GEOPHYSICAL RESEARCH LETTERS, VOL. 32, L02105, doi:10.1029/2004GL021912, 2005

An auroral source of hot oxygen in the geocorona

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Received 4 November 2004; revised 10 December 2004; accepted 28 December 2004; published 29 January 2005.

[1] The high-energy proton-hydrogen (H^+/H) beam associated with proton auroral precipitation transfers momentum in elastic and inelastic collisions with ambient thermal atomic oxygen in the high latitude thermosphere. This process provides a localized novel source of hot oxygen atoms in addition to exothermic photochemistry, charge exchange and momentum transfer from O^+ ion precipitation and charge exchange with accelerated ionospheric O^+ ions. We suggest that this source contributes to the population of the hot oxygen geocorona and to the flux of escaping oxygen atoms. For an incident proton energy flux of 1 mW m^{-2} and a mean energy $E_{mean} \approx 5$ keV, we calculate a density of hot oxygen atoms with energy above 1 eV of 2.0×10^3 cm^{-3} and a mean kinetic energy of about 3.5 eV at 700 km. The total upward flux of hot oxygen atoms with energies higher 1 eV is estimated as 3.5×10^8 cm^{-2} s^{-1}. **Citation:** Shematovich, V. I., D. V. Bisikalo, and J.-C. Gérard (2005), An auroral source of hot oxygen in the geocorona, *Geophys. Res. Lett.*, *32*, L02105, doi:10.1029/2004GL021912.

1. Introduction

[2] The hot oxygen geocorona has generated recent studies for several reasons. It is a source region of energetic neutral atoms, it contributes to the maintenance of the nighttime ionosphere, it plays a role in the formation of the escape flux of neutral atoms, and it controls the energetic ion populations in the thermosphere. Theoretical and observational studies have established the role of the following sources of hot oxygen in the Earth's upper atmosphere:

[3] • exothermic photochemistry: FUV and electron impact dissociation of O_2, dissociative recombination of O_2^+ [*Rohrbaugh and Nisbet*, 1973; *Yee et al.*, 1980; *Shematovich et al.*, 1994], and exothermic ion-molecular reactions [*Richards et al.*, 1994; *Gérard et al.*, 1995]

[4] • charge exchange and momentum transfer from O^+ ion precipitation at high geomagnetic activity [*Torr et al.*, 1974; *Ishimoto et al.*, 1992; *Bisikalo et al.*, 1995]

[5] • charge exchange with accelerated ionospheric polar wind O^+ ions [*Yau and André*, 1997; *Gardner and Schunk*, 2004].

[6] The LENA instrument on board the IMAGE spacecraft has provided the first global observations of low energy neutral atom (ENA) emissions in the terrestrial atmosphere. First analyses of the observations [*Wilson et al.*, 2003] show the presence of a flux of low-energy (<50 eV) oxygen atoms. They found two different patterns in the ENA images probably corresponding to different sources of these hot atoms. One is localized in the auroral zone and produces more energetic particles with a high degree of time variability. Another source exhibits less variability within images and is possibly connected with the hot oxygen geocorona.

[7] In the polar regions, an additional source of hot oxygen due to momentum transfer to thermospheric atomic oxygen from precipitation of high-energy proton-hydrogen (H^+/H) flux in the proton aurora must be considered. In this paper we provide estimates of the importance of this additional auroral source and its contribution to upward fluxes of hot oxygen.

2. Formation of Hot Oxygen Atoms by Proton/Hydrogen Auroral Precipitation

[8] Interactions of precipitating energetic protons of magnetospheric origin with the main atmospheric constituents include momentum and energy transfer in elastic and inelastic collisions, ionization of target atmospheric molecules/atoms, charge transfer and electron capture collisions. Energetic H atoms produced by proton impact further interact with the main constituents of the atmosphere, transferring their momentum and kinetic energy by elastic and inelastic collisions, ionization and stripping (i.e., impacting hydrogen atom ionization) processes. The collisional processes describing the penetration of energetic H^+/H into ambient atmosphere can be written as:

$$H^+(H) + M \rightarrow \begin{cases} H_{f'}^+\left(H_{f'}\right) + M^* \\ H_{f'}^+\left(H_{f'}\right) + M^+ + e \\ H_{f'}\left(H_{f'}^+\right) + M^+(M) + e \end{cases} .$$

Here, M denotes the major atmospheric constituents – O_2, N_2, and O. Secondary fast $H_{f'}$ atoms and $H_{f'}^+$ protons produced by momentum transfer and stripping reactions recycle the reaction set given above. Consequently, the interaction of the precipitating protons with the main neutral thermospheric constituents must be considered as a cascade process producing a growing set of translationally and internally excited particles M^* of the ambient atmospheric gas.

[9] To analyze the penetration of energetic H^+/H into the auroral atmospheric gas, we use the kinetic Boltzmann equations [*Gérard et al.*, 2000]. These coupled equations

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take into account both scattering and transport of the high-energy H^+/H flux in elastic, inelastic, ionization, and charge transfer collisions with the ambient atmospheric gas. One of the consequences of the penetration of a high-energy H^+/H flux into the upper atmosphere is the production of suprathermal oxygen atoms O_h by momentum transfer in elastic and inelastic collisions of the auroral H^+/H beam with atmospheric oxygen O_{th}:

$$H^+(H) + O_{th} \rightarrow H^+(H) + O_h \qquad (1)$$

3. Kinetic Model of Hot Oxygen

[10] The fresh suprathermal oxygen atoms loose their excess kinetic energy in collisions with other atmospheric particles and are distributed in the transition region between the thermosphere and the exosphere [*Shematovich et al.*, 1994, 1999]. Their kinetics and transport is described by the kinetic Boltzmann equation:

$$\mathbf{v}\frac{\partial}{\partial \mathbf{r}}f_{Oh} + \mathbf{s}\frac{\partial}{\partial \mathbf{v}}f_{Oh} = Q_{Oh}(\mathbf{v}) + \sum_{M=O,N_2,O_2} J_{mt}(f_{Oh}, f_M), \qquad (2)$$

where $f_{Oh}(\boldsymbol{r}, \boldsymbol{v})$, and $f_M(\boldsymbol{r}, \boldsymbol{v})$ are the velocity distribution functions for hot oxygen atoms, and components of the ambient gas, respectively. The left side of the kinetic equation describes the transport of suprathermal oxygen in the planetary gravitational field $\boldsymbol{s}$. In the right-hand side of the kinetic equation the Q_{Oh} term describes the formation rate of suprathermal oxygen atoms in the elastic and inelastic collisions of H^+/H flux with atmospheric oxygen atoms. The elastic and inelastic scattering terms J_{mt} for hot oxygen collisions with ambient atmospheric species are written in a standard form [*Shematovich et al.*, 1994]. It is assumed that the ambient atmospheric gas is characterized by the local Maxwellian velocity distribution functions.

[11] The Direct Simulation Monte Carlo (DSMC) method is an efficient tool to study such complex kinetic systems in the stochastic approximation [*Shematovich et al.*, 1994; *Bisikalo et al.*, 1995; *Gérard et al.*, 2000]. The details of the algorithmic realization of the numerical model were given earlier [*Shematovich et al.*, 1994, 1999; *Bisikalo et al.*, 1995]. The essence of the DSMC method is to generate a sample of paths for the state of the physical system under study – the hot oxygen collisions and transport in the transition region of the polar upper atmosphere in this case. Therefore, during the numerical realization of the kinetic model of the proton aurora, statistics for collisional processes forming suprathermal oxygen is accumulated and provides the source function Q_{Oh}. The source function due to the process (1) is used as an input into the stochastic model (2) of hot oxygen thermalization and transport in the transition region. The results of the hot oxygen model are the steady state energy distribution function of oxygen atoms and the energy spectra of the upward fluxes of hot oxygen atoms at the upper boundary of the transition region under study.

[12] The thermalization rate of hot oxygen is determined by the collisional cross sections with the ambient neutral atmosphere. A key aspect of this model is the stochastic treatment of the scattering angle distribution in elastic and inelastic collisions of hot oxygen with the ambient atmospheric gas. This effect influences both the pitch angle redistribution and the energy degradation through losses of energy in the momentum transfer collisions that are proportional to the *sine* of the scattering angle. Recent detailed calculations of cross sections for elastic and inelastic collisions between suprathermal oxygen and atomic oxygen [*Kharchenko et al.*, 2000], and molecular nitrogen [*Balakrishnan et al.*, 1998a] were adopted. To take into account the scattering angle distribution, we used the calculated differential cross sections for O – O from *Kharchenko et al.* [2000], and for $O - N_2$ collisions we adopted the values calculated for $N - N_2$ by *Balakrishnan et al.* [1998b]. The mentioned above calculations of differential cross sections were made for energies up to a few eVs, and we extrapolated the cross sections to higher collision energies with an $(\text{energy})^{-1/2}$ dependence according to the discussion by *Gérard et al.* [2000].

[13] Kinetics and transport of hot oxygen was considered in an atmospheric region with a lower boundary set at 80 km where the hot atoms are efficiently thermalized and an upper boundary at 700 km where the atmospheric gas flow is practically collisionless. The region of the atmosphere under study was divided into 49 radial cells. The altitude dependent cell size was chosen so that it is equal to or smaller than the free path length for hot oxygen. The altitude distributions of the main neutral species – O_2, N_2, and O, and their temperature were calculated with the MSISE-90 reference model [*Hedin*, 1991] for high solar ($F_{10.7}$ = 200) and low geomagnetic activities (A_p = 6) at 70.0° latitude and UT = 16:30 conditions. The source function Q_{Oh} of fresh hot oxygen atoms was calculated by our proton auroral code for a precipitation with an initial kappa distribution (κ = 3.5) and for an energy flux of Q_0 = 1 mW m^{-2}, with a characteristic energy E_0 varied from 1 to 5 keV (the corresponding mean proton energy is changing in a range between 5.0 and 25 keV). The fresh hot O atoms formed following momentum transfer in collisions with the incident H^+/H flux are distributed by the energy up to 100 eV.

4. Results

[14] Using the kinetic model described above, we calculate the energy distribution functions (EDFs) of the hot oxygen atoms produced by H^+/H precipitation into the auroral upper atmosphere. As an example of hot oxygen EDFs the energy spectra at the exospheric height 700 km are shown in Figure 1 for the thermal case and for two cases with proton precipitation with characteristic energies E_0 = 1 and 5 keV. It is seen that processes of momentum transfer of H^+/H flux to atomic oxygen result in the production of a significant amount of energetic (>1 eV) oxygen atoms, leading to the formation of suprathermal tails in the distribution functions. Further evidence of the importance of this auroral source of hot oxygen geocorona can be seen in Figure 2 where the height profiles of the population of oxygen atoms with kinetic energies higher 1 eV are given for the thermal Maxwellian distribution (at the exospheric temperature T = 1150 K) and for the nonthermal distributions corresponding to proton precipitation with E_0 = 1 and 5 keV. The hot oxygen population produced by an auroral 1 mW m^{-2}, 1 keV source (solid line) becomes dominant

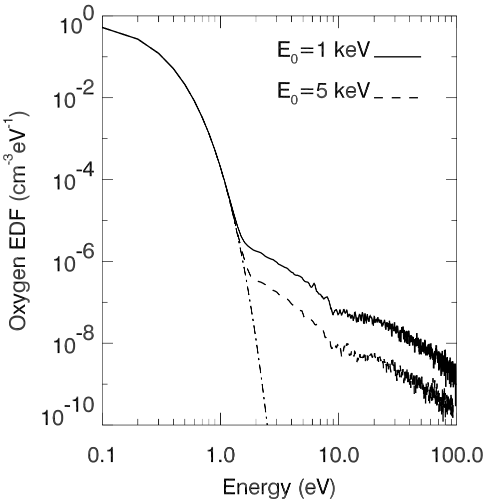

Figure 1. Normalized energy distribution functions at 700 km of thermal (dot-dashed line) and nonthermal oxygen calculated for two cases of proton precipitation with characteristic energy E_0 = 1 (solid line) and 5 keV (dashed line).

over the hot fraction of the thermal population (dash-dotted line) at altitudes above 520 km. It is important to note that for the auroral source produced by more energetic precipitation (E_0 = 5 keV) the nonthermal fraction is much less (dashed line in Figure 2), and exceeds the thermal fraction only at heights above 650 km. In spite of their different densities, the height scales for both auroral cases are very similar, both significantly exceeding the height scale of hot thermal oxygen.

[15] The energy spectra of the upward flux of hot oxygen through the upper boundary at 700 km are presented in Figure 3 for both precipitation cases. It is worthwhile to note that collisional thermalization of primary O atoms is accompanied by the production of secondary O atoms. Some of the recoil O atoms receive enough energy to make additional contribution to the upward flux of hot oxygen. The role of secondary O atoms can be estimated from Figure 3, where the energy spectra of the upward fluxes for the two cases discussed before, with and without secondary hot O atoms, are shown by thick and thin lines respectively. It is seen that the secondary atoms mainly populate the hot oxygen geocorona, i.e., the suprathermal fraction of oxygen atoms with energies below the oxygen escape energy. The escape flux of atomic oxygen is insensitive to the cascade formation of secondaries, as it is mainly formed by direct momentum transfer from precipitating H^+/H flux to atomic oxygen.

5. Conclusions

[16] In this paper we estimate the role of auroral proton precipitation in the formation of the hot oxygen corona in the polar upper atmosphere. It is found that this source contributes to the population of the hot oxygen geocorona and to the flux of escaping oxygen atoms. For a proton energy flux $Q_0 = 1$ mW m^{-2} and a characteristic energy E_0 = 1 keV (5 keV), the density of hot oxygen atoms with energy above 1 eV is equal to 2.0×10^3 cm^{-3} (3.6×10^2 cm^{-3}) and their mean kinetic energy is about 3.5 eV (2.8 ev) at 700 km. The total upward fluxes of hot oxygen atoms with energies higher 1 eV are estimated as 3.5×10^8 cm^{-2} s^{-1}, and 5.1×10^7 cm^{-2} s^{-1} for E_0 = 1 keV and 5 keV cases, respectively. The absolute value of this auroral source contribution depends on the specific characteristics of the auroral proton precipitation. The dependence on the characteristic energy E_0 can be estimated from the sample calculations described above. The dependence on the proton energy flux Q_0 is linear and the upward oxygen flux for a

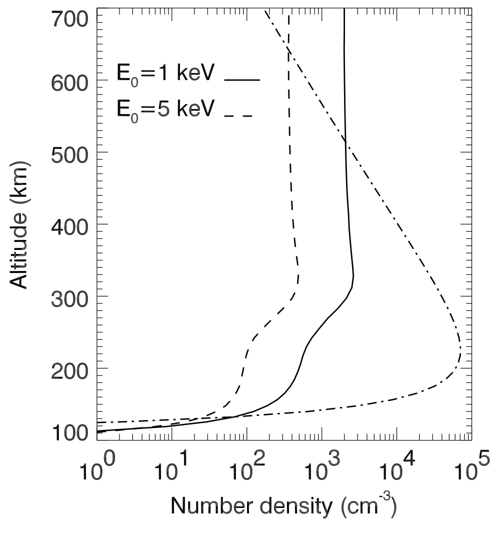

Figure 2. Altitude profiles of the population of oxygen atoms with a kinetic energy >1 eV for the thermal Maxwellian distribution (for an exospheric temperature T = 1150 K) and for nonthermal distributions corresponding to proton precipitation with E_0 = 1 and 5 keV. Line styles are the same as in Figure 1.

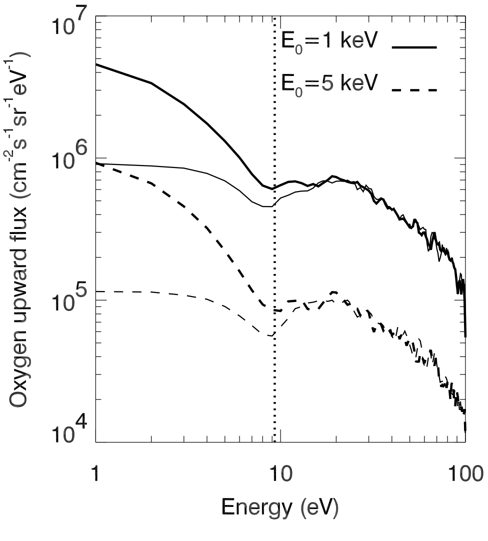

Figure 3. Energy spectra of the upward flux of hot oxygen at 700 km for two precipitation cases (solid lines for E_0 = 1 keV, and dashed lines for E_0 = 5 keV). The upward flux calculated with and without secondary hot O atoms is shown by thick and thin lines, respectively. The vertical dotted line shows the oxygen escape energy at 700 km.

specific value of Q_0 can be simply obtained by scaling the results presented here.

[17] The relative role of this novel source of hot oxygen in the polar atmosphere can be estimated by comparison of the calculated upward fluxes of hot oxygen with observations. As it follows from the analysis of LENA IMAGE observations [*Wilson et al.*, 2003] the oxygen atoms with energies below 50 eV were always observed during the perigee passes. The observed fluxes of energetic neutral atoms (mainly oxygen) strongly depend on the level of geomagnetic activity and show significant diurnal variations. For $Ap = 6$ and $UT = 16{:}30$ used in our example the observed flux presumably consists of fast O atoms, and has a typical value about 5×10^8 cm^{-2}s^{-1} [see *Wilson et al.*, 2003, Figures 5 and 6]. Recently, *Gardner and Schunk* [2004] found that auroral ion outflow causes the formation of the escaping total neutral flux of about 10^9 cm^{-2}s^{-1} for the same geophysical conditions. According to their study this neutral polar wind consists from hydrogen atoms only. It is important to note that our model predicts the formation of rather high upward flux of escaping oxygen atoms in contrast to the models of neutral polar wind [*Gardner and Schunk*, 2004] and of photochemical hot oxygen geocorona [*Richards et al.*, 1994; *Gérard et al.*, 1995]. The LENA IMAGE observations analyzed by *Wilson et al.* [2003] were made during summertime when the average energy flux of precipitating protons can be as large as 0.43 mW m^{-2} [*Coumans et al.*, 2004]. This means that for moderate mean proton energy ($E_{mean} \approx 5$ keV) the calculated upward flux can be as high as 1.5×10^8 cm^{-2}s^{-1}. From the comparison of the calculated and observed fluxes it follows that an auroral novel source of hot oxygen studied in this paper can make a substantial contribution into the total flux of energetic neutrals. The detailed comparison of the proposed auroral source of hot oxygen with other known sources (exothermic photochemistry, O^+ ion precipitation, O_2 electron impact dissociation, O_2^+ dissociative recombination, and etc...) as well as a study of their variation with latitude and geomagnetic activity will be made in a future paper in preparation.

[18] **Acknowledgments.** J. C. Gérard is supported by the Belgian Fund for Scientific Research (FNRS). This work was also supported by grant RFBR and funded by the Belgian National Fund for Collective Fundamental Research (FRFC grant 2.4517.02) and by the PRODEX programme of the European Space Agency (ESA).

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