Atmospheric Loss for Hot Exoplanets

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Abstract. Photolysis and radiolysis of the atmospheres of hot exoplanets by stellar UV radiation and stellar wind plasma leads to the formation of suprathermal particles, which are important drivers of thermal and non-thermal processes of atmospheric loss by hot exoplanets. To study this problem, a set of Monte Carlo kinetic models was developed to consider the detailed kinetics of formation, transport, and relaxation of suprathermal particles in the atmospheres of hot exoplanets. In particular, it allows us to calculate the atmospheric loss rate for exoplanets in orbits close to the parent star and, accordingly, to estimate what fraction of the primary H_2-He envelopes can be preserved at the early stages of the evolution of the residual disk. An overview of the current research results on the problem of atmospheric loss by hot exoplanets is provided. Using as an example of a hot exoplanet, the hot Neptune GJ 436b exoplanet, the theoretical estimates of the atmospheric loss rate due to both thermal and non-thermal processes are presented and compared with the results of other authors and with data from recent ground and space observations. These estimates provide important knowledge about the physical state of the planetary atmospheres under study, and atmospheric loss rates for them.

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1 Introduction

The discovery of hot exoplanets, i.e., hydrogen- and volatile-rich exoplanets located at orbital distances ≤ 0.1 AU, raises important questions concerning the structure of the upper atmosphere and their resistance to escape into open space (loss) of atmospheric gases. Since more than 40% of all detected exoplanets orbit their parent stars at distances closer than the orbit of Mercury in the Solar system, the atmospheres of these celestial bodies evolve under much more extreme conditions than those known for the planets of our Solar system. More intense stellar radiation fluxes in the ranges of soft X-rays (1–10 nm) and extreme ultraviolet (EUV, 10–100 nm), the so-called hard stellar radiation (XUV) in the wavelength range of 1–100 nm, at such close orbital distances will significantly change the structure and composition of the upper atmospheric layers of these objects (Massol et al. 2016; Owen 2019) and, in particular, lead to the formation of extended gas envelopes of hot exoplanets (see, for example, Bisikalo & Shematovich 2020).

Observations on the Hubble space telescope (HST) (Kulow et al. 2014; Ehrenreich et al. 2015; Lavie et al. 2017) showed that the warm Neptune Gliese 436b has an extended gas envelope comparable to the disk of the parent star. Two independent series of transit observations using COS/HST showed $\sim$50% absorption in the Lyα line. In addition to the extended tail, hydrogen absorption also shows early ingress, i.e. the presence of a dense cloud extending in front of the planet at a distance comparable to the size of the star's disk. The theoretical study of the upper atmospheres of hot exoplanets was developed on the basis of both hydrodynamic and kinetic description.

Photolysis of the hydrogen-rich atmosphere of a hot exoplanet by the extreme radiation from the parent star leads to the local heating of its atmosphere and to the formation of supratermal particles (i.e., particles with an excess of kinetic energy)—primary photoelectrons due to the photoionization of the main components H_2/H/He and supratermal hydrogen atoms in the dissociation and dissociative ionization of H_2 (Shematovich 2010). These particles with excess kinetic energy are an important source of thermal energy in the upper atmosphere of a hydrogen-rich exoplanet. The study of the role of suprathermal particles in modern aeronomic models of planetary atmospheres is a complex computational task, since it requires solving the Boltzmann equation for a nonthermal population of suprathermal particles (Shematovich & Marov 2018; Shematovich 2019). The paper assesses the effect of the stellar XUV radiation on the atmosphere heating and the formation of suprathermal hydrogen atoms in the $H_2 \rightarrow$H transition region in the upper layers of the hydrogen-rich atmosphere of GJ 436b.

2 Thermal Atmospheric Loss

Because of the proximity of hot exoplanets to the host star, their atmosphere is affected by intense plasma and radiation fluxes. The latter heat the upper atmosphere to high temperatures, change significantly its chemical composition, and affect strongly the character of the planet evolution via high escape fluxes hydrogen from the atmosphere. In the one of the first papers (Lammer et al. 2003), it was shown that extreme stellar XUV radiation penetrating the hydrogen-rich thermosphere should lead to a gas-dynamic outflow. Accordingly, in the first gas-dynamic models of Gliese 436b (Loyd et al. 2017; Berezutsky et al. 2019), it was found that the thermosphere of this exoplanet is relatively cold ($\leq$ 5000 K), and the outflow is supersonic and does not exceed the speed of 10 km/s. Numerical simulations using gas-dynamic models show that the exoplanet Gliese 436b must be surrounded by a extended, relatively cold, dense partially ionized gas envelope with the presence of molecular hydrogen, covering the entire disk of the star. Current gas-dynamic models (Loyd et al. 2017; Berezutsky et al. 2019) provide the thermal mass-loss rate in the range of $(2.5–5.0)\times10^8–3.0\text{-}5.0)\times10^9$ g s^{-1}, which today is far too small to deplete the atmosphere of a Neptune-like planet in the lifetime of the parent star, but would have been much greater in the past. For example, the results obtained in a self-consistent gas-dynamic 2D model (Berezutsky et al. 2019), in which the processes of radiation heating and ionization and hydrogen photochemistry were taken into account, agree well with the results of one-dimensional aeronomic model (Loyd et al. 2017). Both models provide the thermal atmospheric loss rate with values in the range of $(3.\text{-}5.)\times10^9$ g s^{-1}. The calculated peak temperatures approach values between 4000 and 5000 K at distances below 1.9R$_p$, and the H_2 half-dissociation point was located at 1.35R$_p$. It is necessary to point out that both gas-dynamic models do not consider in detail the input of the fresh photoelectrons, which could be important in the calculations of the atmospheric gas heating rate (Ionov et al. 2018) resulting in the lower thermospheric temperatures. These studies require further comparison of the rates of both thermal and non-thermal atmospheric loss (Massol et al. 2016; Owen 2019).

3 Non-Thermal Atmospheric Loss

The excess thermal energy of the hydrogen atoms formed as a result of dissociation of molecular hydrogen is found from calculated and experimental distributions. They contain a fraction of relatively slow hydrogen atoms with kinetic energies of 0–1 eV with the peak near the thermal energy and a fraction of fast hydrogen atoms with kinetic energies of 1–10 eV with the peak near 4 eV. In the case of suprathermal hydrogen atoms, the efficiency of energy transfer from hot to thermal atoms and hydrogen molecules in elastic collisions is determined by the phase functions – scattering angle distributions. As follows from the experimental and calculation data, phase functions are generally characterized by the presence of peaks in the range of small scattering angles at relatively large elastic-scattering cross sections. Correspondingly, the, energy transfer efficiency depends strongly on the collision energy. These specific features of the formation of suprathermal hydrogen atoms and their elastic scattering on the thermal components of H_2, He, and H determine the input of the suprathermal hydrogen fraction into the heating and loss of the upper atmosphere of hot exoplanet.

The developed kinetic Monte Carlo model (Shematovich 2010) takes into account that the hydrogen atoms are formed with an excess kinetic energy; therefore, their distribution in the H2→H transition region of exoplanet's upper atmosphere is determined by solving the kinetic Boltzmann equation with a photochemical source of suprathermal hydrogen atoms. The model calculates the production rate and energy spectrum of hydrogen atoms that are formed with an excess of kinetic energy during H_2 dissociation. Then, a stochastic model of a hot planetary corona (Shematovich 2010) is used to study the kinetics and transport of superthermal hydrogen atoms in the extended upper atmosphere and to calculate the rate of mass loss in the atmosphere. Calculations were performed in the transition H_2 →H region of the extended upper atmosphere of GJ 436b in the altitude range (1.3-2.0)R_p, where the maximum absorption of stellar XUV radiation is observed. Calculations are performed for stationary conditions in the daytime upper atmosphere in the planet-star direction. Figure 1 shows the calculated energy spectra of the upward fluxes for the suprathermal hydrogen atoms at altitudes of 1.5R_p (upper panel), 1.66R_p (middle panel), and 1.84R_p (lower panel). The blue lines show the energy spectra of upward fluxes calculated with the locally equilibrium distributions of atomic hydrogen in accordance with the temperature profile from the model (Berezutsky et al. 2019). Vertical red lines show the escape energies of hydrogen atoms at the given heights. The calculated energy spectra shown in Figure 1 are presented only in the region of superthermal energies above 1 eV. It follows from the calculations that the energy spectra of the upward flux of superthermal hydrogen atoms are significantly nonequilibrium in comparison with locally equilibrium distributions, forming the high-energy tails in the energy spectra. At altitudes near 1.5R_p and below, where the production of hydrogen atoms in the H_2 dissociation process is close to the maximum values, a significant fraction of hydrogen atoms with energies above the escape energy is already formed. At a height of 1.84R_p, close to the upper limit of the H_2 →H transition region, the values of the calculated fluxes significantly exceed the values of locally equilibrium ones for kinetic energies higher than 4 eV, and, therefore, the hot hydrogen fraction input in to the atmospheric loss becomes very important. The non-thermal escape flux of H atoms in the direction exoplanet-star is estimated to be 3.0×10^{12} cm^{-2} s^{-1} for a moderate level of stellar activity in the considered range of XUV radiation. It exceeds the value 1.78×10^{12} cm^{-2} s^{-1} of the thermal escape flux of atomic hydrogen calculated with the Jeans formula for the local Maxwellian distribution (shown by blue line in the bottom panel of Figure 1). If we average the calculated flux over the illuminated hemisphere of the upper atmosphere, the upper estimate of

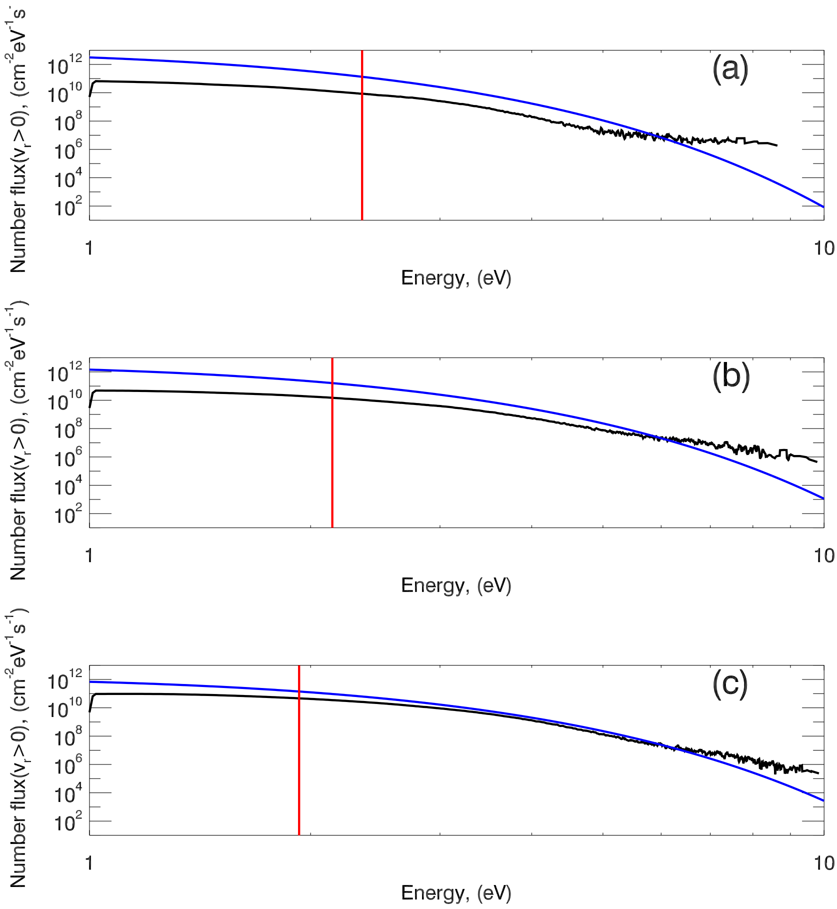

Fig. 1. Calculated energy spectra of the upward fluxes for the suprathermal hydrogen atoms at altitudes of $1.5R_p$ (upper panel), $1.65R_p$ (middle panel), and $1.84R_p$ (lower panel). The blue lines show the energy spectra of the upward fluxes calculated with the locally equilibrium distributions of atomic hydrogen in accordance with the temperature profile from the model (Berezutsky et al. 2019). Vertical red lines show the escape energies of hydrogen atoms at the given heights.

atmospheric loss rate due to H_2 dissociation processes is 7.8×10^8 g s^{-1}, which is close to the upper limit of the estimates of the possible of atmospheric loss rate obtained from observations in the range (3.7×10^6–1.1×10^9) g s^{-1} (Kulow et al. 2014; Ehrenreich et al. 2015). It could be mentioned that the calculated value of the H escape flux for the exoplanet GJ 436b can be considered as a safe estimate because the calculations had been performed for a moderate stellar activity in the UV emission and the minimum value of 0.1 for the predissociation probabilities of excited electronic levels of H_2 molecule was used. Naturally, in conditions of high stellar UV radiation the contribution in to the formation of the non-thermal H escaping flux of the H_2 dissociation processes by the stellar XUV and the acompanying flux of photoelectrons will become more significant.

4 Conclusions

Observations are most actively accumulated and theoretical models are being developed for hot exoplanets that are located in orbits close to the parent star and, consequently, their atmospheres are exposed to extreme flows of extreme ultraviolet radiation from the parent star. An overview of the current research results on the problem of atmospheric loss by hot exoplanets was given in the paper. Using as an example of a hot exoplanet, the hot Neptune GJ 436b exoplanet, the theoretical estimates of the atmospheric loss rate due to both thermal and non-thermal processes were discussed and compared with the results of other authors and with data from recent ground and space observations. These estimates indicate that the aeronomic models of hot exoplanets should include both thermal and non-thermal processes such as the exothermic photochemistry and the atmosphere forcing by the stellar wind.

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