

FIRST MEASUREMENTS OF SUPERSONIC POLAR WIND IN THE MAGNETOSPHERE

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Abstract. Measurements from the Retarding Ion Mass Spectrometer (RIMS) on Dynamics Explorer (DE) have, for the first time, revealed a supersonic polar wind (Mach number is greater than 1) along polar cap field lines. The observations reported were obtained on the nightside (22:30 to 23:30 MLT) from 65° to 81° invariant latitude and at altitudes near 2 R_E. Fitting the data using a thin-sheath model gives a range of temperatures of 0.1 to 0.2 eV with corresponding flow velocities of 25 to 16 km s⁻¹ over the estimated range of spacecraft potential of +3 to +5 V. For these values the Mach number ranged from 5.1 to 2.6 (with a most likely value of 3). Characteristics of the H⁺ flow are in general agreement with those predicted by "classical" polar wind theory, but high variability of the He⁺/H⁺ ratio was observed.

Introduction

Since the possibility of escape of light ions (H⁺ and He⁺) from the Earth's polar ionosphere was first suggested, considerable theoretical work has been done on the characteristics of such an out-flow of plasma [see the recent review by Raitt and Schunk, 1983, and references therein]. Existence of the outflow of H⁺ and He⁺ ions has been supported by observations of the depletion of these ions in the polar ionosphere by Explorer 31 [Hoffman, 1970] and upward motion of these ions relative to O⁺ ions by ISIS II at 1400 km altitude [Hoffman and Dodson, 1980]. However, there has been no direct measurement of the characteristics of this flow in the polar magnetosphere, leaving unanswered the fundamental theoretical question of whether the light ion flow is supersonic ("polar wind") or subsonic ("polar breeze").

The theoretically predicted characteristics of the polar wind result in energies for H⁺ ions of less than 5 eV. Typically, a satellite in the low density plasma outside the plasmasphere is charged a few volts positive so that very low-energy ions are repelled by the spacecraft, and hence not measured. The spacecraft potential problem has, until recently, prevented routine measurements of very low-energy plasma such as the polar wind. The Retarding Ion Mass Spectrometer (RIMS) on Dynamics Explorer 1 (DE 1) has the capability of applying a negative bias voltage to a metal ring around the detector aperture to overcome a positive spacecraft potential [see Chappell et al., 1981].

When the first measurements of H⁺ and He⁺ ions with the bias mode were carried out on October 14-15, 1981, RIMS successfully detected a light ion flow along polar cap field lines in the magnetosphere. The purpose of this paper is to demonstrate the supersonic nature of the observed ion flow, providing an answer to the long unresolved question.

Observations

The data used in this study were obtained from the radial head of the RIMS instrument on DE 1. DE 1 is in a highly elliptical polar orbit and is spinning (period = 6 s) with its spin axis perpendicular to the orbital plane. The RIMS radial head is mounted perpendicular to the satellite spin axis allowing it to sample pitch angle from 0° to 180° in the spin plane. The energies of simultaneously measured H⁺ and He⁺ ions are analyzed by a Retarding Potential Analyzer (RPA) in 32 steps over the 0 to 50 eV range. In the nominal aperture bias mode, the potential of the aperture is cycled from 0 to -2 V, back to 0 V, then to -4 V, back to 0 V, then to -8 V, remaining at each value for 60 s.

Figure 1 shows the data in RPA (energy)-time and spin phase-time spectrogram format, respectively, for H⁺. In the bottom panel, the two dashed lines indicate when the RIMS detector was looking at ions moving parallel (short dot-dashed lines) and anti-parallel (long dashed lines) to the geomagnetic field. Note that the peak H⁺ flux occurs when the RIMS is looking at ions moving anti-parallel to the field, out of the northern polar cap ionosphere. The low count rate trace (blue-green trace at spin phase angles greater than 90° in the H spectrogram is a Sun pulse. During the time interval of this observation, DE 1 was moving near midnight in the polar cap from 81° invariant latitude to 65° IL. Ground magnetograms near the midnight meridian [from Dixon and Abisko] show that a large substorm was in progress. The Kp value during this observation was 5-.

H⁺ and He⁺ ions were observed near the direction of the magnetic field flowing up from the northern ionosphere during the whole observation period. The enhancements of the ion counts are related to the bias voltage indicating that the aperture bias was compensating for the positive spacecraft potential. The shift of the peak count position from the field-aligned direction is attributed to the combined effect of an anti-sunward convection motion of the plasma and the satellite motion. The measurement of this ion outflow is suppressed by the positive spacecraft potential, but can still be observed in the 0 V bias observations during a portion of the observed time interval.

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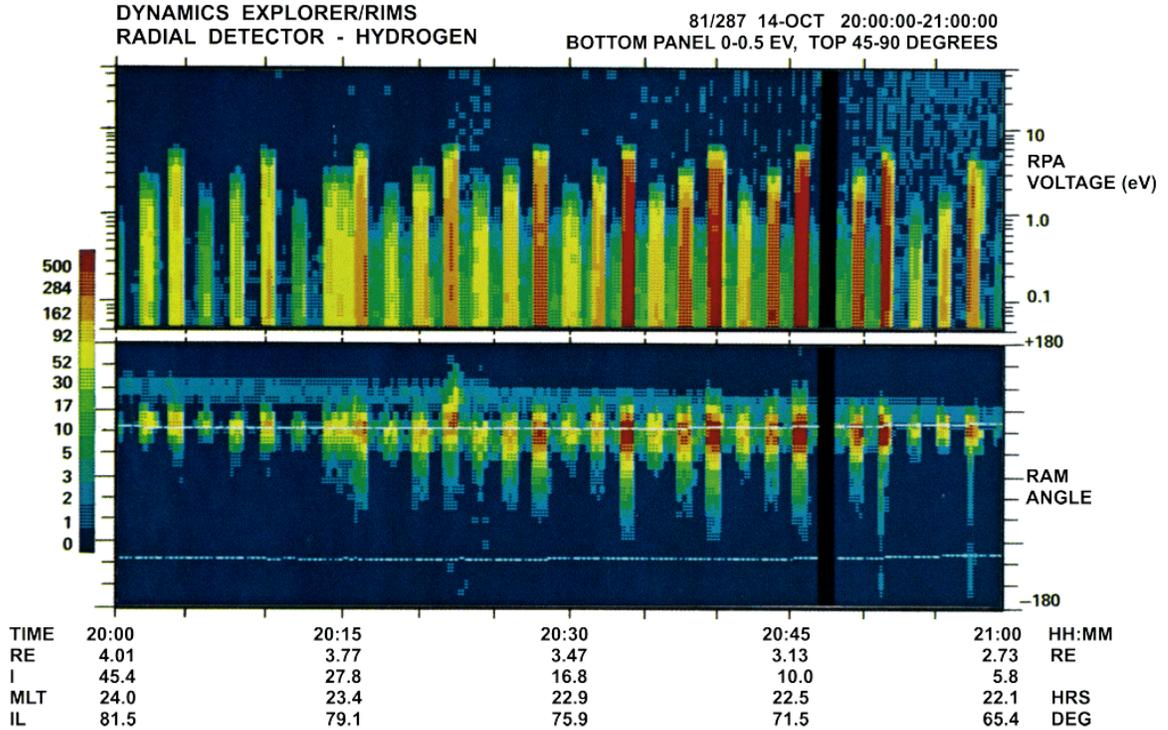


Fig. 1. RPA (energy)-time and spin-time spectrograms depicting color-coded H+ count rates (counts per 12 ms accumulation) for the same time periods on October 14, 1981. The four bias voltages are easily seen in the data.

Characteristics of the Flow

RPA curves for the field-aligned component of H+ during the time period 20:33:30 to 20:46:10 UT are presented in Figure 2a. Note both the temporal stability and the consistency of the data at the

different aperture bias levels. The plasma parameters (flow velocity, temperature, and density) are derived by fitting a one-dimensional drifting Maxwellian to the RPA data for a given spacecraft potential value using the thin-sheath approximation [Comfort et al., 1982]. Although the spacecraft

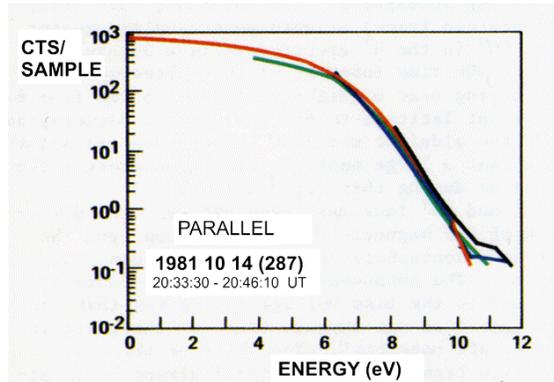


Fig. 2a. RPA curves for the field-aligned H+ ions. The orange curves are the data for the -8 V bias periods. The curves for the -4 V bias periods (green), for the -2 V bias periods (blue), and for the 0 V bias periods (black) are shifted by 4, 6, and 8 V, respectively, to put them into a common RPA voltage scale. potential was not directly measured, we can

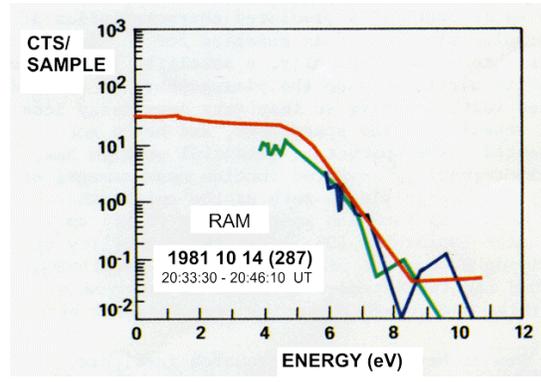


Fig. 2b. RPA curves for the ions at spin angles of from -30° to 0° in the near ram direction of the spacecraft which is almost perpendicular to the magnetic field at this time. A break point for the curves exists at 5 V. The presentation format is the same as in Figure 2a.

obtain information about the spacecraft

potential during this period from the negative aperture bias data. The lower limit of the spacecraft potential can be obtained from the RPA data for ions near the ram direction, which is approximately perpendicular to the magnetic field line direction. The RPA curve for these ions is largely unaffected by the field-aligned drift motion of the polar wind. The RPA curves for the ions at spin angles from -30° to 0° with respect to the ram direction for the -8, -4, and -2 V bias periods are presented in Figure 2b. The data show a consistent break point in the RPA curves near 5 V, referenced to the -8 V bias zero level. If there were no drift energy, the data could be explained by a +3 V spacecraft potential and a net 5 eV acceleration by the negative aperture bias. If there is any convective drift energy present, the spacecraft potential required to produce a RPA curve break point at 5 V will be larger. Therefore, +3 V represents the lower limit of the spacecraft potential. The upper limit of the spacecraft potential can be deduced from the spacecraft photoelectron observations by the High Altitude Plasma Instrument (HAPI) on DE I [J. L. Burch, private communications]. The spacecraft photoelectrons disappeared from the HAPI data during this period, indicating that the spacecraft's photoelectron energy was lower than the lowest energy limit of the HAPI instrument, 5 eV. Therefore, the spacecraft potential was less than 5 V. We conclude that the spacecraft potential was somewhere between +3 and +5 V.

The extreme stability of the H^+ energy distribution through this entire period (see Figure 2a) leads to a well-defined statistically significant data set even for an aperture bias voltage of zero. Analysis of the data to determine plasma parameters is performed by fitting a thin-sheath model [Comfort et al., 1982] to the unbiased RPA data averaged over the time period 20:33:30 to 20:46:10 UT. The normalization (unretarded count rate) is taken from the -8 V bias data. This normalization affects only the density (and flux) determination and does not affect the determination of the Mach number of the flow.

Plasma parameters derived from this analysis of H^+ are presented in Table 1. This table covers the range +3 to +5 V in spacecraft potential. Flux values have been mapped to 1000 km to facilitate comparison with observed and model values for the escape flux. The results of the fitting, shown in Figure 3, indicate that the shape of the RPA

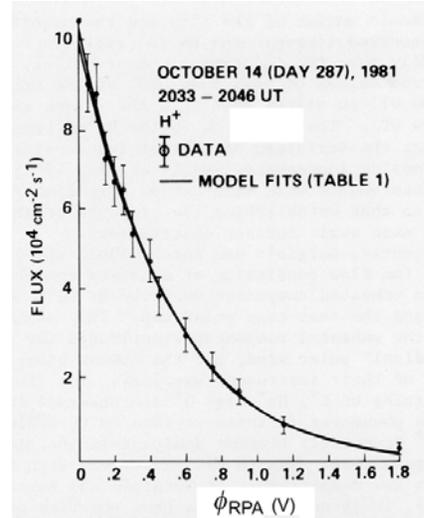


Fig. 3. RPA curves using the model fit parameters described in Table 1 and data points for the time-averaged field-aligned H^+ ion flow for the time period from 20:33 to 20:46 UT when the aperture bias voltage was 0 V.

curve is well represented by a drifting Maxwellian and clearly show the flow to be supersonic throughout the range of parameter values which can be considered consistent with the observations. The indistinguishability of the model curves illustrates the difficulty of determining the appropriate plasma parameters from the unbiased RPA data alone without the additional information (in this case spacecraft potential) provided by the aperture bias procedure.

The escape flux values fall within the range predicted by the "classical" polar wind model [e.g., see Banks and Holzer, 1968], although the models are for daytime conditions. These flux values are not very different from the values ($\sim 5 \times 10^7 \text{ cm}^{-2} \text{ s}^{-1}$ for H^+) observed by ISIS II at 1400 km [Hoffman and Dodson, 1980] when one considers that the ISIS observations were made under quiet conditions and the RIMS observations presented here are for disturbed conditions.

Observations of He^+ during this interval were quite variable, with a general trend toward higher peak counting rates in the latter part of the interval. Although the cause of the variability in He^+ , with H^+ remaining relatively stable, is not clear, it is consistent with the winter solstice observations of the polar ionosphere measured by the ISIS II satellite [Hoffman and Dodson, 1980].

Discussion and Conclusions

Supersonic H^+ flows along polar cap field lines have been observed for the first time by DE 1/ RIMS, enhanced by using a negative bias voltage on the aperture plane of the instrument. The observational results are generally in good agreement with those for the supersonic flow predicted by the "classical" polar wind model first proposed by Banks and Holzer [1968] both

TABLE 1. Polar Wind Parameters Derived from Model Fits to the H^+ Data

Spacecraft Potential (V)	Temp. (eV)	Vel. (km s^{-1})	Mach No.	Equivalent Flux at 1000 km ($\text{cm}^{-2} \text{ s}^{-1}$)
+3	0.2	16	2.6	2.26×10^8
+4	0.15	21	3.9	2.26×10^8
+5	0.12	25	5.1	2.26×10^8

in terms of the supersonic nature of the flow and the magnitude of the observed fluxes. The He^+/H^+ ratio increased steadily over the interval of observations, varying from values of less than 0.01 at the beginning (20:00 UT) to values near 1 in the plasma sheet (21:00 UT). The variation in the He^+/H^+ ratio may reflect the variation of thermal ion densities in the topside ionosphere [Heelis et al., 1981]. No O^+ measurements were made during this time interval, so that establishing the presence or absence of O^+ must await further observations.

Recently, Gurgiolo and Burch [1982] reported a polar ion flow consisting of a heated component and an unheated component observed by DE 1 in the cusp and the near-cusp polar cap. They suggested that the unheated component constituted the 'classical' polar wind, but the lowest energy limit of their instrument was 5 eV. Ion flows consisting of H^+ , He^+ , and O^+ are observed to be common phenomena in these regions by DE 1/RIMS, and O^+ frequently becomes dominant in the near-cusp polar cap. Due to the relatively high energy of the ion measurements of Gurgiolo and Burch [1982], it is quite possible that the flow was an O^+ ion outflow and not the 'classical' polar wind, or an ion flow caused by other processes acting on the topside ionosphere in the region of the polar cusp where ion acceleration processes may be quite different from that proposed by the 'classical' polar wind theory.

Ion outflow observations made in the bias mode in the dayside magnetosphere (closed field lines) were reported by Chappell et al. [1982] and Sojka et al. [1983]. In these papers, the spacecraft potential was not clearly determined, so that the plasma parameters could not be determined unambiguously. As such, this paper represents the first experimental verification of the supersonic nature of the polar wind.

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