DAVID G. SIBECK

THE AMPTE PROGRAM'S CONTRIBUTION TO STUDIES OF THE SOLAR WIND–MAGNETOSPHERE–IONOSPHERE INTERACTION

The Active Magnetospheric Particle Tracer Explorers (AMPTE) program provided important information on the behavior of clouds of plasma artificially injected into the solar wind and the Earth's magnetosphere. Now that the releases are over, data from the satellites are being analyzed to investigate the processes by which the ambient solar wind mass, momentum, and energy are transferred to the magnetosphere. Work in progress at APL indicates that the solar wind is much more inhomogeneous than previously believed, that the solar wind constantly buffets the magnetosphere, and that ground observers may remotely sense these interactions as geomagnetic pulsations.

INTRODUCTION

The Sun continually emits a supersonic stream of cool (3×10^4 K), low-density (5 cm^{-3}) plasma known as the solar wind. The Earth's magnetic field is an obstacle to the oncoming solar wind plasma. Figure 1 shows that the Earth's bow shock decelerates the solar wind plasma, thereby transforming the solar wind kinetic energy into an equivalent thermal energy and pressure in the magnetosheath. The warm (10^6 K), dense (30 cm^{-3}) plasma in the magnetosheath behind the bow shock continues to flow away from the Sun and compresses the Earth's magnetic field. The Earth's magnetic field deflects the oncoming plasma and carves out a cavity in the magnetosheath flow. The magnetospheric plasma is tenuous (1 cm^{-3}) and hot (10^7 K). The outer boundary of the magnetosphere lies at the locus of points where the magnetosheath and magnetospheric pressures balance and is known as the magnetopause.

A small fraction of the incident magnetosheath (i.e., solar wind) mass, momentum, and energy enters the magnetosphere. Spacecraft in the outermost magnetosphere often observe a boundary layer of antisunward-flowing magnetosheath-like plasma on magnetospheric magnetic field lines. The incoming mass, momentum, and energy are stored in the nightside magnetosphere. The sudden release of this energy during geomagnetic substorms disturbs magnetic field lines, produces polar auroras, and disrupts radio communications and power line transmissions.

Any of the solar wind's mass, momentum, or energy entering the magnetosphere must cross the magnetopause. Although many transfer mechanisms have been suggested, no general agreement exists on which is most important. Observations indicate that most solar wind mass, momentum, and energy are transferred to the magnetosphere during periods when the solar wind magnetic field has a southward ($B_z < 0$) component, that is, at times when the solar magnetic field lies parallel to the Earth's magnetic dipole axis. Magnetic merging is a mechanism for the solar wind–magnetosphere interaction that invokes the interconnection of magnetosheath and magnetospheric magnetic field lines. Theoretical work suggests that magnetic merging is most likely to occur

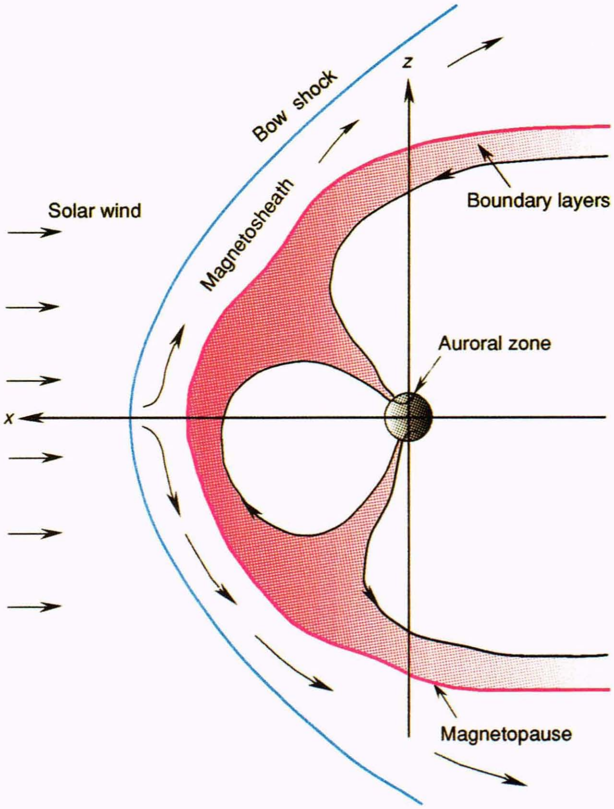


Figure 1. The magnetosphere and its environment.

during periods when the solar wind has a strong southward component, which is consistent with observations.

We have no reason to suppose that magnetic merging is a steady-state process. Thus, many transient magnetospheric phenomena that have durations of about 1 min and recur every 5 to 10 min during periods of southward solar wind magnetic field are taken as evidence that merging is sporadic; that is, solar wind mass, energy, and momentum enter the magnetosphere via some transient, localized process. According to this sporadic entry model, the magnetopause is most unstable during periods of southward solar wind magnetic field, when an unsteady boundary instability regulates the inflow of solar wind mass, momentum, and energy into the magnetosphere.

To enhance our understanding of the interaction, we would ideally like to have a continual monitor of solar wind conditions just upstream of the Earth's bow shock to provide *in situ* solar wind observations. We would also like to have several satellites in the outer dayside magnetosphere to provide information on the magnetospheric response. In the past, such spacecraft constellations have been as much a matter of chance as intention, because spacecraft never remain stationary and are seldom arranged in such ideal patterns.

In contrast to the satellite measurements in space, large arrays of ground stations make nearly continual measurements and are relatively easy to maintain. The footprints of magnetic field lines in the outermost magnetosphere lie in the Earth's polar ionosphere, where auroras are observed. Ground stations located in the auroral zone provide information on magnetic field perturbations, the flux of precipitating magnetospheric particles entering the ionosphere, the intensity of visible auroras, and ionospheric flows. These ground stations can also be used to remotely sense processes occurring routinely in the outer magnetosphere, but the ground signatures must first be compared with *in situ* observations of outer magnetospheric processes to determine what each ground signature represents.

In this article, we consider studies of the solar wind–magnetosphere–ionosphere interaction using observations recently obtained during the Active Magnetospheric Particle Tracer Explorers (AMPTE) satellite program, efforts to identify ionospheric signatures with corresponding processes in the magnetosphere, and attempts to produce models explaining these interrelationships.

THE AMPTE PROGRAM

After years of careful planning,[1] the three AMPTE satellites were successfully launched from Kennedy Space Center on 16 August 1984. The Ion Release Module (IRM) and United Kingdom Subsatellite (UKS) followed nearly identical orbits with apogees of 18.8 R_E (Earth radii), whereas the Charge Composition Explorer (CCE) followed an orbit with an apogee of 8.8 R_E. The satellites were equipped with instruments to measure magnetic fields, plasma waves, energetic particles, plasma densities, temperatures, and velocities.

During the first phase of the joint mission, the IRM released tracer elements into the solar wind, magnetosheath, and magnetosphere, which were monitored by the UKS and the CCE. This phase of the mission provided important new data about the artificial comets created and the means by which artificially injected plasma enters and circulates within the near-Earth environment.[2]

Attention has now turned to the second phase of the mission, which addresses the ambient magnetospheric plasmas and magnetic fields. These studies are no less exciting—they provide the clues that will tell us how solar wind mass, momentum, and energy enter the Earth's magnetosphere.

The AMPTE satellites have an important advantage over previous magnetospheric missions. The IRM and UKS satellites spent much time at their apogees just sunward of the bow shock, an ideal location for monitoring the solar wind input to the magnetosphere. In addition, these two satellites carried the instrumentation necessary to make solar wind plasma measurements with a higher time resolution (6 s) than previous satellites. The CCE hovered for prolonged periods near its apogee just earthward of the magnetopause, an ideal location for monitoring the magnetospheric response to solar wind variations.

SOLAR WIND VARIABILITY

When the AMPTE spacecraft were launched, it was generally recognized that the solar wind magnetic field had a filamentary structure, even on very brief (5–10 min) time scales. Even so, there was also a tacit consensus that solar wind parameters were relatively steady over such short time periods. Figure 2 shows the first stretch of high-time-resolution IRM solar wind magnetic field and plasma observations examined at APL.[3] From top to bot-

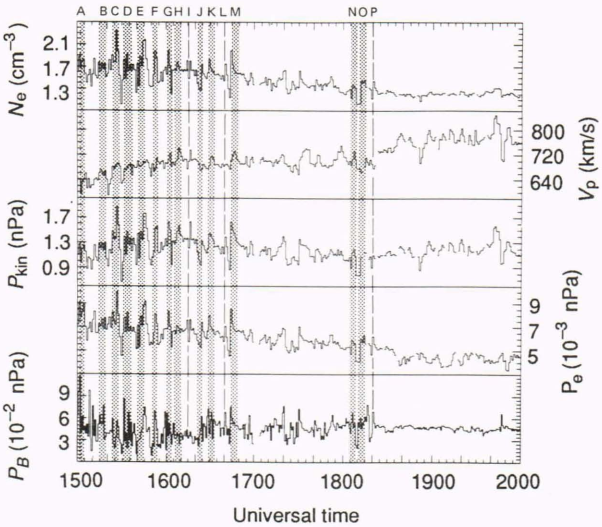


Figure 2. Solar wind observations made by the Ion Release Module on 10 September 1984. The plot shows plasma (top four panels) and magnetic field (bottom panel) observations. Several solar wind dynamic pressure increases are labeled A to P. The term N_e is the electron density, V_p is the proton velocity, P_{kin} is the dynamic pressure, P_e is the electron thermal pressure, and P_B is the magnetic pressure. All values are averaged over 60 s. (Reprinted, with permission, from Ref. 3, © 1989 by the American Geophysical Union.)

tom, the figure shows the electron density N_e, the proton velocity V_p, the dynamic pressure $P_{kin} = N_e M V_p^2$, the electron thermal pressure $P_e = N_e K T_e$, and the magnetic pressure $P_B = B^2/2\mu_0$. Here, M is the mass of a proton, K is the Boltzmann constant, B is the magnetic field strength, and μ_0 is the permeability of free space.

Figure 2 demonstrates that the dynamic pressure greatly exceeds both the thermal and magnetic pressures. Thus, the solar wind dynamic pressure determines the location of the Earth's magnetopause. Closer inspection of the figure reveals the occurrence of quasi-periodic, factor of 3 increases in the solar wind dynamic pressure. Several are labeled with the letters A to P. The increases tend to last about 1 min, to recur every 5 to 10 min, and to be associated with enhanced solar wind magnetic and thermal pressures. Such brief, large-amplitude variations in solar wind dynamic pressure had not previously been reported, nor had their effects on the magnetosphere been considered. They cannot be steady-state features advected with the solar wind, because they are not in pressure balance with their surroundings; that is, the sum of the thermal and magnetic pressures does not remain constant. A more extensive study[4] revealed that similar, large-amplitude variations in the solar wind dynamic pressure are common in the region just upstream of the Earth's bow shock, and suggested that they represent *in situ* observations of a previously unreported bow shock process.

Other types of variation in the solar wind dynamic pressure can be interpreted as steady-state features advected with the solar wind.[5] They may be distinguished from those at the bow shock by their thermal and magnetic pressure variations, which are out of phase. These features, which are carried along with the solar wind flow, must have great extent, since they have been observed far from the bow shock. Work continues to determine the characteristics and relative occurrence rates of the two categories of variation in solar wind dynamic pressure.

MAGNETOSPHERIC AND IONOSPHERIC EFFECTS

Because the dayside magnetopause lies at the locus of points where incident solar wind and magnetospheric pressures balance, a transient increase in the solar wind dynamic pressure should briefly compress the magnetopause and increase magnetospheric magnetic field strengths. Figure 3 shows magnetospheric magnetic field measurements begun at the same time as the measurements in Figure 2. From top to bottom, the figure shows the total magnetic field strength, the three components of the magnetic field vector, and two angles defining the magnetic field orientation. The z-axis points along the Earth's rotation axis, the x-axis points radially inward toward the Earth, and the y-axis completes the right-handed triad. Angle θ indicates the elevation of the magnetic field from the x–y plane, and angle ϕ indicates the azimuthal angle in the x–y plane, measured positively from the x-axis toward the y-axis.

The letters A to M in Figure 3 mark a series of increases in magnetospheric magnetic field strength (B) that were observed both at the AMPTE/CCE, which was located near its dayside apogee, and at the Geostationary Operational Environmental Satellite (GOES-6). The GOES-6 observes a stronger magnetic field strength than does the CCE because the Earth's dipole magnetic field strength decreases with distance from the Earth. Assuming that solar wind features require about 2 min to traverse the distance from the IRM satellite to the magnetosphere, each of the labeled magnetic field strength increases at the CCE can be associated with the similarly labeled increase in the solar wind dynamic pressure shown in Figure 2. The correspondence between the solar wind and magnetospheric observations indicates that each increase in the solar wind dynamic pressure compressed the magnetopause and enhanced magnetospheric magnetic field strengths. The observations of nearly simultaneous compressions at CCE and GOES-6 indicate that these magnetospheric compressions were widespread.

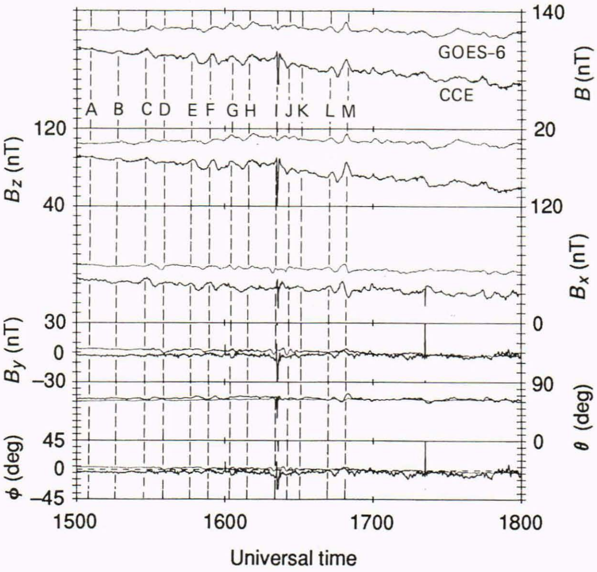


Figure 3. Magnetospheric magnetic field observations made by the Charge Composition Explorer (CCE) and the Geostationary Operational Environmental Satellite (GOES-6) on 10 September 1984. Several magnetic field strength increases are labeled A to M. The term B is the total magnetic field strength, and B_x, B_y, and B_z are its three components. The z-axis points along the Earth's rotation axis, the x-axis points radially inward toward the Earth, and the y-axis completes the right-handed triad. Angles θ and ϕ define the magnetic field orientation. Angle θ indicates the elevation of the magnetic field from the x–y plane, and angle ϕ indicates the azimuthal angle in the x–y plane, measured positively from the x-axis toward the y-axis. (Reprinted, with permission, from Ref. 3, © 1989 by the American Geophysical Union.)

Similar results obtained for several other days[4] indicate that brief variations in the solar wind dynamic pressure are a major cause of transient events, such as magnetic field strength increases, in the outer dayside magnetosphere. An instability at the dayside magnetopause does not appear to be a required condition to modulate incoming solar wind energy and to explain these events. In addition, many magnetospheric events appear to be widespread rather than localized, indicating a global magnetospheric compression by solar wind features with large dimensions rather than a localized magnetopause instability.

A transient increase in the solar wind dynamic pressure briefly compresses the magnetospheric magnetic field. Although a step-function increase in the solar wind dynamic pressure compresses the magnetosphere, it may also excite resonant magnetic field oscillations, which continue long after the compression.[6] The oscillation frequency of a given field line depends on the length of that field line, its magnetic field strength, and the plasma density.

Figure 4 illustrates the magnetospheric response to both kinds of solar wind dynamic pressure variation. From top to bottom, the figure shows the three components of the solar wind magnetic field, the total solar wind magnetic field strength B, the angle θ_{xB} that the magnetic field makes with the x-axis (Earth–Sun line), the elevation angle θ_{zB} of the magnetic field from the x–y plane, the solar wind velocity, and a comparison of the solar wind density with the detrended CCE magnetic field component parallel to the mean magnetic field. (Detrending is the removal of the average magnetic field components, leaving only the variations.) The solar wind velocity V was relatively steady, but sharp variations were seen in the density N. The step function increase in the solar wind density (and therefore dynamic pressure NMV^2) observed by the Interplanetary Monitoring Platform (IMP-8) at 0320 UT excited a magnetic field oscillation with a period of about 3 min at the location of the CCE, whereas the magnetosphere responded directly to each solar wind density variation from 0400 to 0430 UT without strong oscillations being excited. Finally, we note that the events occurred for a northward solar wind magnetic field, that is, for B_z (or θ_{zB}) > 0. This northward orientation indicates that the transient events were not associated with the occurrence of magnetic merging at the dayside magnetopause.

Magnetic field variations in the outer magnetosphere propagate down field lines to the polar ionosphere in the form of magnetohydrodynamic waves. One such wave is the Alfvén wave, which has special properties making it readily identifiable. This wave propagates parallel to the magnetic field and disturbs only the magnetic field components perpendicular to the field line. Thus, a low-altitude satellite just above the ionosphere should observe downward propagating transverse magnetic field variations when the outer magnetospheric portions of the same magnetic field lines are compressed. By good fortune, the Viking satellite was about 2 R_E over the auroral ionosphere at the time of the observations shown in Figure 4. Figure 5 shows detrended CCE observations from 0300 to 0500 UT and compares them with detrended Viking observations for the period beginning at 0350 UT. The top panel of the figure shows the radial compo-

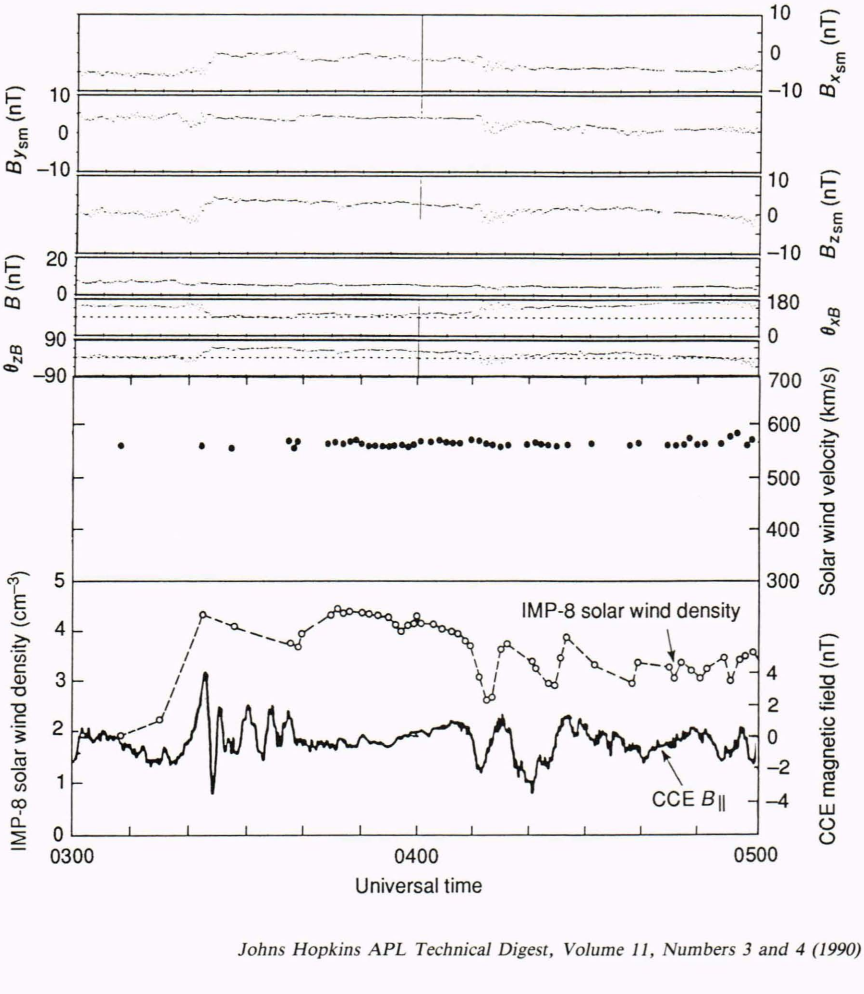


Figure 4. The Interplanetary Monitoring Platform (IMP-8) magnetometer data for 24 April 1986. The terms $B_{x\mathrm{sm}}$, $B_{y\mathrm{sm}}$, and $B_{z\mathrm{sm}}$ are the three components of the solar wind magnetic field; B is the total solar wind magnetic field strength; θ_{xB} is the angle that the magnetic field makes with the x-axis (Earth–Sun line); and θ_{zB} is the elevation angle of the magnetic field from the x–y plane. The bottom panel is a comparison of IMP-8 solar wind density observations and Charge Composition Explorer (CCE) magnetospheric magnetic field observations on 24 April 1986. (Reprinted, with permission, from Ref. 6, © 1989 by the American Geophysical Union.)

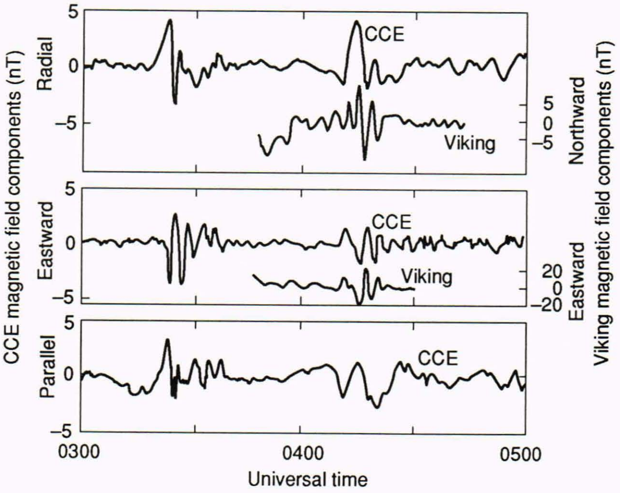


Figure 5. A comparison of high-altitude Charge Composition Explorer (CCE) and low-altitude Viking magnetospheric magnetic field observations on 24 April 1986. (Reprinted, with permission, from Ref. 6, © 1989 by the American Geophysical Union.)

nent of the magnetic field at the CCE and the corresponding northward component of the magnetic field to which it maps at Viking. The middle panel shows the eastward component of the detrended magnetic field at both satellites, and the bottom panel shows the detrended component of the CCE magnetic field parallel to the main field at that satellite. The parallel component of the Viking field is not shown, because variations were smaller than 2 nT, the Viking magnetometer's resolution.

Figure 5 demonstrates that Viking observed a transverse magnetic field disturbance similar to that seen at the CCE. Viking observed no significant variation in the magnetic field component parallel to the mean magnetic field, confirming that the field variations propagated to Viking in the form of an Alfvén wave.

Auroral-zone ground magnetometers should also be able to observe the disturbances. Figure 6 compares the detrended southward magnetic field component at the CCE and Viking with magnetic field measurements along a north–south axis as observed by a network of auroral-zone ground magnetometers in northern Scandinavia. The CCE observations have been delayed by 2.5 min to account for the finite time required for signals to propagate down the geomagnetic field lines. Similar waveforms are seen at all locations, confirming the widespread extent of the magnetospheric compressions induced by the variations in solar wind dynamic pressure.

CONCLUSIONS

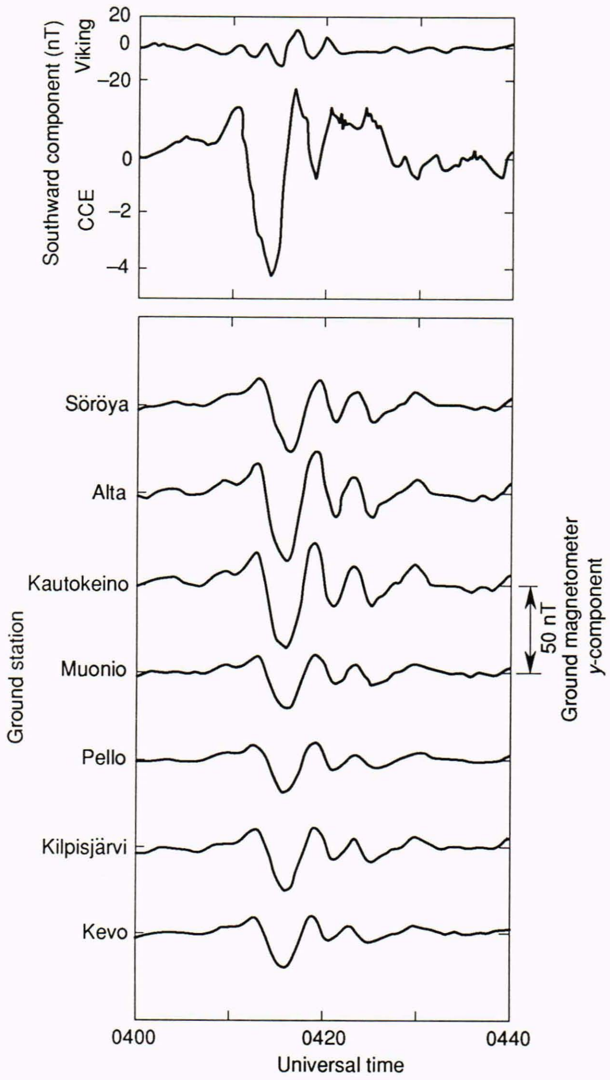


Figure 6. A comparison of Charge Composition Explorer (CCE), Viking, and ground magnetic field observations on 24 April 1986. (Reprinted, with permission, from Ref. 6, © 1989 by the American Geophysical Union.)

The outlines of a qualitative model for the magnetospheric effects of solar wind dynamic pressure variations may now be discerned.[7,8] Solar wind dynamic pressure variations, both intrinsic and bow-shock–generated, are swept anti-sunward into the magnetosheath. The increases in pressure briefly compress the magnetopause and increase the magnetospheric magnetic field strength. The compressions may couple to natural magnetospheric magnetic field line resonances and launch magnetohydrodynamic waves that propagate down to the ionosphere, where they may be observed by low-altitude satellites and ground stations. The transient events occur for solar wind magnetic fields with both northward and southward components.

In this review, we have emphasized recent work at APL that uses the AMPTE satellites to investigate solar wind–magnetosphere–ionosphere coupling. The AMPTE program was fortunate in that the IRM and UKS satellites provided high-time-resolution solar wind measurements made in the region just upstream of the Earth's bow shock. These observations were essential in identifying large-amplitude variations in solar wind dynamic pressure and demonstrating that many resulted from the solar wind interaction with the bow shock.

The AMPTE/CCE observations served a double role. First, the CCE observations were used to determine the magnetospheric response to a variable solar wind, in particular to the sudden sharp variations in solar wind dynamic pressure. Each increase in solar wind dynamic pressure briefly compresses the magnetosphere. Although transient compressions in the magnetospheric magnetic field strength are direct evidence for the transfer of solar wind energy to the magnetosphere, the CCE observations suggest that it is not necessary to invoke magnetic merging or a regulatory magnetopause instability to explain these events. Second, initial work with the CCE observations indicates that they will be very useful in calibrating low-altitude, ionospheric, and ground observations. Although statistical studies will be required, it should be possible to associate the various ground signatures with differing phenomena in the magnetosphere and then to use arrays of ground stations to remotely sense the spatial characteristics of the magnetospheric phenomena. When these associations are made, continual remote observations of magnetopause phenomena will be possible from high-latitude ground stations.

REFERENCES

[1] Krimigis, S. M., Haerendel, G., McEntire, R. W., Paschmann, G., and Bryant, D. A., "The Active Magnetospheric Particle Tracer Explorers Program," *Johns Hopkins APL Tech. Dig.* **4,** 3-11 (1983).

[2] McEntire, R. W., "An Update on the Active Magnetospheric Particle Tracer Explorers (AMPTE) Program," *Johns Hopkins APL Tech. Dig.* **8,** 340-347 (1987).

[3] Sibeck, D. G., Baumjohann, W., Elphic, R. C., Fairfield, D. H., Fennell, J. F., et al., "The Magnetospheric Response to 8-Minute Period Strong-Amplitude Upstream Pressure Variations," *J. Geophys. Res.* **94,** 2505 (1989).

[4] Fairfield, D. H., Baumjohann, W., Paschmann, G., Luehr, H., and Sibeck, D. G., "Upstream Pressure Variations Associated with the Bow Shock and Their Effects on the Magnetosphere," *J. Geophys. Res.* **95,** 3773 (1990).

[5] Sibeck, D. G., and Croley, D. J., "Solar Wind Dynamic Pressure Variations and Possible Ground Signatures of Flux Transfer Events," *J. Geophys. Res.* (in press).

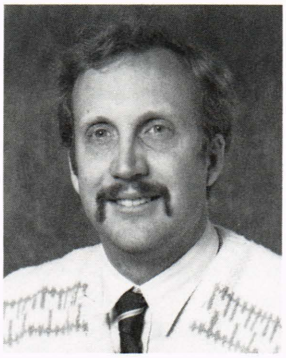
[6] Potemra, T. A., Luehr, H., Zanetti, L. J., Takahashi, K., Erlandson, R. E., et al., "Multisatellite and Ground-Based Observations of Transient ULF Waves," *J. Geophys. Res.* **94,** 2543 (1989).

[7] Sibeck, D. G., "A Model for the Transient Magnetospheric Response to Sudden Solar Wind Dynamic Pressure Variations," *J. Geophys. Res.* **95,** 3755 (1990).

[8] Lui, A. T. Y., and Sibeck, D. G., "Dayside Auroral Activities and Their Implications for Impulsive Entry Processes in the Dayside Magnetosphere," *J. Atmos. Terr. Phys.* (in press).

ACKNOWLEDGMENT: This work was supported by NASA under Space and Naval Warfare Systems Command contract N00039-89-C-5301 of the Navy.

THE AUTHOR



DAVID G. SIBECK was born in Norman, Oklahoma, in 1958. While at UCLA, he received a B.A. (1979) in meteorology, an M.S. (1982) in atmospheric sciences, and a Ph.D (1984) in atmospheric sciences. He became a member of the Senior Professional Staff at APL in 1987 after joining the Space Sciences Branch in 1985. At APL, he has used AMPTE/CCE observations to address questions concerning the nature of the solar wind-magnetosphere-ionosphere coupling and the structure of the magnetopause.