the process of particle acceleration is presently the subject of conjecture, we shall not deal with it here. Also the experimental processes observed are generally the subject of a separate treatment and shall not be dealt with except for summary remarks. General conclusions from experiments prior to those of Freeman, Van Allen, and Cahill [1963] are shown in figure 10. From the Pioneer IV experiment of Van Allen and Frank [1959] it was shown that hot electrons in the range of tens of kilovolts could exist in the transition zone. This result together with the early observations of the interaction region between the solar wind and the magnetosphere is shown in this figure. Reference to the discussion concerning the electron observations of Van Allen are given by Sonett [1963].

In regard to the transmission properties of the transition
region insofar as propagating disturbances from the solar wind to the
surface of the earth, it is well known that sudden commencements are
seen on the surface ostensibly caused by rapid compression of the
magnetospheric boundary in response to a sudden change in the momen-
tum density flux of the solar wind. Thus it appears that whatever
the details of the flow pattern it seems safe to regard the transi-
tion region as capable of transmitting pressure changes from the
free-stream wind to the magnetosphere with the subsequent generation
of magnetohydrodynamic waves which we regard as transmitted to the
surface of the earth to produce the sudden commencement or impulse.

6. Recent Experiments

The Explorer 18 or IMP satellite is the latest in a series of spacecraft designed for investigating the magnetosphere and adjacent interplanetary space. Basically, this satellite had an orbit of extreme eccentricity with apogee at about 32 R_e. The extreme orbit meant that the period was 3 to 4 days and that the spacecraft spent about two-thirds of its time beyond 20 R_e. The data system is quite complex, utilizing a data burst technique where a high data rate is interspersed with blanks, for any one instrument. Only the 5-min averages of the magnetometer data have been reported to date, and these tend to confirm earlier spacecraft findings regarding the magnetic properties of the transition region and the rather turbulent character of the interplanetary gas. The data have also yielded substantial information regarding the existence of a sudden discontinuity in the magnetic field which is interpreted as a shock wave [Ness, Searce, and Seek, 1964] though the plasma experiments do no correspond to this view rigorously all the time.

Two plasma experiments were carried on this spacecraft; these
were of radically different design, one being a Faraday cage and the
other an electrostatic analyzer. The limitations of telemetry
allowed space to be divided into three sectors for the electrostatic
analyzer, henceforth referred to as the Ames experiment [Wolfe, Silva,
and Myers, 1964]. Threshold for this instrument was about 10^{-14} amp,
corresponding to 3×10^5 H^+/cm^2 sec. The energy resolution was 6.5 to
7.5 percent and the electrometer was of the peak reading variety,
reading the peak current in each of the angular sectors. Results of
this experiment are complex and the reader is referred to the original
paper for details. The results show variations in the direction of
arrival of flux changing from a highly directed beam when in the solar
wind to a pseudoisotropic flux when in the transition region, though
this behavior is by no means common to all the orbits. When this
type of behavior was noted, the character of the velocity spectrum
also underwent significant changes, confirming the view that the
solar wind is a relatively cool gas compared to the gas of the transi-
tion region. Some of the preliminary results are summarized in
figure 11 which shows a display of the boundary crossings according
to a prescribed set of rules given by Wolfe et al., together with a
comparison to the theory of Spreiter and Jones [1963]. The time the
plasma probe crossed a zone was indicated by the appearance or disap-
pearance of the characteristic spectrum in both velocity and angular
distribution. The crossing of the inner boundary, i.e., the termina-
tion of the regular magnetosphere, was indicated by the cessation of

sensible readings on the plasma probe for inbound orbits and an onset for outbound cases. The dashed lines are those cases where the definition was difficult to satisfy. In particular, there were many times when an outer or shock boundary was difficult or impossible to find and at other times the time of crossing was different from that indicated by the magnetometer. At other times the agreement was quite good and the supposition for the shock appears to rest upon reasonable data. This may suggest a high degree of variability in the gas parameters or perhaps tends to underline present ignorance of the true meaning of these experiments. Results of some of the other experiments of this spacecraft tend to confirm the view that the transition region contains a remarkably hot gas. Little can be said regarding the manner of leakage of this gas into the regular magnetosphere and whether it supplies some or all of the flux of electrons of the Van Allen radiation.

Calculations being carried out by Olbert seem to confirm that collision-free shocks require a scale far in excess of the gyro radius geometric mean to damp into the post-shock downstream state irreversibly. These calculations, carried out for the bow shock and based upon the plasma experiment of Bridge et al. and Ness et al., also suggest the applicability of the MHD Rankine-Hugoniot equations. In the instance of Olbert's calculation it is found that the downstream gas has a very low ratio of specific heats, this conclusion being arrived at from the very large density jump across the shock. Insofar as the generation of entropy is regarded as the true test for a shock even in the collision-free domain, it appears that the properties of the downstream flow directly behind the onset of the shock will play a leading role in the next few years in establishing a foundation for collision-free shock theory.

The very preliminary status of reporting of the data from the majority of the IMP experiments together with the necessary brevity of this report preclude the possibility of reviewing the majority of the results. It is probable that forthcoming results from the IMP series will provide much of the information required in order to obtain a meaningful physical basis for much of what today must be regarded as only partially understood physical phenomena.

ACKNOWLEDGMENT

7. Bibliography

Axford, W. I., and C. O. Hines (1961), A unifying theory of high-latitude geophysical phenomena and geomagnetic storms, Can. J. Phys. 39, No. 10, 1433-1464.

Beyer, M. (1953), Brightness of comets and solar activity, Soc. Roy. Sci. Liége 13, No. 1-2, 276-86.

Chandrasekhar, S. (Dec. 1955), Hydromagnetic turbulence II. An elementary theory, Proc. Roy. Soc. London, A-233, No. 1194, 330-50.

Davis, L., Jr., E. J. Smith, P. J. Coleman, Jr., and C. P. Sonett (1964, to be published in book entitled The Solar Wind), Interplanetary magnetic measurements. Presented at Solar Wind Conf., JPL, Pasadena, Calif., April 1-4, 1964.

de-Hoffmann, F., and E. Teller (1950), Magneto-hydrodynamic shocks, Phys. Rev. 80, No. 4, 692-703.

Freeman, J. W., J. A. Van Allen, and L. J. Cahill (1963), Explorer 12 observations of the magnetosphere boundary and the associated solar plasma on September 13, 1961, J. Geophys. Res. 68, No. 8, 2121-2130.

Greenstadt, E. W. (April 1963), Effect of solar activity regions on the interplanetary magnetic field, Ap. J. 137, No. 3, 999-1002.

Ness, N. F., C. S. Searce, and J. B. Seek (1964), Initial results of the Imp 1 magnetic field experiment, J. Geophys, Res. 69, No. 17, 3531-69.

Olbert, S., private communication.

Parker, E. N. (Nov. 1958), Dynamics of the interplanetary gas and magnetic fields, Ap. J. 128, No. 3, 664-676.

Sears, W. R. (Oct. 1960), Some remarks about flow past bodies, Rev.
of Modern Phys. 32, No. 4, 701-705.

Sonett, C. P. (1963), The distant geomagnetic field 4: Microstructure
of a disordered hydromagnetic medium in the collisionless limit,
J. Geophys. Res. 68, No. 5, 1265-1294.

Sonett, C. P., D. S. Colburn, L. Davis, Jr., E. J. Smith, and
P. J. Coleman, Jr. (1964), Evidence for a collision-free magnetohy-
drodynamic shock in interplanetary space, Phys. Rev. Lt. 13,
No. 5, 153-156.

Spreiter, J. R., and W. P. Jones (1963), On the effect of a weak
interplanetary magnetic field on the interaction between the solar
wind and the geomagnetic field, J. Geophys. Res. 68, No. 12,
3555-3564.

Spreiter, J. R., and A. L. Summers (1963), Effect of uniform external
field and oblique incidence of the solar wind on the terminal shape
of the geomagnetic field, NASA TR R-181.

Snyder, C. W., and M. Neugebauer (1964, to be published), Interplanetary
solar wind measurements by Mariner II, Space Res. IV.

Van Allen, J. A., and L. A. Frank (1959), Radiation measurements to
658,300 km with Pioneer 4, Nature 184, No. 4682-1, 219-24.

Walters, G. K. (1964), Effect of oblique interplanetary magnetic field
on shape and behavior of the magnetosphere, J. Geophys. Res. 69,
No. 9, 1769-83.

Wolfe, J. H., and R. Silva (1964, to be published), Explorer 14
plasma probe observations during the October 7, 1962 geomagnetic
storm.

Wolfe, J. H., R. Silva, and M: Myers (1964, to be published), A

preliminary survey of the NASA/Ames plasma probe experiment on the

Imp-1 satellite.

Figure Captions

Figure 1. One-day average values of the radial component of the inter-
planetary magnetic field. A 27-day periodicity is clearly evident
in this figure and is presumed to be due to asymmetries in the field
resulting from regions of high field on the sun. In the lower part
of the figure is shown the standard deviation of the radial component
for different average times [Davis, Smith, Coleman, and Sonett, 1964].

Figure 2. Intensity and direction of the interplanetary magnetic field
shown in solar ecliptic coordinates; β is the ecliptic latitude, Λ
the longitude measured from the earth-sun line, and B the intensity
of the field. The 27-day variation is seen to be associated with the
magnitude of the field; the longitude is compared to the ideal spiral
angle defined by the mean plasma velocity, and, for these 1-day
averages, displays one gross change in polarity that lasts a number
of days; the latitude which measures the out-of-the-ecliptic component
shows continuous variations even over the average times used here
[Davis, Smith, Coleman, and Sonett, 1964].

Figure 3. Plan and elevation view of the magnetic field vector for the
2-hour period encompassing the onset of storm conditions. The spike
in the field signifies the onset. The plan view is looking down on
the ecliptic, and the elevation view is a cross section along the
earth-sun line. Complementary changes took place in the plasma data
at this time. Note the increasing disorder in the field following
the onset of the storm.

Figure 4. Surfaces of constant phase for the fast and slow modes. A is the Alfvén velocity; C the sound velocity; and Q is defined as the smaller of the sound velocity and Alfvén velocity. The semi-minor axis of the outer ellipse is given by the larger of the two velocities. The Alfvén velocity consists of two points on the field (H) axis lying either on the semi-minor axis of the outer ellipse or semi-major axis of the inner ellipse depending upon the relative magnitude of the two velocities.

Figure 5. Construction of the propagation normal vectors along the surfaces of constant phase. The locus of the normals define the surface of constant group velocity. The figure is to be rotated about the axis of the magnetic field so as to create a figure of revolution [Sears, 1960].

Figure 6. Mach cones defining the locus of limiting characteristics and wakes for several cases having fluid velocity along the axis of the magnetic field but with different amplitudes [Sears, 1960].

Figure 7. Swath of two-dimensional cut in the transition region field showing amplitude, and direction and rate of turning. Reversals in field direction are distinctly seen and generally are associated with zeros in the magnitude [Sonett, 1963].

Figure 8. Longitudinal wave power density in the transition region magnetic field for three typical swaths of data. The straight line is for a theoretical Kolmogoroff spectrum. Magnetometer response was about 2 cps between half power points [Sonett, 1963].

Figure 9. Angle of arrival of peak plasma flux vs. number of observations. The peak at about 35° is approximately toward the subsolar point distinctly showing the expected blunt body flow pattern [Wolfe and Silva, 1964].

Figure 10. Summary of early observations of the transition region of the magnetosphere showing Pioneer I, Pioneer IV, and Pioneer V data [Spreiter and Jones, 1963].

Figure 11. Locus of outward and inward bound IMP orbits as the satellite crossed the transition region. The definition of crossing for the purposes of this diagram is based upon the Wolfe experiment and will vary from the findings of other experimenters because of the differing instrument response and definition of crossing. The reference idealized shocks for the two different ratios of specific heat are from the calculations of Spreiter and Jones [1963].
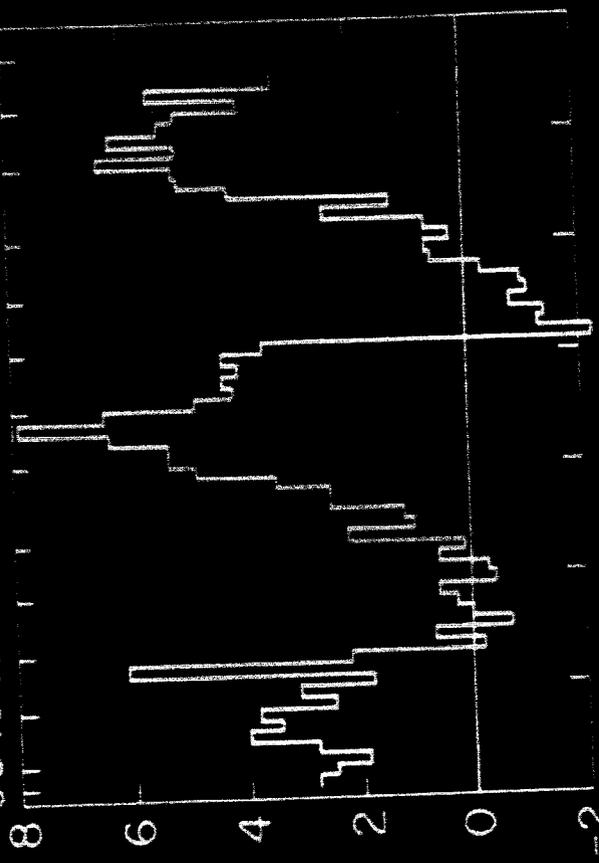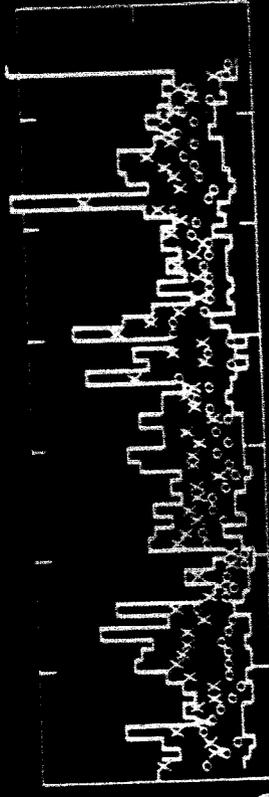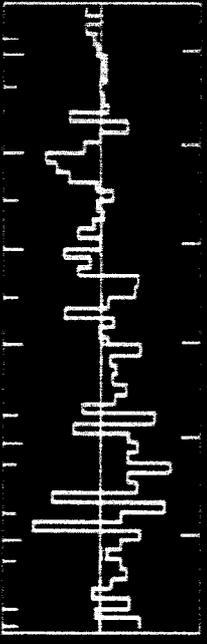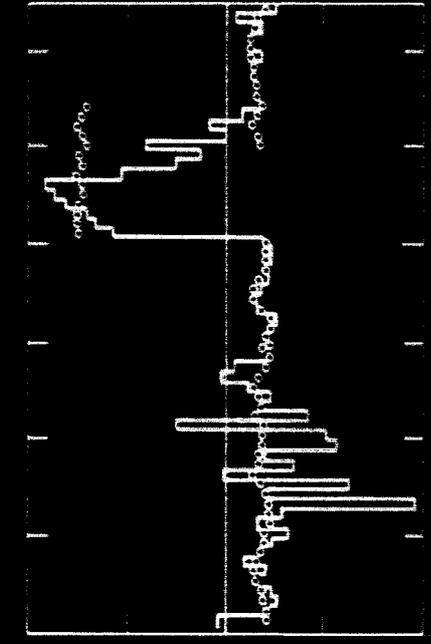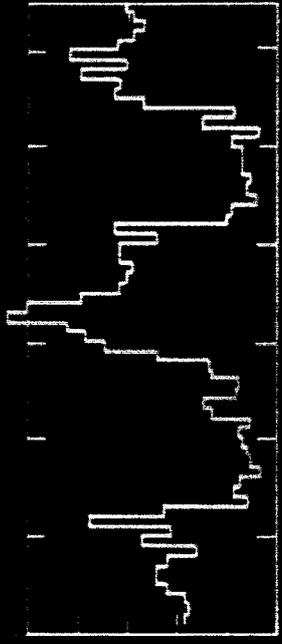
PLAN VIEW IN ECLIPTIC PLANE

ELEVATION VIEW IN ECLIPTIC PLANE

FIELD MAGNITUDE

TO SUN

GAMMA

20

10

0

5:00   15:30   16:00   16:30   17:00

TIME, U.T.

$\sqrt{A^2 + C^2}$

POWER DENSITY, γ^2-SEC

FREQUENCY, c/s

B$_1$(500)
B$_1$(840)
B$_1$(1190)

15.1 a_e

10.5 a_e
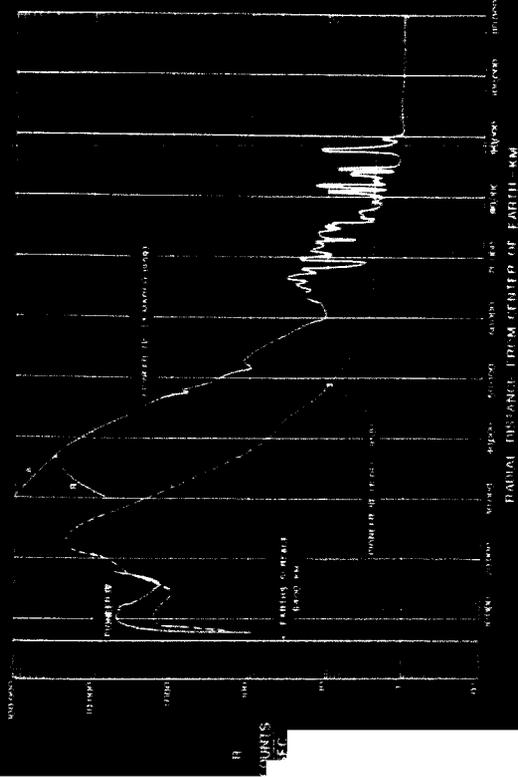
Pioneer V (Coleman, Sonett,
Judge and Smith, 1960)

14.8 a_e

Pioneer I (Sonett, Smith and Sims, 1960)
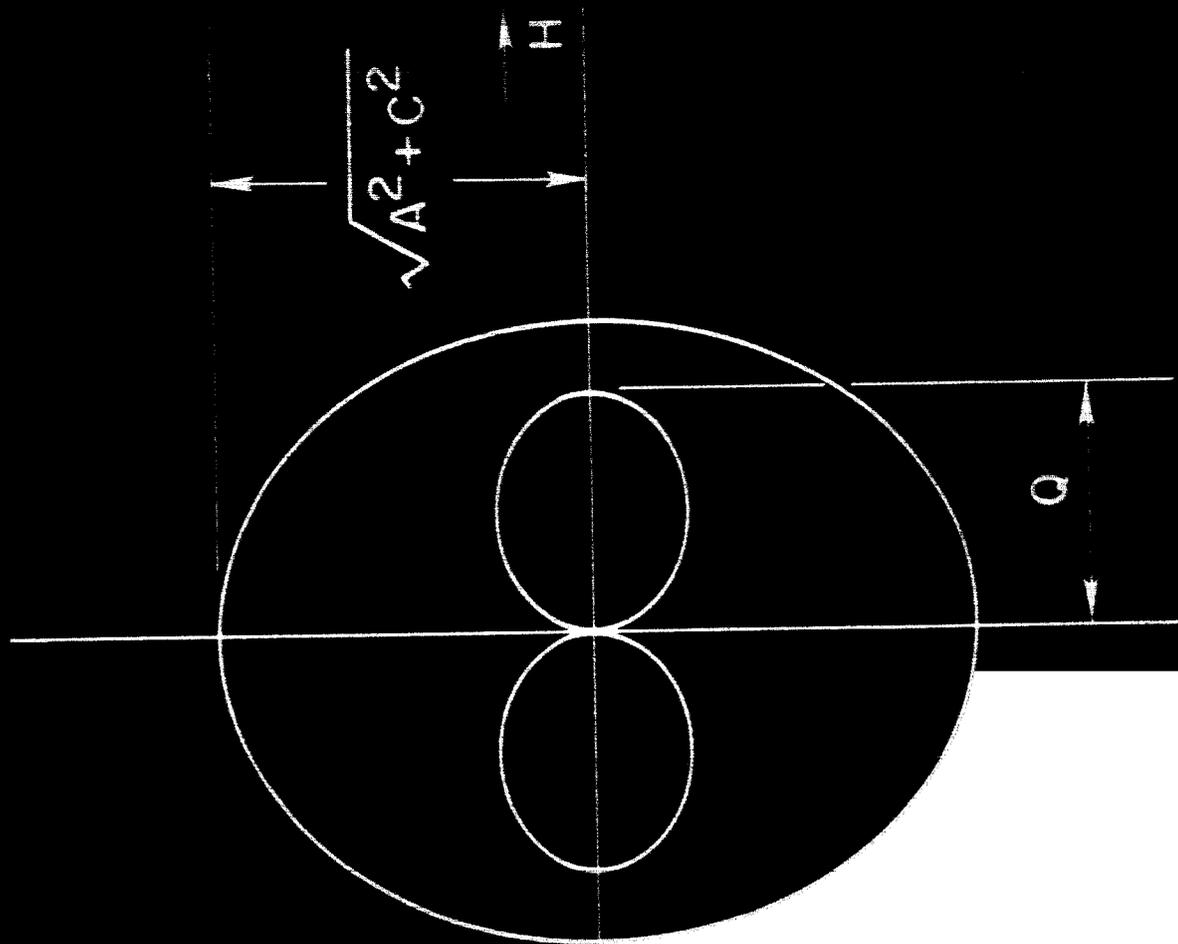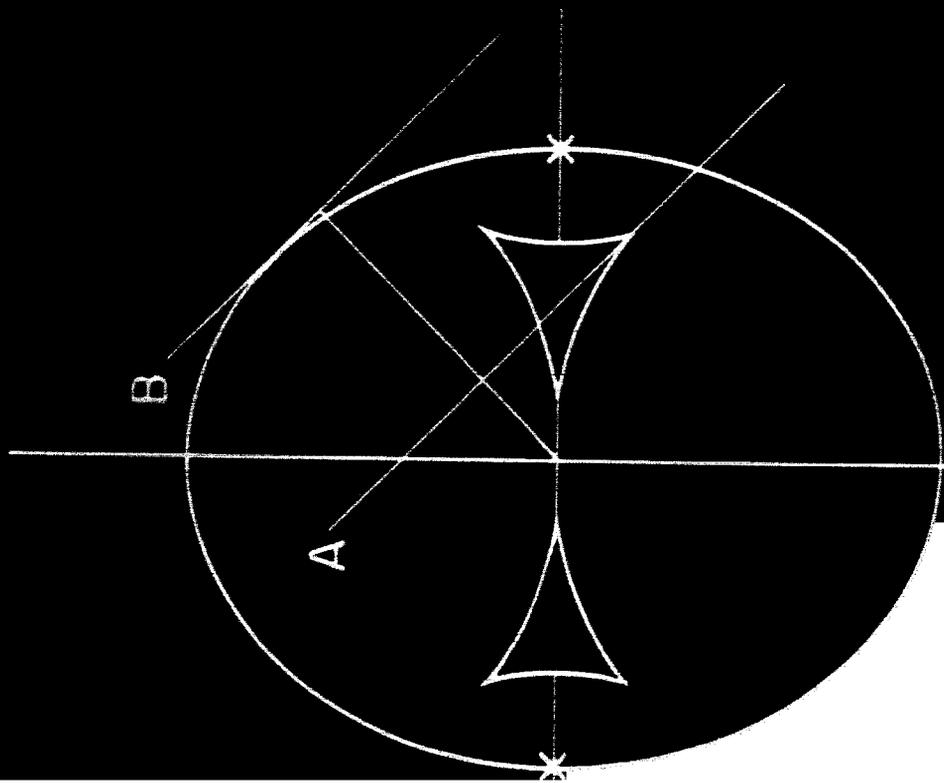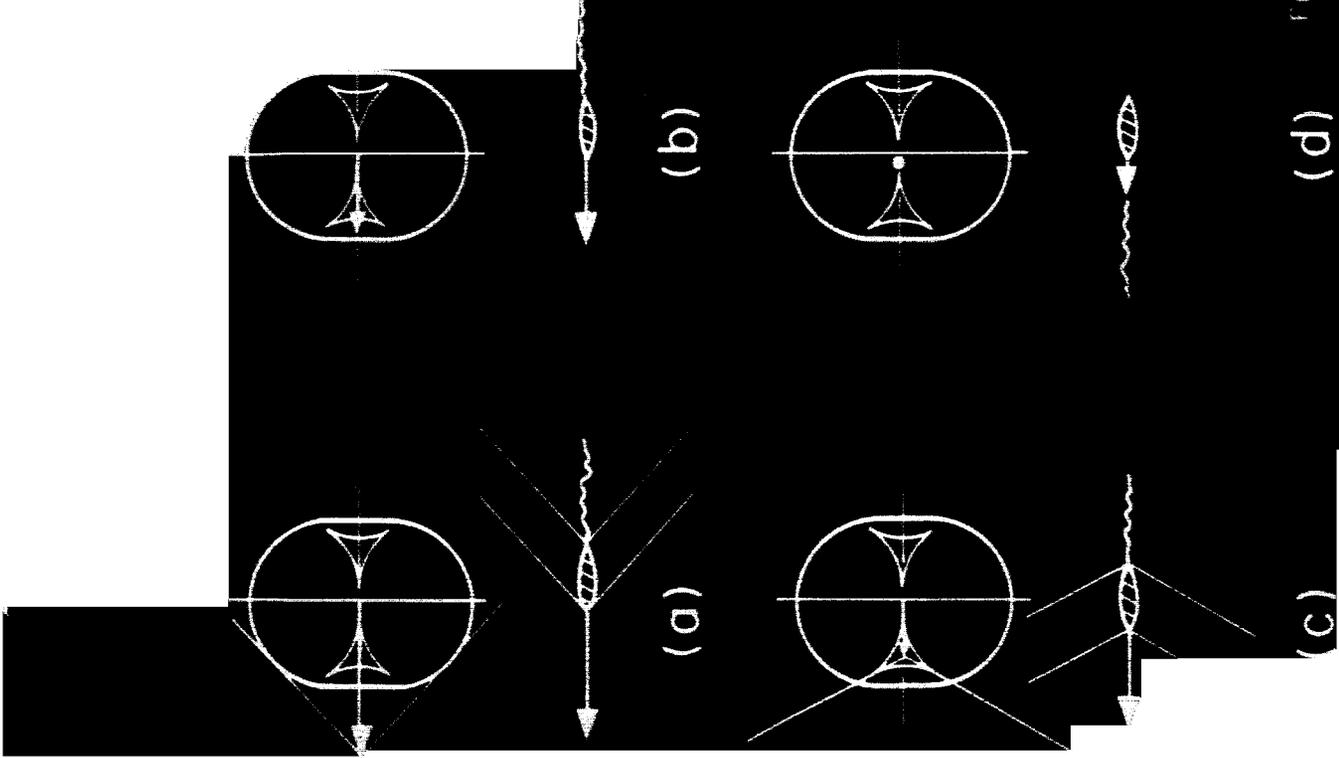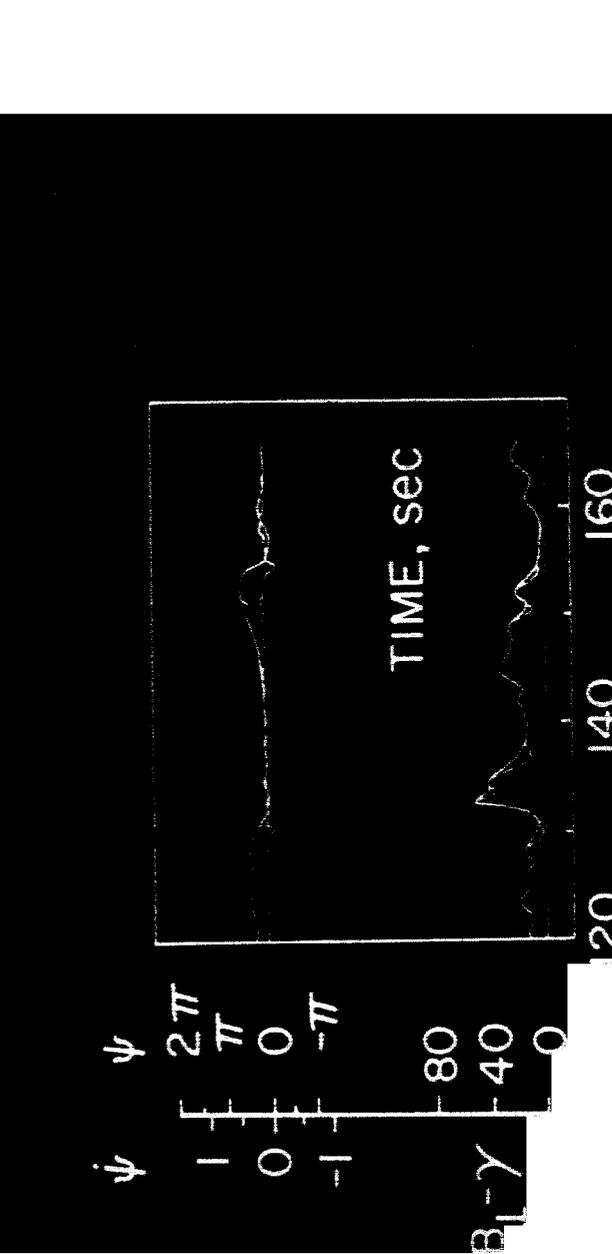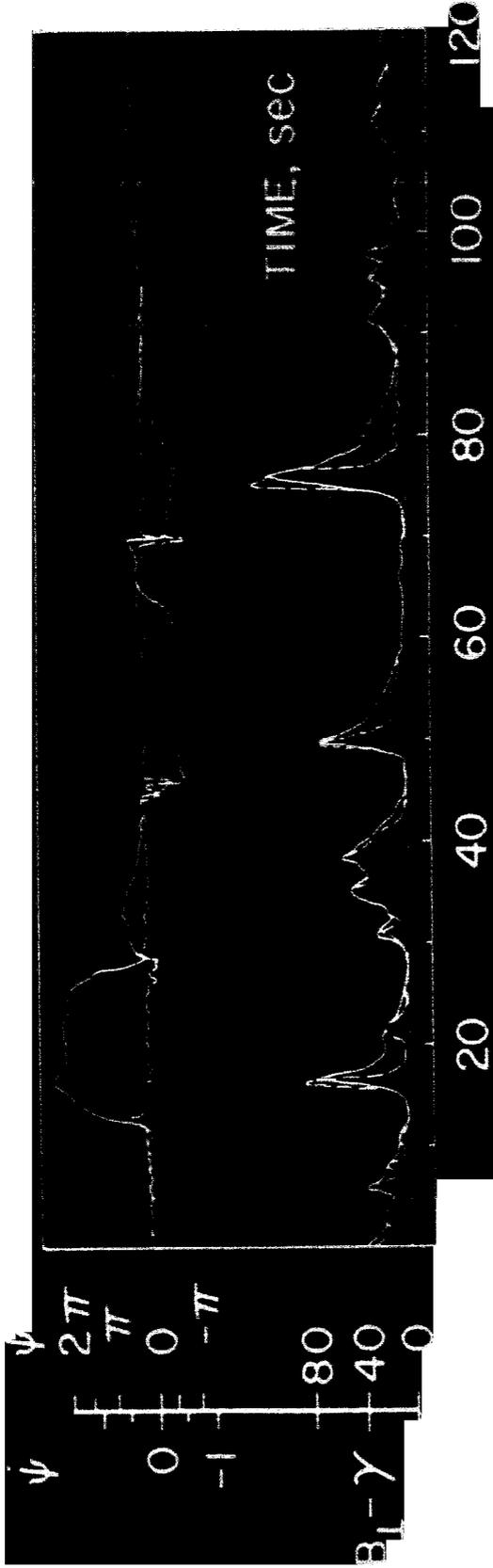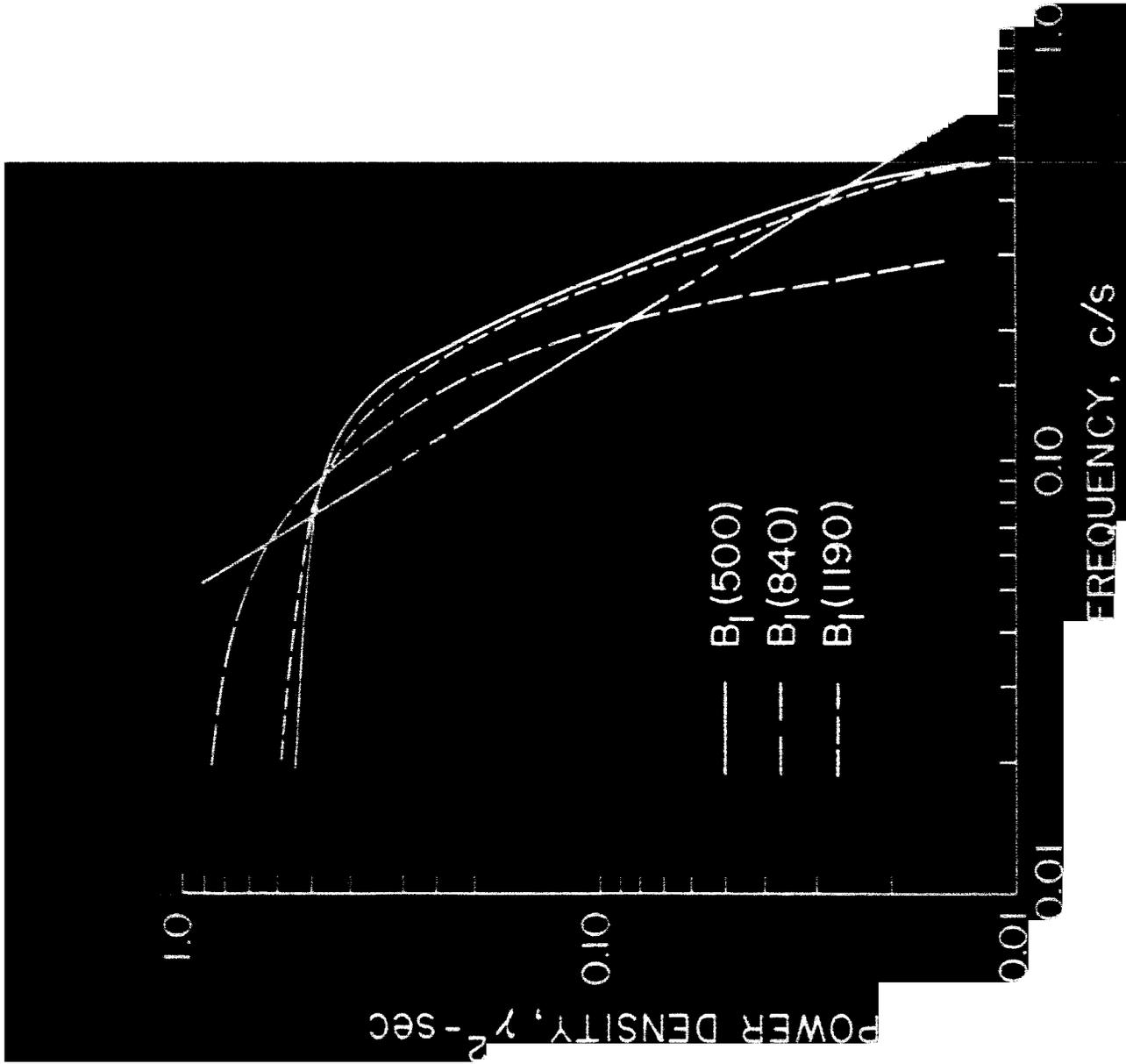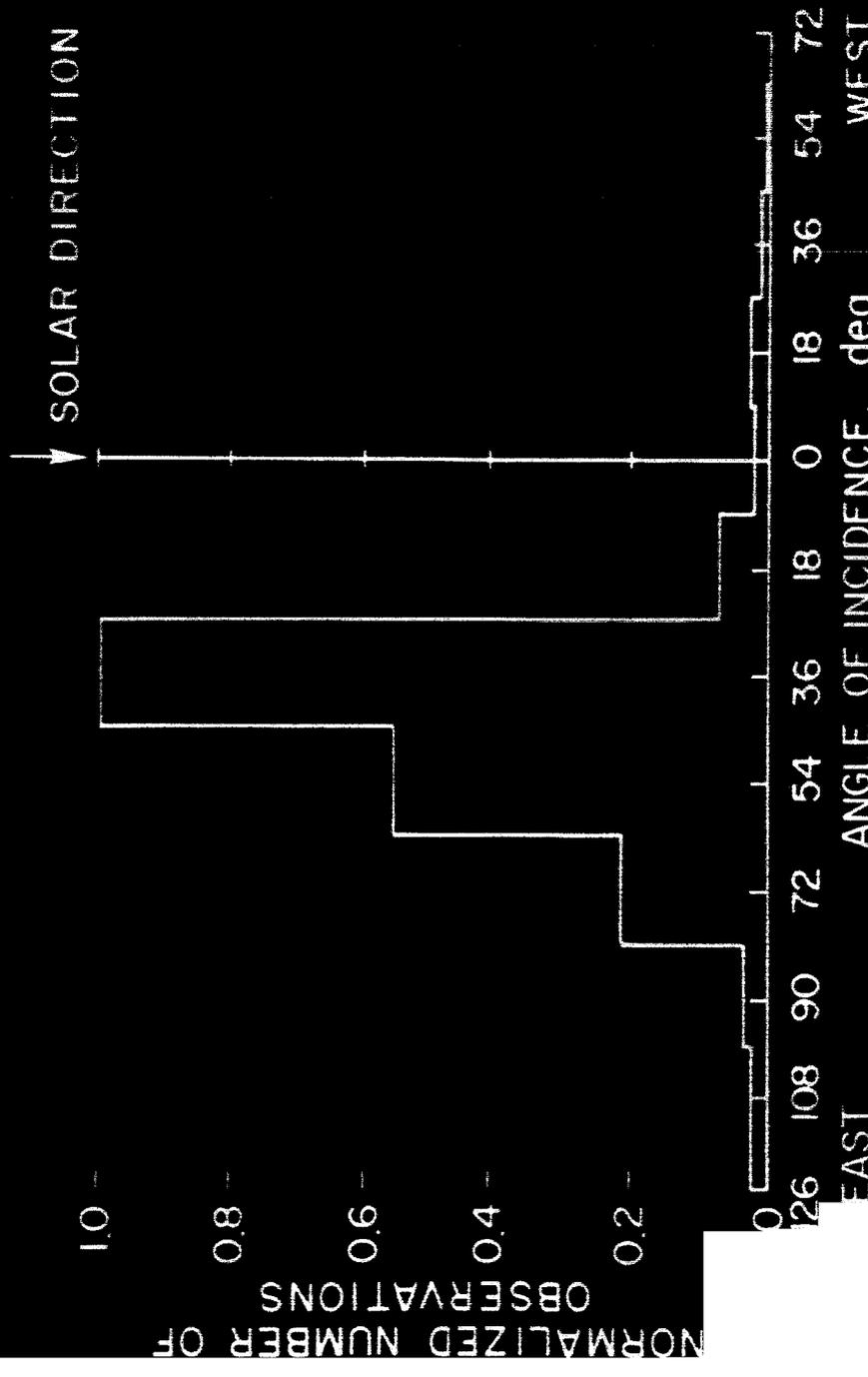
Pioneer IV (Van Allen, 1959)

12.6 a_e
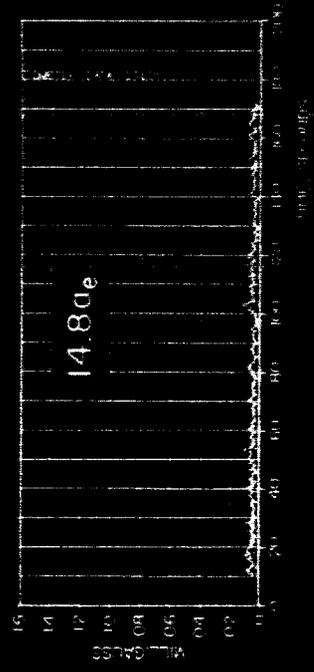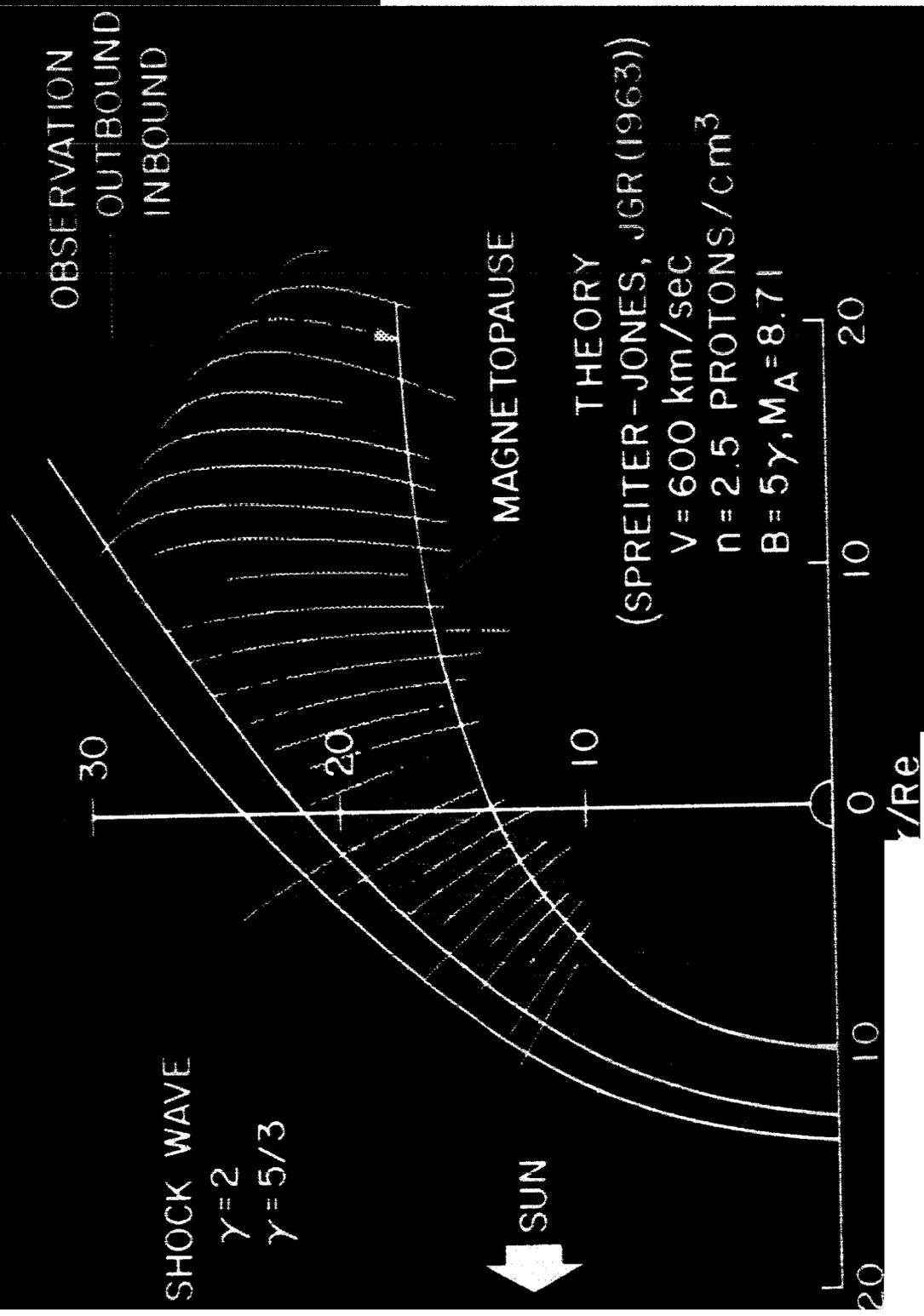
SHOCK WAVE
γ=2
γ=5/3

OBSERVATION
OUTBOUND
INBOUND
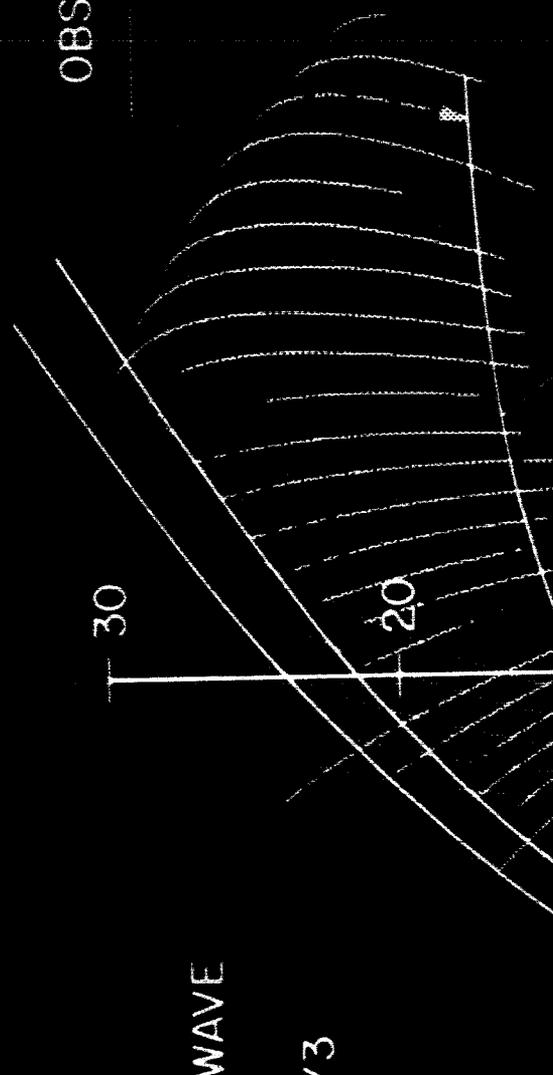
MAGNETOPAUSE

THEORY
(SPREITER–JONES, JGR (1963))
V= 600 km/sec
n=2.5 PROTONS/cm³
B=5γ, M$_A$=8.71

SUN

30

20

10

10

0

10

20

X/Re