

POLAR/TIMAS STATISTICAL RESULTS ON THE OUTFLOW OF MOLECULAR IONS FROM EARTH AT SOLAR MINIMUM

O.W. Lennartsson, H.L. Collin, W.K. Peterson and E.G. Shelley

All at Lockheed Martin Missiles & Space, ATC, 3251 Hanover St., Palo Alto, CA 94304, USA

ABSTRACT

Ion composition data from the first 22 months of operation of the Polar/TIMAS instrument, covering the 15-eV/e to 33-keV/e energy range, have been surveyed to determine the typical abundance, at solar minimum, of N_2^+ , NO^+ and O_2^+ ions in the auroral ion outflow, as compared to that of the better known O^+ ions. The results indicate that molecular ions have roughly the same energy distribution as the O^+ ions, with maximum differential flux occurring below 400 eV, but are far less abundant, by two orders of magnitude. The molecular ions also differ from the O^+ ions in that they seem more specifically associated with enhanced geomagnetic activity.

INTRODUCTION

Since the discovery almost three decades ago (Shelley *et al.*, 1972) that singly charged atomic oxygen with keV energies is a large component of Earth's energetic plasma environment, O^+ ions have come to symbolize, more than any other ions, the strong and complex electrodynamic interaction between the solar wind and Earth's ionosphere. The focus on O^+ ions has been justified both by their great abundance and by their virtually certain terrestrial origin (e.g. Young *et al.*, 1982). However, with spaceborne ion mass spectrometers becoming increasingly sophisticated, the study of ionospheric ion outflow is beginning to include less abundant species, in particular the molecular N_2^+ , NO^+ and O_2^+ ions (e.g. Craven *et al.*, 1985; Klecker *et al.*, 1986; Yau *et al.*, 1993; Christon *et al.*, 1994; Peterson *et al.*, 1994; Wilson and Craven, 1998a and 1998b). These are chemically less stable than O^+ ions, and therefore likely to contribute less to the ion outflow, but may be a more sensitive indicator of certain electrodynamic processes (Wilson and Craven, 1998a and 1998b). This paper reports on an initial study of these molecular ions using one of the latest generation instruments.

THE TIMAS INSTRUMENT

The Toroidal Imaging Mass-Angle Spectrograph, or TIMAS, on the GGS Polar satellite (Shelley *et al.*, 1995) is the first spaceborne ion mass spectrometer for the sub-keV to keV range to combine magnetic mass analysis with simultaneous recording of all species (all M/Q) and a nearly omnidirectional field of view. This combination is accomplished by accepting ions within a 10° by nearly 360° wide window and, following the energy selection, magnetically dispersing them on a large annular detector (MCP). The total field of view scanned over the course of each 6-sec Polar spin cycle is 98% of the full 4π . The energy range is 15 eV/e to 33 keV/e, covered in 28 channels, of which the 14 even-numbered channels are used on even-numbered spins, and the 14 odd-numbered ones on odd spins. Each set of 14 channels (plus a pure background sampling) is swept 16 times per spin.

Data are partially processed onboard by binning and summing the detector counts into various arrays, in accordance with energy channel and view direction. These data arrays include 48 separate 64-step mass spectra, sorted by 8

selected energies, or energy bins, and 6 view angles. The angular bins used for mass spectra are roughly 90° by 90° solid angles centered on the de-spun Polar x-, y- and z-axes (parallel and antiparallel). Unlike the other data arrays, mass spectra are always summed over multiple spin cycles, often as many as 32.

The Polar orbit, with perigee and apogee at 1.8 and 9.0 R_E (geocentric), respectively, carries the TIMAS instrument through the auroral regions four times each 17.63-hour revolution, presently at perigee altitude in the southern hemisphere and, depending on geomagnetic conditions, at some 4 to 8 R_E (geocentric) in the northern hemisphere.

STATISTICAL METHOD

The principal TIMAS data for this study have been the mass spectra, all summed over 32 spin cycles, either onboard (most commonly) or by a combination of onboard and ground processing. With the emphasis on detection of molecular ions, rather than on detailed analysis of selected events, the spectra have been further summed on the ground over the 6 different view directions at each energy, so as to maximize the number of counts of an ion population that is expected (and found) to have rather low density. It is presumed that ions with M/Q in the 28- to 32-range are singly charged molecular ions (N₂⁺, NO⁺ or O₂⁺) of terrestrial origin, irrespective of angular distribution. The actual angular distribution has been found to agree, roughly, with a terrestrial source in cases of enhanced molecular ion count rates (not shown), although it may extend over several of the 6 solid angles at any one time.

For the most part, the mass spectra have been analysed visually with the help of high-quality printouts of color-coded 24-hour plots of count rates versus time and mass step at each of 8 energies. This method allows clear separation of M/Q ≈ 30 from M/Q = 16, for energies below 5 keV/e, at least, but does not generally allow N₂⁺, NO⁺ and O₂⁺ ions to be separated from each other. Gif file versions (of reduced image quality) can be found on the TIMAS WWW home page (ftp://timas.spasci.com/timas/survey_plots).

The color coding on these plots is such that, in principle, a barely visible trace at low count rates corresponds fairly closely to the 3-σ level of Poisson statistics, that is 10 counts per 32-spin accumulation (per pixel). Due to residual weak detector background even far outside of Earth's radiation belts, it has proved necessary, however, to define the minimum "significant" count level about three times higher, or 30 counts per 32 spins. In a typical situation, with the molecular ion flux essentially confined to the lowest energy bin (see below), this 30-count limit corresponds to a minimum detectable number density at M/Q ≈ 30 of about 0.01 cm⁻³. As a standard reference, the count rate of the far better known atomic O⁺ ions has been recorded along with that of molecular ions. Table 1 summarizes the major boundary conditions for this study.

| | |
|----------------------|--|
| Ion energy range: | 15 eV/e (+ s/c potential) to 33 keV/e |
| Time resolution: | 3.2 minutes (32 spins) |
| Field of view: | 98% of 4π (per spin) |
| Time span: | 16 March 1996 through 31 December 1997 |
| Total sampling time: | 14,887 hours (95% coverage) |
| Average daily ΣKp: | 14- |
| Solar cycle phase: | passing through minimum |

It is important to note that the nominal lower end of the TIMAS energy range, 15 eV/e, falls below the minimum energy of *escaping* N₂⁺, NO⁺ and O₂⁺ ions at the Polar perigee, since the escape energy of N₂⁺ ions, the lightest ones, is 10 eV at that altitude (0.8 R_E), and this energy, associated with upward motion, is added to the instrumental ram energy of 8 eV, associated with horizontal s/c motion. The small surplus ion energy of 3 eV is often offset by a few volt positive s/c charging, but this limiting case probably only applies to a minority of escaping ions.

RESULTS

Table 2 shows the frequency of occurrence and other characteristics of the molecular ions along with corresponding numbers for the O⁺ ions. In this case, the daily ΣKp has been given a relative weight proportional to the length of time

ions were present each day. The daily peak flux usually occurred in the southern auroral zone, at the closest approach to the terrestrial ion source. It is an average over the 3.2-min sampling, that is a spatial average across some 1400 km near perigee, and is an angular average over nearly 4π . The true differential flux may have reached substantially larger values along the upward magnetic field direction. Table 3 elaborates on the geomagnetic aspect. In this case, the average daily ΣKp is unweighted but restricted to days with sufficient ion data. Peak O^+ fluxes exceeding 10^7 all occurred in the southern auroral zone.

Table 2. Comparison of Molecular Ions as a Group With the O^+ Ions

| | N_2^+ , NO^+ and O_2^+ | O^+ |
|---|--|--|
| At or above level of detection, in hours: | 86.7 hrs | 8,828 hrs |
| and in fraction of samplings: | < 1% | 59% |
| Associated weighted daily ΣKp : | 22+ | 14+ |
| Energy at daily peak flux, mostly: | $15 \text{ eV} \leq E \leq 110 \text{ eV}$ | $15 \text{ eV} \leq E \leq 110 \text{ eV}$ |
| and always: | $E \leq 364 \text{ eV}$ | $E \leq 364 \text{ eV}$ |
| Typical daily peak flux; 4π average in $(\text{cm}^2 \text{ sec ster keV})^{-1}$: | $(1.3 \pm 0.6) \times 10^5$ | $(7 \pm 4) \times 10^6$ |

Table 3. Average Daily ΣKp Associated With the Observation of Significant Ion Fluxes

| | N_2^+ , NO^+ and O_2^+ | O^+ |
|--|------------------------------|-------|
| At or above level of detection, <i>at least</i> | | |
| 30 minutes /day: | 27 | 14- |
| 1 hour /day: | 27- | 14- |
| 20 hours /day: | never | 18- |
| Daily peak flux $> 10^7 (\text{cm}^2 \text{ sec ster keV})^{-1}$; | | |
| 4π average; typically $n > 5 \text{ cm}^{-3}$: | never | 19- |

In Figure 1 the occurrence of significant ion count rates is subdivided by months and plotted along with the monthly sunspot numbers and geomagnetic A_p indices.

Fig. 1. Average daily occurrence by month of molecular ions (solid line) and O^+ ions (dots and dashes), along with the monthly sunspot numbers (long dashes) and A_p (short dashes), all on the same scale.

CONCLUSIONS

Possibly the single most striking result above is the rarity of molecular ions in comparison with the virtual omnipresence of the O^+ ions. The rather limited literature on molecular ion outflow acknowledges that these ions are a minor component of the total auroral ion outflow, but the previous emphasis on specific events might give the impression that these ions are somewhat more commonplace. Being that the magnetospheric content of O^+ ions increases substantially with increasing solar activity, that is with increasing EUV radiation (e.g. Young *et al.*, 1982), the strong presence of O^+ ions in these data, taken at solar minimum, implies that the adopted limit for "significant ion fluxes" is indeed low and favorable for the detection of molecular ions.

As expected, the daily occurrence of O^+ ions in Figure 1 does suggest some long-term increase after solar minimum in May 1996, but some part of that may be due to the mass spectra collection being altered at the beginning of September 1996, in effect doubling the sensitivity at low energy. The occurrence of molecular ions is far too variable to allow an inference with respect to long-term trends this early in solar cycle 23.

The O^+ and molecular ions both show the influence of geomagnetic activity, as indicated in Table 3, for example, but this effect seems significantly stronger with the molecular ions. In particular, in Figure 1 the monthly variation in the molecular ion occurrence is consistently in phase with the monthly Ap, sometimes magnifying the variation in the Ap, whereas the O^+ occurrence is partially out of phase.

ACKNOWLEDGMENTS

Geomagnetic and solar indices were obtained from the periodicals *Solar-Geophysical Data* issued by WDC-A for Solar-Terrestrial Physics, NOAA E/GC2, 325 Broadway, Boulder, Colorado 80303, USA. This work was supported by NASA under contract NAS5-30302.

REFERENCES

- Christon, S.P., G. Gloeckler, D.J. Williams, T. Mukai, R.W. McEntire, *et al.*, Energetic Atomic and Molecular Ions of Ionospheric Origin Observed in Distant Magnetotail Flow-Reversal Events, *Geophys. Res. Lett.*, **21**, 3023 (1994).
- Craven, P.D., R.C. Olsen, C.R. Chappell, and L. Kakani, Observations of Molecular Ions in the Earth's Magnetosphere, *J. Geophys. Res.*, **90**, 7599 (1985).
- Klecker, B., E. Möbius, D. Hovestadt, M. Scholer, G. Gloeckler, and F.M. Ipavitch, Discovery of Energetic Molecular Ions (NO^+ and O_2^+) in the Storm-Time Ring Current, *Geophys. Res. Lett.*, **13**, 632 (1986).
- Peterson, W.K., T. Abe, H. Fukunishi, M.J. Greffen, H. Hayakawa, *et al.*, On the Sources of Energization of Molecular Ions at Ionospheric Altitudes, *J. Geophys. Res.*, **99**, 23257 (1994).
- Shelley, E.G., R.G. Johnson, and R.D. Sharp, Satellite Observations of Energetic Heavy Ions During a Geomagnetic Storm, *J. Geophys. Res.*, **77**, 6104 (1972).
- Shelley, E.G., A.G. Ghielmetti, H. Balsiger, R.K. Black, J.A. Bowles, *et al.*, The Toroidal Imaging Mass-Angle Spectrograph (TIMAS) for the Polar Mission, *Space Sci. Rev.*, **71**, 497 (1995).
- Wilson, G.R., and P. Craven, Under What Conditions Will Ionospheric Molecular Ion Outflow Occur?, *AGU Geophys. Monograph Series*, in press (1998a).
- Wilson, G.R., and P. Craven, Molecular Ion Outflow in the Cleft Ion Fountain, *J. Geophys. Res.*, **103**, subm. (1998b).
- Yau, A.W., B.A. Whalen, C. Goodenough, E. Sagawa, and T. Mukai, EXOS D (Akebono) Observations of Molecular NO^+ and N_2^+ Upflowing Ions in the High-Altitude Auroral Ionosphere, *J. Geophys. Res.*, **98**, 11205 (1993).
- Young, D.T., H. Balsiger, and J. Geiss, Correlations of magnetospheric ion composition with geomagnetic and solar activity, *J. Geophys. Res.*, **87**, 9077 (1982).

Monthly Averages

