IGPPWorkshop Report:

Plasma Physics Near the Earth's Bow Shock

by S. Peter Gary

When the supersonic flow of the solar wind first encounters the earth's magnetic field it creates a shock wave. This interaction compresses the magnetosphere on the dayside and shapes it into an elongated teardrop on the nightside (Fig. 1). The ultimate consequences of this interaction are far-reaching disturbances in our atmosphere, such as magnetic substorms that interfere with power transmission and communications and produce the spectacle of the polar auroras. The wave is called the bow shock, in analogy to the bow wave of a boat, and is a jump in plasma density, temperature, and magnetic field associated with the transition from supersonic to subsonic flow.

So turbulent is the shock that we have been unable to model the highly nonlinear processes that determine its structure. But progress has been made in modeling the foreshock region (upstream of the bow shock) where energetic protons reflected from the shock back toward the sun may help to heat, decelerate, and deflect the solar wind.

New data on energetic protons and two plausible models of their interaction in the foreshock were discussed last September at a Workshop on Space Plasma Physics held at Los Alamos and supported by the University of California's Institute of Geophysics and Planetary Physics. Both models rely heavily on data from space probes mounted by NASA's International Sun-Earth Explorer (ISEE) mission. One model, developed by Los Alamos and the Max Planck Institute for Extraterrestrial Physics (Garching, West Germany), postulates a causal relation between various populations of energetic protons. A second foreshock model, proposed by E. W. Greenstadt, postulates that one type of proton population and its associated large-amplitude magnetic fluctuations are intrinsic parts of the bow shock structure.

Under typical conditions, the bow shock stands at about 15 earth radii from our planet along the Sun-Earth line, but since the solar wind is subject to fluctuations in flow speed, the shock can

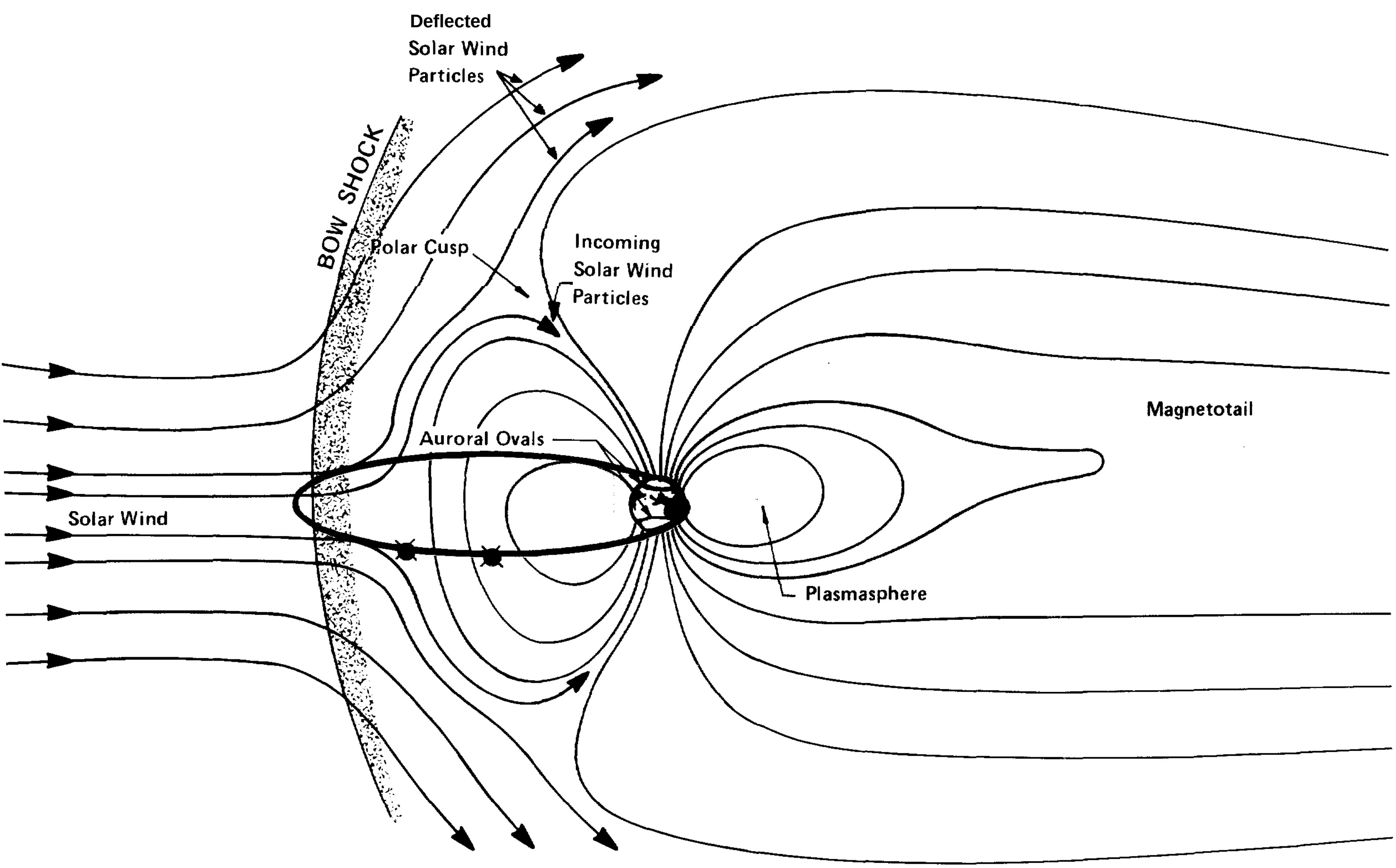


Fig. 1. A current picture of geospace. The solar wind incident on the magnetosphere is less dense than the earth's atmosphere by a factor of ~10^{18} and consists primarily of protons and electrons traveling away from the sun at ~400 km/s with thermal energies of ~10 eV. Particles deflected by the earth's magnetic field are sometimes trapped in the magnetotail. Frequently, magnetic energy stored in the tail is suddenly released, accelerating the plasma toward the earth. Such a magnetic substorm ultimately produces strong magnetic disturbances and spectacular auroras in the earth's polar regions. Two co-orbiting International Sun-Earth Explorer satellites launched in 1977 are gathering important data on the solar wind, bow shock, and magnetosphere.

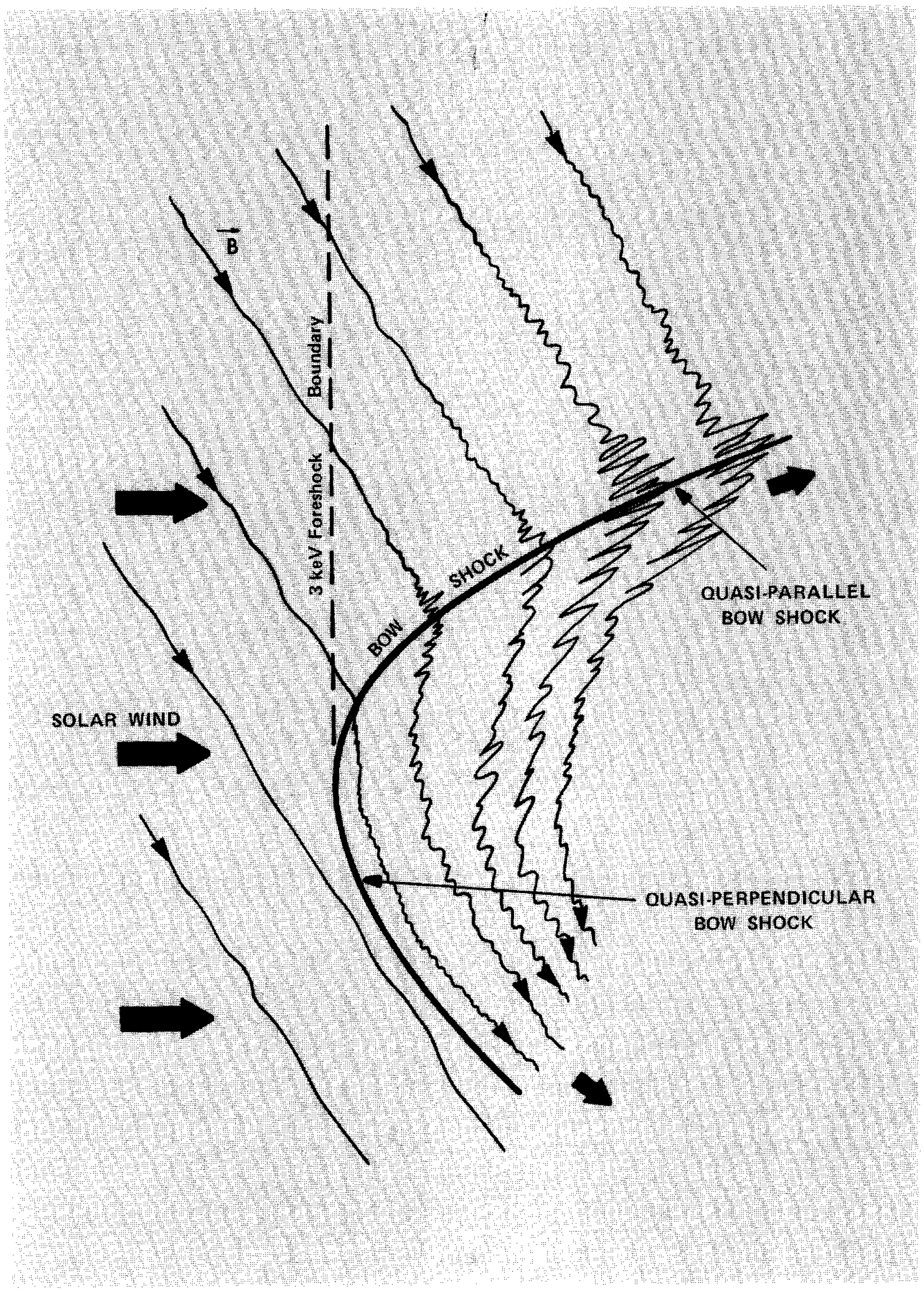


Fig. 2. The earth's bow shock and near upstream region. Also shown is the foreshock boundary for 3-keV protons traveling along $\vec{B}$ against the solar wind. Reflected protons with energies less than 3 keV are found between the boundary and the shock. The detailed behavior of the magnetic fluctuations at the quasi-parallel shock is not well understood and their representation here is only suggestive.

change position quite quickly.

The bow shock's local structure is determined to a great extent by the angle θ between the shock normal and the solar wind magnetic field $\vec{B}$. (Fig. 2). A perpendicular shock ($\theta = 90°$) is a rather abrupt change in plasma properties across a narrow region. A parallel shock ($\theta = 0°$ or $180°$) is hardly a shock in the classic sense but a rather broad transition embedded in large-amplitude fluctuations (turbulence). Between these two extremes are quasi-perpendicular and quasi-parallel shocks.

While the bow shock is capable of reflecting and accelerating charged particles along magnetic field lines back toward the sun, the solar wind continuously sweeps them toward the shock, creating the foreshock boundary that limits the region in which a proton with a given velocity parallel to B can be found.

A plasma, like a fluid, can sustain a diversity of fluctuations termed (at small amplitudes) waves, (if growing) instabilities, or (at sufficiently large amplitudes) turbulence. In the case of plasmas, such fluctuations represent temporal and spatial changes of both magnetic field and plasma properties, such as ion densities and velocities. Consequently, to characterize a plasma wave completely requires careful correlation of field and plasma data.

Such information about the solar wind, bow shock, and magnetosphere has been collected by two Explorer spacecraft launched into the same orbit at an apogee of 22.2 earth radii in October, 1977. Since the distance between the two satellites is variable, the data have allowed space scientists, for the first time, to separate temporal and

Los Alamos Establishes Branch of IGPP

More than 20 years ago, the University of California at Los Angeles formed an Institute of Geophysics and Interplanetary Physics (IGPP) to close the hiatus that had existed between physics and geology into which fell such fields as rock physics and high-temperature mineralogy. The program was so successful that IGPP branches were established at the University of California at San Diego and Riverside and in September last year, a branch was formally initiated at Los Alamos.

Each IGPP branch provides a home within the University for types of research that in the past, at least, have had trouble fitting into existing programs. Special needs were met by each branch. At UCLA, NASA-supported extraterrestrial research and space physics became an important part of the Institute. San Diego's program was founded to support the growth of physical oceanography and marine geophysics, and at the Riverside branch, cosmic ray astronomy was the original thrust.

At Los Alamos, the purpose of the new branch is to provide a strong link between the Laboratory and the University and to foster the joint use of facilities by scientists involved in geophysics and interplanetary physics. The Laboratory hosted its first IGPP Workshop in Space Plasma Physics last fall, to allow researchers to meet and exchange information.

Initially the Los Alamos program will involve faculty exchange, with actual development of research programs evolving with time, The range of research that may be supported by the IGPP will include geothermal energy, tectonophysics, seismology, planetary exploration and planetary geology, and related fields including cosmic-ray study, solar physics, space plasma physics, solar system dynamics, atmospheric science and climatology, solid-state physics, high-pressure physics, and geochemistry. All research sponsored by the IGPP will be unclassified, and one of the duties of the Assistant Director of the Institute will be to advocate opening research facilities at the Laboratory to University scholars. The Assistant Director will report to the systemwide IGPP Director and to the Los Alamos Director regarding Laboratory policy, staff, and programs, and will have both line and program responsibility within the Laboratory's matrix organization.

The Institute's initial budget includes a $250,000 allocation for Regents' Fellowships that provide salary, transportation, and per diem expenses for both scholars and Los Alamos staff members involved in IGPP programs. The terms of Fellowships will be flexible and geared to individual circumstances. Support for a graduate student working here under the direction of a professor at his home university will be limited to $15,000 for a nine-month term. Support for a nine-month visit by a *full* professor will amount to $40,000. It is anticipated that the Fellowship fund will support seven or eight scholars each year. All Fellowships will support visits of more than three months, and thus will not be used for summer study.

Proposals for Fellowships should be submitted to the Los Alamos IGPP Assistant Director, who will endorse those candidates whose proposals are to be forwarded to the applicants' University Department Chairmen for approval. Successful applications will be submitted to the IGPP systemwide Director, who will make the final decision on awards ●

spatial effects and determine velocities and thicknesses of magnetospheric boundaries. Magnetic fields were measured by magnetometers developed by the University of California at Los Angeles and ion velocity distributions were measured by fast plasma analyzers developed jointly by Los Alamos and the Max Planck Institute.

First analyses of data showed that there exist two distinct populations of backward-streaming energetic ions: (1) “reflected” protons with sharply peaked beam-like velocity distributions along $\vec{B}$ and energies seldom extending much above 10 keV (Fig. 3a) and (2) “diffuse” protons with relatively broad velocity distributions extending to considerably higher energies (Fig. 3c). Large-amplitude magnetic field and ion-density fluctuations (with periods ≤ 1 rein) are associated with the diffuse protons, but not with the reflected protons.

At the Workshop, more recent ion velocity distribution data were presented

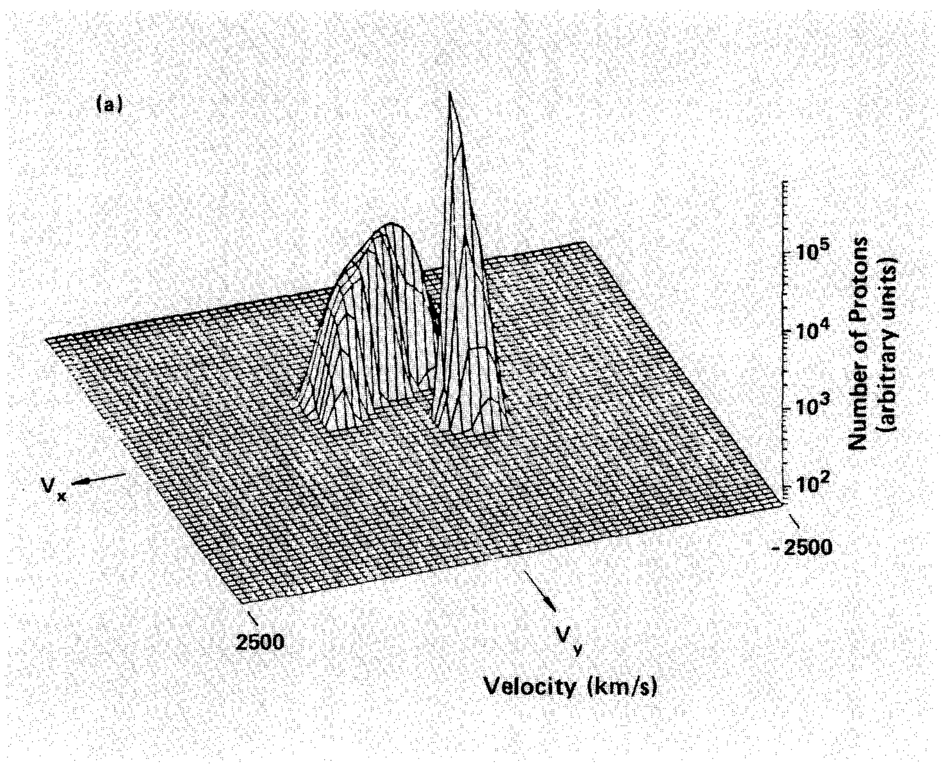
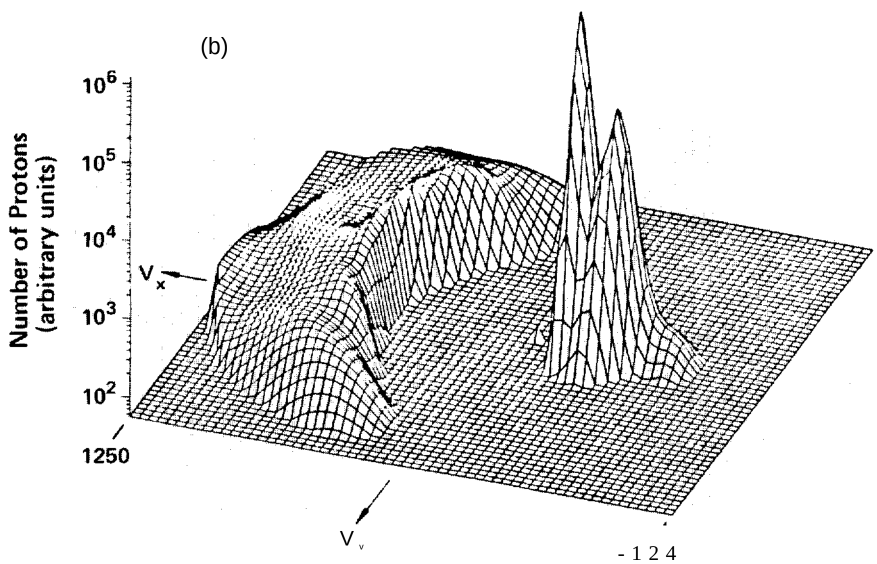
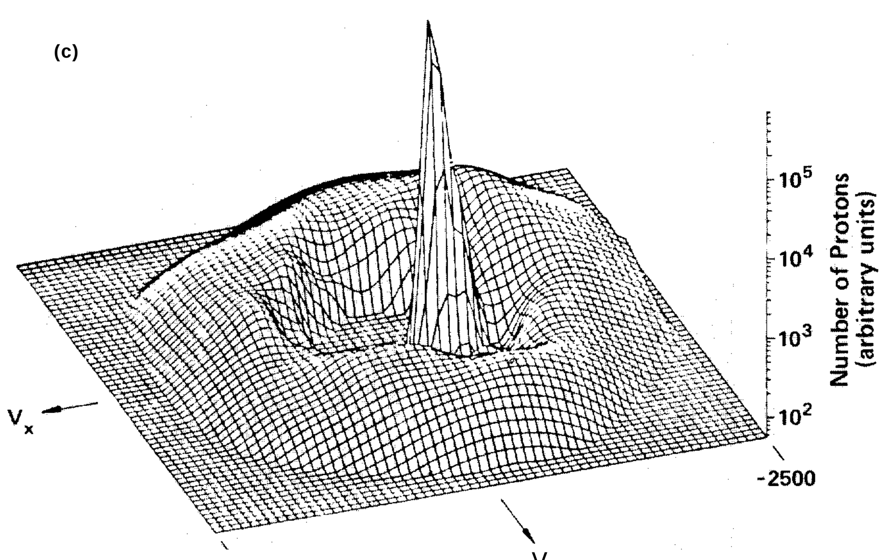


Fig. 3. ***Typical proton velocity distributions in the foreshock region. The component with the higher peak (greater density) corresponds to the solar wind protons. The component with the lower peak represents the (a) reflected, (b) intermediate, and (c) diffuse energetic proton populations. The magnetic field is approximately in the direction of the average velocity of the energetic protons; the v_x axis points back toward the sun.***





showing the intermittent presence of a third proton population. This "intermediate" population (Fig. 3b) is spread out in velocity space and appears to be a transition between the reflected and diffuse proton populations.

Also reported at the Workshop were complementary data on magnetic field fluctuations. Relatively small-amplitude, relatively high-frequency (-1 Hz) magnetic fluctuations accompany the reflected protons. These waves as well as larger-amplitude, lower-frequency (-0.03 Hz) fluctuations are present in association with the intermediate population. In the presence of the fully diffuse proton population, the high-frequency magnetic waves disappear, and the low-frequency fluctuations steepen into shock-like features that often break into whistler-mode packets. Both high- and low-frequency fluctuations have compressive components (that is, plasma density fluctuations accompany the magnetic field fluctuations) and in general propagate at angles oblique to $\vec{B}$.

Los Alamos and Max Planck Institute

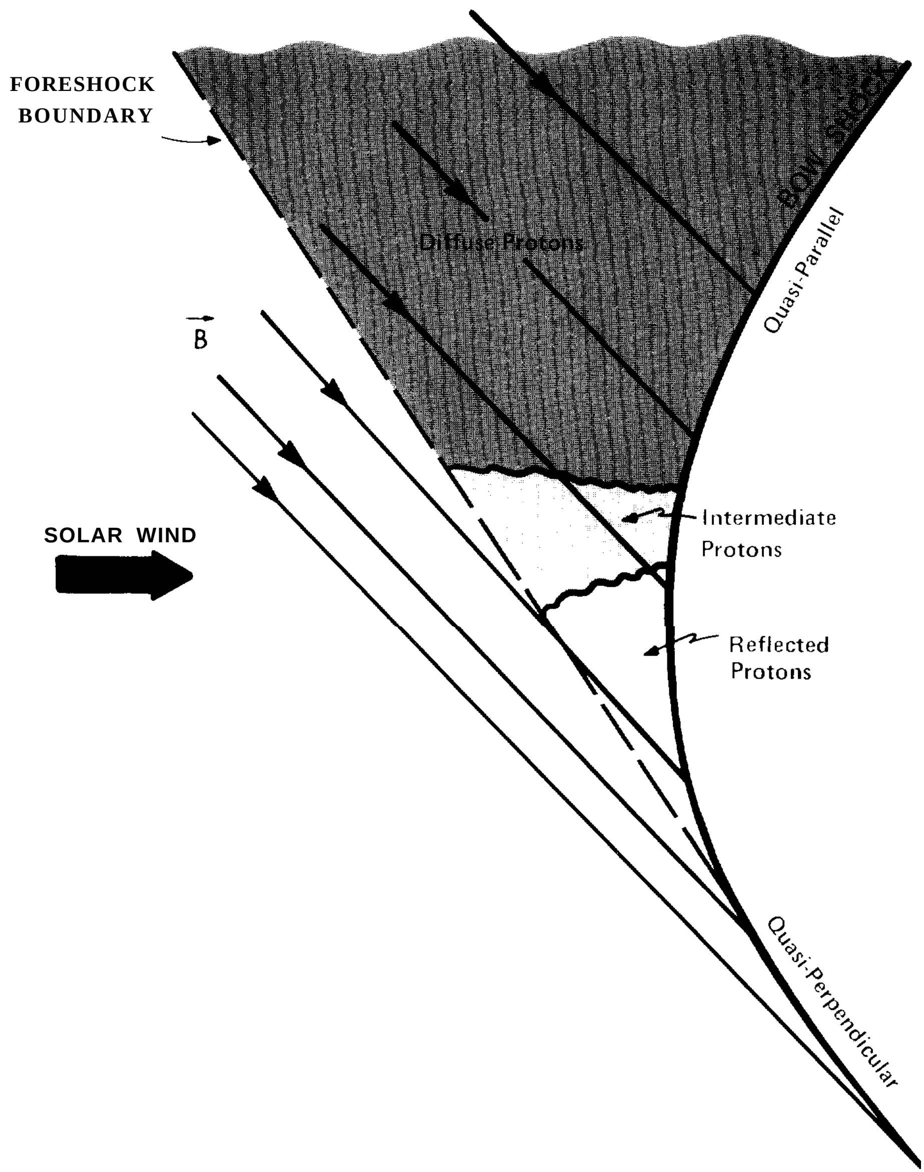


Fig. 4. Spatial distribution of the various proton populations predicted by the Los Alamos-Max Planck Institute model.

researchers postulate a model in which a beam of protons reflected from the shock transfers its backward momentum to the solar wind through wave-particle scattering, thereby decelerating the solar wind and creating the intermediate and diffuse proton populations. In this model the reflected proton population is formed by ion reflection at the quasi-perpendicular bow shock of a small fraction (~1%) of the solar wind protons. (Ion reflection is a characteristic of high Mach number collisionless shocks.) The resulting non-Maxwellian proton velocity distribution is unstable to one or more plasma instabilities, which grow into large-amplitude magnetic fluctuations. These magnetic waves pitch-angle scatter the beam (that is, change the direction of a proton's velocity vector without significantly altering its magnitude). Such wave-particle scattering leads to the intermediate and eventually to the nearly isotropic diffuse distributions.

This model explains the observed deceleration of the solar wind as it enters the upstream region populated by diffuse protons and long-period waves. In addition, it predicts the location of the three proton populations in the foreshock region (Fig. 4). Detailed data analysis is now underway to test this prediction. Early results indicate correlations between reflected protons and quasi-perpendicular shocks and between diffuse protons and quasi-parallel shocks as suggested by the model.

An important limitation on refinement of this model is theoretical. Although the magnetic fluctuations are observed to be compressive, present theories are limited to noncompressive instabilities that cannot produce the high-energy component of a typical diffuse proton population.

The other model of the upstream region, presented by Greenstadt *et al.*, proposes that, rather than a causal link between the two proton distributions, both elements are part of the overall picture of the bow shock. Although Greenstadt's model is at present lacking in details, some such model may eventually provide a better explanation of the observed association of diffuse protons with quasi-parallel shocks, of the high-energy component of the diffuse population, and of the numerous cases of wave appearance immediately after the solar wind magnetic field undergoes a rapid local change from a quasi-perpendicular to a quasi-parallel geometry.

Many other subjects were discussed at the Workshop, including magnetospheric dynamics, the ionosphere, magnetic reconnection, and numerical simulations of space plasmas. There was general agreement that, in spite of the increased sophistication of recent spacecraft and an increased understanding of some small-scale processes in space, scientists are still a long way from a comprehensive theory of plasma dynamics in the earth's environment.

Workshop participants were enthusiastic about the opportunity to exchange information, and a second Workshop, to be hosted by the University of California at Los Angeles, is planned for later this year.

Scientific presentations of the Los Alamos Workshop are abstracted in "Workshop on Space Plasma Physics," edited by M. Ashour-Abdalla and S. P. Gary; this publication is available from S, P. Gary, Group P-4, Los Alamos National Laboratory ■

FURTHER READING

G. Paschmann, N. Sckopke, J. R. Asbridge, S. J. Bame, and J. T. Gosling, "Energization of Solar Wind Ions by Reflection From the Earth's Bow Shock," J. Geophys. Res. 85,4689 (1980).

S. J. Bame, J. R. Asbridge, W. C. Feldman, J. T. Gosling, G. Paschmann, and N. Sckopke, "Deceleration of the Solar Wind Upstream From the Earth's Bow Shock and the Origin of Diffuse Upstream Ions," J. Geophys. Res. 85,2981 (1980).

E. W. Greenstadt, C. T. Russell, and M. Hoppe, "Magnetic Field Orientation and Suprathermal Ion Streams in the Earth's Foreshock." J. Geophys. Res. 85,3473 (1980).

Interested readers are directed to a forthcoming volume of the Journal of Geophysical Research, which will be devoted to research related to the earth's foreshock.