

CHAPMAN CONFERENCE ON MAGNETOTAIL PHYSICS

BACKGROUND

Comets are fascinating objects, distinguishable from other celestial objects by their visible elongated tails. If we could enhance the visibility of the space dominated by the intrinsic magnetic fields or the extended atmospheres of celestial bodies, we would find that many familiar objects in the sky, such as several planets in our solar system and even galaxies, possess extended tails much like those of the comets.

Most tail regions associated with celestial objects are well-ordered in terms of the gross magnetic field pattern within them and are referred to as magnetotails. For instance, the earth's magnetotail, which extends in the nightside for at least a million miles, is permeated by magnetic fields that point more or less toward the sun in the northern half of the magnetotail and away from the sun in the southern half. Between the two opposing regions of magnetic field there is a neutral sheet where the magnetic field strength is weak, about 1/10,000 of the strength of the magnetic field on the earth's surface. The region of the neutral sheet is considered to be an ideal site for a process called reconnection, where oppositely directed magnetic field lines are brought together and the associated magnetic field energy is dissipated by accelerating charged particles. Reconnection has been a prime candidate to account for many of the impulsive energy-release phenomena observed during space and astrophysics investigations. The neutral sheet is embedded in a slab of ionized particles (plasma) known as the plasma sheet. Figure 1 is a schematic diagram of the recent model of the earth's magnetotail, showing both the magnetotail's confinement and some of its complexity. The configuration in Fig. 1 differs dramatically from the concept in the prespace era in which the earth's magnetic field extended indefinitely into space as a magnetic dipole field.

The magnetotail is a very rarefied medium. If the matter contained within it were compressed to atmospheric pressure, all of it could be confined in a volume about equal to that of an office building. Despite its near-vacuum state, the magnetotail is an impressive electric power generator, with its energy output rate more than ten times greater than the average power consumption of a city the size of Baltimore.

Dr. Lui is a member of the Space Physics Group of APL's Space Department and was co-organizer of the Chapman Conference on Magnetotail Physics, held on October 28-31, 1985.

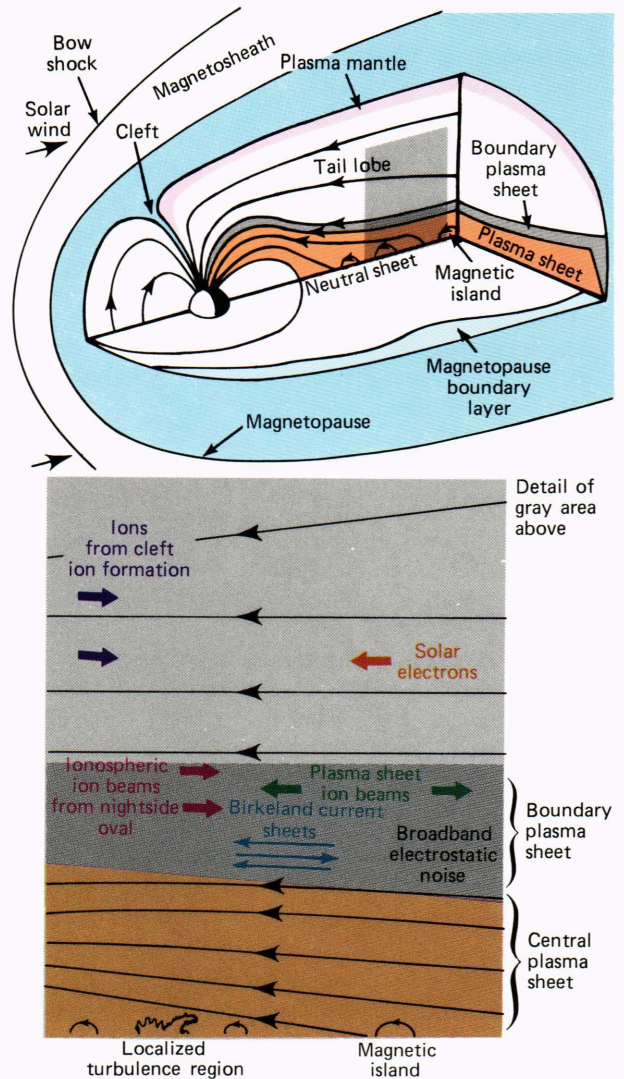


Figure 1—The distortion and confinement of the magnetic field on the earth's nightside to form an extended magnetotail are shown, in addition to several plasma regions with some detailed features. Many familiar objects in the sky possess elongated magnetotails like the earth. The magnetotail is now recognized as a gigantic powerhouse. Understanding the physical processes operating within it may someday help us to harness that energy source or to mimic the efficient particle energization mechanism present in this natural environment.

SOME MILESTONES

Modern space research with artificial satellites began in the late 1950s. Measurements from Explorers 6 and 10 indicated that the earth's magnetic field was distorted to form a magnetotail in the nightside. The mapping of the neutral sheet came with a later spacecraft (IMP-1) that was sent into orbit in 1963. Since then, many scientists worldwide have made extensive efforts to understand the formation of the magnetotail system and the physical processes operating in it. Through many subsequent spacecraft programs as well as efforts in computer simulations and theoretical analyses, the magnetotail is now clearly recognized to be a vital component of the complex plasma systems of planetary space. The ISEE-3 spacecraft extended the magnetotail survey from about the lunar distance (approximately 200,000 miles) prior to 1982 to about three times that distance by 1983. Brief glimpses of the tail were attained by Pioneer 7 as far as 500 times the lunar distance.

The AMPTE mission, with its three spacecraft launched in 1984, marked a new era of magnetotail research. On December 27, 1984, an artificial comet was created for the first time, permitting investigations to be made of the formation and dynamic evolution of the artificial comet tail. In addition, that mission performed four active experiments in the magnetotail by releasing tracer elements under selected magnetospheric conditions.

GOALS AND SESSIONS

Following these many exciting advances in research in magnetotail physics, a conference was held at APL's Kossiakoff Center on October 28-31, 1985 (a) to consolidate our understanding of the near-earth and distant tail observations, (b) to promote computer simulation as a tool for advancing our knowledge of complex tail systems, and (c) to enhance interchange of knowledge between research on the earth's magnetotail and investigations of the magnetotail of other celestial objects.

The conference was organized through the American Geophysical Union and was sponsored by the Air Force Geophysics Laboratory, APL, the Los Alamos National Laboratory, NASA, and the National Science Foundation. It was named after the late Sydney Chapman (1888-1970), who pioneered research in many scientific disciplines, including the modern kinetic theory of gases, geomagnetism, aeronomy, and magnetospheric and ionospheric physics. All special topical conferences organized by the American Geophysical Union honor him in this manner.

The magnetotail conference was the largest Chapman conference ever held. One hundred seventy scientists from the United States, Canada, Japan, and European nations attended, and 16 graduate students were awarded partial travel support to attend.

Sessions were designated by the following topics:

1. *Magnetotail Configuration*, which dealt with the

formation of the magnetotail and the basic processes in it;

2. *The MHD (magnetohydrodynamics) Aspects of Magnetotail Dynamics*, which covered the fluid-like aspects of the magnetotail dynamics;
3. *The Kinetic Aspects of Magnetotail Dynamics*, which addressed the behavior of individual particles and how their collective effects modify the system;
4. *The Active Diagnosis of the Magnetotail*, which emphasized the results of active experiments in the magnetotail and of the creation of artificial comet tails by the AMPTE program;
5. *Magnetotails of Other Celestial Objects*, which concentrated on the comparative approach to magnetotail research so that knowledge gained in the studies of tails of the earth and other celestial bodies can be exchanged;
6. *Dialog on Controversial Topics*, for which three current issues were selected for at-length discussion and debate;
7. *Conference Summary*, which recapitulated what we had learned from the meeting and assessed what urgent problems should be tackled in the immediate future to make progress in this field.

Two new features in the conference format, the dialog session and a general discussion period at the end of each session, were well received by the participants. A monograph for the meeting is being prepared.

HIGHLIGHTS OF PRESENTATIONS

Magnetotail Configuration

Although knowledge of the general structure and domains of the earth's magnetotail is fairly well established through two decades of research, several fundamental issues remain unresolved. Of these, two important topics that still receive much attention are (a) the relative importance of the solar wind and the ionosphere as sources for the particle reservoir in the magnetotail, and (b) the associated problem on the entry mechanisms from these sources. New measurements from the AMPTE/CCE spacecraft were reported, reaffirming the previous results that demonstrated the paramount role played by the ionosphere in populating the near-earth magnetotail during periods of enhanced magnetospheric activity. The solar-wind source becomes dominant only during intervals of magnetospheric quiescence. Ironically, it is during the periods of magnetospheric quiet that the prevailing solar-wind entry mechanism by reconnection is considered to be least effective. This fact has lent support to the thesis held by some participants that significant entry of the solar wind takes place via some viscouslike interaction or impulsive penetration through the boundary of the magnetosphere.

The recently completed survey of the distant magnetotail poses a new puzzle to be solved. The classic picture based on the reconnection idea envisions earthward flowing plasma in the region of the closed mag-

netic field lines (the domain where magnetic field lines emanating from the earth's southern hemisphere eventually return to the earth's northern hemisphere). However, observations uncover a predominant plasma flow down the tail. This result raises concern as to how accurate our view of the reconnection process is, compared to how it actually operates in nature.

The energy transfer from the magnetosphere to the ionosphere depends primarily on electric currents in the system that flow along the magnetic field. The measurements of the APL-built TRIAD satellite revolutionized our field by demonstrating the perpetual presence of a well-defined current system in the low-altitude magnetosphere that presumably extends to the magnetotail. However, the recent search with the ISEE measurements in the near-earth magnetotail revealed a magnetic-field-aligned current system opposite in direction from that expected by mapping the low-altitude magnetic-field-aligned currents into the magnetotail. This disparity has not yet been resolved.

Magnetotail studies over two decades have not exhausted our queries concerning the influence of the external environment in the solar wind on magnetotail phenomena nor have we perfected our ability to model accurately the magnetic field configuration within the system. Continuing efforts in these directions were evident during the meeting.

Magnetotail Dynamics

There is an almost unanimous consensus that the solar wind is the primary agent that powers the solar-wind magnetosphere dynamo, which liberates energy intermittently. These episodic events are referred to as magnetospheric substorms. One key issue under considerable discussion was whether the solar wind drives the system to a substorm directly or whether the power provided by the solar wind is filtered through an intermediate step of storage before it is released near the earth. If the former is true, the implication is profound, because once the appropriate parameters in the solar wind are identified, the solar wind could be monitored well before it hits the earth and the power output of the system and its impact on long-distance communications on earth could be predicted.

Large transient electric fields in the magnetotail during substorms were reported. If this field strength spreads across 10 percent of the dawn-dusk dimension of the magnetotail, it can accelerate the ambient particles to energies of a million electron volts. These fields are believed to be inductive and are interpreted in the context of reconnection. One common model for reconnection occurring in the magnetotail is through a tearing mode instability whereby the current sheet in the magnetotail breaks up into current filaments. Magnetic islands possessing closed loops of magnetic field lines are formed by this mechanism. Theoretical and computer simulation models generally adopt a two-dimensional picture. Observations pertaining to these phenomena often exhibit very complex variations in all three dimensions. Therefore, a

more complete understanding requires a full three-dimensional theoretical treatment of the problem.

Substantial efforts by computer simulations to model fluid and kinetic aspects of observed magnetotail phenomena have met with considerable success. The numerical schemes vary from fully self-consistent treatments to particle-tracing approaches. Two general remarks were made on computer simulations. First, the testing of computer codes is often not documented adequately to permit the validity of the simulation to be evaluated, a serious problem because results arising from numerical errors can confuse and lead to misunderstanding. Second, most simulations do not go beyond reproducing some features of observations; thus, they provide no predictions that can be tested with further observational analyses. This feedback of information is essential if we are to take computer simulation seriously as a tool in advancing our understanding.

The meeting also clearly emphasized the importance of using the motion of single particles to perform remote sensing of the boundaries and of the location of particle acceleration. It also demonstrated the frequent multicomponent state of the magnetotail particle population, with particle beams propagating through the medium. The beams can provide an energy source for driving electrostatic plasma waves in the magnetotail. This possibility has been actively pursued by several groups using computer simulation techniques.

Active Experiments and Other Celestial Tails

Observations of the artificial comets created by the AMPTE program have aroused considerable interest and excitement. There is a rich variety of phenomena associated with the interaction between an artificially injected plasma and a natural plasma. The phenomena include ion acceleration to tens of thousands of electron volts, intense electrostatic waves (many times stronger than at the earth's bow shock), a new plasma wave mode, formation and disruption of a magnetic cavity where the magnetic field strength drops to nearly zero, generation of a tail-like structure that later develops kinks, plasma drainage from the artificial comet coma, and the relatively sudden decrease in intensity of the comet near the end of its visible period. It is apparent from these observations that many of the processes occurring in natural comets are duplicated by these experiments. Releases in the magnetotail also yielded unexpected features, such as ripple formation on the cloud perimeter. All these findings will require more time to be comprehended fully.

The tracer aspect of the AMPTE program has presented another surprise. The tail releases were made with the guidance of model calculations and under carefully selected geomagnetic and local conditions. In spite of an elaborate undertaking to optimize the capture of the released elements (barium and lithium), the measurements indicate concentrations no higher than the upper limits based on the sensitivity thresholds of the instruments. These results have raised doubts about the confidence that can be placed in modeling

particle transport and energization in either the magnetotail or in the magnetosphere.

On the topic of other celestial tails, the logo of the meeting (Fig. 2) illustrates the different types of magnetotails that can be encountered. Studies of the Venusian, Jovian, and Saturnian magnetotails were reported. Twisting of the magnetotail for planets in our solar system was considered theoretically, and a prediction was made that the most significant twisting will be observed in the Uranus magnetotail. This prediction will soon be tested with the upcoming analysis of measurements made during the Voyager encounter of Uranus in January 1986. At the time of this writing, the strength of the Uranian surface magnetic field is reported to be slightly weaker than that of the earth. The Uranian magnetic dipole axis is found to be about 55 degrees from the planet's rotation axis, so that the Uranian magnetotail resembles the earth's magnetotail more than was formerly perceived. The existence of the large angle between the dipole and rotation axes favors the development of considerable twisting of the Uranian tail structures, although the twisting has yet to be determined.

WHAT NEXT?

The next major step is to place several strategically located spacecraft within the near-earth space environment. A new program, the International Solar Terrestrial Physics Program, has been planned according to this scheme. The conferees spoke repeatedly of the urgency in proceeding with this mission.

A second outcome of the meeting was the desire to continue active experimentation in space by conducting further missions like AMPTE. It is desirable to repeat its experiments with more releases and perhaps larger doses for each one, not only in the magnetotail but also in other parts of the magnetosphere. The initial steps have been made by the AMPTE program, and the cost of such dedicated missions is relatively modest.

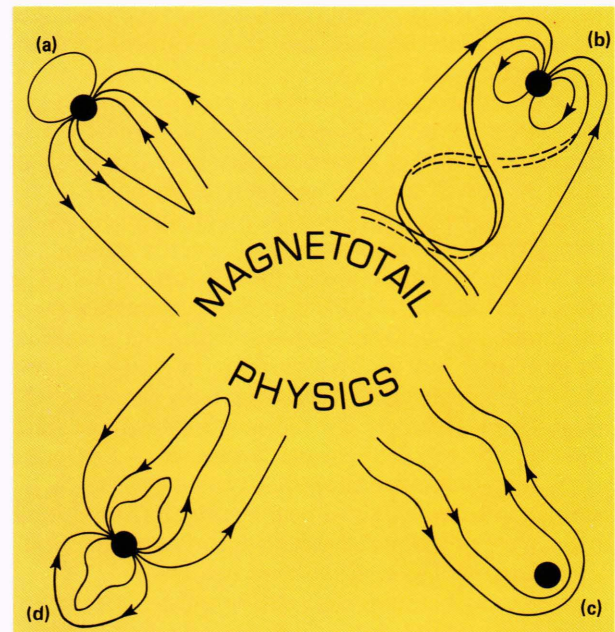


Figure 2—The logo from the Chapman Conference, displaying several magnetotail configurations. (a) A typical configuration, such as the earth's magnetotail. (b) Theoretically predicted magnetotail topology for Uranus when its magnetic axis is pointing toward the sun. (c) The field geometry for a comet. (d) The magnetotail for Jupiter, where centrifugal force may play a key role in the equilibrium force balance of the system.

Finally, it was recognized that global monitoring of the magnetotail plasma is necessary to complement detailed in situ measurements made by spacecraft. In contrast to solar physics, where knowledge gained about the solar atmosphere is accomplished entirely by remote sensing methods without in situ measurements, magnetotail research is at the other end of the spectrum and, as such, would benefit greatly by the availability of global magnetotail images.