Collisional Evolution of the Enceladus Neutral Cloud

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Abstract. Water vapor ejected from Saturn's small moon Enceladus easily escapes its meager gravity to form a Saturn-encircling cloud with a low collision rate. Observations show that the cloud is quite broad in the radial direction, and we show here that collisions, though quite rare, may be largely responsible for this radial spreading. We modeled this cloud using the Direct Simulation Monte Carlo method, as fluid methods would be inappropriate for such a tenuous gas.

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INTRODUCTION AND BACKGROUND

In 2005 the Cassini spacecraft orbiting Saturn discovered that the small moon Enceladus is, amazingly, venting large quantities of water vapor from its South pole[i]. The gas easily escapes Enceladus' meager gravity to enter Saturn's orbit, forming what we call a "neutral cloud" surrounding Saturn, consisting mostly of H_2O and its dissociation products OH and O. The cloud itself was actually discovered by Shemansky et al. [ii] over a decade earlier with the Hubble Space Telescope (HST), which detected OH via UV fluorescence. Shemansky et al had suspected the presence of orbiting neutrals on the basis Voyager mission data, which revealed surprisingly cold electrons in Saturn's magnetospheric plasma. The abundance of H_2O (as ice) on moons in the outer solar system led them to suspect that the orbiting neutrals were H_2O. They searched for OH with HST, rather than H_2O, as it is easier to detect. The cloud is shown in Figure 1, in an image captured by the Cassini UV spectrometer (UVIS) on its way to Saturn. It shows fluorescent emission from atomic oxygen. These radicals can survive for months at a time without reacting because they are in a nearly pure vacuum.
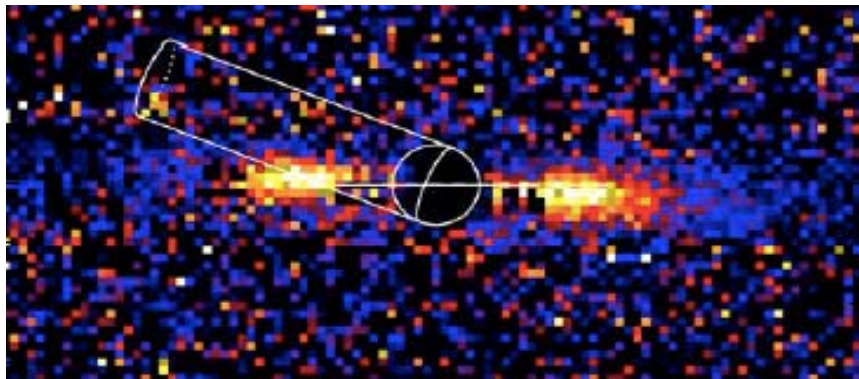

FIGURE 1. Atomic oxygen orbiting Saturn, imaged by the Cassini spacecraft UVIS instrument (reproduced from Melin et al.[iii]). The drawn circle is Saturn (invisible at this wavelength). Its rings are indicated by a horizontal line. The atomic O, as discussed in the text, originates from H_2O ejected from Saturn's small moon Enceladus. The white lines indicate Saturn and its rings (center), along with Saturn's shadow extending to the upper left.

Since its discovery in 1993, the cloud has been modeled in an attempt to explain its various features. The work focused on reproducing the observed abundance of OH (the only component of the cloud observed until Cassini's arrival at Saturn in 2004) and its radial breadth. The breadth requires explanation, as shown in Figure 2. Water vapor

is ejected from Enceladus as a cold gas, and does not have enough energy to travel far from Enceladus' orbit. The observed cloud, however, is seen far out from Enceladus' orbit.
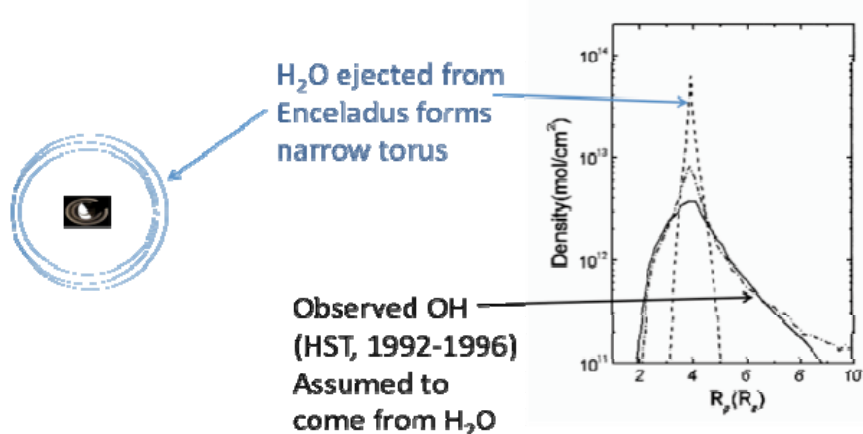

FIGURE 2. Water vapor ejected from Enceladus would form a narrow torus in the absence of some radial spreading mechanism (thin dotted line). Instead, observations by the Hubble Space Telescope (solid line) showed a broad cloud of OH. The dash-dotted curve shows the model results from reference iv. Note that, in contrast to other plots in this paper, this plot (from iv) shows column density of H_2O and OH, that is, density integrated along a line perpendicular to Saturn's equatorial plane.

These models[iv][v] included a variety of physical processes, but attributed the breadth of the cloud primarily to collisions between orbiting neutrals and ions trapped in Saturn's magnetic field. The ions are traveling much faster than the orbiting neutrals, so much so that collisions can easily provide escape energy to the neutrals. Another important process is dissociation by magnetospheric electrons and solar UV photons, which result in high-speed molecular fragments (the observed OH and O). A detailed summary of these processes is given in [vi]. These models were kinetic, that is, the gas is not modeled as a fluid, but as an ensemble of individual atoms and molecules. This was necessary as the cloud was far from equilibrium due to the rarity of collisions and the inclusion of nonthermal processes such as molecular dissociation.

Motivation for New Modeling: New Data Shows a Broader Cloud

New data, published by Melin et al. in 2009 [iii], showed that the cloud is actually much broader than modelers had assumed. Melin et al. reanalyzed the HST OH observations and found that the original analysis had underestimated the breadth of the OH cloud. They also published, for the first time, observations of the atomic oxygen component of the cloud (Figures 1 and 3), which was seen out to an astonishing 25 R_S (Saturn Radii; for comparison, Enceladus is at 3.95 R_S).

Despite the modelers' successes; they did, after all, make estimates of the water vapor source rate that agreed with later in-situ measurements by the Cassini mission (on the order of 10^{28} H_2O s^{-1}), these new observations suggested that something was missing. That same year, Farmer [vii], provided a possible answer: neutral/neutral collisions. The modeling by Jurac et al. [iv] included neutral/neutral collisions, but assumed that they could all be modeled as collisions between oxygen atoms. Farmer pointed out that, unlike O, H_2O and OH molecules have large permanent electric dipoles, which have long-range interactions unlike the non-polar O. The modelers had apparently underestimated the neutral/neutral collision cross section.

Farmer pointed out that neutral/neutral collisions, though rare, should occur more often than the other processes described above. Farmer constructed a simple fluid model to investigate the effect of collisions. By necessity, a fluid model neglects those processes thought to be most important by previous modelers (dissociation, high-speed ion/neutral collisions). Farmer numerically solved fluid equations developed in the study of accretion disks, in which the effect of neutral/neutral collisions is included through the specification of viscosity. Viscosity in an orbiting gas results in radial spreading, as shown in Figure 4.
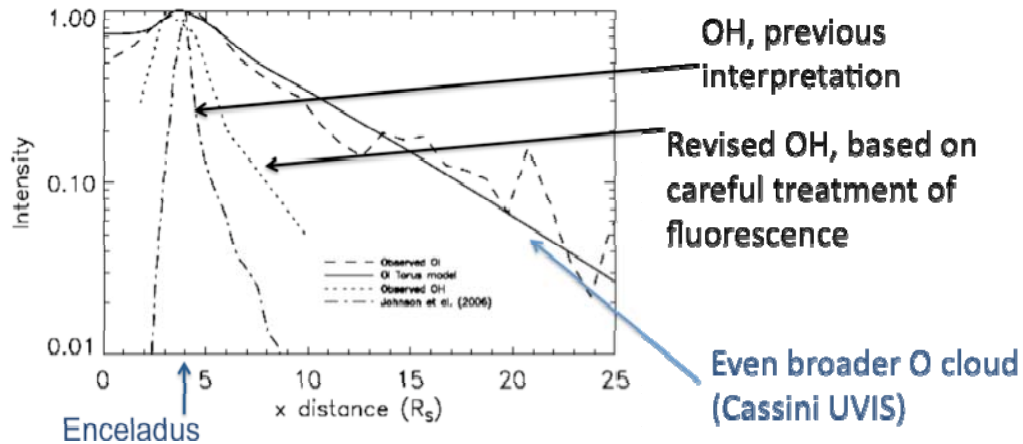
FIGURE 3. Observations of the Enceladus cloud, adapted from Melin et al. [iii] The Cassini spacecraft UVIS instrument first observed atomic oxygen orbiting Saturn via reflected solar light (UV fluorescence at 130.4 nm), and found it out to an astonishing 25 R_S. (note that Saturn's center is at 0 R_S, Enceladus is at 3.95 R_S). Melin et al. also reinterpreted the Hubble observations of OH, finding it to be broader than previously found. The new O and OH observations both required models with new spreading processes.

In the viscous spreading model, the combination of "Kepler shear" and viscosity spread the disk. Kepler shear is simply Kepler's third law: orbital speed decreases with distance from the central body, while viscosity is a property of gases that results in the exchange of momentum between adjacent parcels of gas. Viscosity provides a kind of friction between adjacent orbits: consider two adjacent streams of orbiting gas; the inner stream moving faster than the outer stream, by Kepler's third law. Viscosity transfers momentum between the two streams, speeding up the outer stream and slowing the inner stream. This results in the outer stream moving further outward and the inner stream moving further inward. Farmer concluded that this viscous spreading, alone, can account for the breadth of Enceladus' neutral cloud.
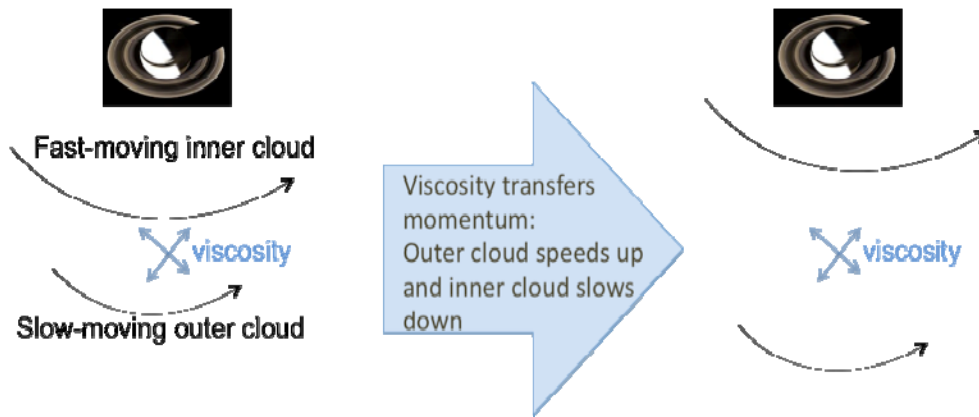

FIGURE 4. Sehematic of spreading process proposed by Farmer [vii], in which collisions between cloud molecules result in viscosity. We tested this fluid concept with our DSMC model.

MODEL DESCRIPTION AND RESULTS

To test Farmer's idea we investigated the effects of neutral/neutral collisions using a "direct simulation Monte Carlo" (DSMC) model, a kind of kinetic model. "Direct simulation" refers to the fact that it calculates the trajectories of individual molecules in the gas. Our model uses on the order of 10^5 "test particles" to represent the cloud, which has a content of $\sim 10^{35}$ atoms and molecules. One reason for using such a model is that a continuum fluid model (such as Farmer's) cannot include nonthermal processes such as dissociation and ion/neutral collisions. Another is the rarity of collisions: according to Bird [x], a contiuum model is only appropriate if the mean free path between collisions is small enough, whereas collisions in Enceladus' cloud only happen about once per orbit in even the densest part of the cloud. Our model uses the methods described Bird [x] and is described in detail by Cassidy and

Johnson (2010)[vi]. It includes physical processes from the earlier kinetic models, dissociation and ion/neutral collisions, along with a more careful treatment of neutral/neutral collisions between the cloud's three main constituents (H_2O, OH and O).

The particle trajectories in our model are approximated as idealized orbits, Keplerian ellipses. A typical molecule in our model orbits Saturn undisturbed for most of the time, except for the occasional event, such as a neutral/neutral collision. The program uses the calculated rate of a given process and a random number generator to determine whether or not that process happens at a given moment (the "Monte Carlo" of DSCM refers to this use of probability). For neutral/neutral collisions, the focus of this paper, the rate is determined by two properties calculated from the particle trajectories, the gas density and relative particle speeds, along with a specified speed-dependent collision cross section.

The details of the collision are determined by the choice of an intermolecular potential, along with the assumption of elasticity, which provides a simple set of equations that determine the molecular velocities following a collision. In the case of H_2O/H_2O collisions, we used an inverse cube potential, as appropriate for a dipole/dipole interaction. After calculating the post-collision velocities, new parameters for the molecule's orbital ellipses are calculated, and the molecules resume their orbit. Eventually, particles are lost through one of several processes. If their orbits intersect Saturn's rings (or Saturn itself), the molecule is assumed to be lost. The other two loss processes are escape (molecules leave the Saturnian system) and ionization by magnetospheric electrons or solar UV photons (our model does not follow the ions). Ionization is another probabilistic process.

We ran our model with and without neutral collisions. The results are shown in Figure 5. We found that the inclusion of neutral/neutral collisions is critical to match the observations. The case without neutral/neutral collisions is similar to earlier modeling efforts [iv] [v], which did not have the benefit of the latest data from [iii].
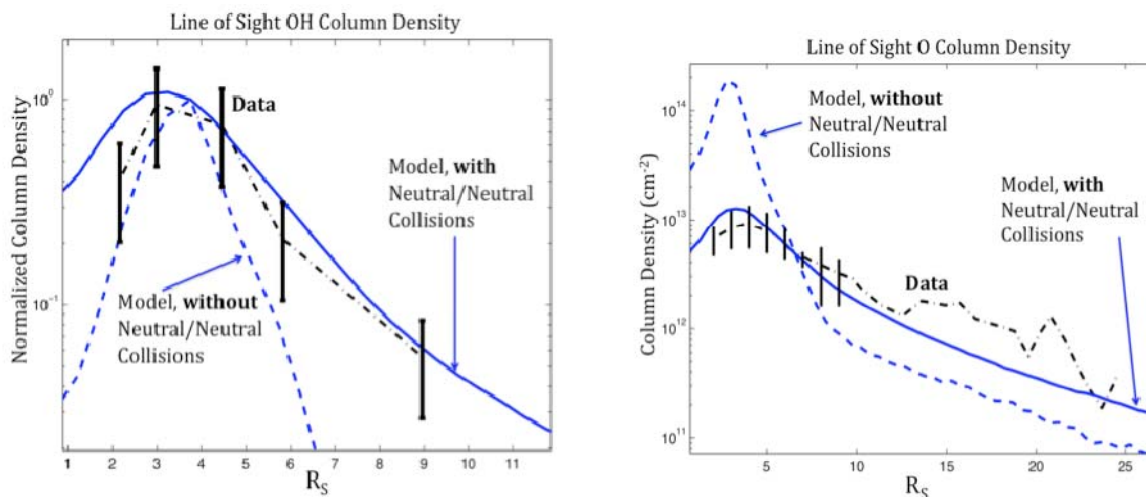

FIGURE 5. DSMC model results compared to data. The vertical axes are the "line of sight" column density, the integral of density along a line of sight. The column densities are derived from the intensity of reflected UV light seen by Hubble (for OH) or Cassini (O). IThe figures above compare model results with and without neutral/neutral collisions; the cases with neutral/neutral collisions clearly do a better job of reproducing the observations. In the simulations without collisions, the cloud is still spread by other processes involving magnetospheric plasma and solar UV photons.

For comparison, we also ran a case that matched, as closely as possible, the parameters of the Farmer fluid model (Figure 6). This version of our model had only neutral/neutral collisions, no ion/neutral collisions or dissociation. The two models, surprisingly, agree quite well. Unfortunately, we cannot compare the two beyond 10 R_S, though Farmer (pers. comm.) said that the fluid model falls off faster with distance than the DSMC model. (Note that neither of these models match the data as well as the full simulation shown in Figure 5, particularly the O observations.)
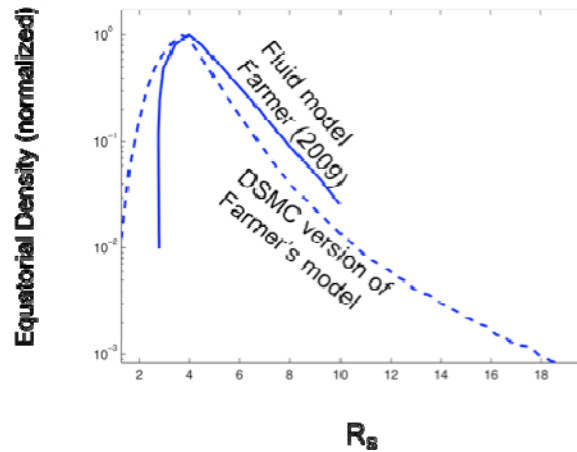
FIGURE 6. Comparison of DSMC model results and Farmer's fluid model. The vertical axis is equatorial density. The two agree fairly well, qualitatively, though the match is poorer at large distances. As described in the next section, the agreement is deceptive.

Discussion: Mechanism for Cloud Spreading in the DSMC Model

The similarity seen in Figure 6 is deceptive. Though they produce similar results for that set of parameters, a closer look at the simulations shows substantial differences. Those differences are illustrated in Figure 7, which shows schematics of particle trajectories from the two models. The fluid model assumes that the orbiting gas consists of particles on nearly circular concentric orbits. The trajectories produced by the DSMC model, by contrast, look nothing like that. In our model, particles that travel out to large radial distances maintain periapses near Enceladus' orbit, there are no circular orbits away from the densest part of the cloud. This results from the fact that nearly all collisions happen in the vicinity Enceladus' orbit.
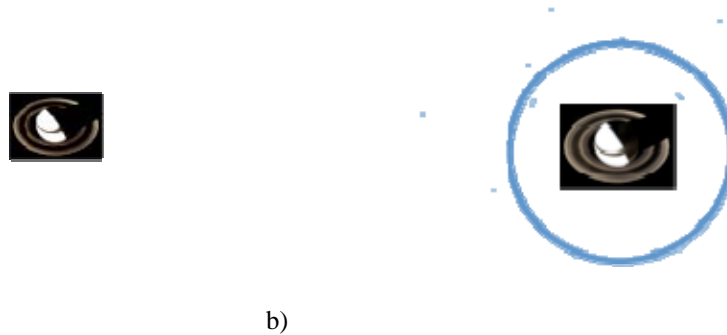

a)   b)

FIGURE 7. Schematics of two different collisionally-spread clouds. a) The particle trajectories that result from a traditional viscous disk fluid model: the particles have concentric, nearly circular orbits and the collisions that produce viscosity happen throughout the cloud. b) Schematic of orbits in the cloud modeled with DSMC. The particles are launched onto eccentric orbits by collisions in the densest part of the cloud at Enceladus' orbit. Collisions are exceedingly rare away from Enceladus' orbit.

We conclude with a description of the mechanism behind collisional spreading in our model. The viscous spreading mechanism described earlier is well understood, but the mechanism that produced our results (Figure 7a) is quite different, and shows the necessity of a kinetic approach. Smyth and Marconi [viii] and Trulsen [ix] reported on similar models, but they did not describe the details of the spreading process. Trulsen wrote, rather cryptically, that "elastic collisions draw energy from the ordered [orbital] motion and put it into random motion," but did not describe how this happens.

Each collision results in an exchange of momentum and some angular deflection[x]. To put it another way, each collision takes a fraction of the particle's relative speed and redistributes it in a random direction. The gas ejected from Enceladus is quite cold (~180 K) [vii], and the relative speeds in such a cold gas are quite small, 100s of ms^{-1}, so it is not immediately apparent how collisions in such a cold gas could provide molecules with the many km s^{-1} necessary to spread the cloud to the observed breadth[1]. But these thermal speeds, though small compared to the orbital speed (12.5 km s^{-1}), provide a slight variety in orbital eccentricity and inclination following their ejection from Enceladus. This eccentricity and inclination provide for much larger collision speeds: in the case of a circular orbit intersecting an eccentric orbit, for example, the relative speed can be approximated as[xi] eccentricity × orbital speed.

Collisions randomly redistribute of some of this relative speed, hence the earlier quote from Trulsen. As the cloud evolves, the particles' orbits became more eccentric (and inclined) [ix], resulting in larger collision speeds, and so a larger fraction of the orbital speed becomes available for random redistribution. In this way, the ordered circular motion of freshly-ejected H_2O from Enceladus is turned into random motion, and the orbiting particles end up with a wide variety of orbital elements; eccentricity, inclination and semi-major axis.

This is quite different than viscous spreading, but, as in that mechanism, the collisions transfer energy and angular momentum (which is, of course, conserved), with the result that at most of the orbiting gas falls inward toward the central body (Saturn and its rings, in this case) while a small fraction receives enough energy and angular momentum to escape the system.

The collisional evolution depends critically upon the elasticity of the collisions involved. We assumed that the collisions in our model are purely elastic, appropriate for the slight deflections that result from the long-range interaction of permanent electric dipoles (H_2O and OH molecules in this case). Inelastic collisions produce very different results. Inelastic collisions *remove* rather than redistribute the relative speed between colliding particles, and so rather than increasing the variety in eccentricity, inclination and semi-major axis, inelastic collisions reduce their variety. This inelasticity is the main reason for the very different nature of Saturn's main rings and our cloud: both are made up of colliding particles orbiting Saturn, but Saturn's main rings are made up of particles on nearly circular orbits in a perfectly flat plane [ix xii].

This "degeneration" of the particle orbits happens for inelastic collisions with coefficients of restitution less than about 0.65 or 0.7. [viii ix] Although we assumed elastic collisions in this model, some collisions in the cloud will be highly inelastic, particularly the occasional high-speed, head-on collision (the vast majority are glancing collisions).

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[1] Note that collisions are not the only process spreading the cloud, as discussed earlier.