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Conservation of total escape from hydrodynamic planetary atmospheres

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ABSTRACT

Atmosphere escape is one key process controlling the evolution of planets. However, estimating the escape rate in any detail is difficult because there are many physical processes contributing to the total escape rate. Here we show that as a result of energy conservation the total escape rate from hydrodynamic planetary atmospheres where the outflow remains subsonic is nearly constant under the same stellar XUV photon flux when increasing the escape efficiency from the exobase level, consistent with the energy-limited escape approximation. Thus the estimate of atmospheric escape in a planet's evolution history can be greatly simplified.

1. Introduction

Recently it is proposed that a high hydrogen content (at least a few percent) in early Earth's atmosphere could be important to keep early Earth warm, contributing to the solution of the faint young Sun problem (Wordsworth and Pierrehumbert, 2013). A hydrogen rich early Earth atmosphere has been proposed based on hydrodynamic calculations of hydrogen escape and such an atmosphere could have been important for prebiotic photochemistry (Tian et al., 2005a). The numerical scheme in Tian et al. (2005a) contains large numerical diffusion especially near the lower boundary where the density gradient is the largest (Tian et al., 2005b). However, the calculated upper atmosphere structures are consistent with transit observations of hot Jupiter HD209458b (Vidal-Madjar et al., 2003) and the calculated escape rates are consistent with follow-up independent works (Yelle, 2006; García-Muñoz, 2007; Penz et al., 2008; Koskinen et al., 2013). On the other hand, it is suggested that nonthermal escape processes could have increased total hydrogen escape (Catling, 2006) so that the hydrogen content in early Earth atmosphere would have been in the order of 0.1% instead of a few percent or greater. But no calculation has been carried out to estimate the nonthermal hydrogen escape rate from early Earth's atmosphere.

Lammer et al. (2007) showed that planets in the habitable zones of M dwarfs should experience frequent exposure to stellar corona mass ejection events and as a result Earth-like planets in such environments could have lost hundreds of bars of CO_2 in the timescale of 1 Gyrs through stellar wind interactions. But the energy consumed in such massive atmospheric loss is not considered. Tian (2009) showed that CO_2-dominant atmospheres of super Earths with masses greater than 6 Earth masses should survive the long active phase of M dwarfs. But nonthermal escape processes were not included.

Observed close-in exoplanets with masses in the range between Earth and Uranus/Neptune, such as Corot-7B (Leger et al., 2009), GJ1214b (Charbonneau et al., 2009), 55 Cnc e (Winn et al., 2011), and several Kepler-11 planets (Lissauer et al., 2011), have inferred densities much different from each other. Considering the small orbital distances between these planets and their parent stars, these planetary atmospheres must be highly expanded and atmospheric escape must be an important physical process controlling the evolution histories and the nature of these objects. A better understanding of the relationship between different atmospheric escape processes and how upper atmosphere structure influences atmospheric escape is urgently needed.

One classical theory on atmospheric escape is the diffusion-limited escape (Hunten, 1973), which provides an upper limit for the total escape rate of minor species. In the case of hydrogen, its escape rate should be proportional to the total mixing ratio of hydrogen-bearing species at the homopause level. The diffusion-limited escape theory is the result of the kinetics at the homopause level and does not consider the energy aspect of atmospheric escape.

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When a planetary atmosphere is exposed to intense stellar XUV photon flux, which occurs on terrestrial planets during their early evolution histories, close-in exoplanets, and small dwarf planets such as present Pluto, the upper atmosphere is heated and temperature rises and the atmosphere expands. For this scenario to occur, thermal conduction through the lower boundary must be less than the net heating. When the atmosphere expands to large distance, the gravity of the planet at the exobase, the top of the atmosphere, becomes weak enough and major atmospheric species escape more efficiently through either thermal or nonthermal processes. When the escape of major atmospheric species is efficient, the upper atmosphere flows outward and the adiabatic cooling associated with the expansion of the rapidly escaping atmosphere becomes a dominant part of the energy budget of planetary atmospheres – the hydrodynamic regime or a hydrodynamic planetary atmosphere (Tian et al., 2008a, 2008b). Because the diffusion-limited theory does not consider energy required to support rapid escape, it cannot provide us a good estimate on escape rate of major atmospheric species.

Note that there is a difference between the above-mentioned hydrodynamic planetary atmosphere and the traditional hydrodynamic escape, or blowoff, in that the hydrodynamic regime is reached when the outflow is important in the energy budget of the upper atmosphere, while the blowoff occurs when the heating of the upper atmosphere is so strong that the kinetic energy of the upper atmosphere overcomes the gravity of the planet. Thus a planetary atmosphere in the hydrodynamic regime does not necessarily blow off. In such an atmosphere the gravitational potential energy is more than the heat content or kinetic energy of the atmosphere and the atmospheric escape is Jeans-like (evaporation) no matter whether the actual escape process is thermal or nonthermal. Thus a planetary atmosphere could be experiencing Jeans-like escape and in the hydrodynamic regime simultaneously (Tian et al., 2008a). On the other hand, blowoff can be considered an extreme case of planetary atmospheres in the hydrodynamic regime and energy consumption in the outflow is the ultimate factor controlling the mass loss rate.

Linking the hydrogen content of early Earth's atmosphere with the nature of close-in super Earths, the key question this paper intends to address is: can the energy requirement in a hydrodynamic planetary atmosphere limit atmospheric escape?

2. Hydrodynamic planetary upper atmospheres and the conservation of total escape rate

Here a 1-D upper planetary atmosphere model, validated against the upper atmosphere of the present Earth, is used to study the problem. The model details can be found in Tian et al. (2008a, 2008b). A key feature of the model is that it can automatically adjust its upper boundary so that the exobase, defined as where the scale height is comparable to the mean free path, can be found and the adjusted Jeans escape rates of all species can be calculated. When increasing the level of solar XUV radiation, both the upper atmosphere temperature and the exobase altitude increase. At 5 times present solar mean XUV level (XUV × 5), the exobase altitude can reach more than 10^4 km and the upper atmosphere temperature can be near 9000 K (Tian et al., 2008b).

To include other escape processes at the exobase level in addition to Jeans escape, the Jeans escape effusion velocity at the exobase is multiplied by 3, 10, and 20 times respectively. The calculated upper atmosphere temperature profiles are shown in Fig. 1. The peak temperature in the upper atmosphere cools with increasing escape efficiency from 9000 K in the Jeans escape only case to 8000, 7500, and 7000 K in the 3×, 10×, and 20× more efficient atmosphere escape cases. Correspondingly the exobase altitude decreases with increased escape efficiency because of decreased scale height. Note that although the scale height is inversely proportional to the temperature, the exobase altitude is not.

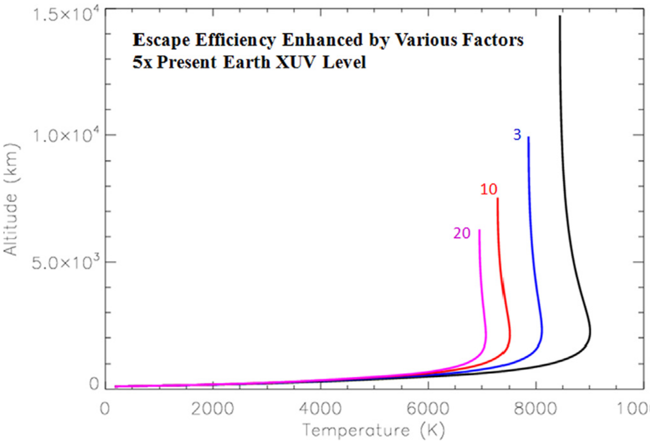

Fig. 1. Upper atmosphere structures of the Earth under 5 times present XUV radiation level with different escape effusion velocities at the exobase level, which are where the curves end.

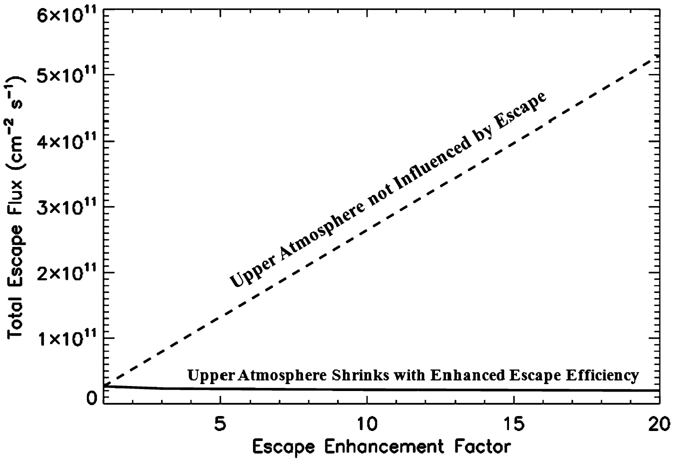

Fig. 2. Total escape rate of major atmosphere species as a function of escape efficiency from the exobase level. The atmospheres used in these simulations have composition the same as that of present Earth but are under 5 times present Earth's XUV radiation level. If the upper atmosphere structure is not influenced by escape of major atmospheric species and the subsequent outflow, the total escape rate would have increased linearly with enhanced escape efficiency at the exobase level as shown by the dashed line. However, when considering the energy consumption of outflow in the upper atmosphere, the upper atmosphere cools and shrinks (shown in Fig. 1) and the total escape rate remains conserved with enhanced escape efficiency at the exobase level.

The shrinking of the upper atmosphere with increasing escape efficiency at the exobase level has an interesting consequence on the total atmospheric escape rate, shown as a solid curve in Fig. 2. In comparison the dashed line in Fig. 2 shows a linear increase of total escape with enhanced escape efficiency if the upper atmosphere structure is not influenced by atmospheric escape. When considering the energy required to support a strong outflow, which is a consequence of rapid escape of major atmosphere species, the total escape rate of such species remains almost a constant (a conservation of total escape rate) when increasing escape efficiency from the exobase level. The conservation of total escape rate from a hydrodynamic planetary atmosphere is a demonstration of the law of the conservation of energy – changing the escape efficiency at the exobase level does not change the total amount of energy heating the upper atmosphere.