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Time-dependent simulations of the global polar wind

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Abstract

It has been clearly established that there is a substantial outflow of ionospheric plasma from the Earth's ionosphere in both the northern and southern polar regions. The outflow consists of both light thermal ions (H^+ and He^+) and an array of energized ions (NO^+, O_2^+, N_2^+, O^+, N^+, He^+, and H^+). If the outflow is driven by thermal pressure gradients in the ionosphere, the outflow is called the "classical" polar wind. On the other hand, if the outflow is driven by energization processes either in the auroral oval or at high altitudes in the polar cap, the outflow is called the "generalized" polar wind. In both cases, the field-aligned outflow occurs in conjunction with magnetospheric convection, which causes the plasma to drift into and out of the sunlit hemisphere, cusp, polar cap, nocturnal auroral oval, and main trough. Because the field-aligned and horizontal motion are both important, three-dimensional (3-D) time-dependent models of the ionosphere–polar wind system are needed to properly describe the flow. Also, as the plasma executes field-aligned and horizontal motion, charge exchange reactions of H^+ and O^+ with the background neutrals (H and O) act to produce low-energy neutrals that flow in all directions (the neutral polar wind). This review presents recent simulations of the "global" ionosphere–polar wind system, including the classical, generalized, and neutral polar winds. The emphasis is on displaying the 3-D and dynamical character of the polar wind.

Keywords: Polar wind; Ionosphere; Storm; Convection

1. Introduction

In the early 1960s, it was suggested that the interaction of the solar wind with the Earth's intrinsic magnetic field would lead to the formation of a magnetosphere (Axford and Hines, 1961; Dungey, 1961). As a result of this interaction, the magnetic field lines in the northern and southern polar caps are not dipolar, but extend deep into the tail of the magnetosphere (past the Moon's orbit). Subsequently, it was suggested that light ions (H^+ and He^+) should be able to escape the topside ionosphere along these so-called "open" field lines, because the plasma pressure in the ionosphere is greater than that in the distant magnetospheric tail. The first models in support of this suggestion were based on a continual escape of light ions via a thermal evaporation process (Dessler and Michel, 1966; Bauer, 1966), while the models that immediately followed were based on a supersonic hydrodynamic formulation and the flow was called the "polar wind" in analogy to the solar wind (Axford, 1968; Banks and Holzer, 1968).

It is now well known that the polar wind is an ambipolar outflow of thermal plasma from the

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high-latitude ionosphere. The outflow consists of both light and heavy ions and begins at about 800 km. As the ions escape the topside ionosphere along diverging geomagnetic field lines, they are accelerated and eventually become supersonic (above 1300 km). However, the upflowing ions also convect horizontally across the polar regions due to magnetospheric electric fields, moving into and out of sunlight, the cusp, the polar cap, the nocturnal auroral oval, and the main electron density trough. The polar wind also interacts in a complex way with several energization processes that operate at high altitudes, as shown in Fig. 1.

Upwelling of thermal plasma from the F-region occurs throughout the entire polar domain as a result of plasma pressure perturbations (e.g., electron and ion density and temperature enhancements). In non-auroral regions, the upwelling driven by pressure variations is an ambipolar flow in which the ions and electrons drift together and charge neutrality is maintained. In general, the pressure in the ionosphere is sufficient to allow the light thermal ions (H^+ and He^+) to escape, which leads to the polar wind. However, a heavy ion like O^+ requires an additional energy gain of about 10 eV in order for it to escape into the magnetospheric tail, and such an energy gain is usually not associated with F-region pressure enhancements.

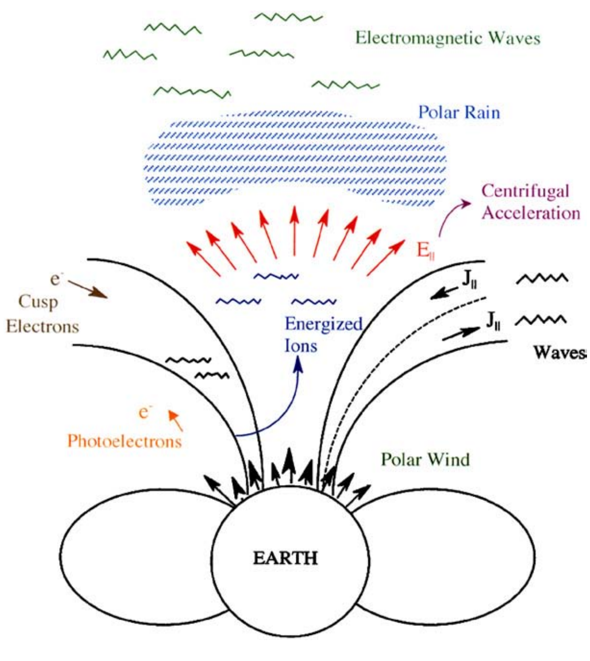

Fig. 1. Schematic diagram showing the polar wind emanating from the ionosphere and the non-classical processes that affect it at high altitudes (from Schunk and Sojka, 1997).

The plasma upwelling described above corresponds to the ‘‘classical’’ polar wind. However, the polar wind is affected by several other processes that are typically not included in a classical description of the polar wind (Fig. 1). In particular, on the dayside, photoelectrons that escape the ionosphere along **B**-field lines provide an additional acceleration of the polar wind at high altitudes ($\geqslant$7000 km) as they drag the thermal ions with them (Lemaire, 1972; Tam et al., 1995; Wilson et al., 1996; Khazanov et al., 1997; Su et al., 1998). In the cusp and nocturnal auroral oval, unstable field-aligned currents and the consequent wave–particle interactions (WPI) can lead to both parallel and perpendicular ion acceleration. This, in turn, can result in auroral ion beams and conics (Ganguli, 1996; Jasperse and Grossbard, 1998; Schriver and Ashour-Abdallah, 1998). After generation, the cusp beams and conics convect into the polar cap and they can then drive the polar wind unstable as they pass through it at high altitudes (Barakat and Schunk, 1989; Chen and Ashour-Abdallah, 1990). In addition, the interaction of the cold, escaping, polar wind plasma with the warm magnetosheath particles in the cusp (Lemaire and Scherer, 1978) and the hot magnetospheric electrons in the polar cap (Barakat and Schunk, 1984; Ho et al., 1992) can lead to the formation of double-layer electric fields (at about 20,000 km in the cusp and 4000 km in the polar cap), which can energize the escaping polar wind ions (Winningham and Gurgiolo, 1982; Barakat and Schunk, 1984). At altitudes greater than about 6000 km in the polar cap, electromagnetic wave turbulence has been detected and this can energize the polar wind via the perpendicular heating that results from WPI (Lundin et al., 1990; Barghouthi, 1997). Finally, centrifugal acceleration will act to increase the ion escape velocities above 3000 km when the plasma flux tubes rapidly convect across the polar cap in an antisunward direction (Cladis, 1986; Swift, 1990; Horwitz et al., 1994; Demars et al., 1996). When the additional non-classical processes shown in Fig. 1 are included in a simulation, the model results pertain to the ‘‘generalized polar wind’’.

The initial studies of the polar wind were restricted to ‘‘one-dimensional’’ steady-state or time-dependent simulations applied to a ‘‘fixed’’ location (e.g., non-convecting plasma flux tubes). Subsequently, ‘‘single’’ plasma flux tubes were