Icarus 226 (2013) 375–384

Contents lists available at SciVerse ScienceDirect

Icarus

journal homepage: www.elsevier.com/locate/icarus

Hybrid fluid/kinetic modeling of Pluto's escaping atmosphere

Justin Erwin [a,*], O.J. Tucker [b], Robert E. Johnson [a,c]

[a] Department of Engineering Physics, University of Virginia, 166 Engineers Way, P.O. Box 400745, Chalottesville, VA 22904, United States
[b] Department of Atmospheric, Oceanic and Space Science, University of Michigan, Ann Arbor, MI 48109, United States
[c] Department of Physics, New York University, New York, NY 10012, United States

ARTICLE INFO

Article history:
Received 13 November 2012
Revised 29 May 2013
Accepted 30 May 2013
Available online 13 June 2013

Keywords:
Pluto
Pluto, Atmosphere
Aeronomy
Atmospheres, Structure
Atmospheres, Dynamics

ABSTRACT

Predicting the rate of escape and thermal structure of Pluto's upper atmosphere in preparation for the New Horizons Spacecraft encounter in 2015 is important for planning and interpreting the expected measurements. Having a moderate Jeans parameter Pluto's atmosphere does not fit the classic definition of Jeans escape for light species escaping from the terrestrial planets, nor does it fit the hydrodynamic outflow from comets and certain exoplanets. It has been proposed for some time that Pluto lies in the region of slow hydrodynamic escape. Using a hybrid fluid/molecular-kinetic model, we previously demonstrated the typical implementation of this model fails to correctly describe the appropriate temperature structure for the upper atmosphere for solar minimum conditions. Here we use a time-dependent solver to allow us to extend those simulations to higher heating rates and we examine fluid models in which Jeans-like escape expressions are used for the upper boundary conditions. We compare these to hybrid simulations of the atmosphere under heating conditions roughly representative of solar minimum and mean conditions as these bracket conditions expected during the New Horizon encounter. Although we find escape rates comparable to those previously estimated by the slow hydrodynamic escape model, and roughly consistent with energy limited escape, our model produces a much more extended atmosphere with higher temperatures roughly consistent with recent observations of CO. Such an extended atmosphere will be affected by Charon and will affect Pluto's interaction with the solar wind at the New Horizon encounter. For the parameter space covered, we also find an inverse relationship between exobase temperature and altitude and the Jeans escape rate that is consistent with the energy limited escape rate. Since we have previously shown that such models can be scaled, these results have implications for modeling exoplanet atmospheres for which the energy limited escape approximation is often used.

1. Introduction

Recent spacecraft exploration of the planets and moons in our solar system and the rapid increase in the discovery of exoplanets has increased interest in atmospheric escape from planetary bodies. The Cassini spacecraft is currently improving our understanding of atmospheric escape from Titan, while in 2015 the New Horizons (NH) spacecraft will flyby Pluto and perform occultation observations of its and Charon's atmosphere (Guo and Farquhar, 2005), and the Maven mission will orbit Mars studying the composition of its escaping atmosphere (Lin and Jakosky, 2012). Furthermore, newly discovered exoplanets, with radii ranging from just a few times that of Earth to of the order of Jupiter, and their atmospheres are also modeled (Yelle, 2004; Lammer et al., 2009; Murray-Clay et al., 2009). Here we carry out simulations of Pluto's upper atmosphere, including atmospheric loss by thermal escape, that can be tested against data to be obtained during the NH encounter. By accurately describing the present loss rates, one can in principle learn about the evolution of Pluto's atmosphere. In addition, doing this accurately for a planet for which we will have in situ spacecraft data can, by scaling, guide our ability to model exoplanet atmospheres for which there will only be remote sensing data.

The previous models of atmospheric escape for Pluto used the concept of hydrodynamic escape by adapting the *critical solution* in Parker (1964). Parker described the expanding stellar corona and stellar wind assuming the temperature and pressure go to zero at infinity, and showed that for this to happen the bulk velocity must increase past the isothermal speed of sound at a critical point that is dependent on the temperature and gravity.

This model was subsequently adapted for planetary atmospheres to include heating by solar radiation (Hunten and Watson, 1982; McNutt, 1989) and was applied to Pluto (Krasnopolsky, 1999; Strobel, 2008) and Titan (Strobel, 2009). It is often referred to as the slow hydrodynamic escape (SHE) model. The model requires solving the fluid equations out to very large distances from the planet to enforce the necessary boundary conditions. However,

* Corresponding author.
E-mail address: jte2c@virginia.edu (J. Erwin).

0019-1035/$ - see front matter © 2013 Elsevier Inc. All rights reserved.
http://dx.doi.org/10.1016/j.icarus.2013.05.042

it is known that at some finite distance from the planetary surface the equations of fluid dynamics fail to describe the flow of mass, momentum and energy in an atmosphere (Johnson, 2010; Volkov et al., 2011). The region of validity of the fluid equation is often defined using the Knudsen number, $Kn = \ell/H$, the ratio of the mean free path of the molecules, $\ell = (\sqrt{2}\sigma n)^{-1}$, to the density scale height, $H = \frac{k_b T}{mg(r)}$, of the atmosphere, where σ is the collisional cross-section of the N_2 molecule, n the local number density, k_b the Boltzmann constant, T the temperature, m the mass of an N_2 molecule, and $g(r)$ the local gravitational acceleration. The fluid equations properly capture the physics where $Kn \ll 1$ so that many collisions occur over relevant length scales keeping the gas in local thermaldynamic equilibrium.

The concept of energy limited escape, which we will also examine here, is heavily used in modeling escape from early terrestrial planet atmospheres (Tian et al., 2009) and the growing body of data on exoplanet atmospheres (Lammer et al., 2009; Valencia et al., 2010). UV radiation drives escape by giving molecule the energy necessary to escape the gravitational well. Assuming that kinetic and thermal energy terms are small compared to gravity and thermal conduction is inefficient, the molecular loss rate is often approximated as

$$\phi_L \approx \frac{Q}{U(r)} \tag{1}$$

Here Q is the EUV energy supplied in the upper atmosphere, and $U(r) = GMm/r$ is the gravitational energy with G being the gravitational constant, M the mass of Pluto, and m the mass of an N_2 molecule. Without doing a detailed heating model one can use $Q = \pi r_{EUV}^2 \eta F_{EUV}$, where r_{EUV} is the mean radius at which the radiation is absorbed and η and F_{EUV} are the heating efficiency and solar energy flux respectively. This depends critically on r_{EUV} which is sometimes assumed to be close to the visual radius so that r_p can be used. Also important is what level of the atmosphere the molecules are being removed from the gravitational well. Again the visual radius is a good choice so that $U(r_p)$ is used.

The alternative to organized outflow is evaporative escape, by which the atmosphere loses gas on a molecule-by-molecule basis driven by conductive heat flow from below. The standard analytic model was originally developed by Jeans (1925) and is referred to as Jeans escape. The escape rates are found to depend predominately on the Jeans parameter $\lambda = U(r)/k_bT$, the ratio of gravitational to thermal energy of the molecules. For large Jeans parameters (i.e. when gravitational energy dominates thermal energy) the escape rate is obtained by integrating the velocity distribution over the portion of molecules that are moving upward with speed in excess of the escape velocity. Assuming a Maxwell–Boltzmann velocity distribution, the molecular escape rate ϕ and energy escape rate ϕ_E from an altitude r are given by

$$\langle\phi\rangle_J = \frac{1}{4} n\bar{v} \cdot (1+\lambda)\exp(-\lambda) \cdot 4\pi r^2 \tag{2}$$

$$\langle\phi_E\rangle_J = \langle\phi\rangle_J \cdot k_b T\left(\frac{C_p}{k_b} - \frac{3}{2} + \frac{1}{1+\lambda}\right) \tag{3}$$

Here $\bar{v} = \sqrt{8k_bT/m\pi}$ is the mean molecular speed. To be consistent with the fluid equations, we consider expressions using a drifting Maxwell–Boltzmann to include the bulk velocity u in the velocity distribution (Yelle, 2004; Tian et al., 2009; Volkov et al., 2011). Typically these equations are applied at a level called the exobase where $Kn \approx 1$, as there are few collisions above this level to inhibit a molecule from escaping.

The Jeans escape boundary condition has been used in modeling planetary atmospheres, notably by Chassefière (1996), Yelle (2004) and Tian et al. (2008). In modeling the response of the Earth's thermosphere to EUV heating, Tian et al. (2008) used the Jeans escape expression to determine the velocity at the upper boundary (the exobase in their case); however at the upper boundary a zero temperature gradient was applied to neutrals, and a fixed heat gradient was applied to electrons separately. In modeling extra-solar gas giants at small orbital distance, Yelle (2004) also used Jeans escape, with a drifting Maxwell–Boltzmann velocity distribution, to get an upper boundary velocity. However, this was applied at a fixed upper boundary of 3 planetary radii rather than at the exobase.

Accurate calculations of thermal escape can be obtained, in principle, by solving the Boltzmann equation or, more often, by using the direct simulated Monte Carlo (DSMC) method as in Tucker and Johnson (2009) and Volkov et al. (2011). In this method, representative particles are used along with a model of molecular collisions to calculate the temperature, density and other macroscopic values from the velocity distribution in both the dense and rarified regions. In this respect, DSMC can model the exospheres with better accuracy than hydrodynamic model, but can only model the lower, denser regions of the atmosphere at great computational cost. Using the DMSC method Volkov et al. (2011) demonstrated earlier that for a monatomic or diatomic gas in the absence of heating above some lower boundary for $\lambda \gtrsim 3$ the molecular escape rate is Jeans-like at the exobase (i.e. $\phi/\langle\phi\rangle_J \approx 1.5$ for the range of Jeans parameters studied). For our model of Pluto, the lower boundary of the simulated domain has $\lambda = 22.8$, and the exobase values exceed 4. Using the above results as guidance, we model the principle component in Pluto's atmosphere to obtain a description relevant to the NH encounter. We did this in order to test energy-limited escape, and to better understand the transition from Jeans to hydrodynamic escape.

2. Model description

The steady state equations of mass, momentum, and energy have been used to study hydrodynamic escape. They can be solved to give the radial dependence of number density n, outward bulk velocity u, and temperature T in the region in which the atmosphere is collisional. However, as we have shown (Tucker et al., 2012; Volkov et al., 2011) they cannot be used by themselves to determine the escape rate unless the Jeans parameter is very small, in which case the solutions are somewhat insensitive to the boundary condition at infinity. The equations, neglecting viscosity can be written as

$$4\pi r^2 nu = \phi \tag{4}$$

$$nm\frac{\partial}{\partial r}\left(\frac{1}{2}u^2\right) + \frac{\partial p}{\partial r} = -nmg(r) \tag{5}$$

$$\frac{\partial}{\partial r}\left(\phi\left(C_pT + \frac{1}{2}mu^2 - U(r)\right) - 4\pi r^2\kappa(T)\frac{\partial T}{\partial r}\right) = 4\pi r^2 q(r) \tag{6}$$

Here ϕ is the molecular escape rate through the one dimensional atmosphere, p is the pressure (related via the equation of state, $p = nk_bT$), m is the mass of a N_2 molecule, $\kappa(T)$ is the conductivity, $C_p = \frac{7}{2}k_b$ is the specific heat at constant pressure, and $q(r)$ is the net heating/cooling rate per unit volume. In Eq. (6), the first term on the left side is work done by adiabatic expansion and the second is the work done by conduction.

For the conductivity, we use the power law $\kappa(T) = \kappa_0 T^{\omega}$ to approximate the temperature dependence. Some authors use an empirical fit for the conductivity, e.g. Hunten and Watson (1982) used $\omega = 1.12$, while McNutt (1989) used $\omega = 1$ since it simplifies the analytic solutions to Eq. (6). In this paper we use $\kappa_0 = 9.37 \times 10^{-5}$ J/m K and $\omega = 1$ to compare with Strobel, 2008 and because this is consistent with the variable hard sphere model for collisions between N_2 molecules used in the DSMC model of the exosphere (Tucker et al., 2012; Volkov et al., 2011).

The lower boundary of our fluid domain is set at 1450 km, consistent with the occultation results and the assumptions of Strobel