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Kinetic modeling of auroral events at solar and extrasolar planets

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Abstract. Auroral events are the prominent manifestation of solar/stellar forcing on planetary atmospheres and are closely related to the energy deposition by and evolution of planetary atmospheres. Observations of auroras are widely used to analyze the composition, structure, and chemistry of the atmosphere under study, as well as charged particle and energy fluxes that affect the atmosphere. Numerical kinetic Monte Carlo models had been developed allowing us to study the processes of precipitation of high-energy electrons, protons and hydrogen atoms into the planetary atmospheres on molecular level of description, taking into account the stochastic nature of collisional scattering at high kinetic energies. Such models are used to study auroras at both magnetized and non-magnetized planets in the Solar and extrasolar planetary systems. The current status of the kinetic model is illustrated in application to the auroral events at Mars.

Keywords. solar system: general, stars:planetary systems, radiation mechanisms: nonthermal

1. Introduction

The interaction of the solar wind with atmospheres of the terrestrial planets played an important role in their atmospheric loss over billions of years of its existence (Ramstad & Barabash 2021). The values of the current losses by Mars, Venus, and Earth are comparable, but for the total mass and composition of the main components for Venus and Earth, the losses caused by the solar wind are insignificant. This is not a case for Mars because of significant difference between Mars and Venus in the processes of interaction of the solar wind with the atmosphere. Mars has an extended exosphere, the outer part of the atmosphere that extends for thousands of kilometers. This is due to the fact that the gravity of Mars is small. In addition, the processes of recombination dissociation of $O_2{}^+$ ions (see, e.g., Groeller et al. 2014) lead to formation of an extended oxygen exosphere. The relatively low gravity and the extended exosphere lead to the fact that kinetic processes on Mars play a major role in the interaction of the solar wind with the planet and in atmospheric processes.

The Sun influences the upper layers of the terrestrial planet atmosphere through both the radiation absorbed in the soft X-ray and extreme UV wavelength ranges and the solar wind plasma forcing, which results in the formation of the extended neutral corona populated by suprathermal (hot) H, C, N, and O atoms (see, e.g., Shematovich & Bisikalo 2021a). For example, one of the important results of the current Mars Atmosphere and Volatile Evolution (MAVEN) mission was that the Imaging UV Spectrograph (IUVS) observations confirmed the presence of the extended corona composed of hydrogen, carbon, and oxygen atoms (Deighan et al. 2015). Such extended corona contains both thermal and hot fractions (see, e.g., Shematovich & Bisikalo 2021a) and, in turn, is changed due to the solar wind plasma inflow and the local fluxes of ions picked up from

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the ionosphere to the planetary exosphere. This inflow leads to the formation of superthermal atoms (energetic neutral atoms – ENAs) escaping from the neutral atmosphere of Mars because of the charge exchange with precipitating high-energy ions.

Proton auroral events are indicators of enhanced solar activity and are accompanied by rather intense losses of neutrals from the upper atmospheres of the terrestrial planets. Proton auroras at the Earth were first observed in the polar atmosphere by the Doppler shift of spectral hydrogen lines H-β and H-α. These auroras are strongly controlled by our planet's magnetosphere: protons penetrate the atmosphere along the terrestrial magnetic field lines and lose their initial energy near the magnetic poles, where the proton auroras are observed (Frey et al. 2003). Proton auroras are among a few observable Martian phenomena which result from direct interaction of solar wind protons with an extended hydrogen corona. Studying Martian proton auroras can also supply an additional understanding of the evolution and loss of the atmosphere, since the processes responsible for the formation of Martian auroral events (for example, interactions between the solar wind and the extended hydrogen corona) are also responsible for the loss of the neutral atmosphere (Shematovich 2021). There were attempts to estimate the contribution of atmospheric sputtering during proton auroral events at Mars to the atomic oxygen loss rate (see, e.g., Shematovich 2021, and references therein). These attempts have a particular importance, because this process was ignored in the recent analysis of the atmospheric loss of Mars based on the MAVEN data (Jakosky et al. 2018).

Proton auroras were recently discovered in observations of the enhanced Ly-α emission of atomic hydrogen in the dayside atmosphere of Mars (Deighan et al. 2018; Hughes et al. 2019) and they are induced by the fluxes of high-energy hydrogen atoms (ENA-Hs) penetrating into the atmosphere (Deighan et al. 2018). We use a set of the kinetic Monte Carlo (kMC) models (Shematovich et al. 2019, 2021; Shematovich 2021) to calculate the the energy deposition rates by neutral atmosphere and source functions of suprathermal hydrogen and oxygen atoms formed in the precipitation processes. For example, kMC1 model (Shematovich et al. 2021) makes it possible to analyze the charge-exchange process for solar-wind protons in the extended hydrogen corona of Mars and to obtain the spectra of hydrogen atoms penetrating into the atmosphere through the boundary of the induced magnetosphere of Mars. The calculated spectra and fluxes of ENA-Hs are strongly non-equilibrium and were used as an upper boundary condition for the kMC2 model (Shematovich et al. 2019) of precipitation of energetic hydrogen atoms into the upper atmosphere allowing us to calculate the characteristics (Shematovich & Bisikalo 2021b) of proton auroral events at Mars. Specifically, we obtain the formation rate and energy spectra of suprathermal hydrogen and oxygen atoms produced in elastic and inelastic collisions between atmospheric hydrogen and oxygen atoms and ENA-Hs penetrated into the atmosphere. And, finally, these formation rates of suprathermal hydrogen and oxygen atoms are used as a source function in the kMC3 model (Shematovich 2021) aimed to study the kinetics and transport of suprathermal hydrogen and oxygen atoms in the upper atmosphere, which results in the formation of extended hot atomic coronas of the terrestrial planet.

In this paper, we present a set of the MC kinetic models that describe the influence of the proton flux of the undisturbed solar wind on the upper atmosphere of the terrestrial planet in the Solar and extrasolar planetary systems. With this set, the the change of the solar-wind proton spectrum due to the cascade charge-exchange process in the extended hydrogen corona of Mars has been modeled to obtain the energy fluxes and energy spectra of hydrogen atoms penetrating into the daytime upper atmosphere through the boundary of the induced magnetosphere. These characteristics make it possible to estimate the parameters of proton auroral events observed in the upper atmosphere of the teresstrial

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planet, and for Mars to validate the models by comparison of kinetic calculations with observations by the IUVS instrument onboard the MAVEN spacecraft.

2. Results of the kinetic modeling of auroral events

The process of proton aurora formation at Mars is markedly different from the scenario for Earth. The exosphere (or corona) of Mars is mostly populated by atomic and molecular hydrogen and extends over several Martian radii. The absence of a global internal magnetic field on Mars allows the solar wind to interact with the hydrogen corona on the illuminated hemisphere of Mars, starting from the bow shock region and flowing around the planet along the boundary of the induced magnetosphere (IMB). The source of proton auroras at Mars is a flux of energetic neutral hydrogen atoms that enter the atmosphere through the IMB and participate in collisions with neutral particles in the lower atmosphere. It is known that the instruments onboard the MAVEN spacecraft do not have the ability to measure the energy spectra of neutral particles, so a kinetic model is required to calculate both the ENA-H flux and its energy spectrum. We present the kinetic calculations of the ENA-H flux penetration, which is formed due to the charge exchange between solar-wind protons and thermal hydrogen atoms in the extended hydrogen corona of Mars, into the planetary upper atmosphere. The estimates of the energy flux and the energy spectra of hydrogen atoms and protons, which are formed due to the charge exchange in the Martian upper atmosphere, have been obtained. The calculation results of the auroral event parameters are presented for the basic case, within which the boundary of the induced magnetosphere is at an altitude of 820 km. The calculations were performed for a basic case (M1), with the profiles of the temperature and the number density of the main components (CO_2 and O) of the upper atmosphere corresponding to a low level of solar activity. The distribution of hydrogen atoms in the extended corona of Mars was specified by the Chamberlain model for a planetary exosphere, the parameters of which were chosen as follows: the exobase height is $h_{exo} = 200$ km, at which the temperature is $T(h_{exo}) = 179$ K and the number density of hydrogen atoms is $n_H(h_{exo}) = 1.48 \times 10^6$ cm^{-3} according to the results of Chaffin et al. (2018). Then, as a boundary condition for the kMC1 model at an altitude of 3000 km, we used the energy flux and the energy spectrum of protons of the undisturbed solar wind measured with the SWIA/MAVEN instrument for the orbit on February 27, 2015 (Halekas et al. 2015). The calculated spectra of hydrogen atoms were assumed to be an upper boundary condition in the kMC2 model (Shematovich et al. 2019) for the precipitation of high-energy hydrogen atoms into the daytime upper atmosphere through the induced magnetosphere boundary (IMB). Observations onboard the MEX and MAVEN spacecraft resulted in detecting significant variations of the atomic hydrogen content in the corona of Mars (Chaffin et al. 2018; Girazian & Halekas 2021). These variations induce changes in the efficiency of the charge exchange between protons of the undisturbed solar wind and hydrogen atoms in the corona (Shematovich et al. 2021). Consequently, analogous calculations were performed for the case, within which the variation in the column density of hydrogen in the corona of Mars was taken into account (case M2). Namely, under the same exobase parameters, the number density of hydrogen atoms $n_H(h_{exo})$ increased twofold at the exobase level, which corresponds to the position of the IMB at an altitude of 1260 km (for details, see Shematovich et al. 2021). In case M2, the charge-exchange efficiency approaches a value of 6%, i.e., the energy flux of ENA-Hs penetrating into the upper atmosphere is 1.5 times higher than the corresponding value in case M1. The calculations were made for the solar zenith angle equal to zero.

The fluxes and energy spectra of high-energy hydrogen atoms and protons, which were obtained with the kinetic Monte Carlo model, allow us to calculate all of the necessary parameters of proton auroral phenomena in the upper atmosphere of Mars. For example,

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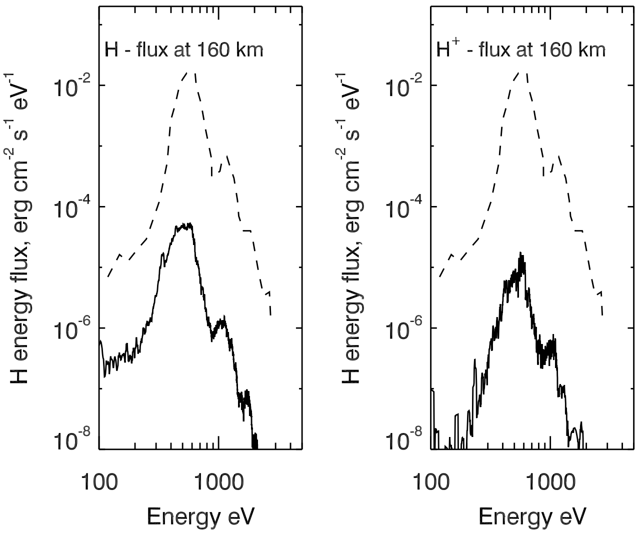

Figure 1. The energy spectrum of downward fluxes of ENA-H (left panel) and protons (right panel) at height of 160 km, at which the peak of energy deposition of ENA-H flux is usually found. Dashed line – the energy spectrum of protons of the undisturbed solar wind measured with the SWIA/MAVEN instrument for the orbit on February 27, 2015 (Halekas et al. 2015), which was taken as the upper boundary condition of kMC1 model.

in Fig. 1, we show the energy spectrum of downward fluxes of ENA-H (left panel) and protons (right panel) at height of 160 km, at which the peak of energy deposition of ENA-H flux is usually found. It is seen that both spectra still keep the form and structure of the energy spectrum of protons of the undisturbed solar wind shown by dashed line. These spectra were calculated for the case M1with the IMB at 820 km of the precipitation of high-energy hydrogen atoms ENA-Hs penetrating into the Martian atmosphere through the IMB calculated for cases M1 (red line) and M2 (brown line). Such energy distributions of the ENA-H flux allow us to calculate the H Ly-α excitation rates and in conjunction with the radiative transfer model to estimate the excess in the H Ly-α emission during a proton auroral event in the Martian atmosphere (Gerard et al. 2019).

An additional source of hot oxygen atoms - collisions with the momentum and energy transfer from the flux of precipitating ENA-H particles with high kinetic energies to atomic oxygen in the upper atmosphere of Mars - is included in the Boltzmann kinetic equation, the solution of which was obtained using the kMC3 model (Shematovich 2021). This allows us to determine self-consistently the sources of suprathermal oxygen atoms, as well as their kinetics and transport, and to estimate the population of the hot oxygen corona of Mars and the atmospheric losses of atomic oxygen during proton auroral events. We derived the kinetic-energy distribution functions for suprathermal oxygen atoms in the thermosphere-to-exosphere transition region of the penetration of undisturbed solar-wind protons into the illuminated atmosphere of Mars due to the charge exchange in the extended hydrogen corona (Shematovich et al. 2021). It has been found that the exosphere is inhabited by a significant number of suprathermal oxygen atoms with kinetic energies up to the escape energy of 2 eV, i.e., the hot oxygen corona (Fig. 2) of Mars forms due to the interaction with solar wind. It is seen that height scale for hot oxygen distribution for cases M1 (red line) and M2 (brown line) is larger than the one (black line) for thermal O atoms, therefore hot O corona extends into the upper regions of the Martian corona and should be taken into account in the consideration of the solar wind interaction with upper atmosphere of Mars. The values of (3.5 - 5.8)$\times 10^7$ cm^{-2}s^{-1} of the loss rate for

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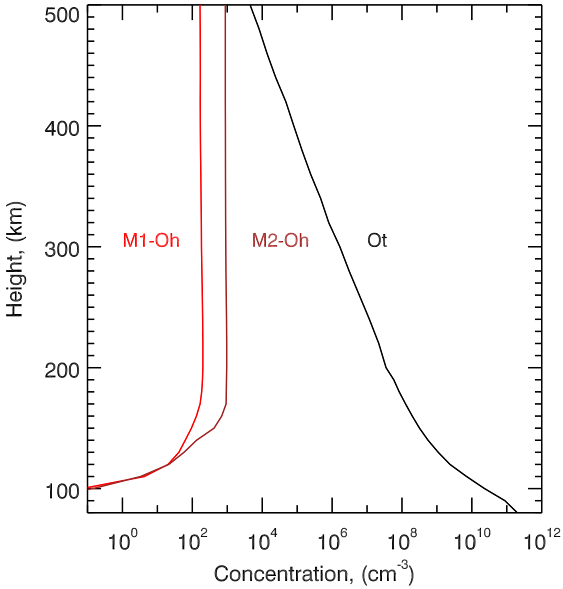

Figure 2. Height profiles of suprathermal oxygen concentration in the upper atmosphere during proton auroral events at Mars. O_h indicates the calculated height distribution of hot O atoms, and O_t – of thermal O atoms in the upper atmosphere of Mars.

oxygen atoms from the Martian atmosphere during proton auroral events on Mars were obtained in self-consistent calculations and are comparable to the oxygen loss rate of $(1.5 - 3.5)\times10^7$ $cm^{-2}s^{-1}$ due to the exothermic photochemistry (Groeller et al. 2014; Jakosky et al. 2018). Though proton auroras are sporadic events, the kinetic calculations showed that the precipitation-induced flux of escaping hot oxygen atoms may become dominant under conditions of extreme solar events: solar flares and coronal mass ejections (Deighan et al. 2015; Jakosky et al. 2018; Shematovich et al. 2021). The analysis of the atomic oxygen loss due to atmospheric sputtering during proton aurorae on Mars should be taken into account especially when studying the climate evolution of the planet on geological time scales.

3. Conclusions

We have developed a set of kinetic Monte Carlo models, which could be considered as a discovery tool to investigate the auroral events caused by the precipitation processes of high-energy charged and neutral particles from the solar/stellar wind into the upper atmospheres of terrestrial planets in the Solar and extrasolar systems. This set of kinetic MC models was used to study and interprete the recently discovered discrete, diffuse and proton auroras at Mars observed and measured by the Mars Express, MAVEN spacecraft. Such application allowed us to evaluate both the characteristics of the precipitating high-energy particles from the solar wind plasma, and the space distribution and brightness of ultraviolet and optical emissions in the auroras induced by the precipitation processes. Estimates of the neutral atmosphere loss due to the forcing of solar wind plasma onto the upper atmosphere of Mars were also obtained. By studying auroral events we can better understand the relations between energy fluxes coming from the Sun/host star, the extended hydrogen corona, and the circumplanetary plasma environment. In addition, the appearance and the intensity of proton polar auroras can indirectly indicate the changes occurring in the dynamics of underlying atmospheric layers such as the neutral atmosphere chemical composition and the input of the dust activity. These kinetic models

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would be used in the studies of the stellar wind forcing on the upper atmospheres of terrestrial type planets orbiting other stars (Savanov & Shematovich 2021).

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