FORMATION OF SATURN'S E-RING BY EVAPORATION OF LIQUID FROM THE SURFACE OF ENCELADUS

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If a liquid is emplaced by volcanism on the surface of Enceladus, some of it will evaporate into space. The resulting cloud of gas will expand and supersaturate as its temperature drops and ice grains will nucleate. It is possible that the E-Ring around Saturn is created by such a process.

The E-Ring was well imaged during the Earth's last ring crossing in 1979-80. Analysis of CCD observations indicates that the ring has a brightness peak at the orbit of Enceladus, suggesting that the satellite is the source of the ring material [1,2]. Pang et al. [3] have concluded that Voyager star tracker data are consistent with ring particles that are narrowly distributed in size (1.0 - 1.25 μ radius) and roughly spherical in shape. Although an impact origin [4] cannot be ruled out, the existence of a ring associated with the most recently active of the Saturnian satellites seems more than coincidental. Some regions on Enceladus show evidence of resurfacing within the last 10^9 years [5]. Heating due to tidal dissipation is the most likely mechanism for melting the tiny moon, but the present orbital eccentricity is too small to maintain a molten interior unless the thermal conductivity is lowered by the presence of clathrate hydrates [6]. The resurfacing of Enceladus is probably due to volcanic eruptions of a water-ammonia magma, as the NH_3-H_2O system has a eutectic point at 173°K [7].

Y. P. Raizer [8] examined the condensation of a gas sphere expanding adiabatically in vacuo. Using homogeneous nucleation theory, he derived approximate expressions for number of condensation centers and number of molecules per particle. Given the initial pressure, temperature, and radius of the gas cloud, the maximum supersaturation, degree of nucleation, and final grain radius can be calculated. If a pool of NH_3-H_2O liquid is erupted onto the surface of Enceladus, ammonia will evaporate into space (as will H_2O, but the vapor pressure of NH_3 is 3 to 4 orders of magnitude greater than that of H_2O at 173-193°K). The ammonia gas will expand, saturate (at 144°K) and then supersaturate, at which point solid-phase nucleation will commence [Fig. 1]. Nucleation rate is exponentially dependent upon supersaturation, which reaches a maximum and decreases as the thermodynamic pathway of the system follows the solid/vapor equilibrium curve. The nucleated particles continue to grow until the system has expanded to the point where evaporation is as likely as nucleation, then the grains cool to the ambient temperature (about 60°K). 1μ ammonia ice grains will result from a 173°K NH_3 cloud of radius 500 m over a pool of eutectic NH_3-H_2O liquid of similar radius. Larger source regions or higher magma temperatures yield larger particles, and smaller or cooler clouds produce smaller particles. For an ammonia cloud with initial radius R at 173°K, the final radius of nucleated grains is approximately $r = 7.9 \times 10^{-9} R^{0.88}$ (cgs units). The degree of nucleation weakly depends on initial conditions and is about 30% at 173°K. Raizer's theory can be modified to consider a cylindrically symmetric gas cloud expanding away from a linear source (crack). An initial cloud radius similar to that in the spherically symmetric case yields only slightly larger grains. Although nucleated grains will not in general be spherical, they will tend toward sphericity as they are eroded and evaporate. Formation of 1μ water droplets by this mechanism requires a 20 m radius pond of pure water at 273°K.

The velocity of the ammonia ice grains (7.7×10^4 cm s^{-1} at 173°K) is greater than Enceladus' escape velocity (2.1×10^4 cm s^{-1}), but less than the escape velocity from Saturn (1.8×10^6 cm s^{-1} from the orbit of Enceladus), so the particles go into orbit around Saturn. The lifetime of 1μ H_2O or NH_3 motes against sputtering by energetic oxygen ions in the Saturnian magnetosphere is on the order of 10^3 years, requiring very recent rejuvenation of the ring [9,10]. Evaporation lifetimes vary strongly with temperature, being longer than sputtering lifetimes at NH_3 grain temperatures below 70°K, or for H_2O below 110°K. The sputtering loss rate is about 10^{-16} g cm^{-2} s^{-1}, so a mass flux of about 0.8 g s^{-1} from Enceladus is required to maintain the ring. This flux corresponds to a loss of at least 1.4×10^{-6} of the mass of Enceladus over the age of the solar system. More than this fraction of Enceladus must be melted to provide the above mass of ammonia since the eutectic mole fraction of NH_3 is 34.6%. The surface of the "lava" will freeze rapidly, but volatiles dissolved in the magma may cause the frozen surface to break and expose fresh liquid to space.

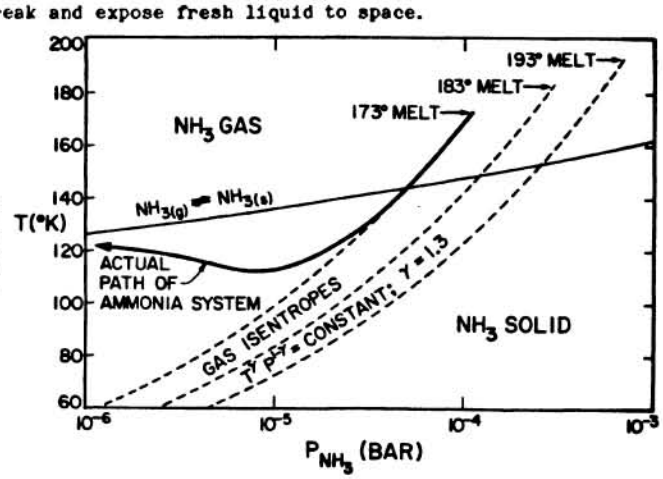

Figure 1: Pressure-temperature diagram illustrating the approximate path followed by an expanding and nucleating ammonia gas cloud derived from an evaporating eutectic NH_3-H_2O liquid. The triple point of NH_3 is at 195.7°K, 6×10^{-2} bar.

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The observed geometry of the E-ring has not been adequately explained, in particular, the vertical thickening with increasing distance from Saturn is not understood. Dynamical evolution requires more than the short lifetime of the ring to produce the present configuration: at the present grain density of 4×10^{-9} cm^{-3}, the mean time between collisions is at least 200 years. NH_3 particles nucleated from a 173°K melt will leave Enceladus at 7.3×10^4 cm s^{-1} and form a lens-shaped ring extending from 3.15 to 5.01 R_s with a vertical thickness of about 3×10^4 km [Fig. 2]. To achieve the present shape of the ring, some other mechanism(s) must be invoked. Gravitational scattering by the larger satellites Tethys and Dione may be important to the evolution of the ring. The magnetospheric plasma probably imparts an electrostatic potential on the grains, causing orbital perturbations due to Lorentz forcing. If a 1μ ammonia grain is charged to a voltage similar to the plasma electron energy (over 20 eV), the Lorentz force will be over 1% of the gravitational force. Radiation pressure will make the orbits gradually decay, and direct particle drag from impinging ions and distant Coulomb drag spread the ring at a rate dependent on the grain charge and plasma parameters. A numerical model including these effects would contribute much toward the understanding of the E-ring's structure.

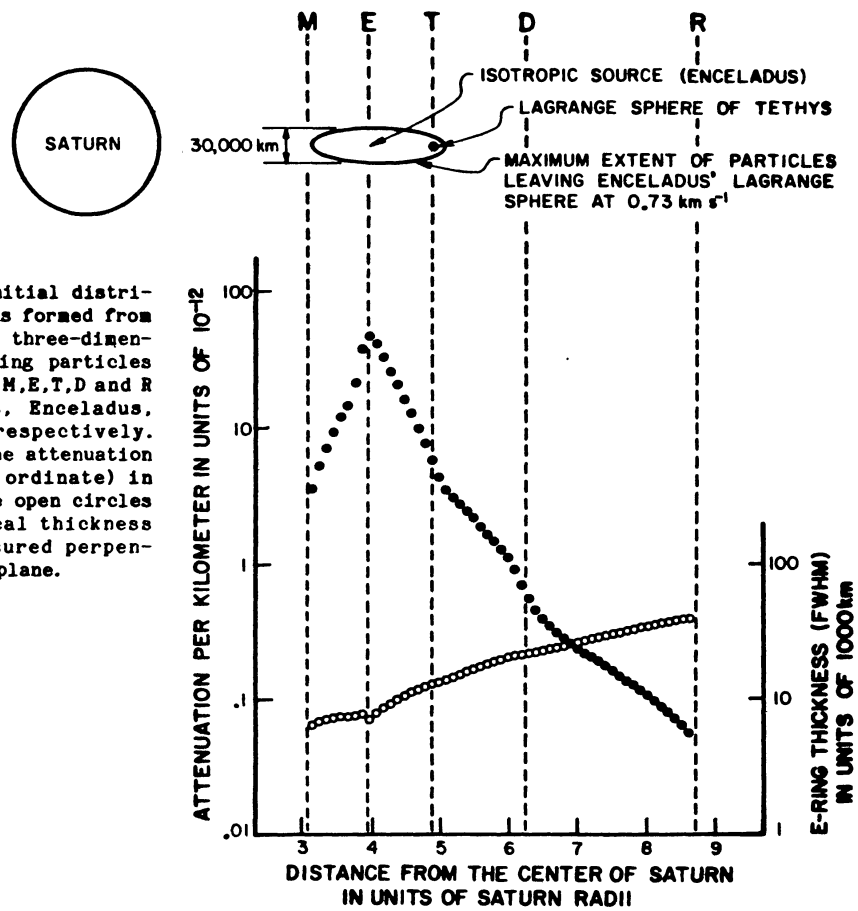

Figure 2: Comparison of initial distribution of ammonia ice grains formed from a 173°K melt (top) and the three-dimensional distribution of E-ring particles found by Baum et al. [1]. M,E,T,D and R mark the orbits of Mimas, Enceladus, Tethys, Dione and Rhea, respectively. Filled circles represent the attenuation per kilometer (left-hand ordinate) in the equatorial plane, while open circles represent the true physical thickness (right-hand ordinate) measured perpendicular to the equatorial plane.

REFERENCES

[1] Baum, W. A. et al. "Saturn's E-Ring" (pre-print, 1983)
[2] Baum, W. A. et al. Icarus 47, 84 (1980)
[3] Pang, K. D. et al. Lunar and Planetary Science abstracts 14, 592 (1983)
[4] McKinnon, W. B. Lunar and Planetary Science abstracts 14, 487 (1983)
[5] Smith, B. A. et al. Science 215, 504 (1982)
[6] Squyres, S. W. et al. Icarus 53, 319 (1983)
[7] Stevenson, D. J. Nature 298, 142 (1982)
[8] Raizer, Y. P. Soviet Physics JETP 37, 1229 (1960)
[9] Haff, P. K. et al. "Ring and Plasma: The Enigma of Enceladus" (preprint, 1983)
[10] Morfill, G. E. et al. J. Geophys. Res. 88, 5573 (1983)