Solving a Four-Decade-Old Mystery

Anthony T. Y. Lui

Dynamic auroral displays at polar latitudes are visual manifestations of the space disturbance known as a substorm, which can affect space assets used in our daily lives and cause blackouts by disrupting operations of ground power grids. The location where a substorm is initiated is a four-decade-old mystery. APL is part of the international team in the NASA mission THEMIS (Time History of Events and Macroscopic Interactions during Substorms) with five satellites to solve this mystery. Two competing substorm models with different predictions on the initiation site exist. The orbits of the five THEMIS satellites are designed to make definitive measurements that will evaluate these two models.

A NATURAL WONDER POSING A MYSTERY

A survival instinct for all living creatures is to know the immediate environment and be alert for impending danger. What has contributed significantly to the ascent of humankind above other living creatures is arguably the innate quest to go deeper and try to understand the nature of the environment. For instance, we are not only captivated by the beauty of a colorful rainbow but also curious about its origin. Unbeknown to most inhabitants of this world, another colorful natural phenomenon frequently paints the sky with ever-changing forms, incessant movements, and vivid displays of colors. It occurs both at the northern and southern polar latitudes and is known as the aurora borealis and the aurora australis, respectively. Aurora is the name of the Roman goddess of dawn and Borealis is derived from the Greek god Boreas of the north wind.

Auroral displays appear in many colors, including red, pink, yellow, green, blue, and violet, although green and pink are the most commonly seen. Those who are fortunate to witness such heavenly fireworks often attest to the unparalleled magic and mystery of these luminous, undulating displays. The enchantment of this natural phenomenon has recently been recognized as one of the seven natural wonders of the modern world by a panel representing a wide range of professions. Auroral displays have been seen and photographed from space shuttle flights. A Russian cosmonaut who went through an active auroral display remarked that he felt like he

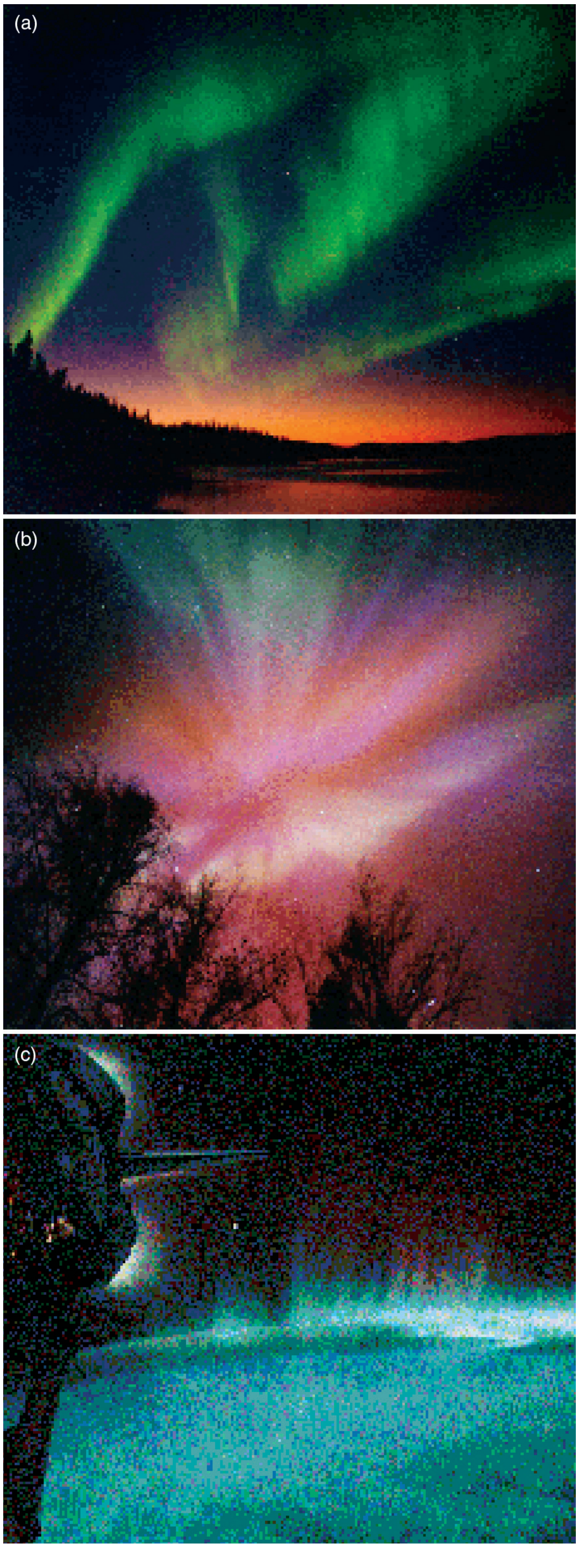

Figure 1. Auroral displays: (a) East–west aligned auroral arcs in the polar sky, (b) aurora viewed from directly below the form, and (c) auroras seen from a space shuttle (Courtesy of NASA).

was passing through magnificent columns of divine light.

Legends about auroras abound, e.g., associating auroras with battles in the sky, the wrath of Heaven, or the actions of a fox named Repu from Finnish lore who splashed snow into the air with his long tail. Some examples of auroral displays are shown in Fig. 1.

HIDDEN MESSAGE IN THE SKY

Auroral displays can be thought of as hidden messages in the sky, broadcasting violent activity in space at high altitudes. Hidden behind the visual image is the huge electrical current (on the order of 1 million amperes) associated with a disturbance, i.e., auroras are indicators of electrical currents in space. Space disturbances revealed by auroral activity result from the interaction between our Sun and the Earth's magnetic field.

The nearby space environment consists of several domains of charged particles. Figure 2 is a schematic diagram of the prominent regions. Our Sun's atmosphere expands continuously, producing a fast outflow of particles. The outflow stream consists almost entirely of electrically charged particles (a state known as plasma) and is called the solar wind. The Earth's magnetic field is distorted by the supersonic solar wind, creating a shock wave (bow shock) to deflect the oncoming solar wind from reaching the Earth's surface. The deflected solar wind forms a sheath, known as the magnetosheath, to enclose the Earth's magnetic field in a magnetic bubble called the magnetosphere. On the side away from the Sun, the Earth's magnetic field is stretched downstream for a long distance, forming the magnetotail, much like the tail of a comet.

AURORAL DEVELOPMENT REVEALING THE SUBSTORM FRAMEWORK

In the early 1960s auroral activity was discovered to undergo systematic, repeatable development if one expands the perspective of an observer on the ground to one in a spacecraft viewing the entire polar region. This evolution of activity, known as the auroral substorm, is illustrated schematically in Fig. 3 from the vantage point of a viewer at a considerable altitude above the pole. It was constructed from synthesizing simultaneous observations of aurora by a network of all-sky cameras.[1]

Before the onset of substorm activity, auroral displays occur in curtain-like forms aligned nearly in the east–west direction, referred to as auroral arcs (Fig. 3a). Auroral forms during an auroral substorm differ and depend on the local time of observation. The disturbance begins when the auroral arc in the near-midnight or late-evening hours suddenly brightens. When several auroral arcs are present, the one at the lowest latitude typically brightens first (Fig. 3b). The brightened arc then starts to move toward the pole. As a result, the auroral pattern

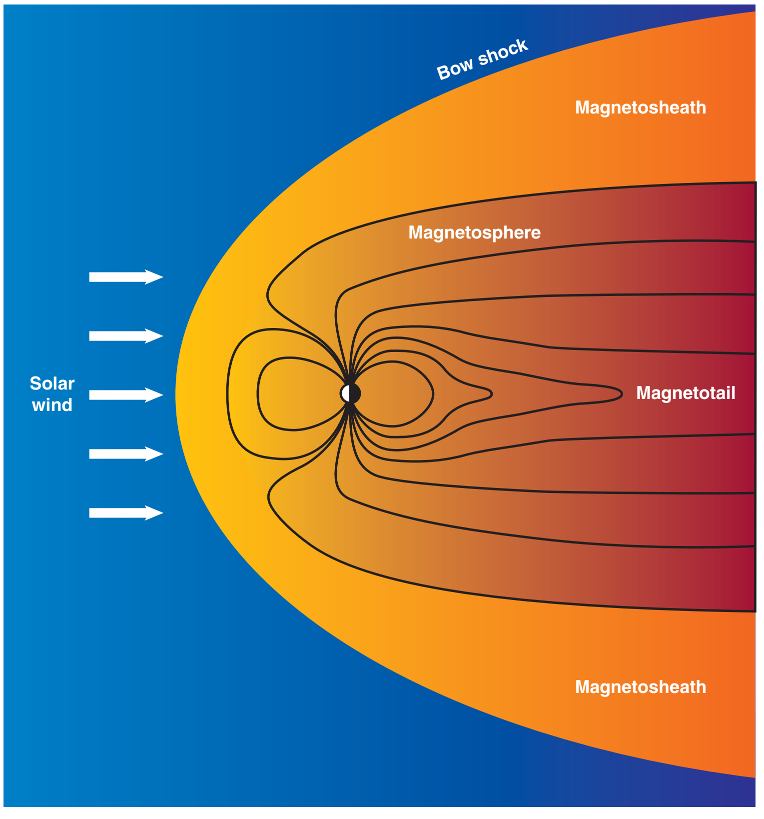

Figure 2. Some key regions in the interaction between our Sun and Earth's magnetic field.

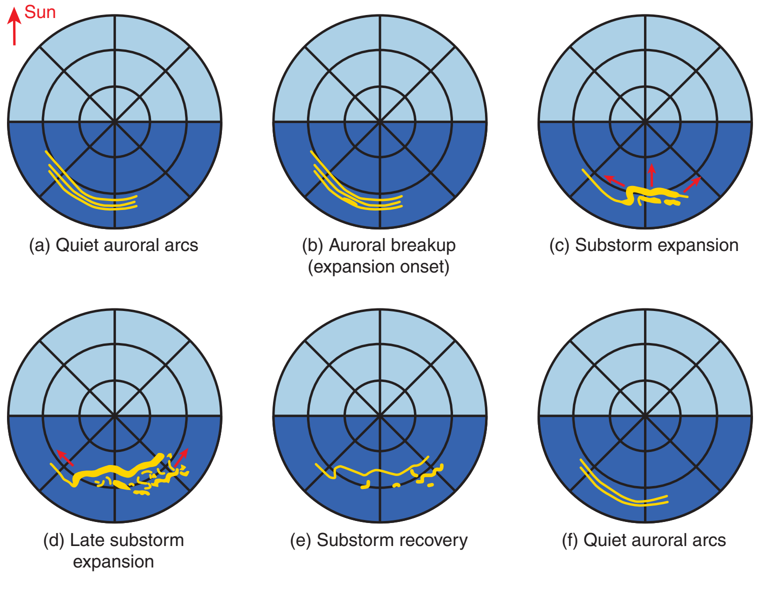

Figure 3. A schematic diagram showing the temporal sequence of the auroral pattern during an auroral substorm viewed from space directly above the magnetic pole. The concentric circles denote latitudes with 10° spacing.

appears to form a bulge (Fig. 3c). A large-scale wavy structure forms at the western end of the bulge in the late evening hours and propagates westward (Figs. 3c and 3d). This wave structure is associated with a variety of folds and violent auroral motions. In the morning hours, the auroral arcs tend to break up into patches drifting eastward. This furious activity begins to cease when the bulge stops its advance to higher latitudes and the auroral brightness begins to dim (Fig. 3e). The auroral activity gradually subsides, and auroral arcs become the dominant form in the night sky (Fig 3f).

MOTIVATION FROM THE APL AMPTE PROGRAM

The origin of the furious activity in auroral substorms has intrigued space scientists since the inception of the substorm description. What are the prevailing ideas? To address this question, one may return to the early 1970s and the trilateral mission known as Active Magnetospheric Particle Tracers Explorers (AMPTE). This mission, jointly conceived by former APL Space Department head Dr. Stamatios M. (Tom) Krimigis and Dr. Gerhard Haerendel from the Max Planck Institute at Garching, consisted of three satellites: the Charge Composition Explorer (CCE) from the United States, the Ion Release Module (IRM) from Germany, and the United Kingdom Subsatellite (UKS). AMPTE's goal was to unravel the transport mechanisms of plasma in the nearby space by performing multiple ion releases in the solar wind, the magnetosheath, and the magnetotail from IRM with nearby measurements by UKS to monitor the local plasma interaction, and to have the released ions captured at a remote location by the CCE. Several interesting results emerged from this mission, including the first artificial comet.[2–4] One surprising spin-off concerns the location where the substorm disturbance originates as well as the physical process for the energy release in substorms.

TWO COMPETING SUBSTORM MODELS

The conventional wisdom is that substorms are caused by a physical process known as magnetic reconnection. The substorm extracts the stored magnetic field energy to accelerate charged particles by forming a configuration in which the magnetic field may be visualized as having its lines of force cut and joined back in a different manner (Fig. 4). The magnetic field lines at the top and bottom of the figure are visualized to be transported toward the X-type configuration. At the X-point, the magnetic field line from the top is presumed to be cut and then joined with the magnetic field line from the bottom. This alteration leads to two different magnetic field lines, one moving to the left and the other to the right. These magnetic field line motions carry along the charged particles associated with them. This process releases magnetic energy stored in the top and bottom parts of the field configuration to the charged particles moving to the left and right. Substorm theory based on this idea invokes this process occurring in the magnetotail about 20 R_E downstream (R_E = length unit of an Earth radius = 6378 km). This model is referred to here as the mid-tail initiation model.[5,6]

The other competing substorm model, motivated to a great extent by the AMPTE/CCE findings, envisions turbulence from a plasma instability to be the main physical process responsible for the onset of substorms.[7,8] The plasma instability is triggered by the high electrical current density in that region just before the onset of activity. The magnetosphere cannot sustain such a high current density and leads to a sudden disruption of the current. This situation is similar to current disruption in an electrical circuit. The observed plasma turbulence in this region is due to the nonlinear evolution of the instability. Since magnetic field energy is associated with a current system, current disruption essentially releases that energy to the charged particles. The energy release may involve an X-type magnetic field configuration envisioned in magnetic reconnection but is not necessarily present in all current disruption events. The current disruption location is found to be near the transition region at about 10 R_E downstream, where the magnetic field resembling the Earth's dipole field configuration changes to the stretched magnetic field found in the magnetotail, as depicted in Fig. 5. This model is referred to here as the near-Earth initiation model.

A simplified summary of the scenario for the evolution of substorm disturbance from these two competing models is shown in Fig. 6. In the near-Earth initiation model, the first sign of substorm onset occurs in the transition region. A plasma process occurring primarily on the equatorial plane

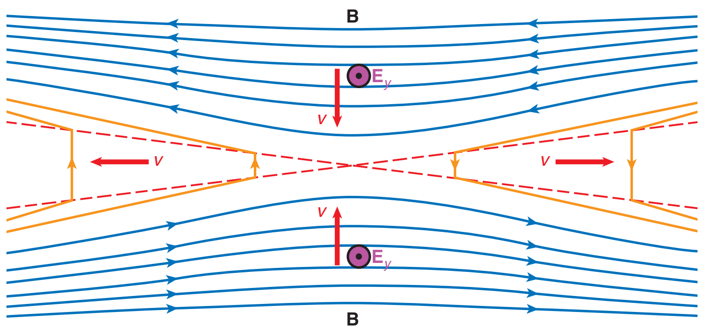

Figure 4. A schematic diagram to illustrate the magnetic reconnection process. The magnetic field lines are drawn in blue before reconnection and in orange after. The red arrows denote the motion of the charged particles (**v**) associated with the magnetic field lines. The accompanying electric field component perpendicular to the reconnection plane $\mathbf{E}_y$ (pointing out of the image) is also shown.

is initiated to disrupt the current that flows duskward there, causing it to divert its path to the ionosphere to form a current system called a substorm current wedge.

The redirected current due to current disruption is responsible for the dynamic auroral display during substorms. Current disruption accelerates plasma primarily to Earth and launches a disturbance wave that propagates away from Earth. This disturbance wave instigates current disruption at other sites, leading to the presence of multiple current disruption sites. Magnetic reconnection may occur in one of these current disruption sites.

In the mid-tail initiation model, the first sign of substorm onset occurs deep in the magnetotail where magnetic reconnection takes place at a site called the near-Earth neutral line (NENL). It produces a high-speed plasma flow directed to the Earth. This flow slows down as it encounters the strong

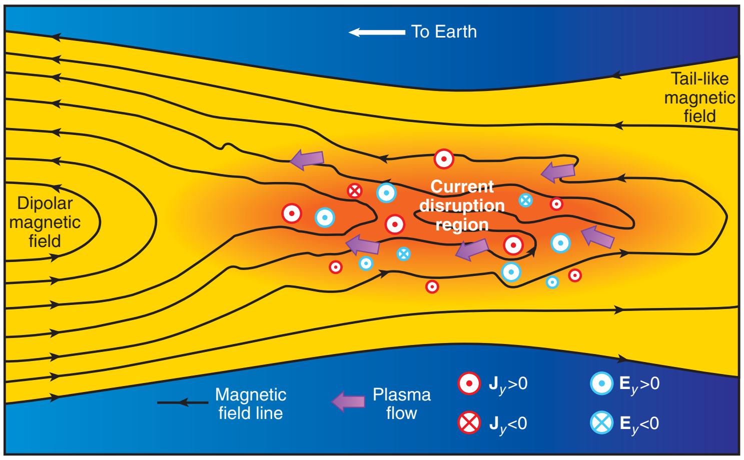

Figure 5. A schematic diagram to illustrate the turbulence in the current disruption region where the electric current is broken up into filaments with various intensities and with some reversing in direction as well. The associated electric field is also highly variable in strength and direction. Plasma is accelerated to high speeds by forces resulting from the current disruption process.

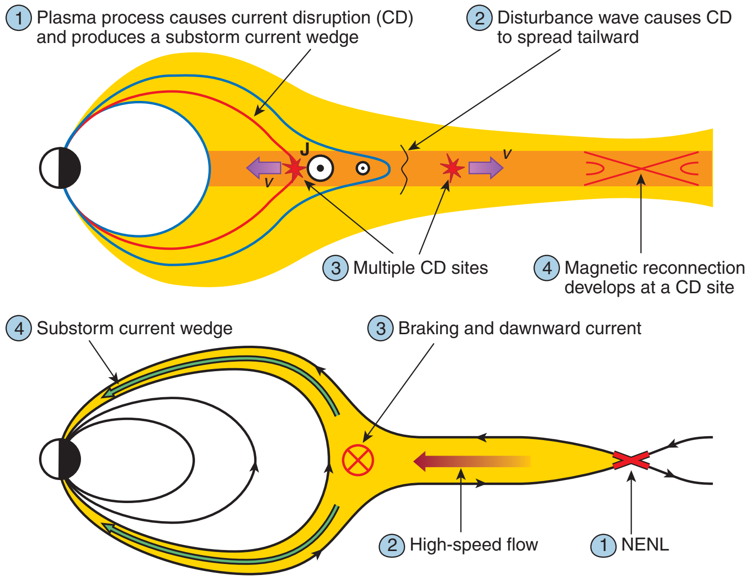

Figure 6. A simple diagram to illustrate the main features of the two competing substorm models. The time sequence for each model is indicated by steps 1 through 4. In the near-Earth initiation model (top), the current intensity (**J**) is indicated by the size of the circle. A plasma process causes current disruption (CD) on the magnetic field line connected to an auroral arc, which in turn generates a disturbance wave propagating tailward. A new current system, called the substorm current wedge, is developed by CD. Magnetic reconnection may subsequently develop in one of the CD sites. In the mid-tail initiation model (bottom), magnetic reconnection occurs in the mid-tail, causing an Earthward plasma jet, which in turn slows down near the inner magnetotail to create a substorm current wedge (NENL = near-Earth neutral line).

magnetic field from Earth, and flow braking creates a dawnward current, generating a substorm current wedge as a result.

Clear distinctions between these two models are the location where the disturbance first appears and the propagation direction of the disturbance, even though the subsequent extent of the disturbance in each model can encompass both the transition region and the magnetotail.

THE THEMIS MISSION

A NASA mission called THEMIS (Time History of Events and Macroscopic Interactions during Substorms) is attempting to resolve this substorm onset mystery. Appropriately, Themis is the goddess of justice, wisdom, and good counsel; the guardian of oaths; and the interpreter of the gods' will in Greek mythology. She is typically depicted with a sword and scales, symbolizing both her power and her impartiality. Her blindfolding dates from the 16th century and signifies her famed neutrality. This accounts for the commonly used term, "blind justice." The modern depiction is of a young woman, often blindfolded, holding her scales and sword (Fig. 7). This image is today prominently displayed in the halls of justice worldwide. The acronym THEMIS conveys the idea that the mission will judge impartially the merits of the two substorm models.

The THEMIS mission consists of five identical satellites which measure particles and fields on orbits that optimize tail-aligned conjunctions over North America. The instrument suite on each satellite consists of a fluxgate magnetometer, an electrostatic analyzer, a solid-state telescope, a search coil magnetometer, and an electric field instrument. Alignment of all five satellites in the magnetotail will occur once every 4 days. Ground observatories will time auroral breakup onsets. Three inner satellites at ≈10–12 R_E downstream distances will monitor current disruption onsets, while two outer satellites, one at 20 R_E and the other at 30 R_E downstream distances, will monitor magnetic reconnection onsets.

The mission principal investigator is Dr. Vassilis Angelopoulos of the Jet Propulsion Laboratory (JPL). The mission involves international collaborations among several countries—Austria, Canada, France,

Figure 7. A painting portraying the goddess of justice. (Reproduced with permission from Chad Awalt, http://www.chadawalt.com/justice2.html.)

Germany, and Japan. Figure 8 shows the five satellites mounted on the satellite carrier at the JPL vibration test facility. THEMIS was launched on 15 February 2007 by a Delta II rocket at the Kennedy Space Center in Florida. Over its 2-year mission, the tail-aligned measurements from the five satellites will enable a definitive determination on the propagation direction of the initial substorm disturbance. The near-Earth initiation model predicts that substorm disturbance propagates away from the Earth whereas the mid-tail initiation model predicts the opposite propagation direction.

APPLICATIONS

Solving the substorm mystery is not just an academic pursuit but also has real-world applications to our societal functions. There is incessant growth in the use of space technology and assets in our daily lives. Much like adverse atmospheric weather can wreak havoc on our homes and facilities, space disturbances can render space assets for communications, global weather monitoring, and navigation inoperative as well as pose hazards to astronauts and people on commercial polar flights. Even power grids on the ground can be affected by blackouts caused by these space disturbances. The THEMIS mission will make progress toward understanding the substorm phenomenon and should eventually lead to better and more timely predictions of these space disturbances and to mitigation of undesirable consequences from them.

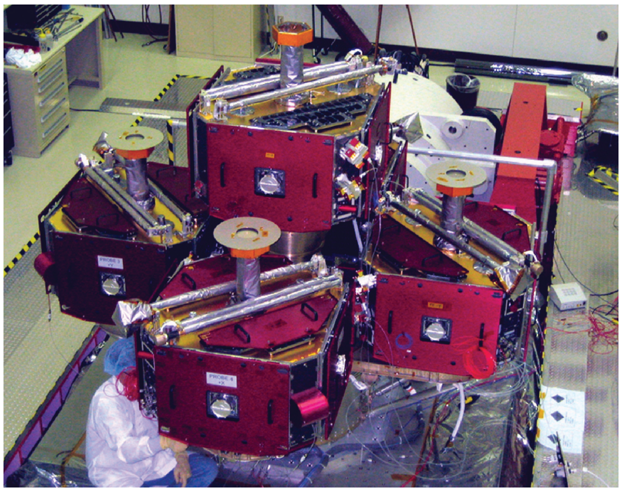

Figure 8. The five satellites of the THEMIS mission on the satellite carrier at the vibration test facility at JPL.

REFERENCES

[1]Akasofu, S.-I., "The Development of the Auroral Substorm," *Planet. Space Sci.* **12**, 273–282 (1964).

[2]Krimigis, S. M., Gloeckler, G., McEntire, R. W., Potemra, T. A., Scarf, F. L., and Shelley, E. G., "Magnetic Storm of September 4, 1984: A Synthesis of Ring Current Spectra and Energy Densities Measured with AMPTE/CCE," *Geophys. Res. Lett.* **12**, 329–332 (1985).

[3]Lui, A. T. Y., McEntire, R. W., and Krimigis, S. M., "Evolution of the Ring Current During Two Geomagnetic Storms," *J. Geophys. Res.* **92**, 7459 (1987).

[4]Haerendel, G., Paschmann, G., Baumjohann, G. W., and Carlson, C. W., "Dynamics of the AMPTE Artificial Comet," *Nature* **320**, 720–723 (1986).

[5]Hones, E. W. Jr., "Transient Phenomena in the Magnetotail and Their Relation to Substorms," *Space Sci. Rev.* **23**, 393–410 (1979).

[6]Angelopoulos, V., Baumjohann, W., Kennel, C. F., Coroniti, F. V., Kivelson, M. G., et al., "Bursty Bulk Flow in the Inner Central Plasma Sheet," *J. Geophys. Res.* **97**, 4027–4039 (1992).

[7]Lui, A. T. Y., "A Synthesis of Magnetospheric Substorm Models," *J. Geophys. Res.* **96**, 1849–1856 (1991).

[8]Lui, A. T. Y., Lopez, R. E., Krimigis, S. M., McEntire, R. W., Zanetti, L. J., and Potemra, T. A., "Case Study of Magnetotail Current Sheet Disruption and Diversion," *Geophys. Res. Lett.* **15**, 721–724 (1988).

The Author

Anthony T. Y. Lui is a Senior Professional Staff scientist in the APL Space Department. He graduated from the University of Calgary, Alberta, Canada, in 1974 with a doctoral degree in space physics. As a graduate student, he analyzed the first auroral images taken from a satellite and discovered the diffuse aurora. He did his post-doctoral work with Dr. Syun-Ichi Akasofu at the University of Alaska who introduced the substorm concept. Dr. Lui has participated in several space missions, including AMPTE, ISEE, Geotail, and Cluster since joining APL in 1979. His research encompasses data analysis, numerical simulation, and analytic theory on space disturbances. He is considered by the space community a prime advocate of the near-Earth initiation model for substorms and is the only person at APL who is a team member of the NASA THEMIS mission. Dr. Lui recently was elected to be a fellow of the American Geophysical Union. Dr. Lui's e-mail address is tony.lui@jhuapl.edu.

Anthony T. Y. Lui