Icarus 277 (2016) 370–380

Contents lists available at ScienceDirect

Icarus

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

DSMC simulation of Europa water vapor plumes

J.J. Berg[a,*], D.B. Goldstein[a], P.L. Varghese[a], L.M. Trafton[b]

[a] Department of Aerospace Engineering and Engineering Mechanics, The University of Texas at Austin, 210 East 24th St, C0600, Austin, TX 78712, United States

[b] Department of Astronomy, University of Texas, Austin, TX 78712, United States

ARTICLE INFO

Article history:
Received 9 February 2016
Revised 29 April 2016
Accepted 19 May 2016
Available online 26 May 2016

Keywords:
Europa
Jupiter, satellites
Atmospheres, dynamics

ABSTRACT

A computational investigation of the physics of water vapor plumes on Europa was performed with a focus on characteristics relevant to observation and spacecraft mission operations. The direct simulation Monte Carlo (DSMC) method was used to model the plume expansion assuming a supersonic vent source. The structure of the plume was determined, including the number density, temperature, and velocity fields. The possibility of ice grain growth above the vent was considered and deemed probable for large (diameter $> \sim 20$ m) vents at certain Mach numbers. Additionally, preexisting grains of three diameters (0.1, 1, 50 μm) were included and their trajectories examined. A preliminary study of photodissociation of H_2O into OH and H was performed to demonstrate the behavior of daughter species. A set of vent parameters was evaluated including Mach number (Mach 2, 3, 5), reduced temperature as a proxy for flow energy loss to the region surrounding the vent, and mass flow rate. Plume behavior was relatively insensitive to these factors, with the notable exception of mass flow rate. With an assumed mass flow rate of ∼1000 kg/s, a canopy shock occurred and a maximum integrated line of sight column density of $\sim 10^{20}$ H_2O molecules/m^2 was calculated, comparing favorably with observation (Roth et al., 2014a).

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1. Introduction

Recent observations of water vapor plumes at Europa (Roth et al., 2014a) may present an exceptional opportunity to study the composition of the subsurface ocean and the geology of the ice crust. Tidal forces experienced throughout the orbit cause interior heating that maintains a proposed water ocean in a liquid state (Pappalardo, 2010). While the existence of this ocean is well supported by evidence, many of the characteristics of the surmounting ice layer are undetermined. This includes the thickness of the ice, its temperature profile, and whether or not there is convection within the ice (Nimmo and Manga, 2009). As the understanding of geology on Europa is in part conjectural, multiple scenarios have been put forward that may explain the existence of plumes (Fagents, 2003). One mechanism is explosive volcanism propelled by volatile species dissolved in the water. Calculations indicate this configuration results in plume exit velocities of up to 600 m/s (Fagents et al., 2000). A popular alternative explanation of the water vapor plumes on Saturn's moon Enceladus involves tidal forces opening cracks or channels in the ice, allowing liquid water to boil near the triple point temperature of 273 K and escape into vacuum (Schmidt et al., 2008). Provided that the channels have a variable cross sectional area, this could result in exit velocities of ∼1000 m/s (Yeoh et al., 2015). On other low gravity bodies like the Galilean moon Io, volcanic plumes have vent exit velocities of 500–1000 m/s (McDoniel et al., 2015).

On Europa, there has only been a single observation of an active plume producing gas densities above the level of a sputtered atmosphere (Roth et al., 2014a). The observation was made by the Hubble Space Telescope using five consecutive images spanning ∼7 h at 130.4 nm, 135.6 nm, and Lyman-α to infer regions of the atmosphere with increased H_2O concentrations relative to background. These emissions are most plausibly explained as radiation from the daughter products of electron impact dissociation. The height of the plume is estimated to be 200 ± 100 km, with a suggested exit velocity of approximately 700 m/s. Column density and total lofted number of H_2O molecules were also calculated to be $\sim 10^{20}$ molecules/m^2 and $\sim 10^{31}$ molecules respectively. An attempt to replicate this detection, with Europa at the same true anomaly, was not successful (Roth et al., 2014b). Roth et al. do not believe this challenges the original observation, but it does imply that the plumes may be an irregular phenomena not deterministically caused by periodic tidal forces. They also rule out an impact because water vapor molecules have short ballistic flight times in such an event, much less than the 7 h Hubble observation duration and in conflict with the persistent nature of the measured plumes.

* Corresponding author. Fax: +1 512 471 3788.
E-mail address: jaredberg@utexas.edu (J.J. Berg).

http://dx.doi.org/10.1016/j.icarus.2016.05.030
0019-1035/Published by Elsevier Inc.

The observations by Roth et al. represent the only data with which to compare simulation results from numerical models. Therefore, they will be referred to frequently throughout this work. The direct link between plume size and exit velocities and temperature means that different plume vent boundary conditions can be evaluated and compared to observation.

Having a flexible, physics-based model of plume phenomena is useful for future Europa missions in several ways: any orbiting spacecraft with the goal of making accurate close range measurements of the plumes must, during the engineering phase, have some model of the structure and behavior of these plumes. This would aid in determining instrument requirements, planning the observation campaign, and as an element of hazard analysis. Predicting the vertical and horizontal extent of possible plumes is also relevant to trajectory and operations design. Flying through a plume may impart torques and drag on the spacecraft that must be countered by the attitude control system (Sarani, 2010). Depending on density, there may also be heating or dynamic effects on the spacecraft structure. Grains or dust embedded in the plume could degrade sensitive instruments, coatings, or solar panels leading to reduced performance (Lorenz, 2015; Landgraf et al., 2004; Liechty, 2007).

The motivation for having a spacecraft in Europa's vicinity at all is obviously scientific. Understanding the plume behavior would give clues to the subsurface geology. Key astrobiological data could be obtained by studying the plumes' chemical composition or even direct detection of cells (Lorenz, 2016). The application of the DSMC method to simulating the plumes of Europa may therefore inform ongoing observation and confirmation efforts and serve as a critical element in preparing for future exploration missions.

2. Method

2.1. DSMC

The direct simulated Monte Carlo (DSMC) method models gas flow by tracking the behavior of individual representative particles instead of relying on continuum assumptions or general governing fluid equations (Bird, 1994). Naturally then, the method is typically employed for rarefied gas flows. Every computational particle in DSMC represents a large number of actual gas molecules, ranging from $\sim 10^{13}$ to 10^{20} in the work below. The domain to be simulated is filled with a continuous structured mesh. Given that the flow is composed of particles alone, macroscopic properties including density and temperature are obtained by averaging over the particles in each mesh cell.

The DSMC implementation utilized here is based on the original by Bird, but has been modified and extended substantially to include additional features. This code has been applied to a variety of flow problems including simulating Io's volcanic plumes (Zhang et al., 2004) and atmosphere (Moore et al., 2009; Walker et al., 2010), comet impacts on the moon (Stewart et al., 2011; Prem et al., 2015), and the water plumes on Enceladus (Yeoh et al., 2015). Code features not relevent to Europa have been disabled.

2.2. Simulation domain

The plume source is assumed to be a circular vent, so an axisymmetric simulation is convenient. The domain is a 0.1° wedge with the boundary conditions specified in Fig. 1 (left). Immediately below the vent, particles are generated in the specified equilibrium state and allowed to pass into the primary domain. The mean velocity profile at the vent boundary is assumed to be uniform, given that the viscous boundary layer would be relatively thin at the relevant Reynolds numbers. Particles that exit the domain via a vacuum boundary are stored in an output file for insertion into a subsequent simulation stage at a patch interface, as described in the next section. Particles crossing a periodic boundary have their velocity vectors appropriately rotated and are placed back into the domain, satisfying the symmetry condition in the azimuthal direction. Particles striking Europa's surface stick with a probability of 1.0, as the icy surface at the south pole is too cold (90 K) to sublime a significant number of water molecules.

2.2.1. Staging

Starting with continuum conditions and exhausting into a vacuum, the plume expands rapidly from the vent through multiple flow regimes. The mean free path (λ) ranges from ∼0.1 mm

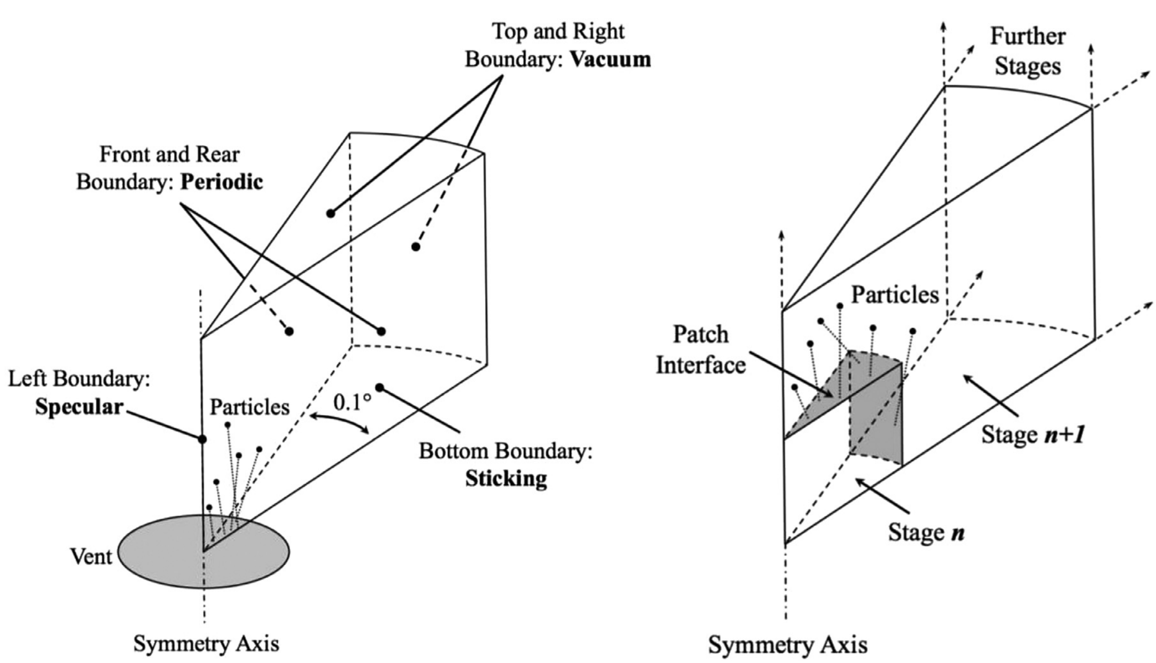

Fig. 1. (Left) Simulation domain with boundary conditions. (Right) Multi-stage calculation schematic; molecules which pass though vacuum boundaries are saved and imported into the subsequent stage at the patch interface.