POLAR measurements of polar rain and photoelectron effects on the high-altitude polar wind

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Short title: POLAR RAIN AND PHOTOELECTRON EFFECTS ON THE POLAR WIND

Abstract. Large ion outflow velocity variations at POLAR apogee (about 8 R_E altitude) have been observed [*Su et al.,* 1998b]. The observed H^+ flow velocities were in the range of 23−110 km s^{-1} and O^+ flow velocities were in the range of 5−25 km s^{-1}. These velocity ranges lie between those predicted by recent simulations of the photoelectron-driven polar wind and "baseline" polar wind [*Su et al.,* 1998a]. The electric current contributions of the photoelectrons and polar rain are expected to control the size and altitude of an electric potential drop, which accelerates the polar wind at relatively high altitudes [*Su et al.,* 1998a]. In this brief report, we compare polar wind characteristics observed by the Thermal Ion Dynamics Experiment (TIDE) with measurements of low-energy electrons sampled by HYDRA, both from the POLAR spacecraft, to examine possible effects of the polar rain and photoelectrons on the polar wind for two high-altitude POLAR passes. During a segment of each pass, an anti-correlation and a correlation, respectively, were found between the polar wind velocities and the polar rain fluxes at POLAR apogee during different polar cap crossings. Both upward and downward (with a cutoff energy about 15 V) photoelectrons are seen at POLAR perigee, which may suggest a potential barrier above the spacecraft. Also, for a perigee pass, upward and downward components of the photoelectron spectra are used to estimates the potential drops above the spacecraft. We interpret these limited observations in terms of the effects that both photoelectrons and polar rain may have on the electric potential along polar cap magnetic field lines.

1. Introduction

The polar wind is an ambipolar outflow of thermal plasma from the terrestrial ionosphere at high latitude to the magnetosphere along geomagnetic field lines, consisting mainly of H^+, O^+, and He^+ ions and electrons. Various characteristics of the polar wind have been modeled using hydrodynamic, generalized transport, kinetic, semikinetic, hybrid, and time-dependent approaches [e.g., *Banks and Holzer*, 1969; *Dessler and Cloutier*, 1969; *Raitt et al*., 1975; *Schunk and Watkins*, 1981, 1982; *Horwitz and Lockwood*, 1985; *Gombosi et al.,* 1985; *Ganguli et al.,* 1987; *Gombosi and Schunk,* 1988; *Swift*, 1990; *Wilson et al.,* 1990; *Wilson,* 1992; *Demars and Schunk*, 1994; *Horwitz et al.,* 1994; *Tam et al.,* 1995; *Schunk and Sojka*, 1997; *Demars et al.,* 1998].

Recently, a coupled fluid-semikinetic model was applied to investigate the photoelectron-driven polar wind including the hot magnetospheric electrons (such as polar rain) and protons with different ionospheric conditions [*Su et al.,* 1998a]. An electric potential layer developed above 3 R_E altitude when the model downward magnetospheric electron (polar rain) fluxes were insufficient to balance the ionospheric photoelectron flux. Such potential layers would accelerate the ionospheric ions to supersonic speeds at high altitude (> 3 R_E), but not at low ionospheric altitudes. It was also found that the strength of the predicted electric potential layer decreased with increasing polar rain for constant polar rain energy.

In a recent observational study, *Su et al.* [1998b] described the results of a survey of the polar wind characteristics H^+, He^+, and O^+ as observed by the Thermal Ion Dynamics Experiment (TIDE) on the POLAR spacecraft at low (~ 5000 km) and high (~ 8 R_E) altitudes. Large ion outflow velocity variations at POLAR apogee (~ 8 R_E altitude) have been observed, where H^+ field-aligned outflow velocities are in the range of 23−110 km s^{-1} and O^+ flow velocities are in the range of 5−25 km s^{-1}. These velocities lie between those predicted by recent simulations of the photoelectron-driven polar wind and of the “baseline” polar wind [*Su et al.,* 1998a]. The typical polar wind velocity ratios at high altitude, $V_{O+}:V_{He+}:V_{H+}$ ~ 2 : 3 : 5, may suggest comparable energy gains for parallel flow, such as via an electric potential layer produced, for example, by the photoelectrons and polar rain.

In this paper, we compare the polar wind measurements by the Thermal Ion Dynamics Experiment (TIDE)/Plasma Source Instrument (PSI) with low-energy electrons measurements from the HYDRA instrument on the POLAR spacecraft at perigee (1.8 R_E geocentric distance) in the southern hemisphere and at apogee (9 R_E geocentric distance) in the northern hemisphere. The TIDE instrument on POLAR samples the three-dimensional ion distributions once per 6 second spin period of the spacecraft with excellent low energy, angular (22.5^o polar angle resolution and 11.25^o spin azimuth resolution), and mass resolution for the 0.3−450 eV energy range [*Moore et al.,* 1995]. The accompanying Plasma Source Instrument (PSI), when operated, allows sufficient diminution of the electric potential to observe the low-energy polar wind ions at very high altitudes [*Moore et al.,* 1997]. The HYDRA instrument [*Scudder et al.,* 1995] is an experimental three-dimensional electron and ion hot plasma detector with a routine 0.5 s time resolution on the POLAR spacecraft. In this paper, we focus on the low-energy electron data from HYDRA. These included measurements of the photoelectrons with energy ranging from several to 30 eV and the polar rain in the energy range of about 30 eV to 1 keV.

2. Polar wind and polar rain at POLAR apogee

The model of *Su et al.* [1998a] indicated that an electron potential layer developed above 3 R_E altitude when the model downward magnetospheric electron (polar rain) fluxes were insufficient to balance the ionospheric photoelectron flux. *Su et al.* [1998a] also found that the strength of the electric potential layer decreased with increasing polar rain density when the polar rain energy (temperature) remained constant. In order to measure the low density and low energy polar wind ions at very high altitude, PSI must be turned on to reduce the spacecraft potential. In this section, we examine two such apogee passes to compare the relationship between the polar wind, polar rain, and photoelectrons.

2.1 Case study for May 28, 1996

Figure 1 displays TIDE ion spectrograms, TIDE derived ion bulk parameters, HYDRA electron bulk parameters (density and mean energy for the energy greater than 30 eV), and HYDRA electron energy spectrograms for the period 1200−1800 UT on May 28, 1996. From top to bottom, Figure 1a presents the O^+ spin angle spectrogram, the H^+ spin angle spectrogram, the O^+ energy spectrogram, the H^+ energy spectrogram, O^+ (red) and H^+ (blue) perpendicular temperatures, O^+ (red) and H^+ (blue) parallel temperatures, and O^+ (red) and H^+ (blue) densities. From top to bottom, Figure 1b presents the O^+ (red) and H^+ (blue) velocities, electron densities and mean energies, the energy spectrograms for electron travelling in the perpendicular direction ($75^o <$ the pitch angle $< 105^o$), in the anti-parallel direction ($150^o <$ the pitch angle $< 180^o$ — downward direction), and in the parallel direction ($0^o <$ the pitch angle $< 30^o$ — upward direction). The electron density and mean energy calculations displayed above are only for electron energies above 30 eV, to exclude most of the photoelectron population.

It is evident that during the period 1400 to 1630 UT, the polar wind velocities appear to be generally anti-correlated with the polar rain densities when the polar rain mean energy is about the order of 70 eV. A plot of the TIDE H^+ parallel velocity (V_{H+}) verses the quantity for the polar rain energy range {electron density (N_e) $\times$ mean energy$^{1/2}$ ($E_e^{1/2}$)} for the period 1406 to 1540 UT on May 28, 1996 is shown in Figure 1c. We have averaged the quantity of $N_e \times E_e^{1/2}$ within 6 bins, where the asterisk represents the average value and the vertical bar represents the standard deviation for each bin. The straight line is the linear least-square fit to these binned averages with the correlation coefficient $r = -0.8$. This anti-correlation trend was suggested by the photoelectron-driven polar wind simulations [*Su et al.,* 1998a]. Enhanced polar rain fluxes imply a reduced need to reflect photoelectrons to achieve zero current; hence a lower potential drop and the lower polar wind ion velocities. Note that we used only data for the polar wind in the polar cap, excluding the auroral arc in the polar cap from 1540−1554 UT and auroral region starting around 1718 UT.

2.2 Case study for June 3, 1996

From top to bottom, Figure 2 displays the HYDRA electron energy spectrogram, the TIDE ion (assumed H^+) parallel velocity and density plots, and TIDE spin angle and energy spectrograms for the period 1400 to 2400 UT on June 4, 1997. Based on the particle observations, the polar cap region was evidently entered at around 1640 UT. The polar wind parallel velocities and energies (second and fifth panels) appear to be positively correlated with the polar rain fluxes (bottom panel) during 1800−1910 UT and 2200−2400 UT. (We were not able to calculated HYDRA derived parameters for this period.) We might speculate that the larger ion upward velocities could result from enhanced ambipolar electric fields associated with heating by the larger polar rain fluxes, an effect which is not included in the simulation model by *Su et al*. [1998a], although effects of enhanced electron temperatures possibly associated with the polar rain effects have been explored by *Ho et al*. [1992] and *Barakat and Schunk* [1984].

3. Photoelectrons at POLAR perigee on May 27, 1996

The simulations by *Su et al.* [1998a] indicated that an electron potential layer should develop above 3 R_E

altitude, and reflect photoelectron electrons with energies below the potential drop back toward the ionosphere. The simulation results suggest the observed upward and downward photoelectrons at low altitude (< 3 R_E).

Figure 3 displays TIDE O^+ and H^+ spin angle spectrograms, TIDE O^+ and H^+ energy spectrograms, a plot representing the asymmetry between upward and downward electron fluxes, where yellow and red represent the data along the field line direction (upward) and blue and purple represent the data for the anti-parallel direction (downward), electrons energy spectrogram ($150^o < \alpha < 180^o$), and upward (parallel direction) electrons energy spectrogram ($0^o < \alpha < 30^o$) from 1230 to 1245 UT on May 27, 1996.

In this perigee case, the upward photoelectron flux (up to about 30–40 eV) is stronger than downward photoelectron flux (cutoff energy about 15 eV), which suggests that there is a reflecting potential drop of about 15 Volts above the spacecraft. This conclusion is similar to inferences from earlier DE 2 measurements at low altitudes [e.g., *Winningham and Gurgiolo,* 1982; *Horwitz et al.,* 1992]. The upward and downward photoelectron fluxes both appeared to vary considerably during the polar cap transit. Four characteristic photoelectron distributions for this perigee pass are shown in Figure 4. There is a surprisingly large component of the low-energy electrons in the perpendicular direction, which requires further investigation.

4. Summary

Three case studies of the polar wind and the low-energy electrons are presented in this paper. We summarize the results as follow:

(1) The polar wind velocities were anti-correlated with the polar rain densities when the polar rain mean energy is about the order of 70 eV at 1400 – 1630 UT on May 28, 1996, at POLAR apogee. We obtained a good correlation coefficient, r = -0.8, between the polar wind parallel velocity and the quantity of (polar rain density) × (mean energy)$^{1/2}$. This anti-correlation is consistent with expectations based on electron current balance [*Su et al.,* 1998a], if this quantity can be regarded as somewhat related to the actual field-aligned current associated with the polar rain.

(2) On the other hand, the polar wind energies were evidently correlated with the polar rain fluxes at 1800–1910 UT and at 2200–2400 UT on June 3, 1997, at POLAR apogee, which is opposed to the *Su et al.* [1998a] prediction. The strong polar rain may energize the ambient electrons, and thus enhance the polar wind velocity in this case (through an enhanced ambipolar electric field). This possible electron heating process

was not included in the polar wind simulations by *Su et al.* [1998a], but hot electron effects which enhance polar flow have been studied by *Ho et al.* [1992] and *Barakat et al.* [1984].

(3) At POLAR perigee, the upward (energies up to 30−40 eV) and downward (upper cutoff energy of ~15 eV) photoelectron fluxes are seen in the HYDRA parallel and anti-parallel energy spectrograms and the pitch angle distributions at 1230−1245 UT on May 27, 1996, which suggests a potential drop above the spacecraft of about 15 V.

Obviously, we cannot draw definitive conclusions regarding such possible relationships from only these brief periods, but they are intriguing. There are probably several mechanisms involving low-energy electrons which may influence polar wind variations at high altitudes. Systematic further analysis involving more complete and detailed electron moment calculations will be useful for more quantitative elucidation of such effects.

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Figure 1a. Top four panels are TIDE O^+ spin angle, H^+ spin angle, O^+ energy, and H^+ energy spectrograms and the bottom three panels are ion perpendicular temperatures, parallel temperatures, and densities, where the red lines represent O^+ moments and the blue dashed lines represent H^+ moments, at 1200 − 1800 UT on May 28, 1996.

Figure 1b. The top panel is O^+ (red solid line) and H^+ velocity (blue dashed line) plot, the second and third panels are HYDRA electron density and mean energy plots, and the bottom 3 panels are HYDRA electron energy spectrograms in the perpendicular (75^o < the pitch angle < 105^o), anti-parallel (150^o < the pitch angle <180^o), and parallel directions (0^o < the pitch angle < 30^o), where the parallel (downward) direction is along the magnetic field line in the northern hemisphere, at 1200 − 1800 UT on May 28, 1996.

Figure 1c. TIDE H^+ parallel velocity (V_{H+}) verses HYDRA electron density (N_e) × mean energy$^{1/2}$ ($E_e^{1/2}$) chosen from 1406 to 1540 on May 25, 1996. $N_e \times E_e^{1/2}$ is divided into 6 bins, where the asterisk represents the average value and the vertical bar represents the standard deviation from each bin. The straight line is the linear least-square fits with the correlation coefficient r = -0.8.

Figure 2. From top to bottom: HYDRA electron energy spectrogram, TIDE ion (assumed H^+) parallel velocity and density plots, and TIDE spin angle and energy spectrograms from 1400 UT on June 3, 1997 to 0120 UT on June 4, 1997.

Figure 3. From top to bottom: TIDE O^+ and H^+ spin angle spectrograms, TIDE O^+ and H^+ energy spectrograms, HYDRA electron "skew" plot (yellow and red represent the data along the field line direction and blue and purple represent the data for the anti-parallel direction), and electron energy spectrograms in anti-parallel (150^o < the pitch angle <180^o)and parallel directions (0^o < the pitch angle < 30^o), where the parallel (upward) direction is along the magnetic field line in the southern hemisphere, at 1230−1245 UT on May 27, 1996.

Figure 4. Four typical photoelectron distribution at POLAR perigee on May 27, 1997, where the positive $V_{||}$ is parallel to the magnetic field line (upward) and the negative $V_{||}$ anti-parallel to the field line (downward).