Theoretical modeling is the umbrella under which the generic features of the various acceleration processes can be explored in a manner emphasizing the physics and identifying the commonalities. Despite great progress, in understanding the fundamental physics of several acceleration mechanisms and in modeling their observable consequences in regions of the solar terrestrial environment, several important questions remain to be solved. In acceleration by adiabatic compression and diffusion, the relevant diffusion mechanism and the associated diffusion coefficient are quite uncertain. Designing observational tests that distinguish among diffusion processes is an important task. The role of injection conditions and of the magnetic geometry on the final energy is a key uncertainty in parallel electric field acceleration. The same holds true for the conditions under which microinstabilities give rise to anomalous resistivity caused by density fluctuations or micro-double layers and how it affects runaway acceleration. Energization during reconnection is usually thought as due to inductive electric fields. The possibility for acceleration caused by the shocks required in the Petschek and Sonnerup reconnection models has not been explored. Understanding of stochastic as well as coherent acceleration by electrostatic waves is far from resolution. On the widely used shock acceleration the basic problems revolve about the issues of (a) the relationship between the microstructure of shocks and the ambient plasma conditions (including, in particular, conditions upstream from the discontinuity), and (b) how the accelerated particle themselves feed back to affect the (micro-)structure of the accelerating shock. These problems are particularly acute for quasi-parallel shocks, which are not well-understood (viz., why is it, for example, that quasi-linear theory seems to ‘work’, even though $\delta B/B \approx 0(1)$? $\delta$, and for high Mach number (collisionless) shocks (including relativistic shocks, which are likely to be important to particle acceleration in the vicinity of pulsars and other collapsed objects). This area is -- just as the problem of the substorm, or reconnection, and the related particle acceleration -- a major research problem in its own right, and is the subject of a companion chapter in this document.

CHAPTER 3 - EVOLUTION OF SOLAR MAGNETIC FLUX

Hale discovered the association of intense magnetic fields with sunspots 75 years ago. Observation of the sunspots for hundreds of years had recorded not only the fairly regular 11-year sunspot cycles but also irregular behavior, such as the Maunder Minimum, a period of about 70 years from 1645 to 1715 when essentially no sunspots were seen. Hale's discovery, however, was the first hint of complex magnetic field activity on the Sun. Today we know that sunspots and the associated bipolar magnetic regions (BMRs) appear on the Sun in large-scale patterns, they evolve, interact, migrate across the solar surface and then disappear following the sunspot cycle. Since the Sun's average dipole field reverses polarity every 11 years, a complete magnetic cycle lasts 22 years. Ground-based observations still provide most of our data base on the sunspots and magnetic activity.

In the last 25 years steadily improving observations, many of which are obtained above the atmosphere, have shown that the dynamic evolution of solar magnetic fields controls most components of solar variability affecting the geophysical environment such as disruptions of global communications. Observational and theoretical advances have given us a better view of the dynamic, sometimes violent, MHD and plasma phenomena which control sunspots and the solar transition region, heat the corona, drive the solar wind, and power flares, bright points, and spicules. Most of the phenomena investigated by the other eleven working groups depend on solar magnetic field variability to drive them or to trigger subsequent mechanisms which drive them.

There are other important reasons why a better understanding of the evolution of the solar magnetic flux is desired. Because the surface features can be observed in some detail, the Sun is an important source of information on plasma and MHD phenomena which can also occur in the laboratory, in our atmosphere, and in space. The Sun's large space scales and correspondingly
longer timescales make possible observations which cannot be obtained on the Earth. The Sun is also a star and therefore provides a wealth of information for extrapolation to and interpretation of other stars.

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To understand the evolution of solar magnetic flux we must answer the fundamental question: how does the solar dynamo work? Recent observations certainly influence models of the dynamo, but we have not been able to deduce the subsurface flows which control the generation of magnetic flux and presumably the entire solar cycle. The universality and importance of the scientific issues have attracted some of our best scientific minds and kept them busy for the better part of a century.

The first modern qualitative model of the operation of the solar activity cycle was provided by Babcock (1961). He considered the evolution of an axisymmetric dipole field of concentrated flux ropes subject to differential rotation. His model was able to account for the reversal of sunspot polarities from cycle to cycle, the drift of sunspot activity from mid-latitudes toward the equator during the cycle, and the reversal of the global dipole field near each sunspot maximum. Leighton (1969) quantified some aspects of the model by obtaining numerical solutions of the linear dynamo equations. These solutions exhibited behavior akin to that of the large-scale magnetic fields on the Sun, including fluctuations in period and amplitude in response to fluctuations in the rate of emergence of new flux.

Perhaps the most striking recent finding about magnetic activity cycles is other evidence of their intermittency and aperiodicity. Observations of stellar spectra over extended periods show that stars also exhibit magnetic cycles, and that some, in particular fast rotators, show aperiodic magnetic activity. It appears that intermittency and aperiodicity may be natural consequences of nonlinear dynamos. Calculations for model dynamos with interactions between the magnetic field and differential rotation have shown a transition from periodic to quasi-periodic to chaotic behavior as parameters of the dynamo change. They have also produced a convective flow which shows both differential rotation and a magnetic cycle.

Lacking a clear view of subphotospheric phenomena, this chapter concentrates on what can be deduced from observations by addressing four issues:

1. How does flux emerge on the Sun?
2. How does magnetic flux disappear?
3. What is seen at the limits of resolution?
4. What large-scale patterns are detected?

The answer to the fundamental question, how does the solar dynamo work, can only evolve from interpreting clues uncovered in research aimed at these more 'visible' questions. Numerous aspects of the first two questions arise repeatedly in theoretical attempts to describe physical processes which occur during the life cycle of magnetic flux on the Sun. The last two questions are observational and arise from needed advances in our ability to resolve and measure small time- and space-scale structures and in our ability to extract weak, large-scale patterns from the
noisy background over a long time period. This chapter considers the Appearance of Magnetic Flux (Section II); The Dynamics of Surface Magnetic Flux (Section III); and The Disappearance of Magnetic Flux from the surface of the Sun (Section IV). In each section the authors first discuss some of the standard models which represent generally accepted views, and then consider observations which seem to defy explanation within the context of these standard models.

Progress on the observational side has been rapid but we still do not have enough detailed, simultaneously obtained information about small-scale structures and dynamics to distinguish among many possible interactions and configurations. Specifically, it is crucial to see into the subarcsecond regime (50-500 km) and to identify and record phenomena in seconds rather than minutes to understand the dynamics of emergence and disappearance of flux. Small structures (~100 km) and correspondingly short timescales (~10 s) in the solar plasma temperature, density, velocity, and vector magnetic fields seem to control much of the dynamics that we do see.

Theory and numerical modeling are being used to bridge this gap, making increased use of supercomputers and simulation techniques. Macroscopic observables are estimated computationally assuming certain mechanisms and configurations which have been postulated but which have not yet been verified by direct observation. This approach will bear more fruit as corresponding observational improvements are made.

Clearly one direction of future research will be to obtain adequate resolution in time and space of the elemental flux tubes as they emerge. Rare pictures under conditions of particularly good viewing yield marginal resolution of some 100-200 km structures. To study emergence, submergence, and reconnection quantitatively will require not only better spatial resolution but also the capability to obtain a whole series of high resolution shots reliably. Space-based telescopes and instrumentation meet these criteria in a way that ground-based observations cannot match.

While theory can lead observation in some areas, it necessarily lags behind in others. Our theoretical understanding does not even encompass some large-scale solar phenomena which have become well established in the last two or three decades. Magnetic activity and related transient phenomena seem to present particularly difficult theoretical problems. Examples of observations waiting for a quantitative theory are coronal heating, solar prominences, coronal transients, the equatorward migration of the sunspot belts from the beginning to the end of each solar cycle, the acceleration of the solar wind, and the solar dynamo itself.

The problem of magnetic flux emergence is receiving more attention with the realization that most of the energy available in the magnetic flux beneath the surface already has been liberated in expansion by the time the persistent magnetic field configurations above the surface have formed. These dynamic flux-emergence problems are very difficult to solve and there has been little incentive to do so since magnetic transients in the low corona have rarely been seen. Though proposed, for example, as flare triggers, or as the output of reconnection, fine-scale magnetic transients have defied all attempts to measure them quantitatively because of the small length and time scales involved. And while there exist many examples of the emergence of a bipolar flux loop through the solar surface, observation of the submergence or disappearance of such loops is generally ambiguous. Only recently a few puzzling cases of 'unipolar' flux emergence or decay have been seen in which the other polarity footprint is missing or hidden.

The second observational issue, detecting weak, large-scale patterns, affects our understanding both of flux disappearance and of the magnetic dynamo-solar cycle. The relationship between the solar cycle and large-scale magnetic flux dispersal across the solar disk resulting from the combined action of the Sun's differential rotation and random walk diffusion has been recognized for two decades. More recently, poleward meridional flows have been invoked to help
explain this large-scale motion of flux and the timing of the polar field reversal. Measurements of meridional flow are difficult, however, and require extraction of ~10 m/s flows over a large area where km/s transient flows are present almost everywhere. Correlating these flows with magnetic fields near the Sun’s poles is further complicated by limb effects which degrade observations and by magnetic fields which lie almost perpendicular to the line of sight.

With roughly two complete solar cycles of regular full-disk magnetic data now available, solar physicists are beginning to understand the evolution of the large-scale, long-lived magnetic patterns. These features must now be related to the large convection cells beneath the solar surface, and hence to the solar dynamo, which may be driven in part by this “giant granulation.” Again, space-based observation will be the key to achieving the continual coverage in both area and duration that is needed to average out short period oscillations and transients effectively.

CHAPTER 4 - MHD WAVES AND TURBULENCE IN THE SUN AND INTERPLANETARY MEDIUM

The deliberations of the working group centered on the current state of knowledge concerning the existence, nature and dynamics of MHD waves and turbulence in the solar atmosphere and interplanetary medium. We first considered remote-sensing observations of global oscillations of the Sun, of nonthermal motions in the chromosphere, transition region, and corona, and their possible interpretations in terms of waves or turbulence. We next considered the region of solar wind acceleration; here coronal imaging, resonance-line spectrometry and radio techniques provide the relevant observations. We then considered fluctuations and discontinuities in the interplanetary medium itself, in which the primary data come from direct sampling of the plasma by spacecraft-borne magnometers and plasma analyzers. We do not address microscopic plasma instabilities or waves/turbulence and there is no attempt to provide a comprehensive review of any of these topics; rather the goal has been to assess how successful past attempts to close theory and observation have been, and to obtain a sense of where future advances may lie.

The energy source of the solar wind is still not known. It is generally agreed that heating or acceleration must occur over an extended region, probably governed by MHD waves/turbulence. Indeed, several studies of radio signals passing through the corona are consistent with existence of a field of large-amplitude fluctuations extended 10-20 solar radii out from the Sun. Such a wave field would exert an outward force on the solar wind plasma, thus accelerating the wind. Dissipation of the waves would heat the plasma (note that observed interplanetary proton temperatures are much hotter than they would be if their adiabatic cooling were modified only by thermal contact with the electrons).

A number of wave-driven models of the solar wind have been developed: models postulating a magnetoacoustic wave field invoke wave dissipation by Landau damping; models postulating an Alfvénic wave field invoke dissipation by nonlinear processes. Both kinds of models are readily tuned to give good agreement with interplanetary observations. Certainly both processes could be acting simultaneously. Observations of the flow and fluctuations within a few tens of solar radii will be necessary to determine which, if any, wave processes are operative. Optical and radio techniques (summarized earlier in this report) are valuable probes of this near-solar region that have only begun to be applied. However, these techniques involve integration over the line of sight, and the associated ambiguities of interpretation may not admit definitive evaluation of wave-driven models. Resolution of this question probably awaits in situ measurements from a space probe in the near solar region.
The wave-driven models also are incomplete in principle. The required amplitudes are large enough that nonlinear effects may be important (indeed the dissipation of Alfvén waves would have to be nonlinear). The physics of large-amplitude hydromagnetic waves in collisionless plasma is only partly understood, and this area is an important element of future progress. If the interplanetary fluctuations are in fact the remnant of fully developed turbulence in the near solar region, nonlinear processes are clearly central. It is conceivable that the wave models (based essentially on linear theory) could be completely misleading.

Interplanetary waves and turbulence are thought to play a significant role in governing a number of processes in the interplanetary medium. For example, even though the solar wind is quite collisionless, the He** generally flows faster than the H*, by as much as the local Alfvén speed. This fact is probably a signature of interaction with waves. At 0.3 AU the associated energy flux may be substantial. Thus, the helium may play an important role in the energy balance, which has not yet been elucidated. Another unexplained class of ion observations is that the ionic kinetic temperature tends to be higher than the proton kinetic temperature by a factor of the order of the ion mass ratio. This behavior is probably another manifestation of wave/turbulence.

Although there is convincing evidence for the solar origin of the Alfvénic component of the interplanetary fluctuations, other kinds of hydromagnetic fluctuations may be generated locally. A familiar example is the large-amplitude compressive turbulence associated with the interface between fast and slow solar wind streams. The firehose or mirror instabilities may regulate the anisotropy of the interplanetary plasma. There is ample evidence for hydromagnetic waves generated by particle beams from planetary bowshocks. The beams in turn are eventually disrupted by the waves they have generated. Hydromagnetic waves may be significant in the acceleration and scattering of energetic charged particles by Fermi acceleration and pitch-angle scattering. Waves and turbulence may also play a large role in governing transport processes involving ions and electrons of the main solar wind plasma. These and many related topics have been discussed over the past two decades, but very little has been accomplished in the way of verifying the operation of specific mechanisms.

CHAPTER 5 - COUPLING OF THE SOLAR WIND TO THE MAGNETOSPHERE

A simple assessment of our present understanding of solar wind-magnetosphere coupling can be made in terms of the four major questions that were posed. The first of these questions is concerned with the process of solar wind plasma entry. Although solar wind plasma entry is not totally understood we do have observational evidence for the efficient injection of plasma through the cusps and into the plasma mantle. The open magnetic topology which is likely associated with reconnection and flux transfer events is at least partially responsible for cusp entry and possibly also for some plasma transport into the low-latitude boundary layer. Impulsive plasma injection also appears to be a quite reasonable hypothesis for the localized efficient injection of plasma into the low-latitude boundary layer. Finally, a number of cross-field diffusion processes have been proposed as closed model entry processes.

Further progress on plasma entry will require energetic particle and plasma measurements with high time resolution and high resolution in phase space, coupled with electric and magnetic field and plasma wave measurements with good coverage of the dayside magnetopause. Full 3-D plasma and particle distribution measurements are especially needed in the region of the outer cusp and the dayside boundary layer poleward of the cusp. Moreover, continuous measurements of the properties of the upstream solar wind in the vicinity of the Earth are critically important for future experimental studies of the solar wind-magnetosphere interaction. The different models that have been proposed to explain plasma entry must be refined into theories that can
be tested by plasma and field measurements. Since reconnection is a major candidate process, suitable modifications to the original Petschek (1964) theory should be made to treat the three dimensional aspects of the solar wind interactions and to examine the kinetic theory of the reconnection diffusion regions.

The second question concerns the processes of energy and momentum transfer from the solar wind to the magnetosphere. In this area we know that both open- and closed-model processes are important. The open models that result from steady-state reconnection and flow transfer events readily provide qualitative explanations for the response of magnetospheric convection and substorm activity to changes in solar wind parameters. On the other hand, closed-model processes are needed to explain the minimum polar cap potential drop of some 15 kV. This minimum potential is likely associated with the low-latitude boundary layer acting as an MHD generator on closed magnetic field lines. The suitability of the impulsive plasma injection model should be more fully explored and tested against spacecraft plasma measurements near the magnetopause. ISEE satellite measurements of waves and structure near the magnetopause provide valuable new information relevant to momentum transport via mechanisms such as the Kelvin-Helmoltz instability.

The third question deals with the physics of magnetospheric boundary layers, specifically their role as generators, loads and plasma transport regions. A major result of recent spacecraft programs has been the establishment of the existence and importance of these boundary layers. A more advanced level of understanding of magnetospheric boundary layers requires high-resolution measurements of their structure and dynamics. Theories of boundary-layer formation need to account for both MHD and kinetic effects and to establish the relationship of these effects to time-varying solar wind parameters.

The final question concerns the global magnetohydrodynamics that characterize the magnetosphere for the various coupling processes and as functions of solar wind parameters. Already the MHD models are capable of approximately describing the coupling between various magnetospheric regimes. As a complement to the global MHD models, magnetostatic equilibrium models are capable of describing the configuration of the quiet magnetosphere with higher spatial resolution. Both approaches to global modeling have now been extended to treat the system in three dimensions. Development of complete models will require an enhanced ability to specify coupling processes and boundary conditions such as the plasma distributions and current systems that characterize the various magnetospheric boundary layers.

The variety of magnetospheric phenomena discussed in this chapter leads to a number of unresolved physical questions that need to be answered in the light of observations, as well as from a theoretical point of view. In order to advance our present understanding, we recommend consideration of the following items:

1. There is observational evidence that the plasma near the magnetopause boundary, and near the plasma sheet boundary as well, is often highly anisotropic. Moreover, we know that some plasma drift mechanisms ultimately lead to an energy dispersion of the thermal plasma. Consequently, global MHD models for the magnetosphere, and magnetohydrostatic equilibrium models as well, should be formulated eventually in terms of multifluid codes and in terms of anisotropic thermal plasma pressure.

2. There is an overall agreement that the interaction between the plasma and the magnetic field within discontinuity regions (e.g., the magnetopause and the plasma sheet boundary layer) is dominated by microphysical plasma processes. The global fluid models need macroscopic physical quantities in their basic equations. It is, therefore, necessary to have a global model for
the resistivity at the magnetopause. Such a model could be obtained from observations or
derived from the kinetic theory. For example, information is essential for a proper calculation of
the normal magnetic field component \( B_n(x) \) at the magnetopause.

3. At the magnetopause, the quantity \( j(x) \cdot E(x) \) is a measure of the conversion rate of magnetic
into mechanical energy and vice versa. The Chapman-Ferraro current density \( j(x) \) is determined
uniquely by the distribution of the magnetic normal component \( B_n(x) \) at this boundary. Is it pos-
able to derive macroscopic boundary values \( B_n(x) \) on the basis of kinetic arguments (see item 2)
in order to calculate the global energy conversion rate at the magnetopause?

4. The magnetic normal component \( B_n(x) \) determines the "openness" of the magnetosphere,
the size of the auroral oval, and the ionospheric convection \( E \)-field pattern. The polar cap
electric field is assumed to reflect the solar wind \((vxB)\) field under the assumption that the ideal
MHD theory is applicable. We know, however, that there exist significant magnetic field-aligned
electric fields along the auroral oval. To what extent do field-aligned electric fields affect the
polar cap convection \( E \)-field which is mapped from the solar wind through the magnetopause
down to the ionosphere?

5. Sources for the plasma sheet are thought to include the ionosphere, the low-latitude
boundary layer, and the plasma mantle. Are these known plasma sources sufficient to account
for plasma sheet replenishment on substorm time scales?

6. Can we improve measurements and understanding of the minimum polar cap potential
during extended quiet periods with northward interplanetary magnetic field \((IMF)\)?

7. From the standpoint of global modeling as well as from our understanding of the time-
dependent reconnection process, it is vital to obtain improved kinetic theory of the diffusion
regions at the reconnection site.

8. Are flux transfer events the "debris" or active signatures of reconnection? Are they
possibly associated with "impulsive injection events" or finite plasma filaments?

9. Can statistical analyses using solar wind and magnetospheric parameters be used to com-
pare the relative efficacy of driven versus indirectly driven models of magnetospheric response
and of closed versus open models of coupling? The results of such studies could act as a guide
to the development of better theoretical models of solar wind-magnetospheric coupling.

10. Does the average plasma flow in the plasma sheet correspond to the predictions of MHD
convection models? Observations of this flow and of \( B_z \) can give the pattern of the convection
electric field. This pattern is likely to be quite different for open- and closed-coupling proc-
esses. Thus, these observations can provide a check on the importance of both processes as
well as on the validity of convection models.

11. A tangential component of the electric field at the magnetopause is predicted as a con-
sequence of magnetic field reconnection, and thus electric field measurements at the magneto-
pause are especially important. Special efforts should be made to develop and apply improved
definitive measurements of vector electric fields at the magnetopause.

Our evaluation of the solar wind-magnetosphere coupling problem leads us to emphasize the
importance of the boundary layers as the primary transport and coupling regions for the magnetos-
phere even though they constitute \(<5\%\) by volume of the total system. We recommend that
future observational and theoretical studies should focus on these boundary regions to deter-
mine the boundary conditions that they impose on the magnetospheric system and to isolate the
dominant coupling processes.
CHAPTER 6 - CORONAL TRANSIENTS AND THEIR INTERPLANETARY EFFECTS

A statistical association between solar flares and geomagnetic storms has been widely accepted since early in the 20th century, and the interpretation of this effect in terms of an expulsion of material from the Sun has been a commonplace in the field of solar-terrestrial physics for nearly as long. In situ observations of outward-propagating interplanetary shock waves made in the 1960s provided direct evidence for such a phenomenon. The masses inferred from the shock wave observations implied that their passage through the solar corona should produce major perturbations of that region. Thus the first identifications of coronal transients or mass ejections by spacecraft-borne instruments in the early 1970s were of interest to a far broader group of scientists than those who specialized in this most tenuous domain of solar physics. The role of coronal mass ejections in solar-terrestrial physics, or more specifically, in the chain of cause and effect introduced above (solar flare-interplanetary shock wave-geomagnetic storm), has remained an important, continuing theme in the study of mass ejections. Analysis of the "first generation" of these coronal observations, development of theoretical models of mass ejections, and comparisons with both solar and interplanetary data have yet to provide definitive answers to the first two questions that arise in pursuit of this theme: (1) What are the solar origins (in both a phenomenological and physical sense) of coronal mass ejections, and (2) What are the interplanetary effects of coronal mass ejections?

These two fundamental and familiar questions concerning the role of coronal mass ejections in the context of solar-terrestrial physics were the foci of our discussions at this workshop. In this document, we first describe some of the necessary background material on flares and geomagnetic storms, on interplanetary shock waves, and on coronal mass ejections themselves. We then describe one of the modern "tools" available for approaching these questions -- theoretical models for the initiation and propagation of transient phenomenon in the solar corona. All of this material has been extensively reviewed in the recent literature, and our coverage of it will be both selective and somewhat abbreviated. We then describe the second our our "tools" -- a new generation of coronagraph observations of mass ejections and complementary set of solar and interplanetary observations suitable for correlative studies.

Several studies of solar wind data have the potential of both improving our understanding of the interplanetary effects of coronal mass ejections and yielding information on the physical mechanisms of the ejections themselves. Some of these topics can be pursued using existing data bases but others require development of new experimental opportunities using state-of-the-art instrumentation.

Magnetic Topology of Driver Gas. Coronal images of mass ejection events show nested loops of bright material moving away from the Sun. At present it is not clear whether these loops represent density-loaded magnetic field lines or shock fronts. If they outline magnetic field lines, as is often assumed, the role of magnetic reconnection before, during and after 'lift off' reappears as an important question. The bearing of this question on the mechanism driving the mass ejection suggests considerable attention in future research. Quantitative analyses of existing solar wind and energetic ion data may provide some useful clues in this regard.

Heavy-Ion Spectroscopy. The ionization state of the solar wind provides information about electron temperatures in the corona between about 1.1 and ~6 solar radii. Any such information bears on the processes that expel coronal plasma. Interpretation of these data would be facilitated by analysis of simultaneously observed soft X-ray images of coronal regions in the neighborhood of disappearing filaments.
Theoretical Models of Chemical Fractionation Mechanisms. A characteristic feature of solar wind plasma associated with the shock-wave driver gas and hence some coronal mass ejections is enhanced yet variable $^4\text{He}$ abundance. Although detailed analyses have not yet been completed, a large data base of $^3\text{He}$ abundances measured aboard ISEE-3 is available to investigate whether $^3\text{He}$ varies in a manner similar to $^4\text{He}$. Regardless of the outcome of such a study, the causes of the known, strong $^4\text{He}$ variations must bear on conditions in, and/or dynamical processes operating within the solar atmosphere near the sites of coronal mass ejections. However, very little is presently known about the mechanisms which can cause chemical fractionation in such regions. This is a wide open field of theoretical endeavor and any information could help organize a large body of data that may prove relevant to the physical mechanisms leading to mass ejections.

Correlative Studies of Coronal Ejections and Their Interplanetary Effects. A fundamental uncertainty in the study of coronal mass ejections is their three-dimensional geometry. Neither 2-D measurements such as provided by coronagraph and X-ray images nor 1-D measurements such as provided by in situ solar wind measurements have resolved this problem. However, a combination of pertinent coronal white-light and X-ray images, type II radio emission intensities, satellite-source radio scintillation measurements, and multipoint in situ measurements are available. A coordinated analysis of these data could yield much detailed information concerning the nature and spatial structure of the driver gas, the spatial relationship between the bright loops so prominent in coronagraph images and a possible shock front near the corona, the 3-D global extent of the resulting interplanetary disturbances and the effectiveness of coronal mass ejections in generating interplanetary shocks.

Type II Generation Mechanism and Spatial Extent. Before type II radio emissions can be used as a sensitive quantitative tool for exploring coronal mass ejection mechanisms and their interplanetary effects, it is first necessary to understand the physical mechanisms which convert a plasma disturbance to radio waves. Although there is overwhelming evidence to indicate that type II emissions come from shock wave disturbances, the relationship known from in situ measurements is not one-to-one. However, recent advances in our understanding of the processes which lead to electron acceleration and wave generation in collisionless shocks lead us to believe that a concerted effort to understand type II emission mechanisms using ISEE-3 data should lead to substantial progress.

CHAPTER 7 - CONNECTION BETWEEN THE MAGNETOSPHERE AND IONOSPHERE

Two decades of space research have produced ample evidence that particles and fields originating in the active Sun can gain entry into the terrestrial magnetosphere and deposit their energy in the ionosphere and atmosphere. The final link in this solar-terrestrial chain is generically referred to as magnetosphere-ionosphere coupling (MIC). Included in the physics of the MIC processes are not only plasma processes associated with the earthward deposition of energy of the active Sun but also the response of the ionosphere-atmosphere system to the energy deposition. Because of its key position in the physics of the near-Earth space environment, MIC processes have been a major focus of space research.

Up until the past several years, the important issue in MIC was the role of the ionosphere in magnetospheric field configuration of the global scale. Through comprehensive formulations of MIC theory the schematic relationships between magnetospheric magnetic and electric configurations and ionospheric plasma flow have been elucidated. Thus, the ionosphere-atmosphere, through dissipative processes inherent in the finite ionospheric conductivity, is thought to regulate the electrodynamic circuit driven by the interaction between the magnetosphere and the solar wind at the magnetospheric boundary.
Despite the highly successful elucidation of the schematic features of MIC by global-scale theory, it soon became clear that MIC involves much more complex plasma kinetic effects. This significant change of theoretical perspective since the latter part of the 1970s was due to plasma and field observations by auroral satellites in the ~1 Re altitude region and by rocket chemical releases. New observations from these auroral satellites have not only confirmed previous suspicions that a parallel electric potential drop may interface with global MIC processes but have also introduced entirely new kinetic phenomena such as upflowing ionospheric ions and complex wave-particle interactions. These are likely to change our perspective of the role of the topside ionosphere in MIC processes. Recent observations of polar region auroral phenomena have indicated that our picture of magnetospheric topology may need to be revised. In short, we have witnessed in the last 4-5 years a dramatic change in perspective on the physics of magnetosphere-ionosphere coupling.

Because of the far-reaching implications of recent discoveries in MIC and because a coherent assessment of them has yet to be made, the principal task in this group was to critically assess these new observations and the new perspectives that they may engender.

Based on our assessment of the progress in magnetosphere-ionosphere coupling physics in the last five-six years, we envisage a period in the near future in which basic and global issues in MIC will be addressed observationally and theoretically. These expectations are derived from the following general conclusions:

- Magnetosphere-ionosphere coupling (MIC) encompasses a complex set of interacting phenomena occurring on vastly different time and spatial scales rather than a set of isolated processes.

- Energy flow in the ionosphere-magnetosphere system is primarily from the magnetosphere to the ionosphere. However, it is now clear that the ionosphere is not a passive element in this system. The spatial distribution of ionospheric conductivity affects magnetospheric plasma transport and the configuration of the magnetospheric current systems. Atmospheric motions may significantly modify magnetospheric plasma circulation. Furthermore, a substantial portion of the plasma population of the magnetosphere originates in the ionosphere.

- Theory has developed considerably along with observation for electrodynamic coupling and related turbulent phenomena. However, the present state of theoretical development does not adequately address the feedback onto the magnetosphere from the dynamic ionospheric response to these processes. Currently, such theoretical analyses are just beginning but are required for complete understanding of magnetosphere-ionosphere coupling.

- The global scale theories of magnetosphere-ionosphere coupling have matured to the point that it is possible to test their assumptions and predictions. Thus, experiments can be designed to test specific aspects of our theoretical understanding of global scale magnetosphere-ionosphere coupling.

While the above general conclusions are concerned with the scheme of magnetosphere-ionosphere coupling as an integrated whole, we have also identified the following pressing issues which address specific areas of MIC:

- Global imagery of the aurora in optical, UV and X-ray is needed to determine a coherent picture of the global configurations of MIC.
What is the specific spatial and temporal relationship between global-scale field-aligned current (J ||) systems, auroral potential structures, and auroral arc structures?

What and where are the generators of the entire scale spectrum of field-aligned currents? In particular, is the MIC dynamo a voltage generator or a current generator? What is the nature of the auroral return current? How does upper atmospheric circulation affect magnetospheric current flow?

Because auroral phenomena are generally associated with topological boundaries of magnetospheric regions, three-dimensional models of the magnetospheric electric field structure is needed.

Quantitative models of ionospheric influence upon magnetospheric phenomena are needed. In particular, the importance of the ionospheric plasma source and of the influence of ionospheric conductivity upon MIC dynamics must be addressed quantitatively.

At present there is a paucity of theories of auroral morphology in relation to MIC processes in the dayside and in the post-midnight sectors.

It is by now clear that auroral plasma kinetic characteristics show both adiabatic and diffusive signatures. However, the feedback effects of wave turbulence generated by the auroral electron beam upon the distribution of \( E || \) have not been quantified.

Currently, there is a noticeable lack of theories of dynamic auroral processes such as the westward traveling surge.

Since auroral arcs at very high latitude regions can involve plasmas from the magnetosheath and from the plasma sheet, quantitative theories of formation for such arcs are needed to understand their relationship to the oval arcs.

Auroral kilometric radiation (AKR) reflects detailed structures of plasma processes of its source region, therefore, AKR can be used as a remote diagnostic tool of MIC processes. Once terrestrial AKR processes are understood, this diagnostic tool can be applied to MIC processes in other planets.

Auroral wave-particle interactions depend on kinetic characteristics of the plasma. Some of these characteristics may result from the plasma transport itself, therefore, it is important to quantitatively understand the kinetic theory of auroral plasma transport.

CHAPTER 8 - SUBSTORMS IN THE MAGNETOSPHERE

In this report a working definition of substorms was developed, the primary relationships within the solar wind-magnetosphere-ionosphere system as they relate to substorms were considered and the role that substorm studies play in the overall discipline of solar-terrestrial research was clarified. In pursuing the last of these topics, the working group addressed the question of which aspects of magnetospheric activity are directly driven by the solar wind and which aspects of this activity represent an unloading process for previously stored solar wind energy.

Substorm studies really comprise a global examination of the interrelationships between many detailed physical processes (see the reports of Working Groups 1, 2, 5, 7, and 11). Furthermore, substorms are a complex combination of the driven and unloading processes which are described in some detail in the body of this report.
EXECUTIVE SUMMARY

Significant progress has been made in understanding substorm phenomenology and, to a large extent, in understanding the underlying physical mechanisms. Nonetheless, considerable disagreement and uncertainty remains. In studying substorms, we are struggling with a truly staggering global problem wherein experimental probing and/or theoretical modeling must deal with extreme variations in scale sizes. To a very large degree, the era in which a single scientific instrument on a single spacecraft can add substantially to the knowledge of substorm processes is past. Global measurements, combined with realistic global 3-D numerical simulations, probably hold the greatest promise of advancing our understanding significantly.

Substorm research has established that a variety of phenomena (e.g., auroral break-up, injections at synchronous orbit, and reconnection signatures in the distant magnetotail) occur at widely separated locations in association with the expansion phase onset. Further research -- both theoretical and observational -- is needed to gain a more detailed, quantitative understanding of the interrelationships among these various phenomena. In particular, the following questions need to be addressed.

- What is the nature of the energy transfer mechanisms between the presumed energy storage reservoir in the magnetotail and the various sites of energy dissipation? Proposed transfer mechanisms such as compression waves and field-aligned currents have been developed only qualitatively to date.
- How do these energy transfer mechanisms relate to and/or arise out of the reconnection process?
- What are the propagation time delays between the magnetotail and the inner magnetosphere/ionosphere, and what ramifications do these delays have for substorm dynamics?

A complete understanding of any given magnetospheric process requires that the role of that process in the global dynamics of the magnetosphere be identified. An essential aid to attaining this global perspective is the world-wide array of all-sky camera, magnetometers, riometers, and other monitors of magnetospheric processes. Note that all points in the outer magnetosphere -- roughly, beyond synchronous orbit -- have their magnetic footprints in auroral and polar regions. A suitably spaced array of stations in these regions thus provides a vital means of continuously monitoring the state of the magnetosphere on a global scale. To fully exploit this monitoring capability, further progress is needed in identifying the ground signatures of specific magnetospheric processes and in improving ground-based indices of energy flow and dissipation.

The auroral electrojet indices (AE, AU, AL) have been extensively used as measures of the auroral electrojet intensity and magnetospheric substorm activity. Their accuracy and limitations have been discussed to some extent by several authors but there had been no systematic way to evaluate or calibrate them. The AE index is an important and useful index when it is used properly, but one must be carefully aware of, and take into account, its limitations. During recent years, the AE(12) index has been used frequently for purposes which require accuracy well above that of the presently available index.

We firmly believe that future correlation studies between the AE index and solar wind quantities must be based on an improved AE index. Moreover it is crucial to continually improve geomagnetic indices and estimates of the global energy dissipation rates for there to be new advances in this particular area of magnetospheric substorm studies.
One of the most important problems in substorms studies has been to examine how the energy accumulated in the magnetotail varies during magnetospheric substorms. Satellite measurements of the magnetic field magnitude, B, provide a measure of the magnetic energy density \( (B^2/8\pi) \) which may be characteristic of the entire volume of the magnetotail. However, B is sensitive to changes of the solar wind pressure and of the local plasma pressure. Furthermore such data usually represent only a single point measurement and the data are only available for limited periods. Therefore, it is important to look for a measure of tail magnetic energy, which is continuous and which is not subject to great uncertainty. One such new measure may be the "diameter" of the auroral oval, since the total open flux in the tail is expected to be roughly proportional to \( B_G(d/2)^2 \) (where \( B_G \) denotes the vertical component of the magnetic field in the polar cap region) and since an increase of the diameter \( d \) indicates an increase of the open flux.

In a related vein, a phenomenon that is observed with striking regularity in the magnetotail beyond \( r = 15 R_E \) is the thickening or recovery of the plasma sheet during the subsidence of negative bays at nightside auroral zone stations. In fact, the plasma sheet thickening sometimes seems to occur in very close coincidence with peak bay activity and with the beginning of final recovery of auroral zone bays and with the onset of bays at low polar cap locations. Thus it has been inferred that a "poleward leap" of the electrojet occurs in coincidence with the plasma sheet's recovery is ascribed to a sudden tailward retreat of the substorm neutral line to large distance. Lobe plasma, carried by convection into the neighborhood of the neutral line and jetting earthward from it, threaded with contracting, newly reconnected field lines is thought to be the material reconstituting the plasma sheet. Theoretical and modeling studies should be directed toward understanding the retrograding neutral line phenomenon.

The conventional description of the auroral substorm contains no reference to the poleward leap, but has the auroras moving to high latitudes during the expansion phase and then retrograding gradually to lower latitudes during a "recovery" phase. The later phase of substorms needs to be studied with the advanced equipment now available (magnetometer chains, auroral imaging from satellites, high-latitude auroral radars) to determine more precisely the features that are attendant upon the retrograding neutral line and plasma sheet recovery.

The interface between the plasma sheet and the tail lobe is a region where very dynamic processes are often found including plasma jetting, beams of energetic particles, and intense plasma waves. These processes are particularly prominent as the interface (i.e., the boundary of the plasma sheet) surges over a satellite during plasma sheet recovery. It is not surprising, in light of the neutral line model of substorms, that this interface should be a site of activity since it contains magnetic field lines connected directly to an X-type neutral line. This interface should receive detailed study both to derive information it may reveal regarding the reconnection process and to further our understanding of the substorm sequence, particularly the phenomena of plasmoid ejection and the retrograding substorm neutral line.

As we consider substorm energy dissipation, we realize that a reasonable first-order estimate can regularly be made for ring current injection rates, Joule heating rates, and auroral particle precipitation rates. Since these dissipation rates can be (at least roughly) estimated, they can be related to quantitative energy input estimates derived from dayside reconnection models, viscous interaction models, etc. A major remaining deficiency as we consider the partitioning of the available input energy is determining (on a regular and routine basis) how much energy simply escapes down the tail in the plasmoid structure. Methods should be developed to monitor this component of substorm energy dissipation.

In the area of injection and energization of hot plasma in the outer equatorial magnetosphere, several problems remain outstanding. Among these are:
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- What is the role of global convection relative to the role of impulsive injections in the formation of the ring current?

- What is the nature of the earthward-propagating compressional waves observed in association with impulsive injection events? In particular, can present models of tail collapse give rise to such a wave?

- Are there other mechanisms that can be invoked, beside the observed compressional wave, to account for impulsive, dispersionless injection events?

- What is the relationship between the injected hot equatorial plasmas and the field-aligned currents which occur in association with substorm auroral displays?

To attack these and other questions in this area, we must experimentally determine the detailed spatial structures of the injection boundary/injection front. Furthermore, very detailed multiple-satellite timings of events in the tail, in the near-geostationary environment, and on the ground must be made in order to relate the earthward injection of hot plasma to substorm processes in the more distant tail. Detailed numerical models being developed to describe tail dynamical processes should be modified to include compressional wave propagation (if possible) and hot plasma injection characteristics. Finally, detailed statistical and event analyses need to be performed in order to relate hot plasma distributions to field-aligned current structures and ring current development.

Numerous other problems remain to be addressed. For example, the mechanisms for triggering plasma sheet instabilities that may be responsible for substorm expansion onsets remain largely undetermined. Detailed theoretical analyses of the possible role of ionospheric ions in lowering plasma sheet instability thresholds should be undertaken and appropriate experimental investigations should be performed. In fact, the entire area of heavy ions in magnetospheric dynamics is just opening up and, furthermore, the appreciation of positive feedback loops (as those involving the ionosphere) is only beginning to come about. As observations have improved and as theory has progressed there has developed a further realization of the very significant analogy which exists between the explosive acceleration of energetic particles in the Earth’s magnetosphere during substorm onsets and on the Sun during solar flare onsets. As we compare and contrast various parts of the solar-terrestrial system, we should more fully exploit such analogous processes in sub-disciplines that are often far-removed from one another.

CHAPTER 9 - IMPACT OF FLARES ON THE SOLAR TERRESTRIAL ENVIRONMENT

The solar flare is one of the most dramatic phenomena in nature. A large amount of energy, in the form of photons and plasma and energetic particles, is released suddenly from the solar atmosphere and impacts the entire solar-terrestrial environment, from the Sun, through the heliosphere to the Earth and beyond. Flares generate natural phenomena such as shock waves and geomagnetic storms; flares affect man’s technology and his ability to survive in space. It is the purpose of this chapter to assess our current understanding of these impacts.

A study of the impacts of solar flares encompasses many of the phenomena that are considered in detail in other chapters of this document. Solar flares are examples of particle acceleration, solar flares affect solar wind-magnetosphere coupling and magnetosphere-ionosphere coupling. We are concerned here only with the effects which are the direct and unique results of solar flares.
Solar flares impact the entire solar-terrestrial environment and cause a host of phenomena, some of which have received considerable study in recent years. Yet despite this study, there are some fundamental points, and many missing details of the impact of solar flares, that remain to be understood which include:

- The flare process yields electromagnetic radiation at all frequencies from radio to gamma rays, energetic particles from solar wind energies to GeV, and enhanced solar wind flow. This radiation and particles provide us with detailed diagnostics of the flare process. Yet with the current observational techniques we do not know the exact location where the flare energy is released, and as a result the exact physical conditions at the flare site. More detailed, higher resolution observations are necessary. These observations can serve as the basis for comprehensive theories of the energy release in solar flares and for shock generation, which do not currently exist, and ultimately for developing models to predict the occurrence of solar flares.

- Solar flares impact the heliosphere primarily through the enhanced solar wind flow that they generate, and the accompanying shock waves. These flows and shocks can heat the solar wind, modulate and accelerate energetic particles, and cause deviations in the direction of the interplanetary magnetic field out of the ecliptic plane which cause geomagnetic disturbances. More comprehensive theories need to be developed to describe the dissipation of enhanced solar wind flows into heat, and the interaction of energetic particles with these flows. For example, theories of galactic cosmic ray interaction are very rudimentary; theories for shock acceleration of energetic particles have developed rapidly in the last several years but need now to be applied in comprehensive models of realistic shocks. Similarly, the mechanisms for causing variations in the interplanetary magnetic field that can drive magnetospheric phenomena need to be understood more fully. Such understanding is an essential component in predicting the impact on the magnetosphere of a given flare.

- Solar flares are responsible for a wide variety of magnetospheric phenomena: they can generate storms and substorms, supply energetic particles to the magnetosphere, and influence the adiabatic and non-adiabatic motion of trapped particles. For some of these phenomena there are conceptual uncertainties that must be resolved; for example, the microscopic plasma processes that are responsible for solar wind energy conversion to magnetospheric phenomena need to be understood. Other phenomena are conceptually understood, but not in detail, e.g., aspects of storm and substorm dynamics, and details of charged particle transport and energization require study.

- Solar flare EUV and X-rays affect the ionospheric electron content and D-region chemistry; solar flare particles affect D-region ionization, ion/neutral chemistry including ozone, and atmospheric electricity. The physics of most of these effects is understood, but their global implications remain to be adequately modeled. For example, an adequate assessment and treatment of global sources, such as magnetospheric electron precipitation, or of global transport of disturbances, needs to be developed. Global modeling is essential if we are ever to determine whether solar flares, or any transient solar effect, influences the weather and/or the climate.

- Solar flares affect many activities in our technological world: radio, satellite and cable communication, power transmission, pipeline corrosion, and manned and unmanned spaceflight. Needed research in this aspect of solar flare impact is difficult to predict, other than to note that as technology becomes more sophisticated our knowledge of the natural environment which can impact that technology must become more detailed. For example, we must improve our modeling of the radiation belt environment of the magnetosphere to
satisfy the current and expected needs of spacecraft designers; we must determine the
scale-sizes of transient ionospheric and magnetospheric currents to set the design specifications
for long, groundbased conductors.

CHAPTER 10 - COLLISIONLESS SHOCK WAVES IN THE
SOLAR TERRESTRIAL ENVIRONMENT

Shock waves are created by the nonlinear steepening of compressive wavemodes in a fluid. Typi-
cally such steepening occurs when a disturbance travels through the fluid at a speed higher than
the characteristic speed with which small amplitude compressive waves can propagate. The shock
formed in front of such a disturbance is the means by which the disturbance communicates with
the ambient plasma into which it is propagating. At the shock the flow normal to the shock
must be changed from super-"sonic" upstream to sub-"sonic" downstream, where "sonic" refers
to the characteristic speed of the small amplitude pressure signals. In plasma this speed is
usually the magnetoacoustic speed. The loss of streaming energy represented by this slowing of
the flow at the shock is converted into other forms of energy. Broadly speaking a shock may be
defined as the entire region over which any portion of the conversion takes place. This
conversion must be accomplished via collisionless dissipation mechanisms. Identifying and
understanding dissipation mechanisms is therefore a central control of many shock studies.

Laboratory experiments, numerical simulations, and space observations all indicate that the
modes of dissipation at a shock depend sensitively upon upstream flow conditions, particularly
the Mach number of the flow, \( M \), and the angle between the local shock normal and the upstream
magnetic field, \( \theta_{BN} \), and the ratio of thermal to magnetic internal energy, \( \beta \). Shocks with Mach
numbers below some critical value, \( M_{C} \), are known as subcritical shocks, whereas those with
\( MD > M_{C} \) are known as supercritical. \( M_{C} \) itself depends upon such things as the upstream plasma
and \( \theta_{BN} \) but is usually within the range 2–3. The fundamental difference between these two
classes of shocks is that dispersion and anomalous resistivity provides most of the dissipation
for subcritical shocks whereas ion reflection at the shock plays an increasingly important role in
the dissipation process as the Mach number increases above \( M_{C} \). A fundamental change in shock
structure occurs also at \( \theta_{BN} \sim 45^\circ \) which is most evident as an increase in turbulence and the lack
of a well defined shock structure when \( \theta_{BN} \leq 45^\circ \). This provides a rough dividing line between
two further classes of shocks: quasi-perpendicular (\( \theta_{BN} > 45^\circ \)) and quasi-parallel (\( \theta_{BN} < 45^\circ \)).

Small amplitude waves can propagate through a plasma with different characteristic speeds
depending upon the mode of propagation. This difference leads to a further classification of
shock structure - slow, intermediate, and fast which, correspond to disturbances exceeding
respectively the slow magnetoacoustic speed, the Alfvén speed, and the fast magnetoacoustic
speed. Only fast shocks have been studied extensively; however, slow shocks have been observed
in the solar wind and may play an important role in field line reconnection processes. In this
report we concentrate exclusively on fast shocks, unless stated otherwise.

Collisionless shocks commonly contain a structural element known as the foreshock which is not
present in ordinary collisional shocks. The foreshock extends for a considerable distance
upstream from the main shock transition and contains suprathermal ions and electrons reflected
at the shock or transmitted through it from the downstream region. These ions and electrons
excite a variety of hydromagnetic and plasma waves, which in turn scatter the particles. As the
wave speeds are generally lower than the convection speed of the upstream plasma flow, the
waves are subsequently convected back toward the shock. Ultimately, scattering of the initial
"seed" populations of reflected and/or leaked particles off of these waves both up and down
stream from the shock can produce a significant acceleration of a small fraction of the ions to
very high energy. Such acceleration appears to be a ubiquitous feature of all shock waves
observed within the heliosphere.

Provided by the NASA Astrophysics Data System
Progress in our knowledge of collisionless shocks, with particular attention to the important contributions made by satellite instruments, has been reviewed extensively in the literature. In this report, we present a summary of selected information pertaining to the current status of our understanding of the physical processes in shocks. Much has been learned lately; even more is being studied and prepared for publication as this is written. Exposing the newest results and their relationships to each other is a major aim of this report.

The working group developed the following list to summarize the foremost outstanding problems, more or less in decreasing order of priority, that are expected to engage investigators of collisionless shock physics in the foreseeable future.

Quasi-parallel Shocks

What is their full field and particle structure?

What role does leakage of downstream into upstream plasma play in their profile?

How are their intrinsic properties separated from those dependent on communication with other sections of the same shock?

Quasi-perpendicular, turbulent shocks

How (by what instabilities) are ions actually thermalized initially in the shock ramp and more completely behind it?

Is there an electrostatic subshock?

Is there a second, supercritical Mach number? If so, what is it, what does it depend on, and how does it affect shock structure?

Where are the sources of seed ions and electrons for the foreshock?

What role do multiple reflections of ions play in the reflection process?

Quasi-perpendicular, laminar shocks

How are ions heated in the laminar shock?

Are standing waves stable? If not, what becomes of them?

Parametric Structure

What is the full, definable, macroscopic, quantitative categorization of shock structures by \( \beta \), Mach number, etc.? What nomenclature should be standardized to describe them, e.g., quasilaminar; quasi-turbulent?
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Ion Acceleration

How, if at all, do suprathermal ions at interplanetary shocks differ from those at the bowshock?

Electrons

What is the detailed origin of the flat-topped distributions?

What control does local geometry have on potential-drop heating of electrons?

Waves

What is the origin of ion sound turbulence?

What role do nonlinear wave-wave interactions play in shock wave dissipation?

How, if at all, do nonlinear plasma waves participate in the thermalization process?

Global Aspects

What is the large scale closure system of the shock currents?

Can (should?) structural factors be incorporated in the jump conditions in multifluid, MHD flow codes for planetary shocks?

To what extent does quasi-parallel/quasi-perpendicular geometry and its variability affect the overall solar wind–magnetosphere interaction?

The study of collisionless shocks can, and has been, pursued by laboratory experimentation, theory/simulation, and natural observation. Recent years have seen an abundance of observational data, and a rising use of numerical simulations. In contrast, laboratory experimentation has been abandoned, and purely analytic theory has been substantially curtailed. It is clear that in the immediate future the predominance of observation and simulation will continue. Nevertheless, each of these approaches has its advantages and its limitations, and none should be excluded from future consideration.

CHAPTER 11 · ASSESSMENT OF PLASMA TRANSPORT AND CONVECTION AT HIGH LATITUDES

The high-latitude ionosphere is strongly coupled to the thermosphere and magnetosphere. The magnetospheric coupling occurs via electric fields, field-aligned currents, and particle precipitation. Owing to the interaction of the shocked solar wind with the geomagnetic field, an electric potential difference is generated across the tail of the magnetosphere, with the resulting electric field pointing from dawn to dusk. Except for isolated regions, typically in the auroral oval, the geomagnetic field lines are equipotentials due to the high electrical conductivity along field lines. Consequently, this cross-tail potential difference is mapped into the high-latitude ionosphere as an electric field that is directed perpendicular to the geomagnetic field. At ionospheric heights, this perpendicular (or convection) electric field is typically 25–50 mV m⁻¹ in the polar cap, but can be much greater than 100 mV m⁻¹ in restricted latitudinal bands at certain times.

Provided by the NASA Astrophysics Data System