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Gridless DSMC models of Callisto's atmosphere

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1. Summary

Preliminary results for a gridless direct simulation Monte Carlo (DSMC) model of Callisto's atmosphere will be reviewed. Callisto's atmosphere is likely in a transitional state in that the inferred atmospheric abundances range from a surface bound exosphere to a quasi-collisional atmosphere with an exobase located above the surface. This variation is likely driven by the diurnal changes in surface temperature as well as incident plasma. A gridless DSMC approach is ideal for modeling rarefied gas flows that undergo significant concentration gradients. Here observations and previous numerical models of Callisto's asymmetric atmosphere are reviewed; a preliminary implementation is discussed; and gridless DSMC results will be presented, which will provide a benchmark for the forthcoming spacecraft observations.

2. Background

The evolution of a planetary body's atmosphere is in large part due to the processes which drive escape. There is now a wealth of spacecraft and telescopic data available on the atmospheres of a number of topical solar system bodies, including Callisto, the outermost of the four large Galilean satellites.

Galileo flybys of Callisto detected a global rarefied, nearly collisionless atmosphere containing CO_2 that appeared to be a potentially transient phenomena [2]. Subsequent flybys of Callisto, however, detected a substantial ionosphere which suggested photoionization of CO_2 alone was insufficient to produce the observed electron density and a predominantly O_2 atmosphere was suggested [6]. The ionosphere was only detected when the trailing hemisphere and ramside of Jupiter's corotating magnetosphere of Callisto was sunlit, indicating that both plasma impact and photoionization are necessary to generate this phenomena.

Hubble Space Telescope (HST) observations of Callisto were subsequently performed to search for the presence of O_2, CO_2, and/or CO atmospheres [11]. As a result of these observations, upper limits were placed on a number of species.

Numerical models were applied to the atmosphere of Callisto in an attempt to reproduce the observed electron densities while satisfying the upper limits of O_2, CO, O, and C [9]. These models accounted for the photochemistry of an O_2-rich atmosphere and successfully reproduced the observed electron profile. However, photodissociation of O_2 generated an abundance of O two orders of magnitude greater than the upper limit. Thus, H_2O vapor was proposed to be present in the atmosphere such that the reactive hydrogen chemistry and resultant escape of H and O would reduce this excess abundance.

Almost a decade later, the HST-Cosmic Origins Spectrograph, an instrument not yet installed during earlier Callisto observations, finally detected and confirmed an O_2-rich atmosphere [3]. Results from these observations indicated the presence of a collisional atmosphere, one which affirmed it to be the fourth densest atmosphere among satellites in the solar system and the second densest O_2-rich atmosphere. These observations, however, occurred when the leading hemisphere was sunlit and suggested the atmosphere could be an order of magnitude more dense when the trailing hemisphere was illuminated, as photoelectrons, rather than magnetospheric electrons, were suggested to be the most likely source of dissociative excitation.

Most recent 3-D models attempted to further constrain the structure and density of Callisto's atmosphere by varying a prescribed atmosphere composed of O_2, CO_2, and H_2O [5]. Results of these models suggest that Callisto's O_2 atmosphere has a significant day-night asymmetry, consisting of a dense subsolar region driven by surface sputtering and a less-dense terminator region where surface sputtering is suppressed due to lower surface ice temperatures.

Over a decade of HST data was revisited to study Callisto's atmosphere and the presence of atomic hydrogen was detected [10]. A strong asymmetry was observed as the abundance of hydrogen changes with Callisto's orbit as a result of varying surface temperatures and, thus, resultant sublimation rates of the icy surface, the primary source of water vapor.

In spite of the abundance of observational data regarding Callisto's atmosphere, there remains a clear lack of understanding of the underlying physics involved. This is due in large part to the complicated surrounding environment, such as the varying solar illumination and corotating Jovian magnetosphere and the effects they can have on atmospheric and surface processes, as well as the gaps in time between observations. The ESA JUpiter ICy moon Explorer (JUICE) spacecraft, set to launch sometime in the 2020s, will look to address some of these discrepancies as it will partake in 12 extended flybys of Callisto, where it will attempt to characterize surface and atmospheric composition and processes as well as assess its coupled interactions with the surrounding magnetospere [4]. In addition, NASA's Europa Clipper mission, also set to launch sometime in the 2020s, will consist of 9 flybys of Callisto prior to ending with a planned impact of the spacecraft into its surface [7].

Since understanding the evolution of planetary atmospheres is one of the most important goals in solar system studies, we will now discuss applying a novel numerical model to Callisto's asymmetric atmosphere to provide a benchmark for the forthcoming JUICE and Europa Clipper flybys. This approach builds upon observations and previous numerical models of Callisto's atmosphere.

3. Method

It is critical to apply numerical models that can accurately describe the transition between collisional to collisionless flow in an atmosphere. Determining where this transition region takes places has been shown to require a molecular kinetics method either to numerically solve the Boltzmann equation or by applying the direct simulation Monte Carlo (DSMC) method [1]. The latter method will be applied herein towards modeling Callisto's atmosphere.

DSMC is a probabilistic method which simulates macroscopic gas dynamics by directly modeling the microscale processes of individual atoms and molecules in the gas. In order to calculate the gas properties of the atmosphere at a molecular level, flow is simulated via computational particles, where each particle represents a large number of real atoms or molecules, and collisions between them are determined by their relative proximity and the collisional cross-sections of the real atoms or molecules they represent. Between collisions particle movement is subject to the surrounding gravitational environment. Thus, with an initial distribution of particle positions and velocities and prescribed boundary conditions, the evolution of an atmosphere can be simulated.

A "gridless" DSMC method has recently been devised [9] which can dynamically determine local groupings of nearest neighbor particles according to their distribution, independent of the geometry of an underlying grid, as in traditional DSMC simulations. The advantage of this gridless structure is that it allows for dynamic localized refinement of a domain at any given instant of time based on local densities. This approach provides significant flexibility for a simulation, particularly when the computational domain represents a complex geometry. Indeed, this gridless approach is an ideal method for modeling Callisto's asymmetric atmosphere and will be applied here.

The gridless DSMC models for Callisto's atmosphere will account for the variations in surface temperature and composition in order to simulate the interactions between the day- and night-side as well as determine the corresponding escape rates. Various species, such as O_2, H_2O, CO_2, and others that could be generated via dissociative processes, will be included in order to characterize their role in the evolution of Callisto's atmosphere.

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