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A Combined Fluid and Kinetic Model of Pluto's Extended Exosphere

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Abstract

Recent missions have renewed interests in the atmosphere of intermediate size objects. A subset of these objects with significant atmospheres may have considerable molecular escape occurring. We show that escape occurs in a kinetic manner and not as an organized outflow as previously modeled on Pluto and similar sized objects. The method introduced couples a fluid model of the lower atmosphere and a kinetic model of the upper atmosphere to determine escape rate and show the transition of atmospheric structure from dense to tenuous regimes.

1. Introduction

New spacecraft exploring outer planetary systems have greatly increased our interest in the exosphere and the process of atmospheric escape from intermediate size planetary bodies. The Cassini spacecraft is investigating the atmospheres of many of the moons of Saturn. In 2015, the New Horizons spacecraft will encounter Pluto, enabling the detailed study of its surface atmosphere. Our work has been developing a model of the upper tenuous atmosphere of Pluto to estimate the structure and escape of gas from the exosphere. Particular attention is spent on the transition between collisional to near collisionless regimes, which cannot be efficiently modeled together using previous techniques.

1.1 Atmospheric Fluid Modelling

Previous models of the atmosphere of Pluto [4,5,7] and similar sized objects [8] have used a purely fluid solution. By using a fluid model out to several radii, they employ Parker's [6] boundary condition on the temperature and pressure by requiring these tend to zero at infinity. Chamberlain [2] criticized this model when applied to collisionless media, as is the case with neutral molecules in the exosphere.

Parker's study of the solar wind resulted in the concept of *hydrodynamic escape,* that is, a persistent loss of atmosphere resulting from supersonic expansion of the atmosphere. Later this model was applied to cooler atmospheres. It was argued that the same escape process would continue until pure Jeans escape takes over [7,11]. This process was labeled *slow-hydrodynamic escape (SHE)* in the intermediate region. In [10] the authors demonstrated that this transition occurs much quicker than previously thought via kinetic modeling, and therefore bodies the size of Pluto and Titan do not support hydrodynamic escape. Further the SHE models typically assume zero energy flow to infinity [4,7], but Jeans theory and DSMC suggest otherwise [9,10].

1.2 Thermal Escape and Exosphere

Jeans proposed a solution to escape that carries his name in which escape occurs from a single altitude (the exobase). The resulting escape depends on the density, thermal speed, and more significantly on the Jeans parameter, which is ratio of thermal energy to local gravitational potential.

A more detailed study of escape was performed by Volkov [10] using the Direct Simulation Monte Carlo (DSMC) method, as introduced by Bird [1], to model the atmosphere. Using a probabilistic model of collisions between molecules, DSMC simulates the transition from collisional below the exobase to near collisionless several radii away from the surface [9,10]. It is clear shown that the type of escape (hydrodynamic, Jeans, etc.) is characterized by the Jeans parameter. Further, a strong decline in the escape rate occurs when the Jeans parameter is between 2.5 and 3.5 [10]. Pluto has a Jeans parameter in excess of 20 below the exobase suggesting that the escape is Jeans-like.

2. Hybrid Model

The need for a combined method arises since the fluid model may not be valid far out in the exosphere and the DSMC model cannot be used to model deep into the dense atmosphere due to computational cost.

We begin by modeling the dominant component (N2) of Pluto's atmosphere with a 1D fluid model, and considering the minor components (CH4 and CO) at fixed mixing ratios when considering heating and cooling processes in a similar manner as Strobel used for SHE model. We apply Jeans escape from the exobase altitude, and iterate to find a consistent solution and escape rate. Yelle [12] used a similar approach to study the escape and atmospheric profile in giant exoplanets, but using a modified Jeans escape rate from the fixed upper boundary. We found that our escape rate (~1.2e27 N2 per sec) is similar to that of SHE (~1.6 N2 per sec) [7] for solar minimum heating rates, while our profile of density and temperature are very different with only Jeans escape.

We improve on the above method by combining a fluid model with a DSMC model of the exosphere. The DSMC domain begins below the exobase where the flow is still in collisional-equilibrium, and the fluid model is used below this. Again iteration is needed to get consistent mass and energy flow between the two domains. The result for Pluto's escape rate (~1.4e27 N2 per sec) is not greatly different from SHE for solar minimum heating rates. However the DSMC provides non-zero temperature and corresponding density out to several radii. This suggested that the environment the New Horizons spacecraft will encounter is different than the SHE model predicts.

3. Summary and Conclusions

The hybrid solutions given here combine a fluid model of the lower atmosphere with a kinetic model of escape and the exosphere. The resulting escape rate in the presence of heating are similar to those found by using pure fluid solution as with SHE models. When we use DSMC to model the exosphere the escape rate is enhanced relative to Jeans by roughly 50% due to the gradual transition to collisionless and escape occurring over a range of altitudes. We believe this method captures the true escape mechanism. Further work to consider multiple species and capture the 3D environment is being pursued.

Acknowledgements

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References

[1] Bird, GA.: Molecular gas dynamics and the direct simulation of gas flow, Oxford University Press, 1994

[2] Chamberlain, JW.: Supersonic solutions of the solar-wind equation, Icarus, Vol 113, pg 450-455, 1995.

[3] Jeans, JH.: The dynamic theory of Gases, Cambridge University Press, 1925.

[4] Krasnopolsky, VA.: Hydrodynamic flow of N2 from Pluto, Journal of Geophysical Research, Vol. 104, pg 5955-5962,1999.

[7] Strobel, DF.: N2 escape from Pluto's atmosphere, Icarus, Vol. 193, pg 612-619, 2008.

[5] McNutt, RL.: Models of Pluto's upper atmosphere, Geophysical Research Letters, Vol. 16, pg 1225-1228, 1989.

[6] Parker, EN.: Dynamic properties of stellar coronas and stellar winds 1: Integration for the momentum equation, Astrophysics Journal, Vol. 139, pg 72-92, 1964.

[7] Strobel, DF.: N2 escape from Pluto's atmosphere, Icarus, Vol. 193, pg 612-619, 2008.

[8] Strobel, DF.: Titan's hydrodynamically escaping atmosphere: escape rates and structure of the exobase region, Icarus, Vol 202, pg 632-641, 2009.

[9] Tucker, OJ.: Thermally driven atmospheric escape: Monte Carlo simulations for Titan's atmosphere, Planetary and Space Science, Vol. 57, pg 1889–1894, 2009.

[10] Volkov, AN, et al.: Thermally driven atmospheric escape: transition from hydrodynamic to jeans escape, The Astrophysical Journal Letters, pg 729-733, 2011.

[11] Watson, AJ, et al.: The dynamics of the rapidly escaping atmosphere: applications to the evolution of Earth and Venus, Icarus, Vol. 48, pg 150-166, 1981.

[12] Yelle, RV.: Aeronomy of extra-solar giant planets at small orbital distances, Icarus, Vol. 170, pg 167-179, 2004.