RAREFIED GAS DYNAMIC SIMULATION OF TRANSFER AND ESCAPE IN THE PLUTO-CHARON SYSTEM WITH THE DSMC METHOD. W. A. Hoey[1], S. K. Yeoh[1], L. M. Trafton[2], D. B. Goldstein[1], and P. L. Varghese[1], [1]Department of Aerospace Engineering and Engineering Mechanics, [2]Department of Astronomy, The University of Texas at Austin. E-mail: whoey@utexas.edu

Introduction: Our application of a rarefied gas dynamic technique to simulations of Pluto's rarefied upper atmosphere is motivated by ongoing New Horizons data analysis and interpretation [1], the extension of plutonian general circulation models (GCMs) [2], and the need for kinetic models in predicting and evaluating escape from Pluto's rarefied upper atmosphere [3][4]. The Direct Simulation Monte Carlo (DSMC) method is well-suited to modeling the dynamics of rarefied and non-equilibrium atmospheric regimes in which continuum techniques break down, i.e. where the ratio of flow mean free path to characteristic length scale exceeds 0.1 [5]. In DSMC applications, the motions and collisions of a representative fraction of molecules in a flow are computed, offering a provably probabilistic solution to the Boltzmann equation. Established applications of our research group's massively-parallel DSMC code in rarefied atmospheric simulation include comprehensive modeling of the Ionian atmosphere, inclusive of jovian plasma torus dynamics [6], and predictive neutral density modeling of the terrestrial upper atmosphere [7][8].

In this work, we present a novel three-dimensional DSMC model of the plutonian upper atmosphere that spans from several hundred km below the exobase – where continuum flow transitions to the rarefied regime – to fully free-molecular flow hundreds of thousands of km from Pluto's center. Our model accounts for the gravitational fields of both Pluto and Charon, the centripetal and Coriolis forces due to the rotation of Pluto in our reference frame, and the presence of Charon as a sink for impacting particles. Using this model, we analyze the escape processes of N_2 and CH_4 from Pluto across a range of solar heating conditions, and evaluate the three-dimensional structure of the upper plutonian atmosphere, including gas transfer to and deposition on Charon.

Methodology: If we take Charon's minimally-eccentric orbit to be circular, the mutual tidal lock of the Pluto-Charon system allows us to construct a steady-state model in a Pluto-fixed coordinate frame. In populating our simulation, representative particles are generated as Maxwell-distributed flux through a lower boundary surface adjacent to the exobase. While the lower, continuum plutonian atmosphere likely exhibits complex three-dimensional and transient structure, these simulations assume an isotropic exobase region in density and temperature at constant radius. The initial New Horizons findings indicate that this is a reasonable approximation [1]. Lower boundary conditions are set with reference to the various cases of solar heating (minimum, nominal, maximum) established in Tucker *et al.* [2], and the preliminary exobase figures given in the initial findings. Particles are permitted to exit the simulation by falling back through the lower boundary, by striking and sticking to Charon's surface, or by escaping to infinity; a simulated steady state occurs when these fluxes equilibrate with the constant flux of particles into the domain. Particle rotational and vibrational states are tracked, though the vibrational modes are rarely excited at the low temperatures about Pluto. Energy exchange occurs between translational and internal modes, as well as among internal modes, through collisions in which particles are modeled as variable hard spheres. Such collisions, which primarily occur in the near-continuum exobase region, drive particles off their otherwise ballistic paths, influencing flowfield structure, gas transfer to Charon, and escape.

Simulations are computed in parallel across hundreds of processors distributed along azimuthal and zenith directions; the scale of each highly-resolved calculation is on the order of 10,000 CPU hours.

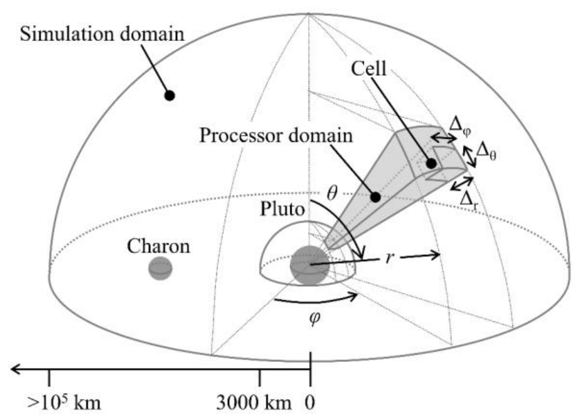

Figure 1. Shape and extent of a hemispherically-symmetric simulation domain. (Cell size not to scale.)

Results and Conclusions: We quantify the processes of gas falling back through the lower boundary, striking and sticking to Charon, and escaping to vacuum, and compare them across solar heating cases. In comparisons between test cases with a full collision model and, alternately, with free molecular flow assumed valid throughout the domain, we demonstrate that collisions within the exobase have the effect of promoting both gas transfer to Charon and escape to infinity, and that these collisions facilitate transfer from Pluto's anti-Charon hemisphere. We also investigate the deposition of gas over the surface of Charon, including the spatial and speed distributions of the impacting particles. This analysis yields deposition distributions in latitude and longitude on the Charon surface for each test case, indicating peak transfer to the equatorial region at about 135° E. We apply our model to investigate the three-dimensional fields of several gas properties, including density and temperature, around Pluto and Charon. This enables us to gain a better understanding of the mechanisms underlying the atmospheric escape process and the transfer of material between Pluto and Charon. The density field about Pluto is observed to break its spherical symmetry as radial distance from the primary increases, ultimately forming a bridging structure that extends through the L1 Lagrange point and into Charon's gravitational influence. This sort of transfer appears comparable to the phenomena of one-way Roche overflow transfer observed between binary stars. As more NH data become available, the current modeling work will provide a framework for future improvements, including two-way coupling to a GCM model of the lower continuum atmosphere for more accurate input conditions at the lower boundary, and the inclusion of additional significant gas species, such as CO.

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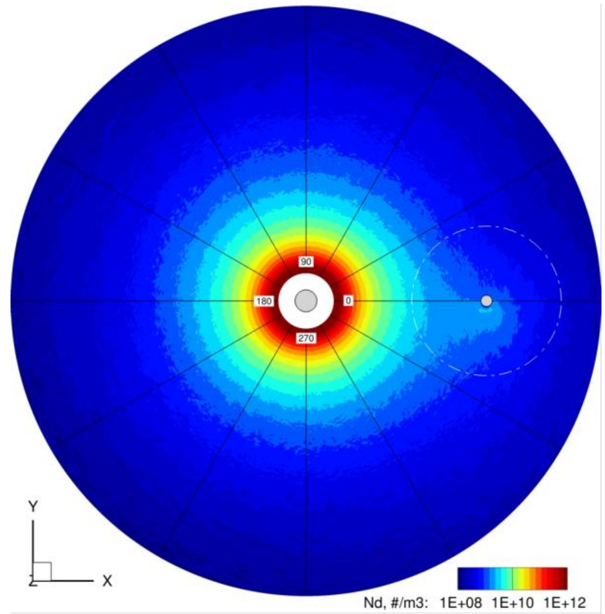

Figure 2. Number density contours as observed in an equatorial slice through the Pluto-Charon system, extending to 32,000 km from Pluto's center. The space between Pluto's surface (the interior gray circle) and the lower boundary of our simulation is colored in white. Note the deformation of the density field toward Charon, specifically the formation of a bridging structure asymmetric about the Pluto-Charon axis.

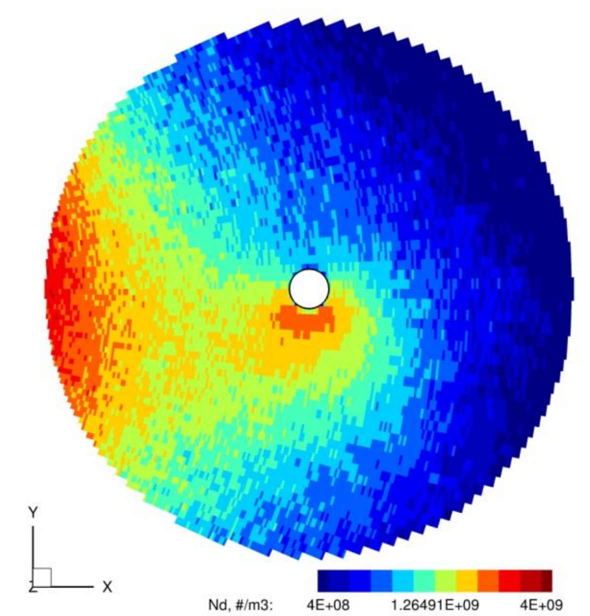

Figure 3. Number density contours in the region within 8,000 km of Charon's center, also in the equatorial plane. This coincides with the indicated white circle in Figure 2.