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VISIONS remote observations of a spatially-structured filamentary source of energetic neutral atoms near the polar cap boundary during an auroral substorm

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Abstract

We report initial results from the VISualizing Ion Outflow via Neutral atom imaging during a Substorm (VISIONS) rocket that flew through and near several regions of enhanced auroral activity and also sensed regions of ion outflow both remotely and directly. The observed neutral atom fluxes were largest at the lower energies and generally higher in the auroral zone than in the polar cap. In this paper, we focus on data from the latter half of the VISIONS trajectory when the rocket traversed the polar cap region. During this period, many of the energetic neutral atom spectra show a peak at 100 eV. Spectra with peaks around 100 eV are also observed in the Electrostatic Ion Analyzer (EIA) data consistent with these ions comprising the source population for the energetic neutral atoms. The EIA observations of this low energy population extend only over a few tens of km. Furthermore, the directionality of the arriving energetic neutral atoms is consistent with either this spatially localized source of energetic ions extending from as low as about 300 km up to above 600 km or a larger source of energetic ions to the southwest.
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1. Introduction

The high-latitude ionosphere serves as a significant source of plasma to the ionosphere (e.g., Chappell et al. (1987)). During periods of substorm activity and during geomagnetic storms, energetic ions have been observed streaming out of the high latitude ionosphere. These ions eventually populate the plasma sheet (Kistler et al., 2005) and ring current (Nose et al., 2005), and during active periods they can dominate the total density or energy density, respectively, of these regions. Modeling work has indicated that the observed concentrations of heavy ions appreciably affect reconnection rates (Shay and Swisdak, 2004), and, therefore, the general response of the terrestrial ionosphere-magnetosphere system to solar wind forcing (Wiltberger et al., 2010; Brambles et al., 2010).

The transport of ionospheric plasma to the magnetosphere occurs as a result of a multi-stage process that includes (1) ionospheric heating, expansion, and upflow, (2) acceleration of ions perpendicular to the geomagnetic field, and (3) conversion of perpendicular energy to parallel escape energy (Strangeway et al., 2005; Zheng et al., 2005). Many physical mechanisms are associated with this pro-

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cess. Frictional heating due to differential ion-neutral drifts produces expansion and upflow (type-1 upflow) (e.g., Wahlund et al. (1992) and Zettergren and Semeter (2012)). Soft particle precipitation can heat the ambient ionospheric electrons and causes field-aligned ambipolar plasma flows (type-2 upflow) (e.g., Su et al. (1999)). These ionospheric processes have been observed most frequently in the cusp or midnight auroral zone regions and are capable of producing bulk ion velocities of ~100–750 m/s below 1000 km altitude (e.g., Ogawa et al., 2003; Foster and Lester, 1996).

At altitudes above the location where upflows are initiated, several additional processes are known to propel ions to escape velocity, resulting in "ion outflow." A large number of broadband ELF and VLF wave measurements have demonstrated concurrence of these plasma waves with ion distributions energized perpendicular to the magnetic field (e.g., Kintner et al., 1996; Andre et al., 1998). Transversely accelerated distributions typically have energies in the ~10–1000 eV range, and the mirror force acts to propel them outward along the magnetic field lines, forming "ion conic" distributions (e.g., Yau and Andre (1997) and Andre and Yau (1997)). Energization via ion cyclotron resonance is thought to play a key role in producing transversely accelerated ions (Crew et al., 1990), though lower hybrid structures may also contribute (Lynch et al., 1996, 1999). Finally, parallel electric fields associated with the auroral acceleration region can produce outflowing ions in the form of ~1–10 keV ion beams (McFadden et al., 1998).

The VISIONS (VISualizing Ion Outflow via Neutral atom imaging during a Substorm) sounding rocket mission was launched 7 February 2013, at 0821 UTC from Poker Flat, AK into the expansion phase of an auroral substorm. VISIONS was expressly designed to take advantage of the sounding rocket trajectory (slow motion through the auroral features and vertical profile) with a unique combination of in-situ and remote sensing instruments to help shed new light on the drivers of low-altitude ion outflow.

VISIONS flew through and near several regions of enhanced auroral activity, and also sensed regions of ion outflow both remotely (via ENA imaging) and directly (using in situ measurements). The observed ENA fluxes result from energetic ions that have exchanged charge with neutral gas along the imager's line-of-sight. Thus, the observations provide remote imaging of the source ion population. The two VISIONS/MILENA instruments observed signatures of outflowing ionospheric ions as the payload crossed multiple auroral arcs spanning over 500 km and moved into the polar cap.

The observed neutral atom fluxes were largest at the lower energies and generally higher in the auroral zone than in the polar cap while the VISIONS EIA observed the most intense ion signatures near the polar cap boundary. As the rocket traversed the boundary between the auroral zone and the polar cap, the MILENA instruments observed a decrease in ENA flux.

In this paper, we focus on the polar cap data from the latter part of the VISIONS rocket flight which included many spectra exhibiting peaks at about 100 eV. The observed angular distribution of the low energy neutral atoms is highly directional and suggests a stable, over the time scale of the rocket flight, spatial low energy neutral atom emitting structure (or structures) which appears to show some correlation to the visible auroral activity observed by the on-board auroral imager (Hecht et al., 2013).

Here we discuss the spin-averaged MILENA data that provide through their anisotropies a measure of the vertical spatial distribution of the source ions. Because the VISIONS rocket data were transmitted at high cadence, MILENA also supplies high time-resolution data binned on the subspin level that allows a determination of horizontal anisotropies. Analysis of these data is still in progress and will be reported in a future publication. Initial examination of the subspin data shows consistency with the results in this paper.

2. VISIONS instruments and the MILENAs

VISIONS carried five instruments to measure the relevant parameters for studying ion outflow (i) two Miniaturized Imagers for Low-Energy Neutral Atoms, MILENA-1 and 2, to remotely sense ion outflow from 50 eV to 3 keV through energetic neutral atom measurements, (ii) an Electrostatic Electron Analyzer (EEA) from 3 eV to 30 keV, (iii) an Electrostatic Ion Analyzer (EIA) from 1.5 eV to 15 keV, (iv) a four-channel visible imager (6300, 3914, H-Beta, and 8446) with a 90° field of view for understanding electron precipitation over a wide area and for comparison with the ENA images (RAI), and (iv) a Fields and Thermal Plasma (FTP) suite that measured electric fields (DC through HF), magnetic fields, and electron temperature and density.

The two MILENA instruments were based on heritage from the Miniature Imager for Neutral Ionospheric atoms and Magnetospheric Electrons (MINI–ME) instrument launched on the FASTSAT spacecraft on 19 November 2010 from Kodiak, Alaska. FASTSAT/MINI–ME collected two years of outflow data in a nearly-circular orbit of Earth at a 650 km altitude and 72° inclination (Rowland et al., 2011).

The MILENAs functioned in a very similar manner to MINI–ME. Fig. 1 shows their general principle of operation. Incident energetic neutral atoms enter the instrument, which has cylindrical symmetry around the center axis, through a set of charged particle rejectors, which keep ions and electrons from entering. The neutral atoms then interact at a shallow incidence angle with a venetian blind style array of highly polished passive tungsten conversion surfaces where a fraction, about 1%, of the incident neutral atoms is converted to negative ions. A very small amount of the kinetic energy is transferred from the neutral during this charge exchange conversion due to the grazing angle