The effect of photoelectrons on kinetic polar wind models

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Résumé. — L'influence des photoélectrons sur un modèle de l'exosphère ionique polaire a été considérée. Le flux d'échappement, la vitesse moyenne, les composantes parallèle et perpendiculaire de la température des électrons thermiques dépendent fortement de la valeur du flux de photoélectrons. Par contre la distribution de la densité ionique ne dépend pratiquement pas de la valeur du flux d'échappement des photoélectrons. Bien que le nombre des photoélectrons reste très inférieur au nombre des électrons thermiques, ces premiers transportent pratiquement toute l'énergie électronique hors de l'atmosphère polaire.

INTRODUCTION

Direct evidence of an outward flow of ionized hydrogen along the polar magnetic field lines has been established experimentaly by Hoffman (1968, 1970). This hydrogen depletion in the polar ionosphere is suggested by: (a) the existence of " troughs " in the latitudinal density distributions of the electrons and the light ions (Muldrew, 1965; Sharp, 1966; Taylor *et al.*, 1969; Thomas and Rycroft, 1970; Grebowsky *et al.*, 1970); (b) the existence of a " knee " in the equatorial electron density observed by Carpenter (1963, 1966), Gringauz (1963), and Binsack (1967) and (c) the depression in the Lyman-alpha emission from the polar region (Meier, 1970; Mange, 1970).

Early arguments were given by Dungey (1961), Dessler and Michel

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(1966), and Bauer (1966) that the thermal plasma could gradually flow out of the polar ionosphere into the magnetotail. Nicolet (1961) suggested that the large amount of He^4 produced in the Earth's mantle could possibly escape as ionized particles and Axford (1968) emphasized that these helium ions are dragged out of the topside polar ionosphere by the escaping photoelectrons. In view of this, Banks and Holzer (1968, 1969) proposed a hydrodynamic description of this outward flowing plasma which was called the Polar Wind.

In the transition region near 2000-3000 km altitude the deflection mean free path of the charged particles (e^-, H^+, O^+, He^+) becomes equal to the density scale height, and the validity of Euler's hydrodynamic equations above 2000-3000 km, i.e. in the *ion-exosphere*, was therefore questioned by Dessler and Cloutier (1969). They proposed a simple kinetic model in which it was assumed that the polarization electric field is given by the Pannekoek-Rosseland field

$$e\vec{E} = -\frac{1}{2} m_{O^+} \vec{g}$$

where $\vec{E}$ is the electric field, $\vec{g}$ the gravitational acceleration, e the elementary electric charge, and m_{O^+} the mass of the oxygen ion.

Lemaire and Scherer (1969) have shown that this field, which maintains the quasi-neutrality for an ($O^+ - e$) isothermal plasma in hydrostatic equilibrium, cannot be assumed in the collisionless region of the ionosphere, because it would lead to an escape flux of the electrons which would be approximately 43 times larger than the escape flux of the protons. To reduce the electron escape flux and to increase the outward ion flux a larger polarization electric field is required. In a stationary model these fluxes must be equal to satisfy the zero-electric current condition. Kinetic models for a polar ion-exosphere in which the total electric current along the magnetic field lines is zero and for which the plasma is quasi-neutral, have been proposed by the authors (Lemaire and Scherer, 1970, 1971).

The supersonic proton flow predicted by Banks and Holzer (1968, 1969) has been confirmed by the exospheric theory. The kinetic approach, however yielded an O^+ escape flux which was 10^4 times smaller, than the O^+ flux in the hydrodynamic and semi-kinetic models (Banks and Holzer, 1968, 1969; Holzer *et al.* 1971).

In the present paper we discuss the effect of photoelectrons on the polar wind. We consider a model ion-exosphere in which oxygen ions, protons and electrons are present. The collision dominated region or barosphere is assumed to be separated from the collision free exosphere by a sharply defined surface, called the baropause. Moreover we assume that at this level the actual velocity distribution for each species, can be approximated by the Maxwellian

$$f_j(\vec{r}_0,\vec{v}) = N_j(m_j/2\pi kT_j)^{3/2} \exp(-m_j(\vec{v} - \vec{u}_j)^2/2kT_j)$$

where j stands for O^+, H^+, and e respectively; r_0 is the radial distance of the baropause; k is Boltzmann's constant, and N_j, T_j and $\vec{u}_j$ are parameters which are determined in such a way that the calculated densities, temperatures and bulk velocity are equal to the actual values at the baropause. For a detailed description of the method of calculation we refer to our previous papers (Lemaire and Scherer, 1971, 1972).

Since the effusion velocity of the electrons and oxygen ions is much smaller than the corresponding thermal speed, we assume $u_{O^+} = u_e = o$. For the hydrogen ion, however, the effusion velocity is nearly sonic, and it is quite reasonable to assume that

$$u_{H^+} = \frac{1}{4} C_{H^+} = \left(\frac{kT_{H^+}}{2\pi m_{H^+}}\right)^{1/2}.$$

Moreover, we have shown that most properties of such an $(O^+ - H^+ - e)$-exosphere are not affected qualitatively by considering an asymmetry in the velocity distribution (Lemaire and Scherer, 1972).

2. The photoelectron flux

It has been argued by Axford (1968) that a photoelectron flux of 2×10^8 cm^{-2} sec^{-1} is required at 400 km altitude to drag into the magnetotail the protons and helium ions produced in the sunlit ionosphere. Nisbet (1968), Nagy and Banks (1970), and Shawhan *et al.* (1970) have shown that photoelectron fluxes of this order of magnitude escape from a sunlit ionosphere. Maier and Rao (1970), and Heikkila (1971) recently observed in the high altitude (~ 2000 km) polar ionosphere suprathermal electron (i.e. with an energy larger than 5 ev) fluxes of $5 - 10 \times 10^7$ cm^{-2} sec^{-1}.

In this section we will show how the exospheric plasma distribution in the polar regions will be modified by increasing values of the photoelectron flux. The total ion escape flux, mainly carried by the lightest ions, is, at the baropause, of the order of

$$F_i \approx F_{H^+}(r_0) = \frac{1}{2} n_{H^+}(r_0) C_{H^+} [\sqrt{\pi}\ U_{H^+} + \exp(-U_{H^+}^2)/\text{erfc}(-U_{H^+})]$$

where

$$U_{H^+} = (m_{H^+}/2kT_{H^+})^{1/2} u_{H^+},$$

$n_{H^+}(r_0)$ denotes the actual proton density at the baropause; and the complementary error function is defined by

$$\text{erfc}(z) = \frac{2}{\sqrt{\pi}} \int_z^\infty \exp(-t^2) dt.$$

Unless the termal electron gaz implodes (i.e. $F_{th.e} < 0$), the total photoelectron flux, $F_{ph.e}$, cannot much exceed the value of $F_{H^+}(r_0)$. For $T_{H^+} = 3000°$ K, $n_{H^+}(r_0) = 100\ \text{cm}^{-3}$, and $u_{H^+} = o$, the proton escape flux is equal to $4 \times 10^7\ \text{cm}^{-1}\text{sec}^{-2}$. Photoelectron fluxes larger than this value imply a higher proton density or/and temperature, or a highly asymmetric velocity distribution ($u_{H^+} \gg C_{H^+}$) at the baropause. For example, to support a photoelectron flux of $10^8\ \text{cm}^{-2}$ sec^{-1}, the minimum proton density at the baropause would be $250\ \text{cm}^{-3}$ if $u_{H^+} = o$ and $T_{H^+} = 3000°$ K. If however $n_{H^+}(r_0) = 100\ \text{cm}^{-3}$, and $T_{H^+}(r_0) = 3000°$ K, the minimal value of u_{H^+} required to support the same photoelectron flux would be $10\ \text{km sec}^{-1}$.

In the ensuing discussion an intermediate case is chosen in which $n_{H^+}(r_0) = 217\ \text{cm}^{-3}$, which is approximately the minimum proton density required at the baropause, to support a photoelectron flux of $10^8\ \text{cm}^{-2}\text{sec}^{-1}$ when $u_{H^+} = 1/4\ C_{H^+}$. Table 1 gives the values of the particle fluxes (F), the number densities (n), the scale heights (H), the bulk velocities (w), the perpendicular and parallel temperatures ($T_\perp$ and $T_{//}$), the total energy and conduction fluxes (ε and C) parallel to the magnetic field, and the electric field intensity (E) at an altitude of 10000 km for three models which differ by the photoelectron flux entering the base of the ion-exosphere as follows: (a) no photoelectron flux; (b) $F_{ph.e} = 2 \times 10^7\ \text{cm}^{-2}\text{sec}^{-1}$, and (c) $F_{ph.e} = 10^8\ \text{cm}^{-2}\text{sec}^{-1}$. The other parameter values are the same for the models and are given by: $n_{O^+}(r_0) = 783\ cm^{-3}$, $n_{H^+}(r_0) = 217\ cm^{-3}$ and $n_e(r_0) = 1000\ cm^{-3}$; $T_{O^+} = T_{H^+} = T_e = 3000°\ K$; $u_{H^+} = 2$ km sec^{-1}. The baropause is chosen at 2000 km above the polar cap; i.e. $r_0 = 8371$ km.

Discussion

From Table 1 it can be seen that when the photoelectron flux is much smaller than the ion flux, case (b), the plasma distribution does

TABLE I. — Properties of three model exospheres at an altitude of 10000 km above the geomagnetic pole. The models differ by the photoelectron flux at the baropause: (a) $F_{ph.e} = 0$; (b) $F_{ph.e} = 2 \times 10^7\ cm^{-2}sec^{-1}$; (c) $F_{ph.e} = 10^8\ cm^{-2}sec^{-1}$. The other conditions at the baropause are the same for the three models and are given by; $r_0 =$ 8371 km; $T_{H^+} = T_{O^+} = T_e = 3000°$ K; $u_{H^+} = 2$ km sec^{-1}, $u_{O^+} = u_e = 0$; $n_{H^+}(r_0) = 217\ cm^3$, $n_{O^+}(r_0) = 783\ cm^3$, $n_e(r_0) = 10^3\ cm^{-3}$.

Physical quantities at 10000 km		Units	Symbols	*a*	*b*	*c*
ph.e	flux	$cm^{-2}\ sec^{-1}$	$F_{ph.e}$	0	2.67×10^6	1.33×10^7
th.e			$F_{th.e}$	1.39×10^7	1.12×10^7	5.74×10^5
O^+			F_{O^+}	4.38×10^{-3}	5.54×10^{-3}	1.35×10^{-1}
H^+			F_{H^+}	1.39×10^7	1.39×10^7	1.39×10^7
th.e	density	cm^{-3}	$n_{th.e}$	8.47	8.41	8.16
O^+			n_{O^+}	2.30×10^{-2}	2.42×10^{-2}	3.13×10^{-2}
H^+			n_{H^+}	8.44	8.40	8.21
th.e	scale height	km	$H_{th.e}$	5020	5000	4910
O^+			H_{O^+}	1020	1210	1270
H^+			H_{H^+}	5070	5060	4980
th.e	bulk velocity	km sec^{-1}	$w_{th.e}$	16.4	13.4	7.0×10^{-1}
O^+			w_{O^+}	1.9×10^{-6}	2.3×10^{-6}	3.7×10^{-5}
H^+			w_{H^+}	16.5	16.6	16.9
th.e	perpendicular temperature	°K	$T_{th.e}$	1773	1895	2850
O^+			T_{O^+}	2999	2999	2997
H^+			T_{H^+}	374	374	375
th.e	parallel temperature	°K	$T_{th.e}$	2212	2270	2880
O^+			T_{O^+}	2999	2999	2998
H^+			T_{H^+}	473	470	452
Energy flux		erg cm^{-2} sec^{-1}	ε	5.1×10^{-5}	1.3×10^{-4}	4.5×10^{-4}
Conduction flux		erg cm^{-2} sec^{-1}	C	7.9×10^{-6}	1.0×10^{-5}	1.3×10^{-5}
Electric field		Volt/m	E	3.8×10^{-8}	4.0×10^{-8}	5.1×10^{-8}

not differ much from the model (a), where the photoelectron flux is zero. The slightly larger electric field in model (b) decelerates the thermal electrons and, as a consequence, reduces their escape flux by an amount exactly equal to the photoelectron flux, while the proton flux remains unchanged. In case (c), where the photoelectron flux is nearly equal to the proton flux, the electric field intensity is significantly larger than in case (a), and the thermal electron flux is reduced to a relatively small value compared to the total ion flux.

Fig. 1 illustrates the ratio of the electric force to the gravitational force acting upon an oxygen ion ($eE/m_{O^+}g$) as a function of altitude. The larger electric field in model (c), which is a consequence of the large photoelectron flux, accelerates the ions to higher velocities than in models (a) and (b). This is shown in Fig. 2, where the bulk velocity of the H^+ ions (solid lines and lower scale in km sec^{-1})

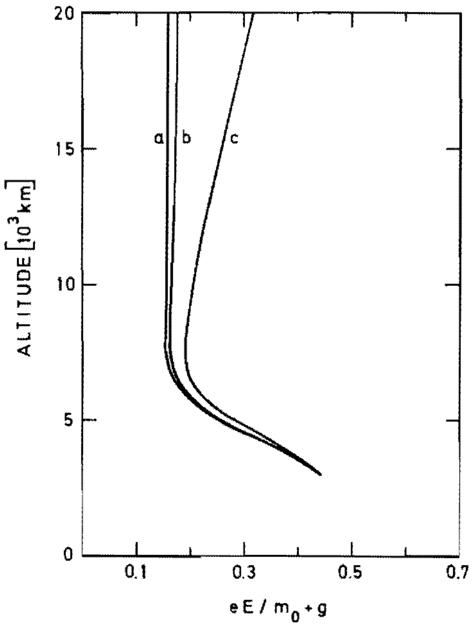

FIG. 1. — Ratio of the electric to the gravitational force acting upon an oxygen ion for three kinetic models of the polar ion exosphere. The baropause conditions are $r_0 = 8371$ km; $T_{H^+} = T_{0^+} = T_e = 3000°$ K; $u_{H^+} = 2$ km sec^{-1}; $u_{0^+} = u_e = 0$; $n_{H^+}(r_0) = 217$ cm^{-3}; $n_{0^+}(r_0) = 783$ cm^{-3}; $n_e(r_0) = 1000$ cm^{-3}; The models differ by the value of the photoelectron flux at the baropause:

a) $F_{ph.e}(r_0) = 0$; b) $F_{ph.e}(r_0) = 2 \times 10^7$ cm^{-2} sec^{-1}; c) $F_{ph.e}(r_0) = 10^8$ cm^{-2} sec^{-1}.

and the O^+ ions (dashed lines and upper scale in cm sec^{-1}) are given versus altitude for the three models considered in Table 1. The density distributions (n_{H^+}, n_{O^+}, $n_{th.e}$) do not depend significantly on the values of the photoelectron flux. The flux ($F_{th.e}$), the bulk velocity ($w_{th.e}$) and the temperatures ($T_{//th.e}$, $T_{\perp th.e}$) of the thermal electrons are, on the contrary, strongly dependent on the value of $F_{ph.e}$.

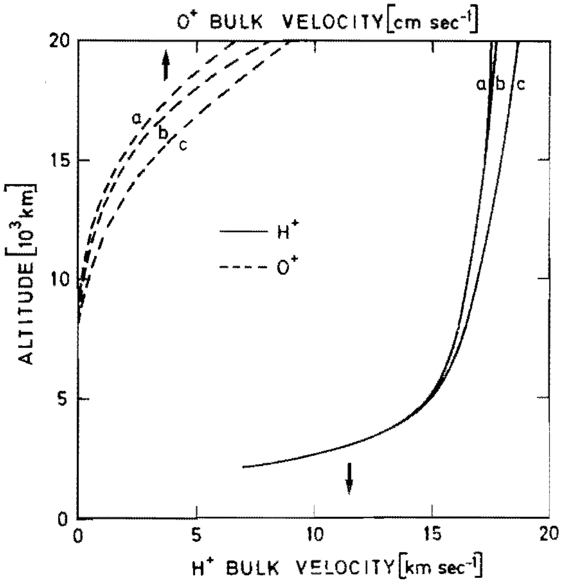

FIG. 2. — Bulk velocities of H^+ (solid lines and lower scale in km/sec) and O^+ (dashed lines and upper scale in cm/sec) for three kinetic models of the polar ion-exosphere. The baropause conditions are : $r_0 = 8371$ km; $T_{H^+} = T_{O^+} = T_e = 3000°$ K; $u_{H^+} = 2$ km sec^{-1}; $u_{O^+} = u_e = 0$; $n_{H^+}(r_0) = 217$ cm^{-3}; $n_{O^+}(r_0) = 783$ cm^{-3}; $n_e(r_0) = 1000$ cm^{-3}; The models differ by the value of the photoelectron flux at the baropause: a) $F_{ph.e}(r_0) = 0$; b) $F_{ph.e}(r_0) = 2 \times 10^7$ cm^{-2} sec^{-1}; c) $F_{ph.e}(r_0) = 10^8$ cm^{-2} sec^{-1}.

For sufficiently high values of the photoelectron flux and a fixed value of the escaping proton flux, the flux of thermal electrons may even become negative. Such a low energy (0.5 e V) electron precipitation can probably exist at the time of a sudden enhancement of the photoelectron emission. Conversely, a large precipitation of highly energetic electrons can be balanced by a nearly equal outward flux of thermal electrons (Shawhan *et al.*, 1970).

In a steady state model, however, where an inward flux of thermal electrons must be excluded, the light ion density $n_{H^+}(r_0)$ and flux $F_{H^+}(r_0)$, will be strongly dependent on the value of the photoelectron flux; very large values of this photoelectron flux must be balanced by correspondingly large values of F_{H^+} and $n_{H^+}(r_0)$ to keep the total electric current equal to zero.

Considering the photoelectrons as a separate type of collisionless particle with a Maxwellian velocity distribution at the baropause and a mean energy of 10 e V, it can be calculated that the escape flux $F_{ph.e}$ is precisely 10^8 cm^{-2}sec^{-1} when the number density $n_{ph.e}(r_0) = 1.051$ cm^{-3}, and $T_{ph.e} = 1.16 \times 10^{5\circ}$ K, (i.e. $3/2\, k\, T_{ph.e} = 10$ e V). With these boundary conditions and those already defined for the model (c) we determined the photoelectron density, bulk velocity and energy flux carried by these energetic particles. Fig. 3 shows the bulk velocity of the protons (solid line), thermal electrons (dotted line), and photoelectrons (dashed-dotted line) up to an altitude of 5×10^5 km (i.e. approximately 80 Earth radii). It can be seen that at large altitudes, and under the assumption that the charged particles do not interact either by Coulomb collisions or by wave-particle

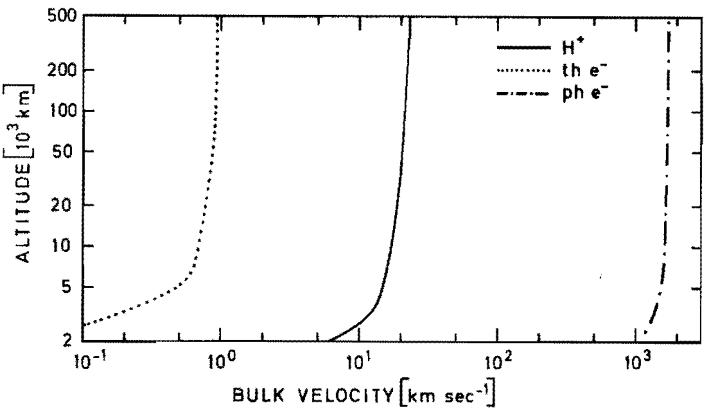

FIG. 3. — Bulk velocities of the proton (solid lines), of the thermal electrons (dotted line), and of the photoelectrons (dotted-dashed line) as a function of altitude above the geomagnetic pole in a kinetic model of the polar ion-exosphere, with baropause conditions: $r_0 = 8371$ km; $T_{H^+} = T_{O^+} = T_{th.e} = 3000°$ K; $T_{ph.e} = 1.16 \times 10^5$ °K; $u_{H^+} = 2$ km sec^{-1}; $u_{O^+} = u_{th.e} = 0$; $n_{H^+}(r_0) = 217$ cm^{-3}; $n_{O^+}(r_0) = 783$ cm^{-3}; $n_{th.e}(r_0) = 998.949$ cm^{-3}; $n_{ph.e}(r_0) = 1.051$ cm^{-3}; $F_{ph.e}(r_0) = 10^8$ cm^{-2} sec^{-1}.

interactions, the protons will have a kinetic energy $\frac{1}{2} m_{H^+} w_{H^+}^2 =$ 2.64 e V, while the energy of the photoelectrons has decreased to 8.53 e V.

Fig. 4 shows the density distributions of the protons (solid line), the oxygen ions (dashed line), the thermal electrons (dotted line), and the photoelectrons (dashed-dotted line) for the model (c).

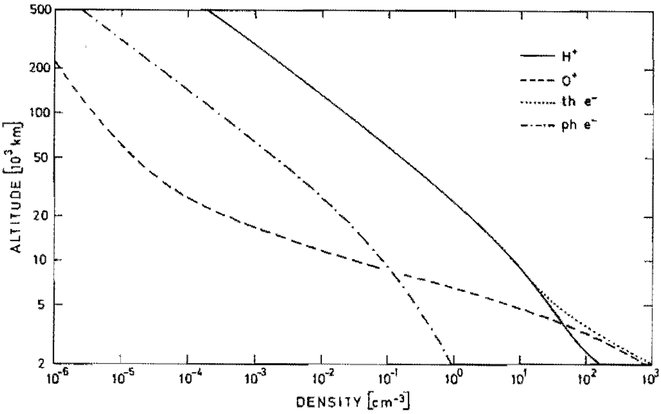

FIG. 4. — Density distribution of the protons (solid line), oxygen ions (dashed line), thermal electrons (dotted line), and photoelectrons (dotted-dashed line) as a function of altitude above the geomagnetic pole, in a kinetic model of the polar ion-exosphere with baropause conditions: $r_0 = 8.371$ km; $T_{H^+} = T_{O^+} = T_{th.e} = 3000°$ K; $T_{ph.e} = 1.16 \times 10^5$ °K; $u_{H^+} = 2$ km sec^{-1}; $u_{O^+} = u_{ph.e} = 0$; $n_{H^+}(r_0) = 217$ cm^{-3}; $n_{O^+}(r_0) = 783$ cm^{-3}; $n_{th.e}(r_0) = 998.949$ cm^{-3}; $n_{ph.e}(r_0) = 1.051$ cm^{-3}; $F_{ph.e}(r_0) = 10^8$ cm^{-2} sec^{-1}.

Finally, it must be mentioned that in all the model calculations it was assumed that the magnetic field strength was proportional to r^{-3}, and therefore, the proton and electron density distributions display a r^{-3} radial distance dependence. If, at large distances, the magnetic field intensity tends to a constant, these densities would decrease to constant asymptotic values. Nevertheless, the example of Fig. 4 shows that the photoelectrons always remain a minor constituent (i.e. $n_{ph.e} \ll n_{th.e}$) although they carry the total flux of the negatively charged particles (i.e. $F_{ph.e} \gg F_{th.e}$).

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