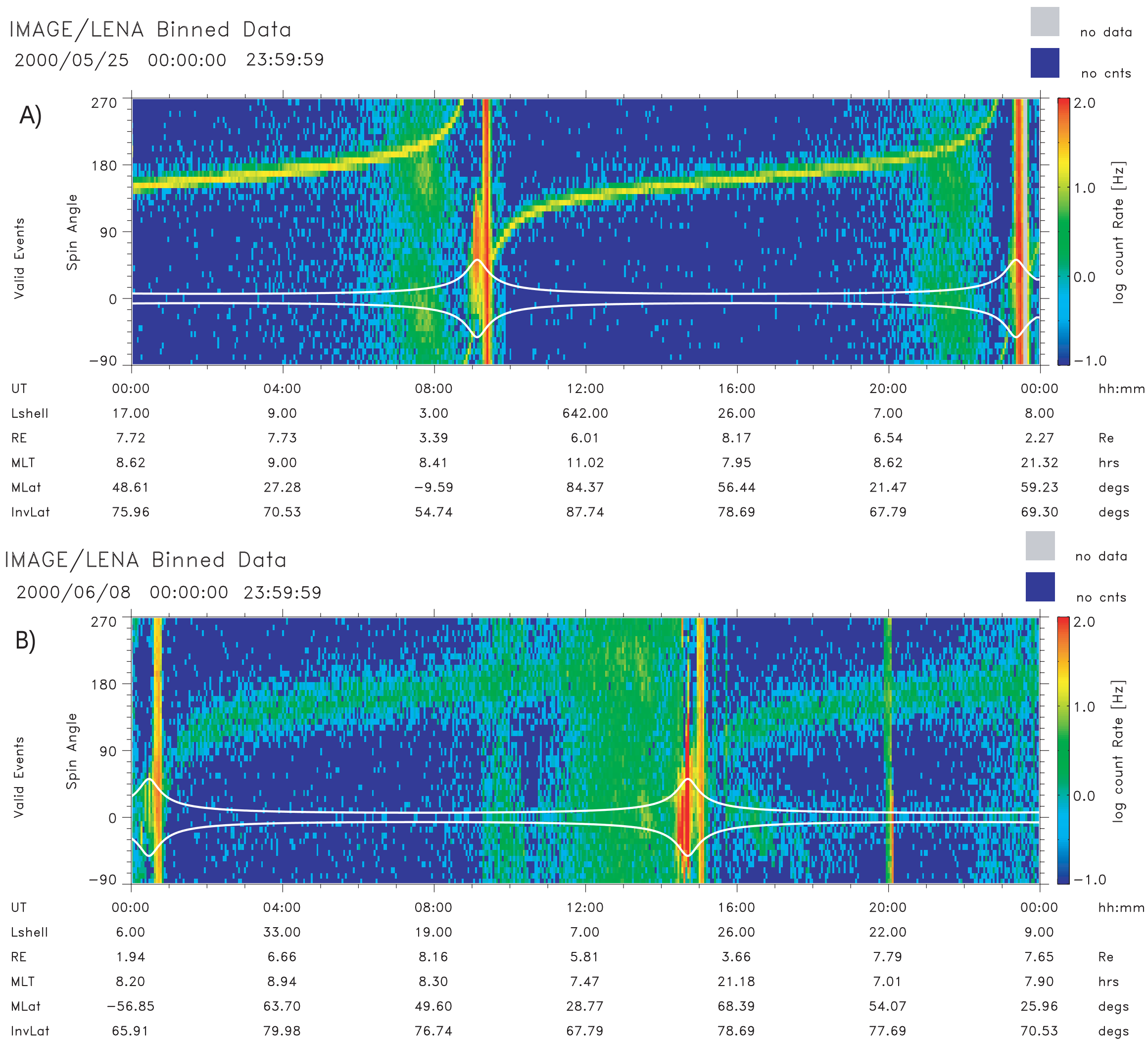
Science Section

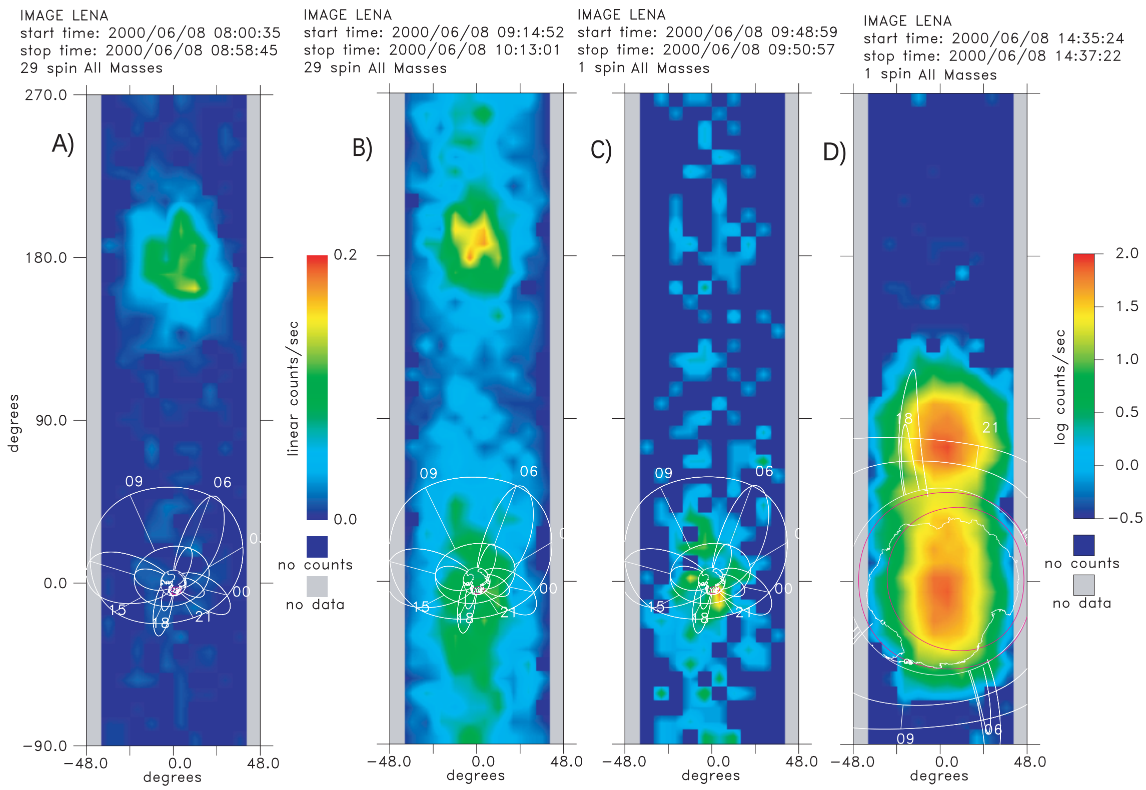
Anticipated Science Insights to Date

1. **What are the dominant mechanisms for injecting plasma into the magnetosphere on substorm and magnetic storm time scales?**
   - **Ionospheric outflows:** The LENA Imager has shown, as expected, that energization of ionospheric ions at low altitudes produces copious escape of fast neutral atoms as well as the ion outflows that have been extensively observed *in situ*. In some cases the neutral atom outflow approaches the ion outflow in magnitude, implying very low altitude energization, as has also been inferred by some direct observations. The fundamental advance in this area is that LENA outflow observations allow remote sensing of ionospheric outflows and therefore permit extended observations with unprecedented temporal resolution.
     - **Plate 1 GRL.** LENA total atoms (coincidence) spin spectrogram for A) the period of 25 May 2000, and B) for the CME event of 8 June 2000. Spin angle increases with time, with reference (0) to the nadir view. White lines indicate the limbs of the Earth.



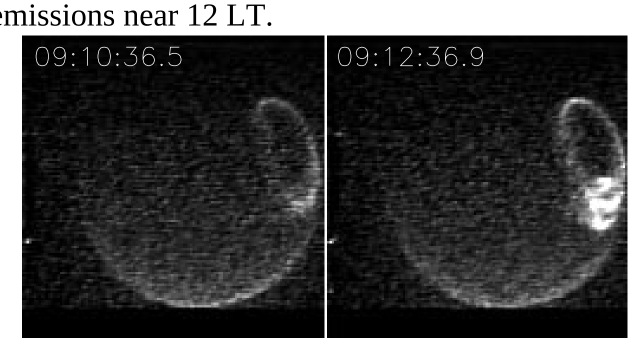
2. What is the directly driven response of the magnetosphere to solar wind changes?

- **CME-Driven Ionospheric Outflows:** Using the capability for remotely sensing LENA emission from the Earth at 2 minutes time resolution, it was shown that a robust solar wind enhancement produces a *prompt* response in the emission of LENA from the Earth, perforce associated with the energization and ejection of ionospheric ions into the magnetosphere. This has significantly refined earlier observations of strong correlations between solar wind pressure and ionospheric outflows, showing that the correlation is indeed causal with a short response time.
    - **Plate 3 from GRL.** LENA image sequence for 8 June 2000; A) hour average before CME arrival at 0915; B) hour average after CME arrival; C) snapshot 35 min after CME arrival ; D) passage over the south polar regions near perigee. Panels A, B, C have linear scaling (color bar C 10x higher than for A, B), whereas D is logarithmic.



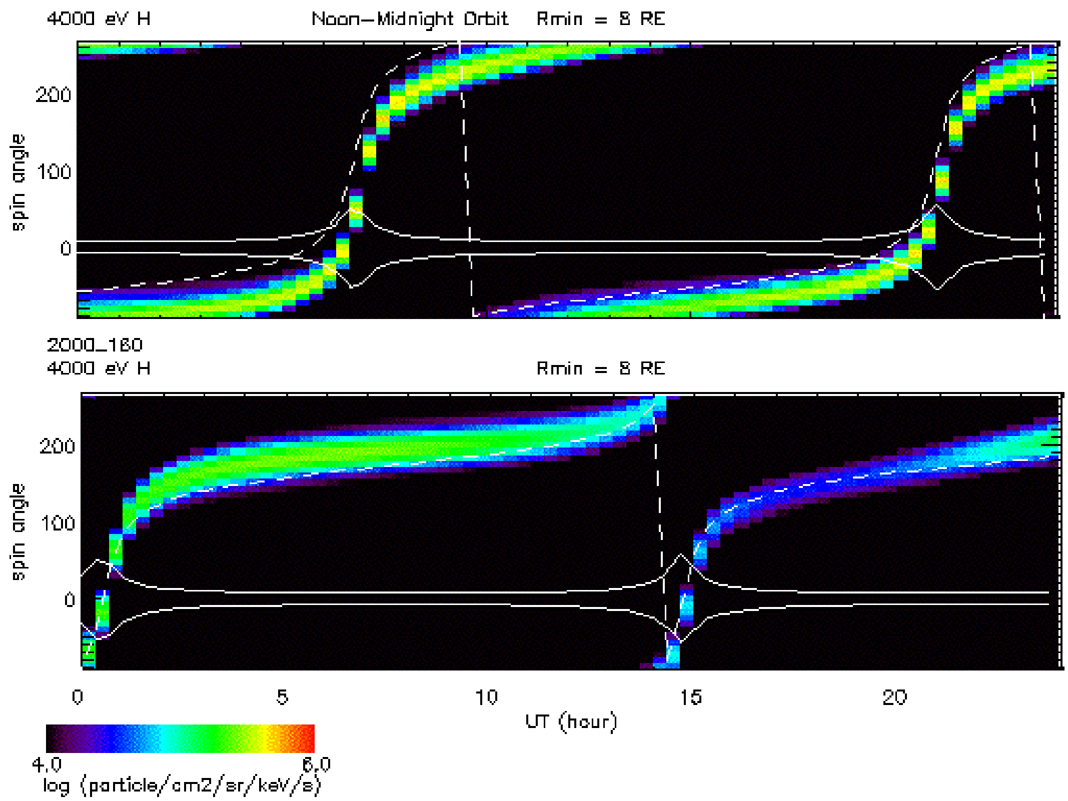
3. **How and where are magnetospheric plasmas energized, transported, and subsequently lost during storms and substorms?**

- **Auroral Driving of Ionospheric Outflows:** Using simultaneous auroral and LENA outflow imaging, it has been shown that these are very closely associated in time during dynamic events involving solar wind intensifications, leading to corresponding auroral intensifications, and ionospheric LENA generation events.
    - **Figure 2 from Fuselier et al GRL.** Two consecutive snapshots of the proton aurora (Doppler shifted Lyman-alpha emissions). The ionospheric response to the CME shock passage is evident in the second image. There is a significant and localized brightening of the emissions near 12 LT.



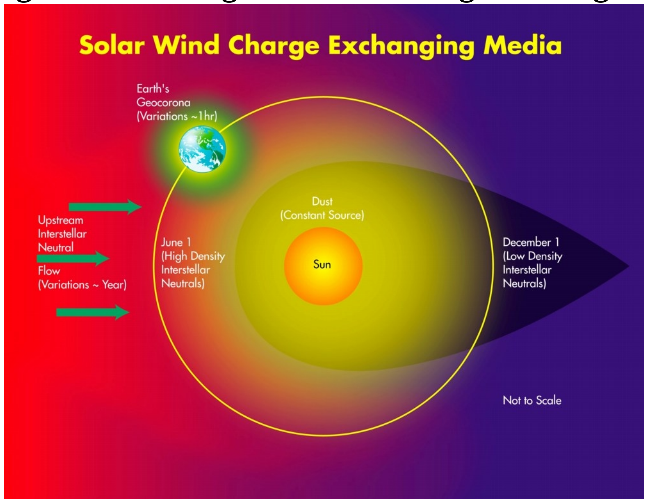
Unanticipated Science Insights to Date

- **Solar Wind Energetic Neutral Atoms:** The LENA instrument was carefully designed for robust rejection of solar UV photons. It was nevertheless a pleasant surprise that LENA was indeed able to stare directly at the sun with a very manageable response. Even better, though, was the realization that the LENA Imager response to the sun was for the most part a response to neutral atoms created from the solar wind protons by charge exchange with interplanetary and near-Earth geocoronal atoms. This allows crude monitoring of the solar wind intensity from the IMAGE spacecraft, inside the magnetosphere, even when the sun is outside the LENA FOV, owing to production of a weak flux of LENA from the geocoronal extension into the magnetosheath.
  - **Figure from Moore SWLENA nugget.** Simulation of M.-C. Fok of LENA spinograms for magnetosheath charge exchange. Compare with Plate 1 from Moore et al GRL.

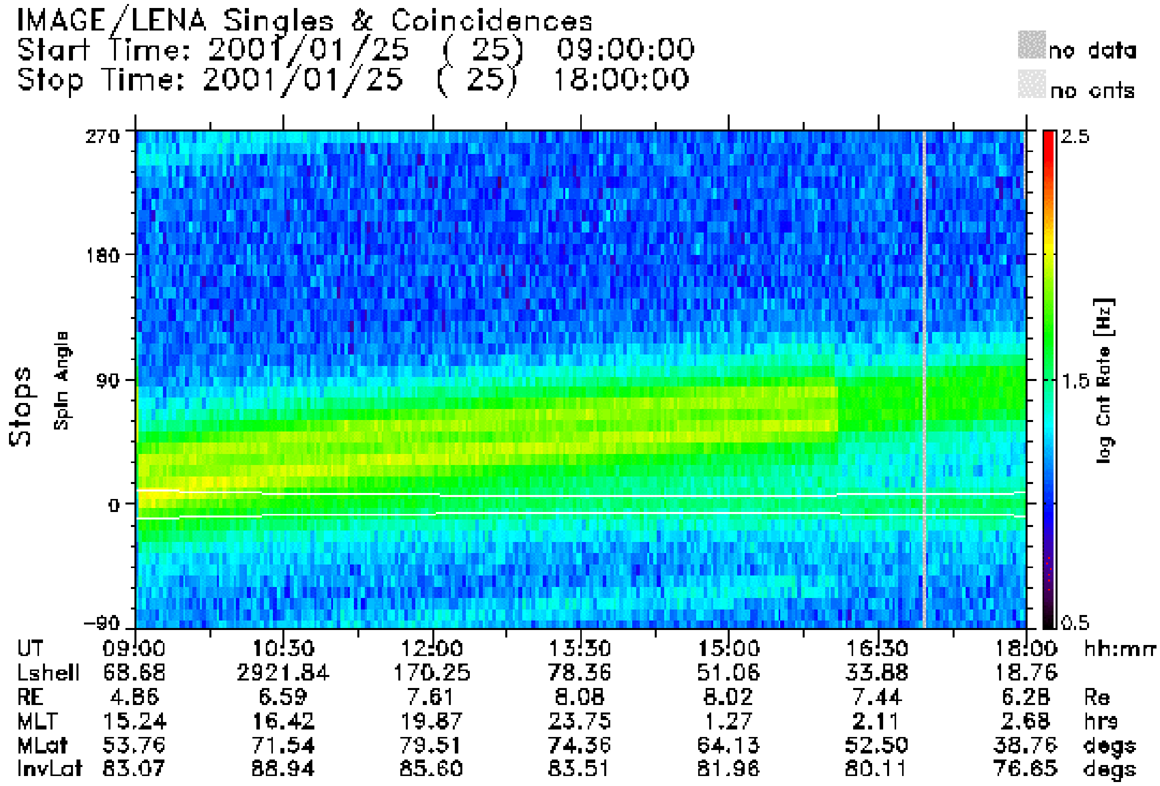


- **Interstellar Neutral Gas Remote Sensing:** Another pleasant surprise was the realization that the solar wind ENAs had a pronounced long-term variation over the first 9 months of the mission. This variation represents an azimuthal variation of the integral neutral gas density between the Sun and Earth, and is loosely aligned with the known direction of motion of the solar system through the galaxy. This work is in progress as this is written, but it appears that these observations of the neutral solar wind will yield information about the distribution of gas in the inner solar system. This distribution is thought to result from a combination of interstellar gas and gas evolved from a distribution of dust in the inner solar system.

- **Figure illustrating solar wind charge exchange.**



- **Interstellar Neutral Atom Sensing:** In addition to indirect observation of interstellar neutral gas via solar wind charge exchange, we have also directly observed the interstellar neutral atoms during January 2001. This signal was exceedingly weak but still quite clear. It appeared about 25 Dec. 2000 and disappeared about 8 Feb. 2001. The signal was narrow in angular distribution and separated from the solar wind ENAs by approximately 90°, i.e. near the ram direction of the Earth’s motion through the solar system. This is the season during which the maximum relative velocity between the Earth and the interstellar neutral flow maximizes for species that are gravitationally deflected as they pass through the inner solar system. Study of this signal is just beginning as this is written.
  - **Example of Interstellar Neutral Signal.**



Scientific Promise of The Extended Mission

- **Ionospheric outflows beyond solar maximum:** IMAGE having been launched near solar maximum, it is of great interest how the LENA emission of the Earth will evolve during the declining phase of the solar cycle. Though the expectation is for lower fluxes of both ions and LENA as the exosphere cools and O scale heights drop while H density increases, there could be some surprises here. For example, the changing structure of the exosphere with solar EUV may lead to changes in the altitude at which plasma heating occurs, or the relative importance of various energization mechanisms may change.
- **Possible early warning of CMEs.** One potential practical application of NSW monitoring is the advance warning of Earth-directed CMEs. Because the triggering of large storms is related to the initial speed of Earth-directed CMEs, it has been proposed that neutral atoms produced in the CMEs in the initial high speed stage may move ahead of the CME as it slows down in its Earthward propagation and may arrive at Earth a few hours earlier than the interplanetary CME, providing storm warnings [Hsieh et al., Proceedings SPIE, 1744, 72-78, 1992; Gruntman et al., JGR, 99, 19213-19,227, 1994]. To test this proposal, LENA must observe a number of Earth-directed CMEs while the Sun is directly in its FOV which will only be likely with an IMAGE extended mission.
- **Neutral exospheric response to space weather:** It is apparent from data obtained to date that the LENA imager responds to neutral atoms with negligible thermal speeds, i.e. to the cold thermal neutral O exosphere. This

leads to a rammed component of the LENA response during perigee passes where the velocity of the spacecraft approaches 10 km/s, so that the energy with which cold O strikes the LENA conversion surface is several eV, placing these otherwise cold atoms within the LENA energy range. It will be very interesting to study the variation of these signals during geomagnetic activity periods, and as the solar activity begins to decline.

- **Long term sampling of neutral solar wind:** It is clear from work to date that monitoring of the solar wind ENA flux is giving us an integral remote sensing of the neutral gas environment between the Sun and the Earth. A clear seasonal variation has been observed during the first year of operation, that is loosely consistent with models of the H distribution expected in the inner solar system. Quantitative observations of the seasonal and longer term variations of this signal are likely to yield new information about the interstellar gas distribution in the inner solar system, the dust distribution in the inner solar system, and the spatial and temporal variations of these media.
    - **Model of the SWENA flux over a solar cycle.**

INTERPLANETARY PARTICLE FLUXES AT EARTH 215

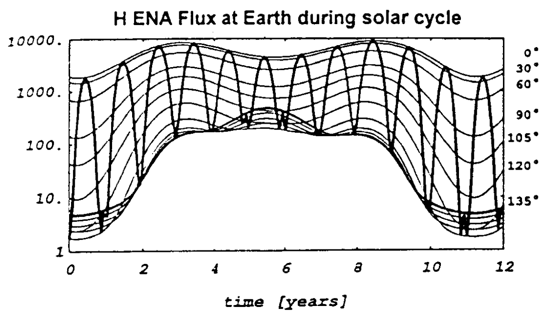


FIG. 6. Shown is the H-ENA flux at Earth as a function of time during solar cycle (thick line) and this flux at selected offset angles from the upwind direction (thin lines). The numbers at the right-hand frame of the figure denote the offset angles. The vertical axis is scaled in atoms cm^{-2} s^{-1}, the horizontal axis in years since solar cycle maximum. The density of neutral hydrogen at infinity is adopted equal to 0.1 atom/cm^3, the abundance of neutral helium there is 0.1, and hydrogen and helium have identical degrees of ionization; no dust-related neutral atoms are present.

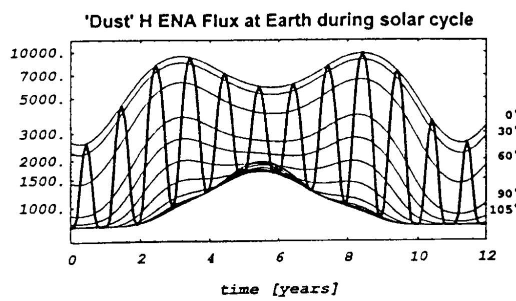


FIG. 8. The same as Fig. 6 but the case when a dust-related population is present in the "seed" neutral gas. Note that the downwind flux enhancement feature is very much suppressed here in comparison with the case of absence of the dust-related gas and that the level of minimum values is by 2 to 3 orders of magnitude higher.

- **Annual direct interstellar neutral gas detection:** During our first year of operation, we observed a weak direct signal of LENA with the gross properties of interstellar neutral atoms passing through our solar system, subject to gravitational deflection effects that affect their trajectories and therefore their wind speed relative to the Earth. It is of great interest to extend the period of observations of this direct interstellar neutral signal, both to get the most information from it regarding the interstellar neutrals, and also to look for variations that may result from solar cycle variations of the sun and its output of both photons and solar wind.

Importance to the SEC Goals and Objectives

Quest 2. How do the planets respond to solar variations?

- **Understanding the geospace environment:** Low energy neutral atoms have now been shown to be an effective medium for monitoring the neutral exosphere as influenced by solar wind driven plasma heating and outflow. These latter flows can be remotely monitored by observing the low energy neutral atoms that they generate, which are in subsequently emitted from auroral regions of energy dissipation. Variations of the neutral exosphere with solar cycle are thought to be dramatic, but we are only on the verge of being able to monitor these effects for a significant fraction of a solar cycle.
- **Comparative planetary space environments:** Similar phenomena involving removal of atmospheric matter by solar wind energy dissipation are expected on other planets, with or without magnetospheres. Recently, there has been a significant amount of attention to this in the case of Mars, where MGS has provided new plasma measurements. LENA imaging hardware is likely to be a useful disgnostic for these other planets, once it is appreciated how valuable it is for observing the Earth's exosphere and ionospheric escape. By fully studying observations of terrestrial LENA imaging over a solar cycle, we will be in a better position to optimize future comparative planetary investigations.

Quest 3. How do the sun and galaxy interact?

- **Understanding the galactic gas and condensed matter inside our solar system:** The measurement of galactic or interstellar material inside our solar system serves as a diagnostic of the source properties of that material, and as a diagnostic of its interaction with the heliosphere, including dust distributions in the inner solar system. While we have had the capability of observing energetic pickup ions as diagnostics of the interstellar gas for some time, and interstellar He was observed from the Ulysses spacecraft, the IMAGE mission has given us the capability to directly observe the interstellar neutrals of any species, and to remotely sense their distribution between Earth and Sun, by means of their charge exchange with solar wind ions. We have therefore entered a new phase of the study of this material, which should lead to many surprises as well as significant tests of theoretical work that has gone beyond observational capabilities in this area. It has even been suggested that the interstellar medium exerts strong influences on the terrestrial ionosphere and ozone layer by modulating the incident neutral H flux [Bzowski et al., 1996].

Quest 4. How does solar variability affect life on Earth?

- **Understanding space weather and its effects:** Imaging of low energy neutral atoms in the magnetosphere has been shown to be an effective and valuable tool for remotely sensing the phenomena and effects of space weather, including heating and escape of ionospheric plasma into the magnetosphere, coupling to the auroral zone and its dynamics, coupling to solar wind intensifications accompanying CMEs, and the contribution of the internal plasmas to the storm-time plasmas of the magnetosphere. In addition, observations of the interstellar gas medium within the solar system, including its effects on the solar wind, may well lead to future advances in our understanding of space weather, in view of their possible effects on the Earth's atmosphere.

References:

Gruntman, M., Neutral solar wind properties: advance warning of major geomagnetic storms, J. Geophys. Res., 99, p.19213, 1994.

Hsieh et al., Forecasting the arrival of fast coronal mass ejecta at Earth by the detection of 2-20 keV neutral atoms, Proceedings of SPIE, 1744, 72-78, 1992.

Bzowski, M., H. J. Fahr, and D. Rucinski, Interplanetary neutral particle fluxes influencing the Earth's atmosphere and the terrestrial environment, Icarus, 124, p.209, 1996.

SCIENCE PUBLICATIONS:

Burch, J L, et al., New views of Earth's magnetosphere with the IMAGE satellite, Science, revision in review, 2000.

Moore, T E, et al., Low Energy Neutral Atoms in the Magnetosphere, Geophys. Res. Lett., 28, p.1143, 2001.

Fuselier, S A, et al., Ion outflow observed by IMAGE: Implications for source regions and heating mechanisms, Geophys. Res. Lett., 28, p. 1163, 2001.

Collier, M R, et al., Observations of Neutral Atoms from the Solar Wind, submitted to J. Geophys. Res., submitted Oct. 2000, accepted Jan 2001, in press, 2001.

Peko, B. L. and T. M. Stephen, Absolute detection efficiencies of H, H-, H+, H2+ and H3+ incident upon a multichannel plate detector, Nucl. Instrum. Meth. B 171, 597 (2000).

Stephen, T. M. and B. L. Peko, Absolute calibration of a multi-channel plate detector for low energy O, O- and O+, Rev. Sci. Instrum. 71(3), 1355-1359 (2000).

SCIENCE PRESENTATIONS

Moore, T E, et al., Internal plasma sources and ring currents, presented at the S-RAMP conference, Sapporo, Japan, October, 2000.

Moore, T E, et al., Low Energy Neutral Atoms in the Magnetosphere, presented at the Huntsville2000 meeting, Callaway Gardens, GA, October, 2000.

S. A. Fuselier, Low Energy Neutral Atom Imaging of Ion Outflow, ISTP workshop, 24 October, 2000.

S. A. Fuselier, The IMAGE science investigation, Lockheed Martin Remote Sensing and Space Sciences Seminar, 31 October, 2000.

S. A. Fuselier, The IMAGE Neutral Atom Imager observations, Lockheed Martin Advanced Technology Center, Seminar, 9 November, 2000.

S. A. Fuselier, Comparison of Neutral Atom Images and FUV aurora, IMAGE FUV science team meeting, Liege, Belgium 15 November, 2000.

Collier, M R, et al., IMAGE/LENA Observations of Neutral Atoms from the Solar Wind, EOS Trans. AGU, 81(48), p.F1035, 2000.

Wilson, G R, et al., Ion energization in the auroral zone: IMAGE/LENA observations of low altitude heating region characteristics, EOS Trans. AGU, 81(48), p.F1035, 2000.

Coffey, V N, et al., The response of the ionospheric cusp to the solar wind through two perspectivies: low energy charged particle in-situ measurements and low energy neutral atom imaging, EOS Trans. AGU, 81(48), p.F1036, 2000.

Fok, M-C, et al., Storm-time ring current seen by IMAGE, EOS Trans. AGU, 81(48), p.F1036, 2000.

Dressler, R A, Reevaluation of charge exchange cross sections related to energetic neutral atom detection in the magnetosphere, EOS Trans. AGU, 81(48), p.F1037, 2000.

Technical/Cost Section