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FOREWORD

This paper has been presented in June 1971 at the 2d open session of Working Group 4, Panel C, at the XIVth Meeting of COSPAR, Seattle, Washington. It will be published in SPACE RESEARCH 12.

AVANT-PROPOS

Cet article a été présenté en juin 1971 à la 2ème session du Working Group 4, Panel C de la XIVème réunion plénière du COSPAR, Seattle, Washington. Il sera publié dans le SPACE RESEARCH 12.

VOORWOORD

Deze tekst werd in juni 1971 voorgedragen tijdens de tweede zitting van de Working Group 4, Panel C, van de XIVe plenaire COSPAR-vergadering welke gehouden werd te Seattle, Washington, U.S.A. Hij zal gepubliceerd worden in SPACE RESEARCH 12.

VORWORT

Dieser Text wurde im Juni 1971, während der 2n Session des Working Group 4, Panel C der XIVn COSPAR Versammlung in Seattle, Washington, vorgetragen, und wird im SPACE RESEARCH 12, herausgegeben werden.

EFFECT OF ESCAPING PHOTOELECTRONS IN A POLAR EXOSPHERIC MODEL

by J. LEMAIRE

Abstract

The effect of a photoelectron escape flux on a new Polar Wind model is discussed. It is shown that the additional electric drag force due to the escaping photoelectrons can accelerate the ions to higher velocities if the photoelectron flux is larger than the escape flux of the thermal electrons. Furthermore, it is shown that, even if the number density of the photoelectrons remains small compared to the number density of the thermal electrons, their kinetic pressure becomes important at very high altitudes. As a consequence a positive gradient in the electron "temperature" can be expected in the sunlit polar cap upper region.

Résumé

L'effet d'un flux d'échappement de photoélectrons sur un nouveau modèle de Vent Polaire est discuté. On montre que la force électrique additionnelle due aux photoélectrons qui s'échappent le long des lignes de force ouvertes du champ magnétique, peut accélérer les ions et leur communiquer des vitesses moyennes plus grandes. Cet effet se marque surtout lorsque le flux d'échappement des photoélectrons est supérieure au flux d'échappement des électrons thermiques. Par ailleurs, on montre que, même si le nombre de photoélectrons par cm^3 reste très inférieur au nombre d'électrons thermiques, la pression cinétique des photoélectrons devient prédominante à très haute altitude. On en déduit la possibilité d'une augmentation de la "température" électronique en fonction de l'altitude dans l'exosphère ionique située au-dessus des régions polaires éclairées par le Soleil.

Samenvatting

De invloed van fotoelektronen op een nieuw model voor de poolwind wordt besproken. De supplementaire elektrische kracht welke te wijten is aan de fotoelektronen die ontsnappen langs de open veldlijnen van het magneetveld, versnelt de ionen en geeft hen een grotere gemiddelde snelheid dan in de modellen zonder fotoelektronen. Dit is vooral merkbaar wanneer de flux der ontsnappende fotoelektronen groter is dan de flux der ontsnappende thermische elektronen. Zelfs indien de deeltjes dichtheid der fotoelektronen veel kleiner is dan het aantal thermische elektronen per cm^3 is het toch de kinetische druk der fotoelektronen die de voornaamste wordt op grote hoogten. Dit laat toe te veronderstellen dat er met stijgende hoogte een toename van de temperatuur der elektronen zal plaats hebben in de ionaire exosfeer boven de polaire gebieden, beschenen door de zon.

Zusammenfassung

Das Effekt eines Photoelektronen Ausfluss auf ein neues Polar Wind Modell wird besprochen. Die zulässliche elektrische Kraft die gefunden wurde kann die Ionen des Polar Windes zu einer höheren Geschwindigkeit fördern, besonderes wenn der Ausfluss der Photoelektronen grösser als der Ausfluss der thermischen Elektronen ist. Der kinetische Druck der Photoelektronen bekömmt wichtiger mit zunehmende Höhe. Deshalb wird es vorgeschlagen dass die Elektronentemperatur in der beleuchteten polare Exosphäre mit der Höhe zunimmt.

1. INTRODUCTION

The Polar Wind concept has been introduced by Axford (1968), who suggested that a flux of 2×10^8 cm^{-2} sec^{-1} of escaping photoelectrons is required to drag out of the polar ionosphere all the He^+ ions produced in the atmosphere. The effects of such photoelectron fluxes on the density, bulk velocity and pressure distributions of a polar wind model, are investigated in the following paragraphs.

2. THE MODEL

The electron and ion temperatures $T_{e,i}$ are assumed to be equal to 3000° K in the models. The neutral particles (O,H,He) are distributed according to Nicolet-Kockarts atmospheric model, T_N= 1000° K; (private communication).

The boundary conditions are taken from the OGO-2 ion-composition measurements (Taylor *et al* 1968) :$n_{O^+} = 7 \times 10^3$ cm^{-3} , $n_{H^+} = 320$ cm^{-3} are typical values observed near 1700 LMT in October 1965 at an altitude of 950 km in the sunlit part of the polar cap. Using these values and $n_{th.e^-} = 7.32 \times 10^3$ cm^{-3}as boundary conditions, we integrated the hydrodynamic equations (mass and momentum equations for each ionic species) described by Banks and Holzer (1968, 1969) or more recently by Marubashi (1970). Each of the hydrodynamic solutions can be characterized by the value of the bulk velocity (or by the upward diffusion flux) at the reference level of 950 km. From the calculated bulk velocity and density distribution one can estimate the deflection mean free path (m.f.p.) of the H^+ ions, and define the baropause as the altitude where the m.f.p. becomes equal to the electron or O^+ density scale height (Lemaire, 1971). Above this altitude a kinetic calculation is adopted to determine the structure of the ion exosphere (Lemaire and Scherer, 1970, 1971). The requirement that the thermal escape flux of the ions must be equal to the diffusion flux in the collision-dominated region is a new criterion to select a unique hydrodynamic solution. This solution is not necessarily the "critical solution" adopted in the completely hydrodynamic polar wind models. Both of these solutions, however, converge rapidly in the lower altitude range.

The *photoelectrons* are considered as a separate kind of collisionless particles with a Maxwellian velocity distribution at the baropause, and a mean energy of 10 eV ($T_{ph.e^-} = 1.16 \times 10^{5}$ K). It is assumed that the trapped photoelectrons with two magnetic mirror and/or gravitational reflection points above the baropause are missing in the velocity distribution. The particles coming from infinity and travelling towards the baropause are also absent in the models No. 1,2 and 3 considered below.

In the models No. 1, 2 and 3, the number density of the photoelectrons at the baropause (h_0 = 1250 km) is respectively : $n_{ph.e^-} = 0$, 0.25 and 0.6. The corresponding photoelectrons escape fluxes are : $F_{ph.e^-} = 0$, 1.3×10^7 and 2.9×10^7 cm^{-2} sec^{-1} at an altitude of 3 000 km.

Heikkila (1971) has observed higher photoelectron fluxes (10^8 cm^{-2} sec^{-1}) in the sunlit polar cap region. However this outward photoelectrons flux decreases with increasing solar zenith angles (Heikkila,1971). Therefore a value of 2×10^7 cm^{-2} sec^{-1} may be representative of the dusk conditions (~ 1700 LMT) considered here.

The flux of H^+ at 3 000 km altitude is calculated to be 3.0×10^7 cm^{-2} sec^{-1}; this flux which is the same for all three models considered here, is determined by the boundary conditions at the baropause described in Table 1.

3. RESULTS AND DISCUSSION

The density distributions of O^+, H^+, of the thermal electrons and photoelectrons are shown for these models in Fig. 1. The dashed lines (model No.4) correspond to a special case where there would be as many photoelectrons flowing in as flowing out of the ionosphere.

It can be seen that the O^+ distribution is influenced by an outward flux of photoelectrons. This effect becomes most important when $F_{ph.e^-}$ is larger than the thermal electron escape flux, $F_{th.e^-}$. In this case (e.g. model No.3) the polarization electric field is

TABLE 1. Densities and escape fluxes at the baropause (1250 km)

Model		1	2	3	4
n_{O^+}	[cm^{-3}]	3613	3613	3613	3613
n_{H^+}	[cm^{-3}]	140	140	140	140
$n_{th.e^-}$	[cm^{-3}]	3753	3752.75	3752.4	3752.4
$n_{ph.e^-}$	[cm^{-3}]	0	0.25	0.6	0.6
F_{O^+}	[cm^{-2} sec^{-1}]	7.0×10^{-2}	1.3×10^{-1}	3.6	6.9×10^{-2}
F_{H^+}	[cm^{-2} sec^{-1}]	5.5×10^{7}	5.5×10^{7}	5.5×10^{7}	5.5×10^{7}
$F_{th.e^-}$	[cm^{-2} sec^{-1}]	5.5×10^{7}	3.1×10^{7}	1.3×10^{6}	5.5×10^{7}
$F_{ph.e^-}$	[cm^{-2} sec^{-1}]	0	2.4×10^{7}	5.37×10^{7}	$\pm 5.4 \times 10^{7}$

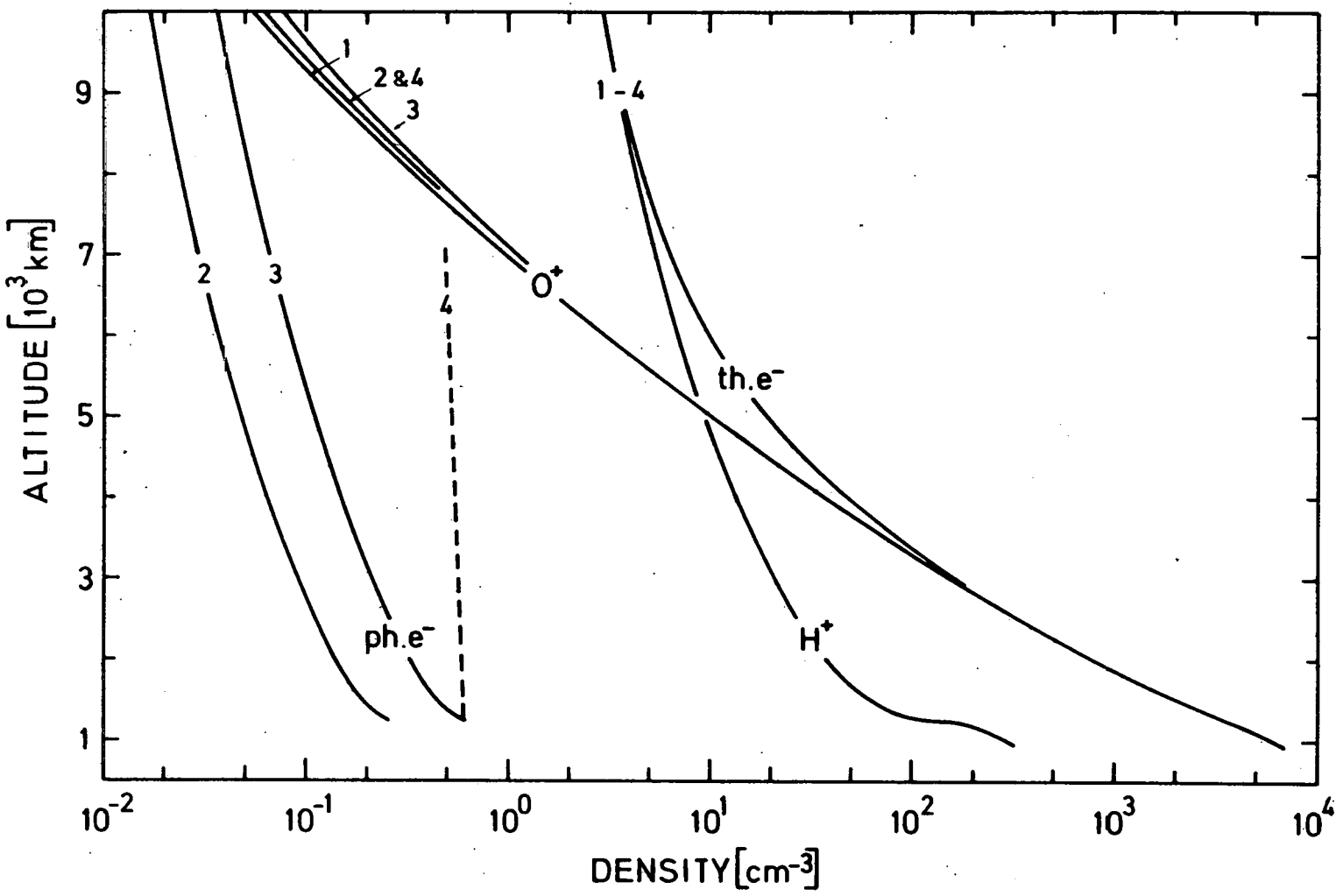

Fig. 1.- Density distribution of the oxygen ions, protons, thermal and photoelectrons in four different polar wind models, with the effect of increasing photoelectron escape fluxes shown.

significantly enhanced compared to that of the model No.1 where no photoelectrons are present. This can be seen in Fig.2 where the ratio of the electric and gravitational forces acting upon an O^+ ion is shown versus altitude for the four models described above.

The additional electric drag due to the escaping photoelectrons is most efficient at very high altitudes where the relative abundance of the photoelectrons reaches its maximum value. The slightly larger O^+ density scale height of model 3 is a consequence of this effect. Furthermore, the larger electric field intensity in a model with escaping photoelectrons increases strongly the subsonic bulk velocity and escape flux of the O^+ ions. This can be seen in Fig. 3 where the O^+ (upper scale) and H^+ (lower scale) bulk velocity is given versus altitude for the models considered.

Although the supersonic proton velocity is nearly unchanged below 10 000 km altitude, it reaches, at very high altitudes, a larger asymptotic value :

$$w_{H^+}(h \to \infty) = \frac{n_{ph.e^-}}{n_{th.e^-}} \; \frac{1 + \dfrac{F_{th.e^-}}{F_{ph.e^-}}}{1 + \dfrac{n_{ph.e^-}}{n_{th.e^-}}} \; w_{ph.e^-} \qquad (1)$$

which depends drastically on the relative abundance of the photoelectrons at large distances ; e.g., in model No.3, $F_{th.e^-}/F_{ph.e^-} = 2.3 \times 10^{-2}$, $n_{ph.e^-}/n_{th.e^-} \to 1.3 \times 10^{-2}$, and $w_{H^+}/w_{ph.e^-} \to 1.3 \times 10^{-2}$.

Fig. 4 shows the normalized total kinetic pressure components versus altitude in the models 1, 2, 3 and 4. The electron gas makes the largest contribution to the total pressure. The anisotropy of the kinetic pressure becomes significant above 7 000 km.

Model No. 4 illustrates a case for which all the escaping photoelectrons would be back-scattered at a high altitude level. From the Fig. 4 it can be seen that the total kinetic pressure would then remain isotropic, and that it would be greatly enhanced. The upward and downward photoelectron flux at 3 000 km, would be equal to 3.0×10^7 ph.e$^-$ cm^{-2} scc^{-1}.

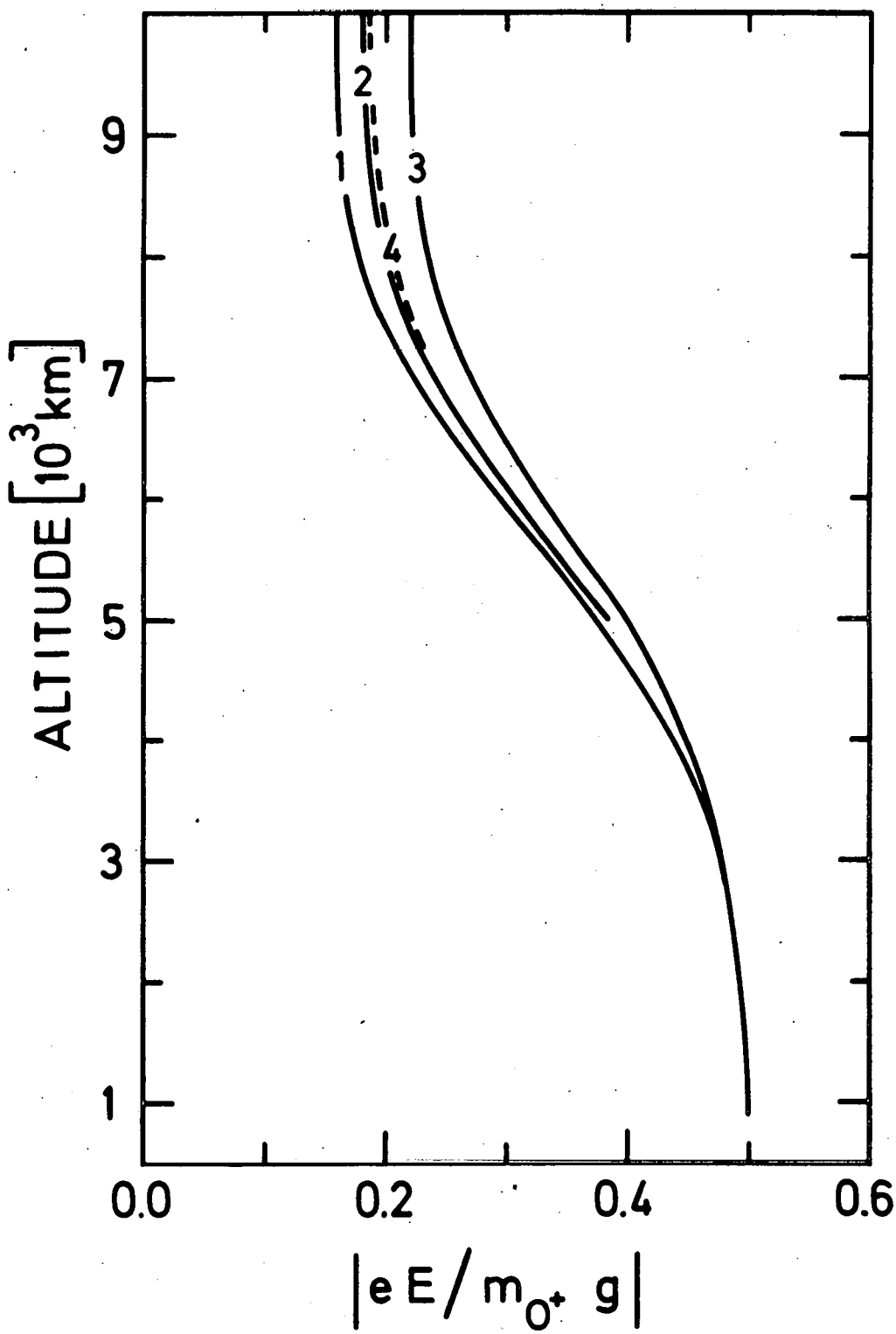

Fig. 2.- Ratio of the electric and gravitational forces acting upon an O^+ ion versus altitude in four different polar wind models, with the effect of increasing photoelectron fluxes shown.

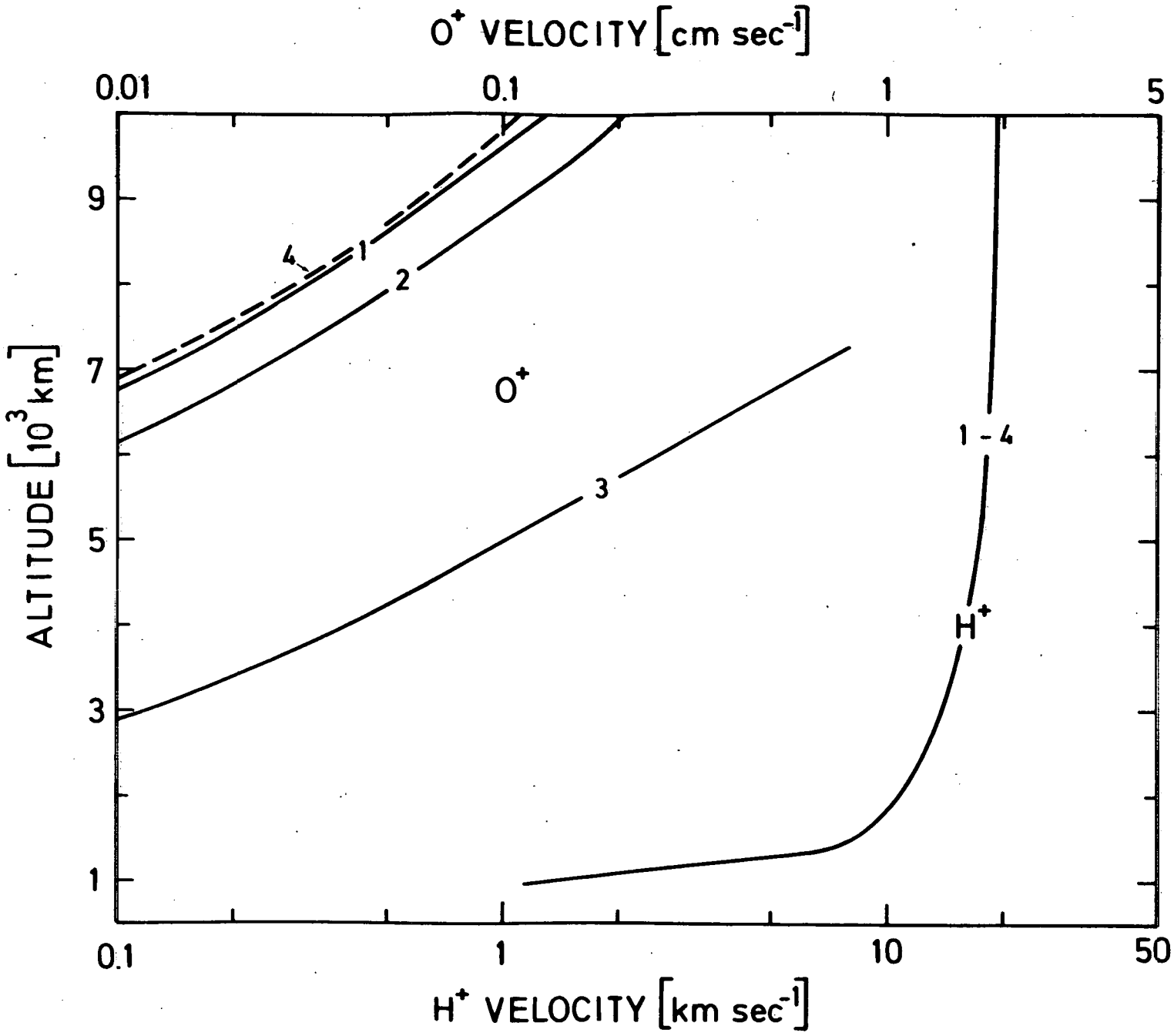

Fig. 3.- Bulk velocity of 0^+ (upper scale) and H^+ ions (lower scale) versus altitude in four different polar wind models, with the effect of increasing photoelectron fluxes shown.

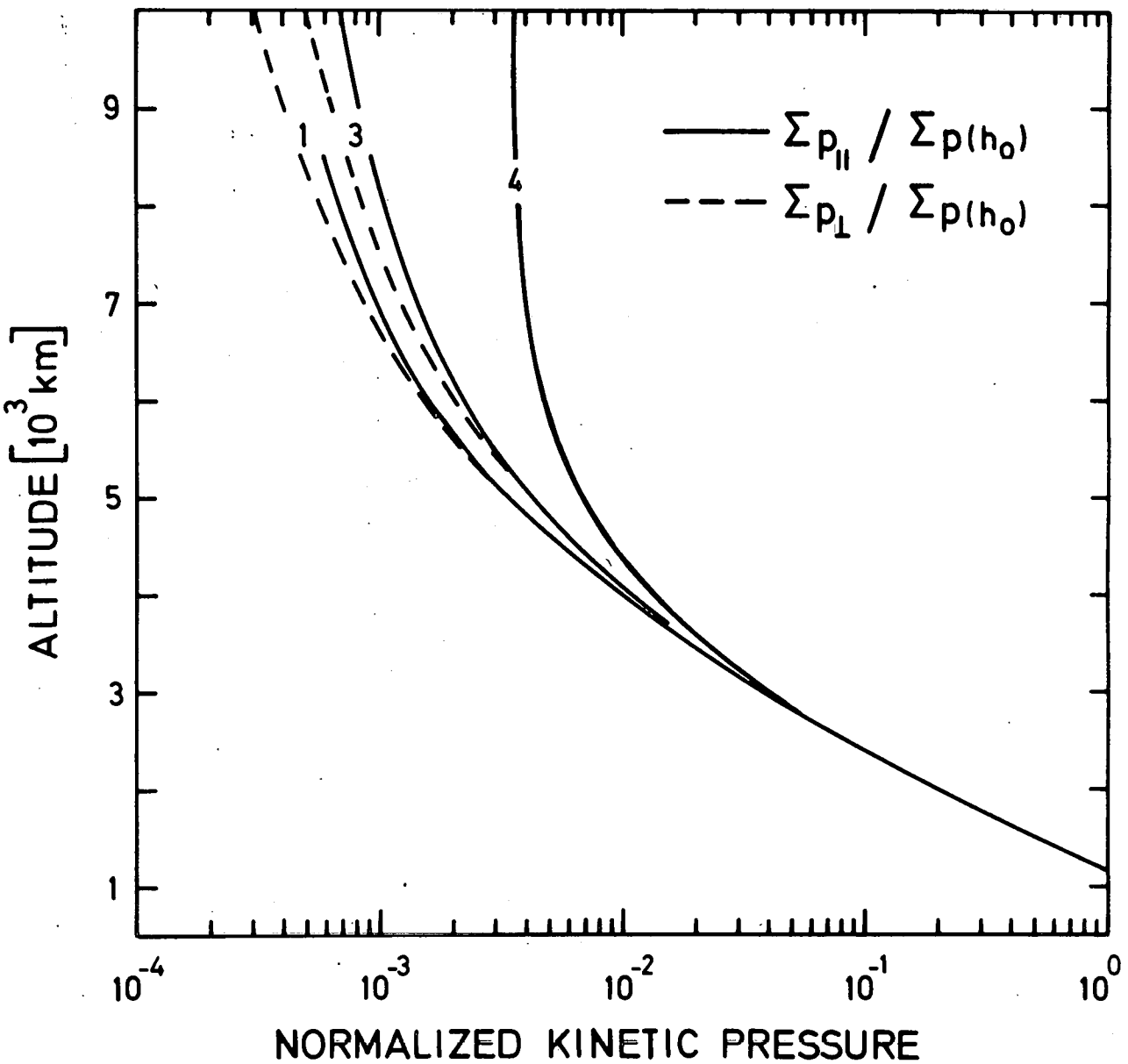

Fig. 4.- Normalized total pressure components (parallel and perpendicular to the magnetic field) in four different polar wind models, with the effect of increasing photoelectron escape fluxes shown.

Although the photoelectrons remain a minor constituent in the model No. 3, it can be seen from Fig. 4, that these particles contribute significantly to increase the kinetic pressure and its anisotropy.

Furthermore, these escaping photoelectrons carry much more energy out of the topside ionosphere than the escaping thermal electrons or ions. For instance at 3 000 km altitude the total energy fluxes, ϵ, transported by the photoelectrons, the thermal electrons and the protons are respectively : 9.4×10^{-4}, 3.1×10^{-6} and 5.8×10^{-5} erg cm^{-2} sec^{-1} in the model No. 3.

In the stationary models presented here, it is assumed that the different kind of particles interact only by the electrostatic polarization field, E, induced in the collisionless plasma to maintain local and global quasi-neutrality

$$n_{th.e^-} + n_{ph.e^-} = n_{O^+} + n_{H^+} \text{ and } F_{th.e^-} + F_{ph.e^-} = F_{O^+} + F_{H^+}$$

However, wave-particle interactions can be more important than Coulomb collisions in the exosphere, and can modify this simple picture by increasing the momentum and energy exchange between the different types of particles. Koons, *et al* (1971) have considered the ion-two-stream instability (H^+/O^+) as such a possible mechanism. When photoelectrons are streaming through a thermal electron gas, as it is the case in the models presented here, similar interactions can transfert momentum and energy from the photoelectron stream to the thermal electrons (Adlam, 1971). A consequence of this would be to increase the temperature of the electrons gas above the value predicted by the kinetic models. It can be shown that for the conditions described in model No. 3, the flux of energy transported into the exosphere by the photoelectrons is large enough to maintain a positive electron temperature gradient in the exosphere. Indeed, if the total energy flux, $\epsilon_{ph.e^-}$, transported outwardly by the photoelectrons is deposited inside of the exosphere and consumed to heat the thermal electrons, it can be calculated that an electron temperature gradient

$$\frac{d\,T_{e^-}}{d\,h} = \frac{\epsilon_{ph.e^-}}{K} = 0.16\ {}^{o}K/km, \qquad (2)$$

(where K is the thermal conductivity coefficient*) is required at 3 000 km, to balance this energy deposition by a downward conduction flux ($\epsilon_{ph.e^-} = 9.4 \times 10^{-4}$ ergs cm^{-2} sec^{-1}).

Although, no direct electron temperature gradient measurement seems to be available in the literature for the topside *polar* ionosphere, such positive gradients have however been observed by Serbu and Maier (1966, 1967, 1970) and Brace *et al* (1967) in lower latitude regions of the magnetosphere. From these observations temperature gradients of the order of 1 ^{o}K km^{-1} have been deduced for the dayside plasmasphere. This value is 5 or 6 times larger than the value obtained from Eq. (2). But this difference can partially be explained by the larger flux of photoelectrons ($F_{ph.e^-} = 2.5 \times 10^{8}$ cm^{-2} sec^{-1} and $\epsilon_{ph.e^-} = 8 \times 10^{-3}$ ergs cm^{-2} sec^{-1}) observed along the lower latitude magnetic field lines (Heikkila, 1970).

It can therefore be concluded that, when "suprathermal" electrons are present in the topside polar ionosphere, the effective temperature of the electrons is expected to increase with the altitude. In the lower altitude region where the thermal electrons density is more than 10^5 times larger than the density of the photoelectrons, the energy spectrum will have a broad peak between 0.3 and 0.6 eV. However at altitudes above 7 000 km where the abundance of photoelectrons is 1 % of the thermal electrons density (in model 3), a secondary peak in the energy and velocity distributions will grow near 10 eV. As such a doubly peaked velocity distribution generally leads to plasma instability, one can expect that wave-particle interactions will play a significant role and give rise to energy redistribution. Electromagnetic or/and electrostatic emissions are therefore expected at high altitudes above the sunlit polar cap (Koons *et al*,1970).

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*If Coulomb collisions are considered, the thermal conductivity coefficient along the field lines of a uniform magnetic field is equal to 6×10^{2} ergs cm^{-1} sec^{-1} $^{o}K^{-1}$ for an electron temperature of 3 000 ^{o}K (Delcroix and Lemaire, 1969). However, when the collision frequency is smaller than the gyrofrequency in a non-uniform magnetic field with diverging field lines, the value of K can be significantly reduced in the direction of the magnetic field gradient (Holzer,*et al*, 1971). Therefore the thermal conduction coefficient, K along the geomagnetic field lines will have a lower value in the downward direction than in the upward direction due to this geometrical effect which has not been considered previously (Mayr and Volland, 1968 ; Bauer *et al*,1970).
As K $= 6 \times 10^{2}$ ergs cm^{-1} sec^{-1} $^{o}K^{-1}$ was used in Eq. (2), it is obvious that 0.16 $^{o}K/km$ is more or less a minimum value for the temperature gradient at 3 000 km altitude.

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