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Neutral atmospheric escape in the Solar and extrasolar planetary systems

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Abstract. New data obtained by space missions to various objects in the Solar system and observations of the outer Solar system and exoplanets by space and ground-based telescopes allowed us to conclude that the atmospheric escape plays an important role in the evolution of the terrestrial planets in the Solar system. We present the recent results of application of the kinetic approach to the problem of neutral escape from planetary atmospheres. As an example, the recent measurements by Mars Express and MAVEN spacecraft are compared with the calculations of neutral escape with the aim to understand the atmospheric loss at Mars. Also the recent calculations of the mass-loss rates of the hot Neptune and Jupiter atmospheres are presented.

Keywords. stars: flare, planets and satellites: formation, ultraviolet: solar system, etc.

1. Introduction

Studies of the evolution of atmospheres of Solar System planets and planetary systems of other stars have significantly advanced during recent decades. Progress has been achieved owing to unique measurement data obtained by spacecraft during their flights to different objects in the Solar System, observations of the outer bodies of the Solar system and exoplanets using space and ground-based telescopes, and the development of mathematical simulation methods. These results have shaped a new basis for the physics of the upper atmosphere, i.e., the aeronomy that is directly linked to planetary cosmogony. In particular, they have allowed to infer a conclusion that dissipation of a planetary atmosphere (or atmospheric escape) plays an important role in the evolution of planets primarily of terrestrial planets of the Solar System, although many details of those events are not fully clear and remain the topic of active discussions (Shematovich & Marov 2018). Observations and theoretical models of the exoplanet atmospheres exposed to the extreme fluxes of X-ray and UV radiation of the parent star provide a remarkable opportunity to test theoretical understanding of the key processes - thermal and non-thermal escape. Such improved models of the neutral escape will lead to a better understanding of the paleoclimate and the evolution of the of primary and secondary atmospheres of terrestrial planets (Massol *et al.* 2016). It is known, that a prediction of escape rates due to thermal and non-thermal processes defines the long-term evolution of planetary atmospheres, therefore atmospheric escape has long been a subject of interest in the comparative planetology, and in recent years especially in understanding of the evolution of exoplanet atmospheres.

2. Neutral Oxygen Loss at Mars

The Martian thermosphere, exosphere, and ionosphere form the tenuous upper boundary - hot planetary corona the region through which all energy and matter from the Sun that encounters Mars must either pass or be deflected. The Martian neutral corona, ionosphere, and crustal magnetic fields interact directly with the incident solar wind plasma, forming a highly dynamic induced magnetosphere that influences the structure and variability of the upper atmosphere, and results in a rich array of plasma processes. Further, the energy input to the atmosphere from the Sun and solar wind energizes atmospheric particles, giving some of them sufficient energy to escape the planet. The close proximity of the solar wind to the Martian ionosphere, as well as the considerable extent of the exosphere relative to the size of the planet, leads to a number of atmospheric escape processes for both neutral and ionized particles. Neutral particles may have sufficient energy to escape on their own by virtue of their thermal distribution (Jeans escape), may receive the energy necessary to escape from solar radiation and subsequent chemical reactions (photochemical escape), or may receive the energy to escape from collisions with particles entering the atmosphere from above (e.g. by sputtering and/or precipitation). Escape rates of neutral particles have been indirectly estimated using a combination of measurements of the atmospheric reservoirs for escape and models (Shematovich & Marov 2018, Jakosky *et al.* 2018). The total atmospheric escape from both ions and neutrals varies with the same drivers observed to modify the solar wind interaction region. This variation can be extrapolated to estimate the total atmospheric loss over Martian history using scaling arguments, or by tuning simulations to match the present-day variation (Jakosky *et al.* 2018).

Neutral O escaping flux due to the photochemistry is about $(0.5 - 1.0)\times10^7$ cm^{-2}s^{-1} depending on the solar activity level (Shematovich & Marov 2018, Jakosky *et al.* 2018). Recently the neutral O escaping flux due to the H^+ and H precipitation was estimated by the values about $(0.7 - 30.0)\times10^5$ cm^{-2}s^{-1} (Shematovich 2017) when the energy spectra of the precipitating protons measured by MEX ASPERA-3 instrument at low solar activity level were used as the inputs at upper boundary. We apply the updated kinetic Monte Carlo model of the proton and hydrogen atom precipitation into the Martian upper atmosphere (Bisikalo *et al.* 2018) to estimate the atmospheric escape of hot oxygen atoms induced by precipitation. As the input at model upper boundary placed at 500 km the energy spectra of penetrating into the atmosphere high-energy particles measured by MAVEN SWIA instrument (Halekas *et al.* 2015) we used. It was found that O escaping flux is changing in the range $(1.7 - 0.8)\times10^7$ cm^{-2}s^{-1} for the MAVEN SWIA spectra of the precipitating protons from magnetosheath (Case 1 in Fig. 1) and hydrogen atoms from the undisturbed solar wind (Case 2 in Fig. 1) respectively. It is seen, that the neutral oxygen escape due to the H^+ and H precipitation can be competitive with the photochemical escape for the extreme solar events.

3. Atmospheric Mass Loss at Hot Neptunes and Jupiters

Observations of exoplanets using ground-based and space telescopes operating in the IR and UV wave ranges enable obtaining first estimates of such very important atmospheric characteristics as the composition and thermal state. Currently, the formation, stability, and evolution of the atmospheres of exoplanets are under active exploration using both observations with ground-based and space telescopes and mathematical simulation. A number of important results regarding the nature of the exoplanets have been obtained, and unique specific features were discovered in the planetary systems of single and binary stars that contain bodies substantially different from Solar System planets such as hot Neptunes and Jupiters, i.e., giant planets in close-in orbits around their host stars. To investigate the atmospheric mass-loss rate for such exoplanets we had developed the aeronomic model (Ionov, Pavlyuchenkov & Shematovich 2018). This one-dimensional aeronomic model of the upper atmosphere of the giant planet was applied to study the reaction of the atmosphere of a hot Jupiter HD 209458b to an additional heating caused

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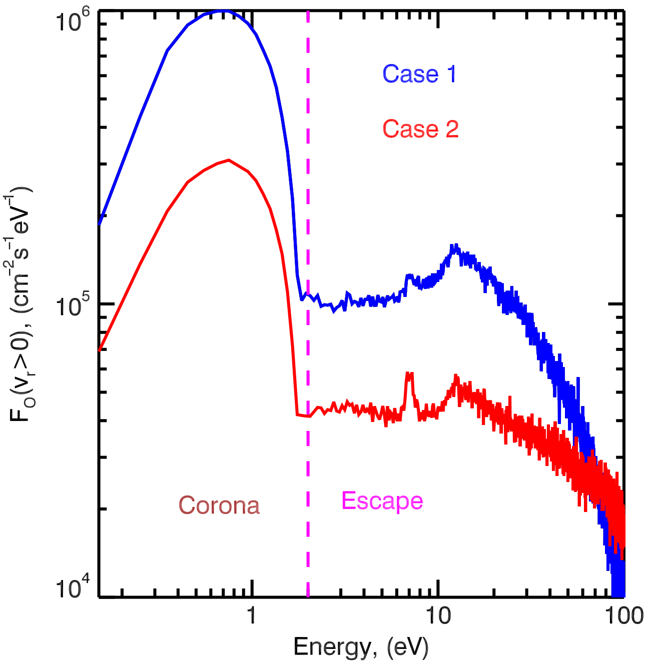

Figure 1. Energy distribution functions of the upward moving hot O atoms at height 300 km were calculated using the kinetic Monte Carlo model of the interaction of energetic H^+ and H particles with the upper atmosphere of Mars. The MAVEN SWIA measurements of proton spectra in the magnetosheath and in the undisturbed solar wind were used as the inputs to the model.

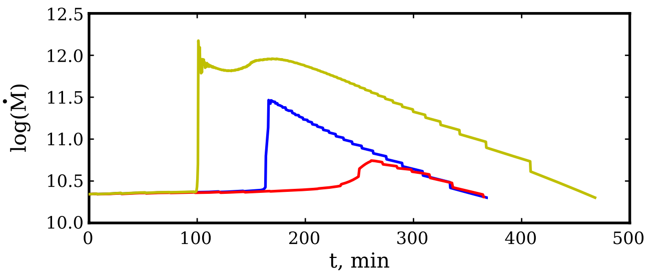

Figure 2. Time evolution of the mass-loss rates (in g s^{-1}) obtained at the exobase for the atmosphere of a hot Jupiter like HD 209458b during the three considered superflares. The red, blue, and green lines correspond to the mass-loss rates obtained considering flares emitting an XUV flux of 10, 100, and 1000 times that of the quiet star, respectively.

by the forcing of a stellar flare. It was found that the absorption of additional energy of the stellar flare in the extreme ultraviolet leads to the local heating of the atmosphere, accompanied by formation of two shock waves, propagating in the upper atmosphere (Bisikalo *et al.* 2018). The development of shock waves significantly affects atmospheric loss. We present this in Fig. 2, which shows the mass-loss rates at the exobase as a function of time for three considered superflares. For the case of the quiet star, we find a mass-loss rate of 2×10^{10} g s^{-1} in the spherical symmetry approach, which increases by 1.9, 4, and 17.5 times during a flare emitting an XUV flux that is 10, 100, and 1000 times that of the quiet star, respectively. Since the excess mass loss occurs for 130, 210, and 380 minutes, the additional atmospheric loss corresponds to 3×10^{14}, 1×10^{15}, and 8×10^{15} g for the three considered flares, respectively.

Depending on the frequencies of the flares the total mass loss from the atmosphere might therefore significantly increase. For old solar-type stars, taking into account that flares emitting an XUV flux 10, 100, and 1000 times that of the quiet star are believed to happen approximately 1, 0.1, and 0.001 times per year, the effect of flares on the evolution of planetary atmospheres of hot Jupiters can be considered to be negligible. However, the impact of flares may be more pronounced for younger systems. The local effect of the flare can be significant and change the gas dynamic structure of the whole envelope.

4. Conclusion

Studies of extrasolar planets make an immense contribution to explaining dissipation of planet atmospheres and, primarily, terrestrial planets in the early Solar System and thus offering an approach to the reconstruction of their formation history. We can expect that the expansion of the research area far beyond the Solar System and further improvement in mathematical models developed on the basis of exoplanet aeronomy will facilitate better understanding of evolution processes and key problems of planetary cosmogony. We acknowledge the support by Russian Science Foundation (Project 18-12-00447).

References

Bisikalo, D. V., Shematovich, V. I., Gerard, J.-C., & Hubert B. 2018, *J. Geophys. Res.*, 123, 5850

Bisikalo, D. V., Cherenkov, A. A., Shematovich, V. I., *et al.*, 2018, *Astron. Rep.*, 62, 648

Halekas, J. S., Lillis, R. J., Mitchell, D. L., *et al.*, 2015, *Geophys. Res. Lett.*, 42, 8901

Ionov, D. E., Pavlyuchenkov, Y. N., & Shematovich, V. I. 2018, *MNRAS*, 476, 5639

Jakosky, B. M., Brain, D., Chaffin, M., *et al.*, 2018, *Icarus*, 315, 146

Massol, H., Hamano, K., Tian, F., *et al.*, 2016, *Space Sci. Reviews*, 205, 153

Shematovich, V. I., 2017, *Sol. Syst. Res.*, 51, 249

Shematovich, V. I., & Marov, M. Ya. 2018, *Physics - Uspekhi*, 61, 217

Discussion

Kedziora-Chudczer: Does your model take into account the evolution of the Sun?

Bisikalo: Not exactly, but we can simulate the aeronomic profiles as a function of the stellar flux which corresponds to the evolution.

Kedziora-Chudczer: How is the atmospheric escape for terrestrial planets modified by the early Sun's lower flux?

Bisikalo: It is a complicated question, because the atmosphere is also changed with age, so I can't give a simple answer.

Khaibrakhmanov: Could you comment on the role of planetary magnetospheres on the mass loss from exoplanet atmospheres?

Bisikalo: Magnetic fields play a significant role in mass loss. Both the internal magnetic field and induced magnetic field prevent the planetary atmosphere from the penetration of solar wind plasma and reduce the mass loss.

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