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A kinetic study of thermal escape of major atmospheric species

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Abstract

The one-dimensional thermal escape problem is studied by the direct simulation Monte Carlo method. The flow structure and the escape rate are analyzed for source Jeans parameters and Knudsen numbers ranging from 0 to 15 and from 0.0001 to ∞, respectively. The transition in the nature of atmospheric loss from escape on a molecule-by-molecules basis, often refereed to as Jeans escape, to an organized outflow, often refereed to as hydrodynamic escape, occurs in a narrow range of the Jeans parameter. It was found that the kinetic results are different from those that are reported based on the slow hydrodynamic escape (SHE) model. In particular, the escape rates found in kinetic simulations differs only by a factor of 2 from the exobase Jeans escape. Simulations reveal only weak effect of the collision model and internal degrees of freedom of gas molecules on the escape rate.

1. Introduction

Recently discovered exoplanets like super-Earths may have hydrogen-rich atmospheres [1] with the exobase values of the Jeans parameter in the order of 10. In this case primary atmospheric species can efficiently leave the atmosphere due to thermal escape. Studies of thermally escaping atmospheres, e.g. Ref. 2, are based on the SHE model that goes back to Parker's model for solar wind [3]. In the present work, we performed a comprehensive study of the exosphere structure and the escape rates based on a kinetic model. This kinetic study reveals many features of non-equilibrium exospheric flows that are qualitatively different from that predicted in simulations based on the SHE model.

2. Mathematical model

The spherically-symmetric one-dimensional outgassing problem from the surface of a spherical source of radius R_0 having a spherically-symmetric gravity field is considered [4,5]. A gas molecule is affected by a gravitational force, $F_G = -GMm/r^2$, where r is the radial distance, m and M are the molecule and planet masses, and G is the gravitational constant.

The flow is modelled by the direct simulations Monte Carlo method [6]. No heating in the considered part of the atmosphere is assumed. On the source surface, the distribution function of molecules entering the computational domain is assumed to be a Maxwellian. On the exit boundary of the computational domain, all molecules, which leave the domain on hyperbolic trajectories, escape, while other ones return to the domain [5].

Monatomic and diatomic gases are considered as characteristic examples. In a monatomic gas, collisions are described by the hard sphere (HS) or variable hard sphere (VHS) model [6] with viscosity index equal to 1. In a diatomic gas, collisions are described by the VHS model coupled with the Larsen-Borgnakke (VHS-LB) model [6]. The atmospheric structure and the escape rate Φ (number flux of molecules escaping the atmosphere) are fully scaled by the source Knudsen number $Kn_0 = l_0/R_0$, and Jeans parameter $\lambda_0 = R_0/H_0$, where l_0 is the mean free path of molecules in the equilibrium state on the source surface [6] and $H_0 = kT_0R_0^2/(GMm)$ is the atmospheric scale height.

3. Computational results

Simulations of the exosphere structure (Fig. 1) and the escape rate (Fig. 2) reveal that the transition from the hydrodynamic to the Jeans escape occurs in a narrow range of λ_0. The boundaries of the transitional range, $\lambda_{c1} \le \lambda_0 \le \lambda_{c2}$, are determined by the number of internal degrees of freedom of gas molecules (or the gas specific heat), but for mon- and diatomic gases λ_{c1} and λ_{c2} do not differ significantly. The effect of the collision model and the number of degrees of freedom of gas molecules on the escape

rate is also fairly weak. Trends in the variation of the atmospheric structure and the escape rate are qualitatively different for subcritical ($\lambda_0 \le \lambda_{c1}$) and supercritical ($\lambda_0 \ge \lambda_{c2}$) Jeans parameters.

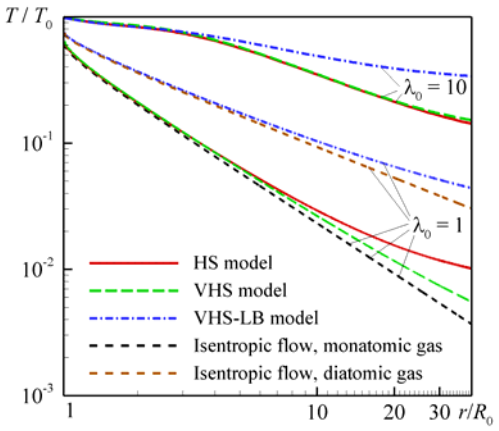

Figure 1: Gas temperature vs. radial distance at $Kn_0 = 10^{-3}$.

Subcritical flows contain a near-surface region of non-isentropic flow, where gas accelerates up to the sonic speed. Above the sonic surface, the flow can be approximated by the model of isentropic flow. The actual escape rate in this case can be in orders of magnitude larger than the Jeans escape rate at the exobase, but this difference is caused mainly by non-zero gas velocity at the exobase.

In supercritical flows the temperature gradients are much smaller than those that are predicted by the SHE model [2]. The terminal value of the Mach number is close to 1, so that neither the hypersonic approximation nor the isentropic model can be used. At $\lambda_0 \ge 6$, the ratio of the escape rate to the Jeans escape rate at the exobase is found to be ~1.4–1.7 unlike the predictions of the SHE model [2].

4. Conclusions

The large set of simulations described here shows that, for $\lambda_0 = 6-15$, which is the suggested domain of the SHE model, the escape rate is fairly close to the Jeans escape rate when heat is deposited below R_0, in drastic disagreement with certain applications of the SHE model, e.g., Ref. 2. The DSMC simulations also reveal that the basic assumptions of this model do not correspond to the real flow conditions at supercritical Jeans parameters. Therefore, escape rates obtained so far for a number of exoplanets and for planetary objects like Pluto based on the SHE model may need re-evaluation in kinetic simulations.

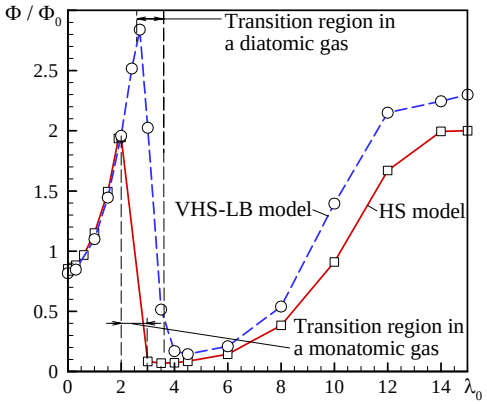

Figure 2: Escape rate vs. Jeans parameter at $Kn_0 = 10^{-3}$. Φ_0 is the Jeans escape rate *at the source*.

Acknowledgements

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