Imaging ion outflow in the high-latitude magnetosphere using low-energy neutral atoms

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Abstract. The measurement of neutral atom fluxes generated by charge exchange with the Earth's geocorona has recently been shown to provide the capability to image the magnetosphere. We investigate neutral oxygen fluxes produced by charge exchange from the cusp/cleft ion fountain population. Using an empirical cusp/cleft ion fountain model, an empirical variation of the geocoronal neutral hydrogen density with distance, and typical values for charge-exchange cross sections, line-of-sight integrations are performed to calculate the neutral oxygen flux at arbitrary locations in space. The resulting images are evaluated for a set of orbital positions of the proposed HI-LITE small explorer spacecraft. The resulting neutral oxygen fluxes are high enough for imaging with a low-energy neutral atom imaging instrument (ILENA) onboard the spacecraft.

Subject terms: magnetospheric imagery.

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1 Introduction

A major objective of space physics is to understand the Earth's magnetosphere and its interaction with the ionosphere and solar wind. Nowhere is that interaction more readily apparent, or more highly variable, than in the high-latitude regions of the Earth's magnetosphere. Input from the solar wind produces significant effects on the Earth's ionosphere including auroral displays and upwelling of ionospheric ions that ultimately become part of the magnetospheric population and interact back on the ionospheric plasma. When the amount of solar wind mass, energy, and momentum added to the magnetosphere is high, the system becomes highly disturbed and the energy imparted to the system is dissipated explosively through the substorm process. The high-latitude magnetosphere plays a central role in this dynamic energy-dissipation process. In the interaction of the solar wind with the ionosphere, the Earth's ionosphere at high latitudes has two principal roles. First, it allows closure of magnetospheric current systems and acts in conjunction with the neutral atmosphere as a damper of plasma motions driven by the solar wind (i.e., ion drag). Second, it acts as an important source of plasma for the magnetosphere, due in part to the energy dissipation associated with the damping of solar-wind-driven plasma motions. We know from statistical sampling of a large number of *in situ* measurements that ion outflow from the high-latitude regions is substantial.[1] Depending on the level of solar and magnetospheric activity, ionospheric ions can contribute from a small fraction to nearly all of the plasma in the Earth's plasma sheet.[2,3] The dynamics of the ion outflow from particular regions within the high-latitude ionosphere are different. The outflow from the polar cap, called the polar wind, is continuously present. It consists of light ions (few electron volt H^+ and He^+) and is relatively independent of interplanetary conditions and geomagnetic activity.[4] The outflow from the high-latitude auroral regions is much more dynamic, contains heavy ions such as O^+, and is correlated with both geomagnetic and solar activity.[1,5]

Studies have indicated that the auroral acceleration region is an important, if not dominant, region of ion outflow.[6,7] However, the discovery of the cleft ion fountain[8–11] and subsequent interpretation of the ion outflow in this region[8] indicate that it is also an important source of low-energy ions in the polar cap and ultimately in the plasma sheet. Since thermal O^+ in the ionosphere is gravitationally bound, its escape from the high-latitude regions requires a pre-energization mechanism.[12] The other major outflowing spe-

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cies H^+ is not gravitationally bound and acquires its energy above ~1000 km, where thermal H^+ dominates the cold plasma. Both ion species are limited[13,14] by charge exchange with the geocorona neutral H. This charge-exchange process gives rise to an intense flux of neutral O and H in the high-latitude magnetosphere.[15]

More than 20 years after the discovery of O^+ in the high-latitude region and the realization that the ionosphere is a significant contributor of magnetospheric plasma,[16] the primary region of low-energy ion outflow remains controversial. Furthermore, the possibilities are diametrically opposite: On the one hand, it is supposed that an intense localized cusp is providing the ionospheric ions for the magnetosphere, and on the other hand, the source is speculated to be a diffuse extensive region comprising the entire auroral zone. One possibility is that both interpretations of the data are correct. For example, one region is the dominant outflow source for one level of geomagnetic activity, while the other source dominates for other conditions. However, it is important to realize that the failure to resolve this controversy is due precisely to the limitations of *in situ* measurements. The global perspective is produced only by interpretation of a large number of individual localized measurements that do not resolve temporal or spatial relationships between various regions. Resolution of these issues requires global imaging of the high-latitude ion outflow regions on timescales commensurate with the solar wind/magnetosphere interaction cycle since individual source regions may be dominant for specific phases of a substorm or for different levels of solar and/or magnetospheric activity.

One of the fundamental dynamical features of the Earth's magnetosphere is the substorm. Some of the energy released during a substorm is transferred to the inner magnetosphere where it appears as ring current enhancement, Joule heating in the ionosphere, and auroral particle precipitation, while the rest of the energy is returned to the solar wind through the geomagnetic tail. Eventually, the magnetosphere recovers from the explosive dissipation phase and energy begins to be stored again in the magnetotail until the next substorm is triggered. The entire process of explosive dissipation and recovery takes an average of about 1 to 2 h and recurs every few hours if energy transfer from the solar wind continues at a high rate [i.e., the interplanetary magnetic field (IMF) remains southward]. Much of the phenomenology of the substorm process has a firm observational basis. Baker et al.[17] argued that a reduction of the plasma sheet half-width during the substorm expansion phase should lead to a demagnetization of O^+ ions of ionospheric origin and enhanced growth of a large-scale ion tearing instability believed to initiate the substorm explosive growth. It is also well documented that larger relative oxygen ion densities are observed in the plasma sheet after the expansion phase than during the growth phase.[18] This O^+ must be supplied from the high-latitude region during the substorm. In addition, the ionospheric ions in the plasma sheet may cause important differences between strings of multiple substorms and isolated substorms.

Considering the potential importance of ionospheric ions in the substorm process, there have been surprisingly few investigations of the ionospheric ion source and its dependence on interplanetary and substorm conditions.[19] Part of the problem in investigating the ion-source morphology with *in situ* measurements is the difficulty in determining the dominant region of ion outflow. However, in the case of substorms the difficulty with the *in situ* measurements is much greater than a simple spatial issue since different segments of the high-latitude region may be important at different phases of the magnetospheric substorm. Hence, *in situ* measurements provide either a snapshot of ion outflow in a very localized region or a statistical sample of a large region lacking any sort of temporal information. Neither of these can be used to determine the importance of ionospheric ions in the substorm process on a global scale. The resolution of these issues requires global imaging of ion outflow over timescales appropriate to the substorm process (5 min over total characteristic times of 1 h). With these measurements, spatial variations of the ion outflow will be separated from temporal changes related to the substorm process and the importance of the ionospheric ions to the substorm process will be determined. Based on concurrent simultaneous observations of the HI-LITE instruments and low-altitude data, we will determine the relative positioning of ion outflow and magnetospheric boundaries. For example, from the shape of the upwelling plume it can be determined whether the ion outflow occurs on sunward or antisunward convecting field lines and how the outflow is related spatially to substorm features such as westward-traveling surges, which are at the base of the evening side of the substorm current wedge.[20] The observations of the spatial distribution could also be combined with magnetic mapping using current models[21] to assess the expected magnetotail plasma injection region.

In this paper we use a cusp ion fountain model, recently developed by Gallagher, to provide the source ion fluxes for the charge-exchange process and subsequent line-of-sight integrations to estimate the observable fluxes at the spacecraft location. In the following we demonstrate that neutral atom imaging of the cusp/cleft ion fountain is feasible using the ILENA instrument[22] (proposed as part of the HI-LITE mission[23]) and will lead to images of both the spatial and temporal evolution necessary to assess the role of the ion fountain in magnetospheric processes.

2 Neutral Atom Imaging

2.1 *Cleft Ion Fountain*

A region of intense O^+ transverse ion energization to energies of 10 eV has been identified extending from 2,000 to 10,000 km on the dayside of the magnetosphere. Although the association of the upwelling ions with field-aligned currents suggested that Joule heating was an important energy source, Moore et al.[24] were unable to identify the driving energy source using *in situ* measurements from one pass through the region. However, Whalen, Watanabe, and Yau[25] obtained data with higher temporal and energy resolution and concluded from the satellite and earlier rocket observations that the localized upwelling ion region is the high-altitude dayside component of a transverse ion energization (TIE) region, which is an annulus covering all local times but at lower altitudes on the nightside. Peterson, Yau, and Whalen[14] noted that the source of the nearly stationary dayside thermal O^+ population with intensity comparable to H^+ at altitudes of 2000 to 3000 km observed just equatorward of the TIE or upwelling ion region is uncertain. These different interpretations are the direct result of the lack of a global view of the cleft ion fountain. Statistical surveys of the fountain from the Dynamics Explorer Spacecraft DE-1 produced ion outflow maps where local time and seasonal variations of the outflow were averaged together as the orbit configuration changed. Such averaging makes it impossible to compare ion outflow rates as a function of local time or altitude to determine the extent of the base of the fountain. The ILENA instrument provides a global view of the base of the cleft ion fountain and TIE regions needed to determine the correct interpretation of previous *in situ* data. Using a combination of the Plasma Ion Mass Spectrograph (PIMS) and ILENA measurements, we can thus determine if the source of the stationary O^+ equatorward of the upwelling ion region is photoionization of neutral O at 2,000 km altitudes, simple transport of O^+ from the ionosphere below, or the result of processes driven by the entry of solar-wind plasma into the cusp/cleft ionosphere.

2.2 *Charge Exchange*

Neutral atom imaging is a new technique that enables global imaging of magnetospheric plasmas to be undertaken.[26] Briefly, the Earth's geocorona acts like an imaging screen for ions in the ionosphere/magnetosphere. These ions charge-exchange with the Earth's geocorona and produce neutral atoms. The neutrals produced in this reaction leave the interaction region with essentially the same energy as the outflowing ion. In addition, the direction of the neutral is that of the ion at the moment of the interaction, i.e., the combination of gyromotion and motion along the field. The neutral then travels in almost a straight line to the imaging point, modified only by gravitational acceleration. For the lowest energies (~10 eV), this leads to an appreciable angular distortion, estimated to be <14 deg for 10 eV O^+ at a distance of 1 R_e (where R_e are Earth radii) from the source region, which is, however, an upper limit to the possible distances during the projected HI-LITE orbit.[23] For energies of 30 eV and above, the angular deflection is less than 4.6 deg, below the limit of the angular resolution of 6 × 6 deg for each pixel. Therefore, energy channels above 30 eV will make it possible to produce an image of the input ion energy and direction by collecting and analyzing the neutrals. Despite the distortion, energies below 30 eV can be used for imaging at distances closer to the source and will provide the total low-energy source flux in any case. Both the density of the Earth's geocorona and the cross sections for H^+ and O^+ on H and O neutrals are well known. It is thus possible to calculate a neutral flux and leave an interaction region for any specified O^+ or H^+ distribution.

2.3 *Line-of-Sight Integration*

Using the Marshall Space Flight Center model for upwelling ion flux (courtesy D. Gallagher), we have performed line-of-sight integration to find the resulting neutral oxygen fluxes (j_O) at the spacecraft location, given by the integral (assuming the source fills the instrument field of view homogenously)

$$j_O=\sigma\int dl j_O+n_H \ . \tag{1}$$

The variation of the $O^+ - H$ cross section with energy is shown in Fig. 1, where we plot the data of Fite, Smith, and Stebbings.[27] The graph shows that within the energy range

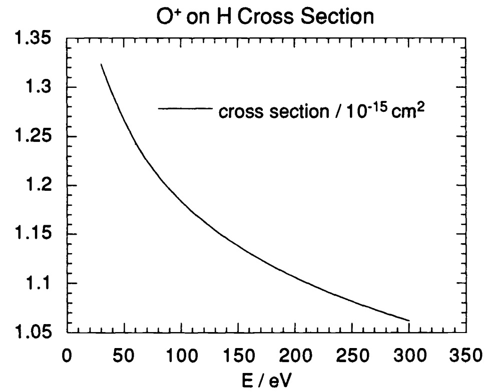

Fig. 1 Charge-exchange cross section for the reaction $O^+ - H$ versus energy.

under consideration, i.e., between 30 and 300 eV, the cross section varies between 1.05 and 1.35×10^{-15} cm². For a conservative estimate, we take in the following a cross section of 10^{-15} cm². The geocorona neutral hydrogen density is adopted from McComas et al.[28]:

$$n_H=3300 \exp(-R/1.6) \text{ cm}^{-3} \ . \tag{2}$$

Assuming an opening angle of $\Delta\Omega$ and an instrument aperture of A, the number of imparting particles per unit time is then given by

$$\frac{\partial N}{\partial t}=A\Delta\Omega j_O=A\Delta\Omega\sigma\int dl j_{O^+}n_H \ . \tag{3}$$

The aperture A, the opening solid angle $\sigma\int dl j_{O^+}n_H$, and the sampling time of the instrument need to be adjusted such that sufficient counts per image will be obtained.

The crucial quantity for this purpose is the neutral oxygen flux j_o at the instrument location. To investigate and predict the flux levels at the spacecraft location, we have performed line-of-sight integrations of Eq. (1). The results are shown in the following section. The center of each image corresponds to a look direction toward a point located at a radial distance of 2 R_e in the noon meridional plane, at an azimuthal angle of 66 deg out of the equatorial plane. The images represent deviations from this direction by ±45 deg in each east or west (horizontal in the image) and north or south (vertical in the image) directions, corresponding to a 90 × 90-deg field of view. Therefore, the images represent the view the observer would see (if the fluxes were visible) and allow assessment of both the range of flux values dependent of sensor orientation and the angular resolution mandated by source properties.

3 Images and Flux at Spacecraft Location

The cusp/cleft ion fountain model using the source j_{o^+} for the calculations is displayed in a noon meridional cut in Fig. 2(a). The panel represents a 2 × 2 R_e cut through the center of the Earth. Clearly visible is the cleft ion fountain in the upper right. The enhancement in the lower left is due to the return flux of the oxygen in the model and will be ignored in the following. The other panels represent the fluxes expected at five locations along the orbit of the HI-LITE Small

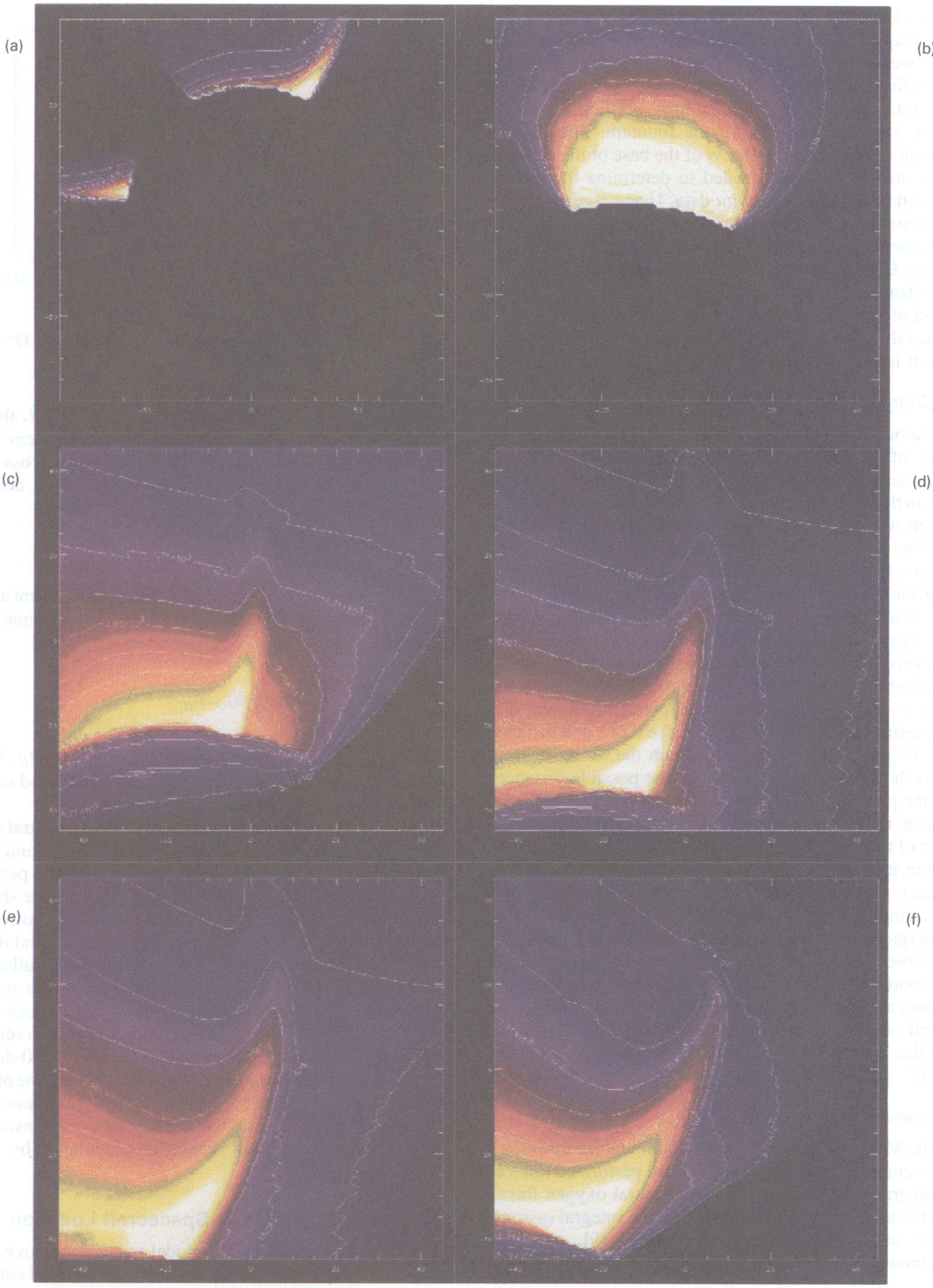

Fig. 2 Source and neutral oxygen fluxes in color representation. Each panel corresponds to a 90 × 90-deg field of view.

Explorer.[23] The locations are [in solar-magnetosphere (SM) coordinates]: (b) $x=-1.29$, $y=-0.72$, $z=0.09$; (c) $x=-0.74$, $y=-0.81$, $z=1.42$; (d) $x=-0.05$, $y=-0.75$, $z=1.65$; (e) $x=0.26$, $y=-0.72$, $z=1.60$; and (f) $x=0.99$, $y=-0.63$, $z=1.08$.

The images of Fig. 2 can be used to estimate the necessary angular resolution of the ILENA instrument. By inspection we find that typical angular dimensions are well in excess of 10 deg and that scale lengths for the angular variations are even larger in some cases. Therefore, the planned 6×6-deg field of view per pixel will be sufficient to resolve the most important detail. Furthermore, the relatively large typical variation angle guarantees that the source fills the field of view of an individual pixel sufficiently well. At last, the images show that the cleft ion fountain is well contained in a 90×90-deg field of view as envisioned in the ILENA design.[22]

For the purpose of studying the expected range of fluxes, the images of Fig. 2 are plotted as surfaces and contours in Figs. 3 through 7. These figures place the emphasis on the maximum and typical ranges of the expected neutral oxygen fluxes. The results are summarized in Table 1.

The figures show that complete coverage of the ion fountain mandates the capability to image fluxes between about $2 \times 10^3\ \mathrm{cm^{-2}\,s^{-1}\,sr^{-1}}$ and $1.5 \times 10^4\ \mathrm{cm^{-2}\,s^{-1}\,sr^{-1}}$ within a time window determined by magnetospheric processes, of the order of 5 min.

As is evident from the plots, typical fluxes are in the range of 2×10^3 to $10^4\ \mathrm{cm^{-2}\,s^{-1}\,sr^{-1}}$ at the spacecraft location, which was chosen to be at a geocentric distance of 2 R_e in all cases. Therefore, we can derive some basic instrument requirements for ILENA: Assuming, say, an angular resolution of 6×6 deg $= 9.6 \times 10^{-3}$ sr for each pixel and an aperture of 1 $\mathrm{cm^{-2}}$, the basic count rate would be 20 to 100 $\mathrm{s^{-1}}$. With an efficiency of 10% taken into account (see Ref. 22) this reduces to 2 to 10 $\mathrm{s^{-1}}$.

To investigate variations over substorm dynamical time scales, a temporal resolution of about 5 min is desirable. In 5 min a total of 600 to 3000 counts would be accumulated. This value is sufficiently high to make an investigation of this kind feasible.

5 Outlook

It is also possible to apply the same technique to the plasma sheet protons of the magnetotail. To demonstrate the feasibility, we have used a late growth phase equilibrium magnetotail model and the results of a substorm simulation (Hesse and Birn, in preparation) valid from about $x_{SM}=-5\ R_e$ outward and assumed a proton temperature of 10 keV to calculate the expected neutral hydrogen fluxes at a hypothetical spacecraft location of $x_{SM}=-5\ R_e$, $y_{SM}=-0\ R_e$, and $z_{SM}=8\ R_e$. The results are shown in Fig. 8. The figure shows a clear change in flux levels and distribution during substorm expansion. The enhanced levels for the substorm expansion phase are due to injection of plasma into the inner magnetotail region. The levels are again well within detection range of ILENA. Therefore, it might be possible in the future to use imaging techniques such as those discussed here to remotely sense plasma sheet dynamics during substorms.

6 Summary

In this paper we have investigated the expected neutral oxygen fluxes from charge exchange of the cusp/cleft ion foun-

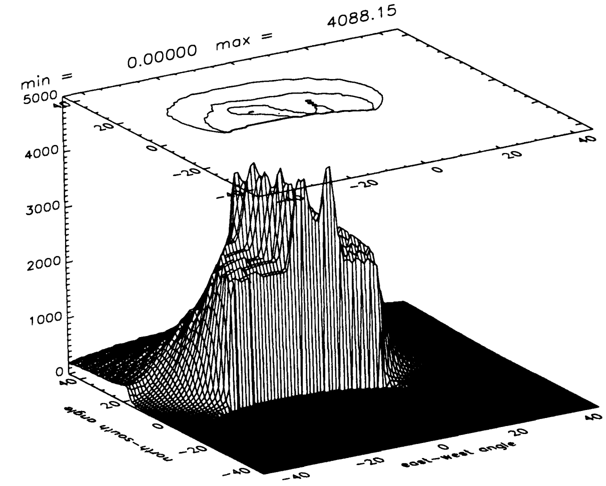

Fig. 3 Neutral oxygen flux levels at $x=-1.29$, $y=-0.72$, $z=0.09$. For comparison, the contours for the angular flux distribution are shown in the top of the figure.

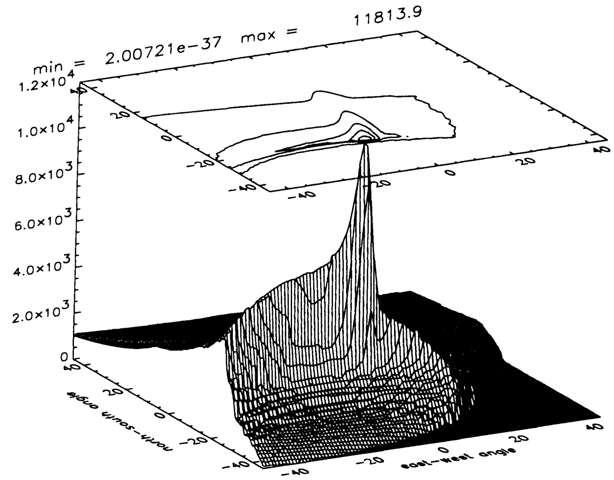

Fig. 4 Same as Fig. 3, but at $x=-0.74$, $y=-0.81$, $z=1.42$.

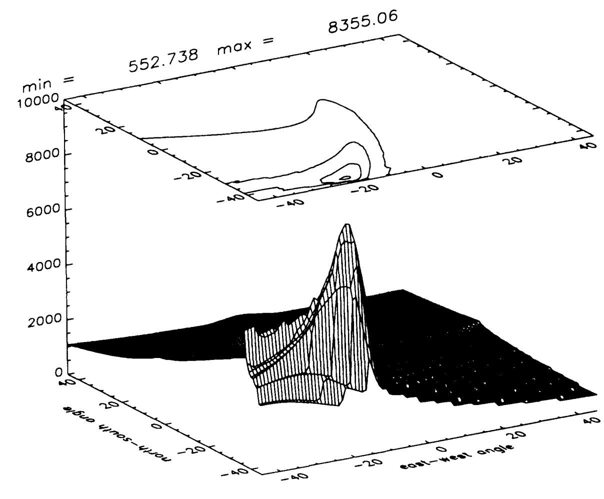

Fig. 5 Same as Fig. 3, but at $x=-0.05$, $y=-0.75$, $z=1.65$.

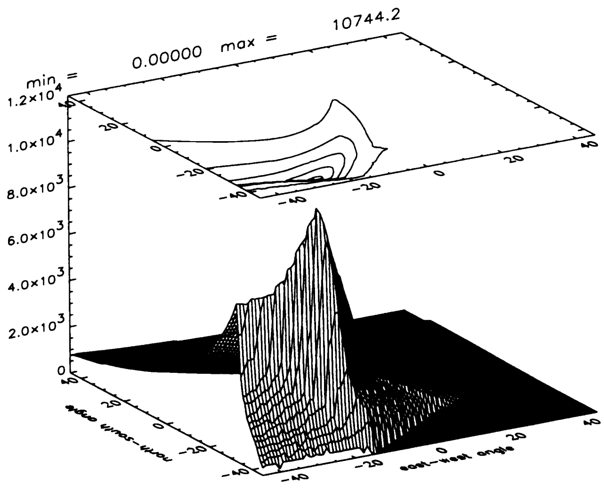

Fig. 6 Same as Fig. 3, but at $x = 0.26$, $y = -0.72$, $z = 1.60$.

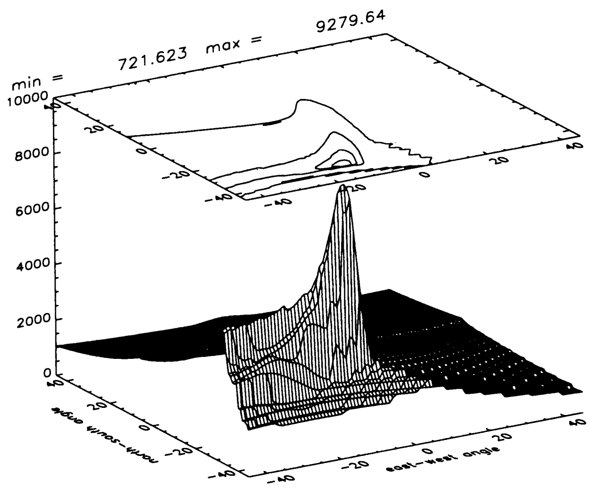

Fig. 7 Same as Fig. 3, but at $x = 0.99$, $y = -0.63$, $z = 1.08$.

Table 1 Summary of results in Figs. 3 through 7.

Fig.	x_{SM}	y_{SM}	z_{SM}	Flux Range $/cm^{-2}s^{-1}ster^{-1}$
3	-1.29	-0.72	+0.09	2×10^3 to 4.1×10^3
4	-0.74	-0.81	+1.42	2×10^3 to 1.2×10^4
5	-0.05	-0.75	+1.65	2×10^3 to 8.4×10^3
6	+0.26	-0.72	+1.60	2×10^3 to 1.1×10^4
7	+0.99	-0.63	+1.08	2×10^3 to 9.3×10^3

tain oxygen ions. The flux distribution in magnitude and look direction was derived for five different orbital locations of the proposed HI-LITE Small Explorer.[23] The angular distribution of the neutral oxygen flux at the spacecraft location was derived from line-of-sight integration of the source, consisting of the oxygen flux of the cusp/cleft ion fountain, the conservatively estimated charge-exchange cross section, and the geocoronal neutral hydrogen density. Based on the conservatively estimated source, we found that flux levels at the spacecraft location typically fall between 2×10^3 cm^{-2} s^{-1} sr^{-1} and about 1×10^4 cm^{-2} s^{-1} sr^{-1}. Typical angular

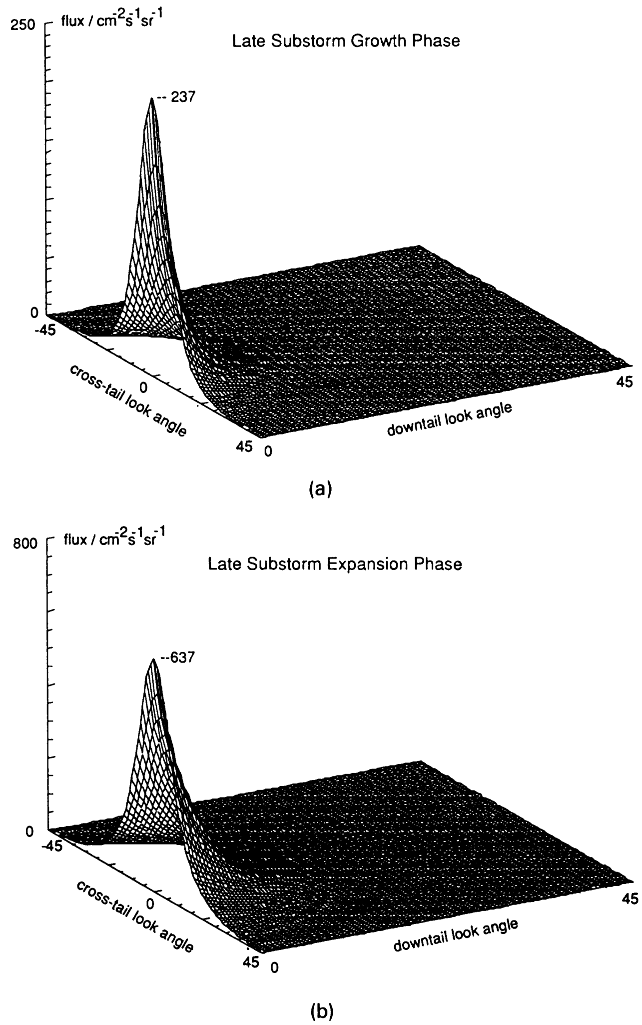

Fig. 8 Neutral hydrogen fluxes with energies below 1 keV derived from (a) a late substorm growth phase equilibrium and (b) a substorm expansion phase state model by 3-D resistive magnetohydrodynamic simulations. In either case, the spacecraft location is assumed to be $x_{SM} = -5\ R_e$, $y_{SM} = -0\ R_e$, and $z_{SM} = 8\ R_e$. Shown is the variation of the flux with crosstail and downtail look angles.

dimensions, also of great importance for instrument design, appeared to be about 10 deg.

These results can be used to derive requirements for instrument design of the ILENA low-energy neutral atom imaging instrument.[22] Using an instrument efficiency of 10%, an aperture of 1 cm^2, and a pixel field of view of 6×6 deg, we found that for a typical substorm dynamical time of 5 min, between 600 and 3000 counts would be accumulated. This expected number shows that the imaging of the neutral oxygen origination in the cusp/cleft ion fountain region using the proposed ILENA instrument on the HI-LITE spacecraft is clearly feasible. Furthermore, extended investigations of the magnetotail using this method as well within reach.

Acknowledgments

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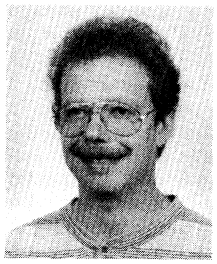
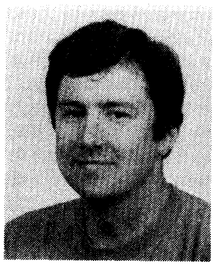
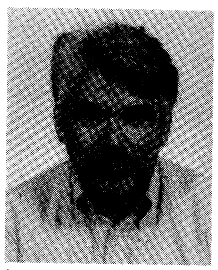


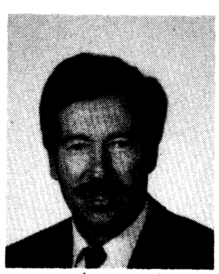
Michael Hesse has been a staff scientist (astrophysicist) at NASA/Goddard Space Flight Center, Maryland, since 1993. His major research areas include analytic theory and numerical modeling of magnetic reconnection in two and three dimensions and magnetotail structure and dynamics. Hesse received the Diplom Physiker (MS) in 1985 and the PhD in theoretical plasma physics from Ruhr University, Bochum, Germany, in 1988. From 1988 to 1991, he was a postdoctoral fellow at Los Alamos National Laboratory. From 1991 to 1993, Hesse was employed at Hughes STX, Maryland. He has published more than 50 papers in journals and conference proceedings. He is a member of the American Geophysical Union and has been a steering committee member for the Geospace Environment Modeling Program (GEM) since 1993.



Mark F. Smith is a space physicist at NASA/Goddard Space Flight Center (GSFC), Maryland. His major areas of research are in the magnetopause, magnetospheric-ionospheric coupling, and space plasma instrumentation. He received a BSc (honors) in physics and astronomy in 1980 from University College London and a PhD in upper-atmospheric physics in 1984. He was a research assistant at Mullard Space Science Laboratory, United Kingdom, from 1984 to 1987. From 1987 to 1990, he was a senior research scientist at the Southwest Research Institute. He joined the Laboratory of Extraterrestrial Physics at NASA/GSFC in 1991. Smith has published more than 60 papers in various professional journals. He is a member of the American Geophysical Union.



Federico Herrero received the BS degree from Spring Hill College in 1965 and the MS and PhD degrees from the University of Florida in 1966 and 1968, respectively, all in physics. Following postdoctoral work at Johns Hopkins University, he joined the faculty at the University of Puerto Rico where he held the positions of professor and chairman of the Physics Department and performed thermospheric physics research at the National Astronomy and Ionosphere Center, Arecibo Observatory. In 1981, he joined the scientific staff of the NASA/Goddard Space Flight Center. His current research interests are in upper-atmospheric and magnetospheric physics.



Arthur G. Ghielmetti is currently a staff scientist at the Space Sciences Laboratory of the Lockheed Research Laboratories in Palo Alto, California. He has been a co-investigator on seven NASA and ESA space research missions. He received his BA degree in physics from Cornell University, and his MS and PhD degrees in physics from the University of Bern Switzerland in 1974. His research interests include electron and ion spectrometry, sensors, space plasmas instrumentation, and space plasma research. He is the author of over 35 papers on ion optics and space plasma research.

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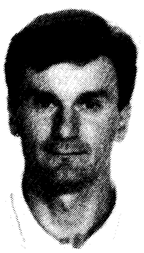

Peter Wurz obtained an engineering degree in electronics and went on to study physics at the technical University of Vienna, Austria. The subject of his MS thesis was sputtering by heavy ion bombardment. He went on to earn a PhD in physics, performing high-resolution laser-based mass spectroscopy of trace impurities in metals and insulators. From 1990 to 1992 he performed post-doctoral work at Argonne National Laboratory, Chicago, Illinois, in the field of molecular mass spectroscopy of fullerenes, biomolecules, and polymers. Since 1992 he has held a position at the University of Berne, Switzerland, in the mass spectroscopy group. He has published research in the fields of ion sputtering, electron-stimulated desorption, ion optics, physical chemistry, laser interaction with solids and particles, and extraterrestrial physics.

Peter Bochsler is an associate professor of physics at the University of Bern/Switzerland. His main research interests include space physics, solar wind, and the history of the Sun and solar system. He graduated from the University of Bern with a thesis on cosmic ray produced nobel gas isotopes in meteorites. His PhD thesis dealt with ^3H (tritium) in lunar soil. He spent two years at the Weizmann Institute of Science in Rehovot/Israel investigating noble gases in terrestrial samples. Returning to the University of Bern, he continued his research on terrestrial samples and, simultaneously, he participated in the development and calibration of the ISEE-3 Composition Instrument. After the successful launch of ISEE-3, he took an active role in the data analysis and interpretation with special emphasis on the abundances of minor elements in the solar wind, the isotopic composition of solar wind helium, and the dynamics of minor ions in the solar wind plasma. Presently, he is involved as a member of an international team in the development of the CELIAS-experiment on the SOHO-payload and, in collaboration with a team from the University of Maryland, in the development of the WIND-MASS and the WIND-SWICS experiments.

Biographies and photographs of remaining authors not available.