IS ENCELADUS A COMET? A COMETARY PERSPECTIVE.

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Introduction: The discovery of icy plumes emanating from Saturn's moon Enceladus by the Cassini spacecraft has raised questions about the cometary nature of this small satellite. The release of gas and dust from cometary nuclei is restricted to "jets" or plumes also and this activity has been observed in comets at distances much further than Saturn's orbit, including comet-like activity and a resolved coma of the Centaur Chiron. Enceladus and Chiron have sizes that are much larger than cometary nuclei but their atmospheres are still largely unbound, similar to the exospheres of comets. With Chiron, Enceladus may represent a transitional object in this respect, intermediate to the tightly bound, thin atmospheres typical of planets and large satellites and the greatly extended atmospheres in free expansion typical of cometary comae.

Measurements of the neutral and ion composition of the plumes reveal the presence of water group species, nitrogen-bearing molecules, and other species that have been found in comets. The nature of the volatile materials in Enceladus may also bear similarities with ideas of cometary ices. In other respects, the large size of Enceladus relative to comets and the presence of Saturn and its magnetosphere nearby, brings into question the validity of applying scaling laws to cometary results in order to understand the environment surrounding Enceladus. In addition, release mechanisms for the icy grains and gases at Enceladus, including liquid water mixtures below the cold, icy surface, are not thought to be applicable to comets. These issues and others are discussed as we offer a cometary perspective on our current understanding of Enceladus.

Observations and *in situ* Measurements: The Cassini spacecraft is opening a new chapter in our understanding of the icy moon Enceladus and the role of venting as the major source of neutral gasses and dust in its surrounding environment. Recent Cassini observations have established that the icy moon Enceladus is actively venting and ejecting water, other neutral molecules, and dust; indicating that it is the origin of the surrounding atmosphere and E-ring torus. The interactions between the subsurface gas source and the jet-like activity of the neutrals and dust are critical processes with significant implications for the evolution of the broader environment. Understanding these interactions would enable us to establish source properties during past and future Cassini flybys and investigate its time variability from encounter to encounter. Due to many similarities to cometary behavior, comparisons to cometary models may allow us to make better estimates of the gas and dust production rates at Enceladus and the likely composition of neutrals and ions in the venting region.

Enceladus and the Surrounding Environment: The Cassini spacecraft has performed several close flybys of Enceladus, revealing the moon's surface and environment in great detail and discovering a water-rich plume venting from its South Polar Region (SPR). The composition of the Enceladean plume as measured by the INMS instrument is similar to that seen at most comets, containing mostly water vapor as well as minor components of CO (and possibly N_2), CH_4, CO_2, and simple and complex hydrocarbons, such as propane, ethane, and acetylene [1]. This discovery, along with the presence of escaping internal heat and very few impact craters in the SPR, indicates that Enceladus is geologically active. The discovery of the plume supports the notion that material released from Enceladus is the source of the E-ring, composed of water ice grains that are primarily 0.3 to 3 mm in size [2]. There are two mechanisms contributing to the ring [3]. The most important source of particles comes from the cryovolcanic plume. For gas or dust to escape from a small icy body, the radial component of the gas velocity must exceed the gravitational attraction. For a satellite orbiting a planet we must also consider the Hill sphere. For Enceladus, the Hill sphere radius is 949 km, the escape velocity from the surface is 239 m/s and this speed is reduced to 205 m/s at the Hill sphere radius. While a majority of particles fall back to the surface, some escape and enter orbit around Saturn. The second mechanism comes from hypervelocity micrometeoroid impacts of Enceladus, raising dust particles from the surface, but this alone cannot explain the dust data [3]. This leaves gas entrainment of dust from the vents as a viable source. Dusty gas interaction is necessary to understand the complex interactions in the plumes and its surrounding environment. We estimate that the maximum grain size that can be rifted due to gas entrainment is about 10 – 100 μm for icy solid spheres. This doesn't appear to be sufficient to lift icy grains that are seen in the E-ring unless the particles are very fluffy.

Cassini images show fine structures within the plumes, revealing numerous filaments (perhaps due to numerous distinct vents) within a larger, faint component extending out nearly 500 km from the surface. Cassini CDA data are compatible with a dust source and the UVIS later observed gas jets coinciding with the dust jet-like features during recent flybys of Enceladus. These structures of dusty gas flow are also observed in comets due to surface topology.

Source Mechanisms: Analysis of the outgassing suggests that it originates from a body of sub-surface liquid water, which along with the unique chemistry found in the plume has important astrobiology implications. Moons of gas giants can become trapped in orbital resonances that lead to forced libration or orbital eccentricity; proximity to the planet can then lead to tidal heating of the satellite's interior, offering a possible explanation for the activity. However, recent work has shown that Enceladus doesn’t oscillate about the tidal equilibrium [4] as required by the tidal heating model of Ojakangas and Stevenson [5], so other mechanisms must be responsible. The combined analysis of imaging, mass spectrometry, and magnetospheric data suggests that the observed south polar plume emanates from pressurized sub-surface chambers, similar to geysers on Earth [6]. Another possible method for generating a plume is sublimation of warm surface ice. Temperatures found near the south pole by CIRS range from 85–90K to as high as 157K in small areas. This is too warm to be explained by solar heating, indicating heating from the interior of Enceladus [7]. Ice at these temperatures is warm enough to sublimate at a much faster rate than the background surface, thus generating a plume. However, the abundance of particles in the south polar plume favors the cold geyser model, as opposed to ice sublimation [6]. Alternatively, Kieffer et al. [8] suggest that the plumes originate from clathrate hydrates, where carbon dioxide, methane, and nitrogen are released when exposed to the vacuum of space by the active, tiger stripe fractures. An additional possibility is the presence of amorphous water ice below the Enceladean surface. The exothermic phase change from amorphous to crystalline ice occurs in the temperature regime at Enceladus and releases sufficient water gas to explain the observed release rate as our preliminary modeling indicates. These mechanisms are appropriate for comets when gravity and low porosity considerations are included.

Dusty Gas Outflow: To test the cometary approach for Enceladus, a preliminary model of Chiron that treats the physics and chemistry of the comet coma in great detail [9] was prepared [10, 11]. CO was assumed to be the only volatile. Being a diatomic molecule, CO is not an efficient emitter in the infrared so the radiative cooling term is negligible. In the simulations, gas and dust are rapidly accelerated upon leaving the nucleus. For standard dust densities, small particles are more efficiently entrained with the gas flow than large particles, resulting in higher terminal speeds. The acceleration zone for all particles is approximately within 10 radii of the surface.

The inclusion of dust has two important effects on the gas flow. The first is an initial mass-loading of the gas, maintaining the gas velocity at subsonic values close to the surface of the nucleus. The second effect is a strong thermal coupling of the gas and dust near the nucleus. Upon release, the dust heats rapidly to its radiative equilibrium value of 95K. Collisions of molecules with dust particles heat the CO gas (initially at 30K) to 85K within a Chiron radius. This results in a terminal gas velocity about 80% higher than that calculated from a pure gas model. Even with a modest amount of dust (dust-to-gas mass ratio of 0.1), the gas is significantly heated in the near-nucleus region.

Summary: Is Enceladus a comet? The simple answer: No! This project represents a consistent evolution from our comet nucleus and coma experience to larger icy bodies in the outer solar system. The major difference is the systematic effects of increased gravity, including more spherical solid bodies (self-gravity), less porosity, the possible existence of liquid water due to internal sources of heat (Enceladus) versus possible cometary cyrovolcanism [12], internal inhomogeneities leading to jet-like features, and the possibility of a quasi-bound dusty gas atmosphere, as opposed to the extensive exospheres of comets [13]. Similarities exist also, including jet-like features with filaments (caused by surface topography in comets) gas and dust emission, surface evolution by dust accumulation, heat and gas transport through the surface layers, and others. Other effects that need to be considered in a realistic model include charging of particles, micrometeorite impacts and complex interactions with the E-ring neutrals and plasma. These topics remain outside the scope of this work as other researchers have considered them in great detail.

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