Received 28 March; accepted 23 May 1985.

1. Hellings, R. W., Callahan, P. S., Anderson, J. D. & Moffet, A. T. *Phys. Rev.* D**23**, 844-851 (1981).
2. Dyson, F. J. *Astrophys. J.* **156**, 529-540 (1969).
3. Murphy, A. J. Savino, J., Rynn, J. M. W., Choy, G. L. & McCamy, K. *J. geophys. Res.* **77**, 5042 (1972).
4. Colombo, G., Gaposchkin, E. M., Grossi, M. D. & Weiffenbach, G. L. *Shuttle-borne Skyhook: A New Tool for Low-Altitude Research* (Smithsonian Astrophysical Observatory Reports in Geoastronomy, No. 1, 1974).
5. Banks, P. *et al. Tethered Satellite System* (Final Rep. Facility Requirements Definition Team, Utah State University Center for Atmospheric and Space Sciences, 1980).
6. Faller, J. E. & Bender, P. L. *Natn. Bur. Stand. Spec. Publ.* **617**, 689-690 (1984).
7. Faller, J. E., Bender, P. L., Hall, J. L., Hils, D. & Vincent, M. A. in *Proc. Colloq. on Telemetric Arrays in Space*, Cargese (in the press).
8. Bisnovatyi-Kogan, G. S. *Astr. Zh.* (in the press).
9. Nulsen, P. E. J. & Fabian, A. C. *Nature* **312**, 48-50 (1984).
10. Woodward, M. Thesis, Univ. California, San Diego (1984).
11. Frohlich, C. in *Variations of the Solar Constant* (ed. Sofia, S.) 37-46 (NASA Conf. Pub. 2191, Washington, DC, 1980).
12. Paik, H.-J. *Spec. Iss. IEEE Trans. Geoscience and Remote Sensing* (in the press).
13. Lanzerotti, L. J. & Southwood, D. J. in *Solar System Plasma Physics Vol. 3* (eds Lanzerotti, L. J. Kennel, C. F. & Parker, E. N.) 109-135 (North-Holland, Amsterdam, 1979).
14. Mo, T. E., Maynard, N. C. & Heppner, J. P. *J. geophys. Res.* **85**, 2099-2106 (1980).
15. Chu, C. K. & Gross, R. A. *Amer. Inst. Aeronautics Astronautics Journal* **4**, 2209-2214 (1966).
16. *Spacecraft Charging Technology* (NASA Conf. Publ. 2071, Washington, D.C., 1978).
17. Fechtig, H., Grün. E. & Morfill, G. *Planet. Space Sci.* **27**, 511-531 (1979).
18. Lanzerotti, L. J. *et al. J. geophys. Res.* **86**, 5500-5506 (1981).

The geomagnetic mass spectrometer—mass and energy dispersions of ionospheric ion flows into the magnetosphere

M. Lockwood*§, T. E. Moore*, J. H. Waite Jr*, C. R. Chappell*, J. L. Horwitz† & R. A. Heelis‡

* Space Science Laboratory, NASA/Marshall Space Flight Center, Huntsville, Alabama 35812, USA
† Department of Physics, University of Alabama in Huntsville, Huntsville, Alabama 35899, USA
‡ Center for Space Sciences, University of Texas in Dallas, Richardson, Texas 75080, USA

NASA's Dynamics Explorer (DE) mission was designed to study the coupling between the Earth's magnetosphere, ionosphere and neutral thermosphere[1]. One area of major interest is the outflow of ionospheric plasma into the magnetosphere, the scale and significance of which is only now becoming apparent with the advent of mass-resolving, low-energy ion detectors. Here we compare observations of ion flows in the polar magnetosphere, made by the retarding ion mass spectrometer (RIMS)[2] on DE1, with those made simultaneously in the topside ionosphere by the ion drift meter (IDM)[3] on the lower-altitude DE2 spacecraft. The results show the dayside auroral ionosphere to be a significant and highly persistent source of plasma for the magnetosphere. The upwelling ionospheric ions are spatially dispersed, according to both their energy and mass, by the combined actions of the geomagnetic field and the dawn-to-dusk convection electric field, in an effect analogous to the operation of an ion mass spectrometer.

The two DE satellites were launched into co-planar polar orbits on 3 August 1981; DE1 being in a highly elliptical orbit which carried it out to a geocentric distance, r, of 4.5 Earth radii (R_E), while DE2 remained at altitudes below about 1,000 km. During the first 18 months of the mission, the DE1 apogee precessed from the north to the south pole.

The RIMS instrument on DE1 comprises three detector heads, each an ion mass spectrometer with a potential analyser input, and each capable of observing ions of two mass-per-charge ratios simultaneously. Ion species of mass up to 32 AMU can be resolved and for each species an integral energy spectrum over the range 0-50 eV (relative to spacecraft potential) is obtained. The RIMS radial head sweeps through a full range of pitch angles twice during each satellite spin period of 6 s: Fig. 1 shows data from this radial head for a pass from north to the south polar regions on 3 April 1982. By this date, DE1 perigee was close to the geomagnetic equator (time C) and no data were obtained between times B and D, when the ambient plasma density was too great for RIMS to operate. Figure 1 shows contours of O^+ and H^+ ion counts per accumulation period (12 ms) as a function of time and satellite spin angle. Count rates are approximately proportional to integral ion flux, one count per sample being roughly equivalent to 3.1×10^4 and 4.4×10^4 cm^{-2} s^{-1} sr^{-1} for H^+ and O^+ respectively; during most of this pass they were largest when the spin angle was close to zero, that is, when the radial head was looking along the orbit path or RAM direction. This indicates that the plasma was cold and isotropic and that ion flow velocities were much smaller than the spacecraft speed ($\sim$7 km s^{-1} at $r = 2R_E$ and 10 km s^{-1} at $r = 1.1R_E$)[4]. Exceptions to this were the behaviour of H^+ ions in the northern polar cap (before 1157 UT, the time A), for which the peak count rate was shifted from the RAM direction towards the upward field-aligned direction (the upper of the two dashed lines), revealing upward field-aligned flow, as predicted for the light-ion polar wind[5,6]; in addition the peak O^+ ion count rates near both magnetic poles (before about 1150 UT and after about 1240 UT) are shifted towards the downward field-aligned direction, indicating the ions are moving downward under the influence of gravity[7]. However, the largest flow features were seen at times A and E when DE1 passed through the morning sector auroral ovals in each hemisphere and strong upward flows were observed of both O^+ and H^+ ions.

These upflows have been termed "upwelling ion events"[4] as all ion species show the effects of equal ion heating below the satellite (to parallel and perpendicular temperatures of $\sim$2 and 10 eV, respectively) and carry an upward heat flux. Ion species observed streaming upwards in these events include H^+, He^+, O^+, N^+ and O^{2+} (ref. 7), and there is evidence that molecular ions $N_2{}^+$, $O_2{}^+$ and NO^+, seen by RIMS in the polar magnetosphere, may also originate from the events. The number fluxes of upwelling O^+ are very large, requiring of the order of 10^9 ions cm^{-2} s^{-1} out of the topside ionosphere, which is an order of magnitude larger than the cold polar wind flux summed over all ion species[5,6]: the total O^+ outflow from both hemispheres has been estimated to average over 10^{25} s^{-1} which compares with an estimated polar wind outflow of 5×10^{25} s^{-1}. A statistical survey of 2 years' RIMS data has shown that these events are a highly persistent phenomenon and are only found in a narrow region near the morning and noon polar cap boundaries[4].

The interaction of the solar wind, and the interplanetary magnetic field (IMF) embedded within it, with the Earth's magnetosphere generates large-scale electric fields which give 'convection' of plasma at high latitudes. If the IMF has a southward component, this flow is anti-sunward over the polar cap.

Solar wind ions injected into the magnetosphere in the dayside auroral zone have been observed to be dispersed in mass, energy and pitch angle by this poleward motion[8]: lower velocity ions are found further poleward because their time of flight is greater and hence they are convected over greater distances. This effect should also be observed for the upwelling ionospheric ions described above, particularly at great altitudes where the dispersion should be larger.

Early in the DE mission, RIMS afforded an excellent opportunity to see dispersion of upflowing ionospheric ions, with DE1 apogee being over the northern polar cap. Figure 2 shows data from 22 October 1981 when DE1 and DE2 were in close magnetic conjunction over the northern dayside auroral region. The level of geomagnetic activity was moderately high ($Kp =$ 5o), for which the occurrence probability of upwelling ions is very close to unity[4]: the IMF was (and had previously been) predominantly southward, giving anti-sunward convection, as was observed by the IDM on DE2.

Figure 2a shows the retarding potentials required to reduce the count rates from the RIMS radial head to below two per sample, for upward field-aligned flows of H^+, He^+ and O^+ ions near 22,000 km in altitude; these are estimates of the peak energy for each ion species. Figure 2c shows the field-aligned flow velocity and flux, as seen by the IDM during the DE2 pass at an altitude near 900 km. The arrows relate the observations to

---

§ Present address: Rutherford Appleton Laboratory, Chilton, Didcot OX11 0QX, UK.

©1985 Nature Publishing Group

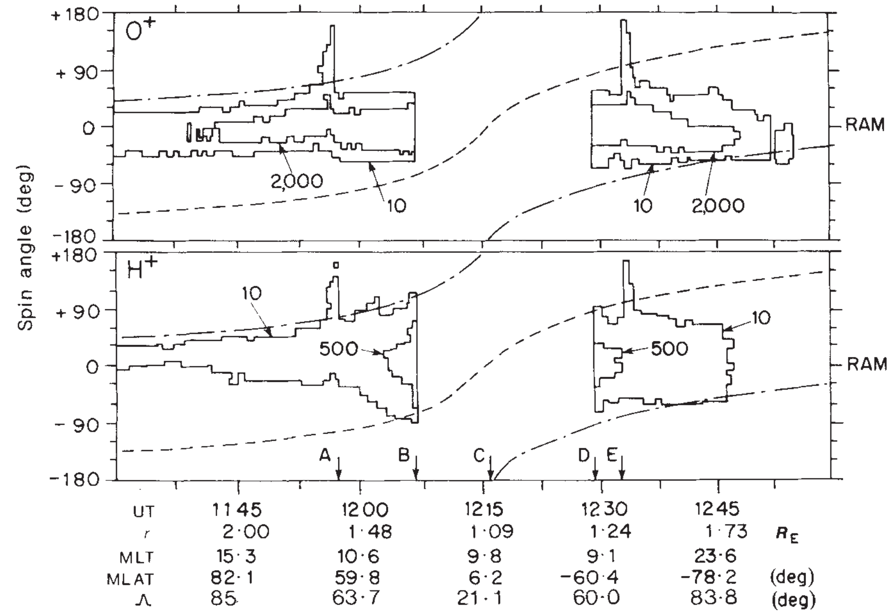

Fig. 1 Spin angle/time plots of count rate contours for O^+ and H^+ ions, observed during a pole-to-pole pass of DE1 on 3 April 1982 by the RIMS radial head. Zero spin angle corresponds to the satellite orbit direction and the upward field-aligned direction is shown by the dashed line in the Southern Hemisphere (MLAT<0) and by the dashed-and-dotted line in the Northern Hemisphere. For each universal time (UT), the geocentric distance (r), magnetic local time (MLT) geomagnetic latitude (MLAT) and invariant latitude (Λ) of DE1 are shown.

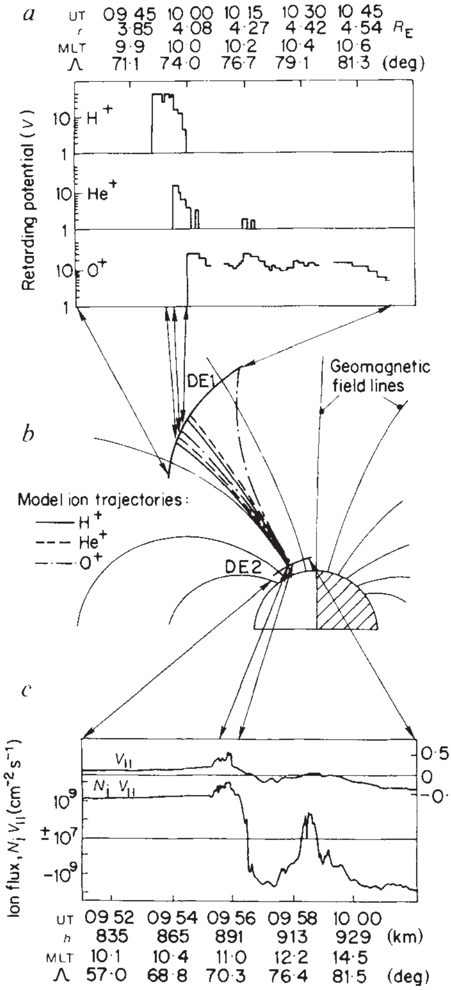

Fig. 2 *a*, Retarding potential required to reduce ion count rates observed by RIMS radial head below two per accumulation period (12 ms) for a high-altitude, polar pass of DE1 on 22 October 1981. *b*, Results for field-aligned flows of H^+, He^+ and O^+ ions. *c*, Field-aligned ion velocity ($V_{\parallel}$) and the flux ($N_i V_{\parallel}$) observed simultaneously by the IDM on DE2. Positive values are upward. Orbital tracks and model ion trajectories for this period are shown projected onto the moon-midnight meridian in *b*: the ion trajectories shown are computed for the highest and lowest energy ions of each species as observed by RIMS. Λ is the invariant latitude of the spacecraft and h is the altitude.

the locations of the satellites, projected onto the noon-midnight meridional plane in Fig. 2*b*. As DE1 moved polewards, RIMS observed first H^+, then He^+ and finally O^+ ions at any one energy and, in addition, the peak ion energy decreased for each ion species. Hence these observations qualitatively show the predicted mass and energy dispersions. That these data are quantitatively consistent with the 'geomagnetic mass spectrometer' concept is demonstrated by the model ion trajectories also shown in Fig. 2*b*. These have been computed from the ion energies observed by RIMS using a two-dimensional kinetic model[9] with a dawn-to-dusk electric field consistent with the IDM observations of field-perpendicular ion flow. It is assumed that the ion motion is collision free and that the electrostatic potential distribution along the geomagnetic field lines of the polar cap is as predicted for the cold polar wind[5], as has recently been inferred from other RIMS data[7]. It can be seen that all ion trajectories converge to a narrow ionospheric source region where an exceptionally large ion upflow signature was observed by the IDM (total ion flux exceeding 10^9 cm^{-2} s^{-1}). Figure 2 shows that O^+ ions were found throughout most of the dayside polar cap where RIMS data were available for this pass of DE1; other passes at high *Kp* ($\geq$5o) also reveal O^+ ions throughout the polar caps[7].

These observations show that the narrow ionospheric source region acts as the collimation slit of the geomagnetic mass spectrometer which can disperse ions, particularly cold and heavy ions, throughout the polar cap; such O^+ ions have already been observed by both ion detectors on DE1[10,11]. Lastly, note that these ions are present in addition to (and are warmer than) the light ions of the classical cold polar wind, which can only observed by RIMS at these altitudes with the application of an input aperture bias potential, which overcomes the repulsive effect of the positive spacecraft potential[12].

We thank the RIMS team and the programming staff of Integraph and Boeing Corporation of MSFC. Support for M.L. came from the US National Research Council, under their resident research associateship programme and for J.L.H. from NASA contract NAS8-33982.

Received 1 April; accepted 25 June 1985.

1. Hoffman, R. A. & Schmerling, E. R. *Space Sci. Instrum.* **5**, 345-348 (1981).
2. Chappell, C. R. *et al. Space Sci. Instrum.* **5**, 477-492 (1981).
3. Heelis, R. A. *et al. Space Sci. Instrum.* **5**, 511-522 (1981).
4. Lockwood, M., Waite, J. H. Jr, Moore, T. E., Johnson, J. F. E. & Chappell, C. R. *J. geophys. Res.* **90**, 4099-4116 (1985).
5. Banks, P. M. & Holzer, T. E. *J. geophys. Res.* **74**, 6317-6332 (1969).
6. Hoffman, J. H. & Dodson, W. H. *J. geophys. Res.* **85**, 626-632 (1980).
7. Lockwood, M. *et al. J. geophys. Res.* (in the press).
8. Burch, J. L. *et al. Geophys. Res. Lett.* **9**, 921-924 (1982).
9. Horwitz, J. L. *Geophys. Res. Lett.* **11**, 1111-1114 (1984).
10. Waite, J. H. *et al. J. geophys. Res.* **90**, 1619-1630 (1985).
11. Shelley, E. G. Peterson, W. K., Ghielmetti, A. G. & Giess, J. *Geophys. Res. Lett.* **9**, 941-944 (1982).
12. Nagai, T. *et al. Geophys. Res. Lett.* **11**, 669-672 (1984).

©1985 Nature Publishing Group