Comparing Enceladus to Comets: Implications for Their Outgassing Activity. C.M. Lisse[1,2], H.A.Weaver[2], M.E. Perry[2], E.P. Turtle[2], C.A. Hibbitts[2], N. Dello Russo[2]. [1]carey.lisse@jhuapl.edu [2]JHU-APL, Laurel, MD 20723

Abstract. The ~ 10^{28} molecules s^{-1} of material emitted from Enceladus flows out in plumes with similar physical properties (densities, speeds, collimation) to the outflows observed for active Jupiter family comets (JFCs). The physical similarities are due mainly to the common physics of low temperature outgassing of water dominated sublimation into a vacuum from a macroscopic body; the energy budgets and total mass outflow rates are similar (~200 kg s^{-1}, 10^{28} mol s^{-1}, and ~7 GW). The much higher escape velocity from Enceladus' surface provides a natural explanation for the micron sized particles in the plume and the ~100 um ice particles covering the South Polar Terrain (SPT) surface. Poorly understood methods of solar energy supply and material release deep into the cometary nucleus are required to produce the jets and non-water species seen in the coma. By contrast, outflow from Enceladus is driven by deep interior heating believed due to dynamical orbital processes. Although cometary jets reflect the bulk composition of the comet, the escape plume of Enceladus seems to represent only the smallish solid particles and gas derived from an interior liquid water reservoir. Comets and the Enceladus plume appear to share similar abundances for gas several species (e.g., CO_2, CH_4, NH_3, HCN), but a detailed compositional comparison awaits the final analysis of the in situ data from the Cassini INMS instrument.

Sizes, Shapes, and Densities. A **comet** is a primitive collection of gas and dust aggregated in the first few million years of the solar system, in the process of building the larger moons and planets. Comets are small enough that they likely experienced little to no processing due to radioactive heating and gravitational accretion. The radii of these highly irregular objects varies between 0.1 – 50 km, and the mean density of comets is ~0.5 g cm^{-3} [1,2], consistent with weakly structured bodies with no differentiation or hydrostatic flow and little to no densification. **Enceladus** is an object with mean radius ~252 km, above the r ~ 150 km radius limit of geological alteration due to large-scale compression, differentiation, and flow for bodies in the Saturnian system [3,4]. **Enceladus' shape** agrees well with an equilibrium ellipsoid for its rotational and orbital periods. Its estimated **mean density** of 1.6 g cm^{-3} is consistent with a 1.7 g cm^{-3} core + 10 km thick surface layer of water ice [3].

Temperature. The local thermal equilibrium temperature for the Saturnian system, where Enceladus presumably formed, is 90 K. **Surface temperatures** on Enceladus between 35 and 145 K have been measured [5]. The best measure of the **formation temperature** of comets is between 20 and 50 K [6], but surface temperatures of cometary nuclei at 1-2 AU vary between 200 and 400 K [7]. The **temperature depth profile** for a comet is set by solar insolation and the thermal conductivity of the nucleus. The Deep Impact experiment measured a mean skin depth due to rotation of ~1 cm, and due to revolution about the Sun of ~ 1 m, for a body of total width ~3 km [7]. Scaling to the 250 km radius of Enceladus, the equivalent thermal depth would be ~75 m. However, cometary jet structures are likely to reach deeper, as evidenced by the presence of CO and CO_2 in their outflow, species which should be present only below 10s of meters. For Enceladus, the estimated depth of the outgassing regions (i.e., the source ocean) is at least 1-10 km, as deduced from the width of the observed thermal hotspots, the dimensions of observed surface grooves and cracks, and the lack of the 10-20 km sized impact craters seen in the northern hemisphere [3].

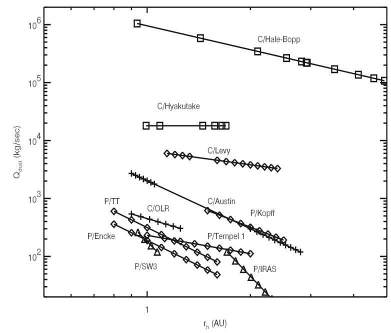

Figure 1 - Mass outflow rates for a small survey of comets [11,15]. Assuming D/G ~ 1, the JFC comets at 1-2 AU show similar outgassing rates to Enceladus.

Surface Gravity. Enceladus' equatorial surface gravity, ~ 0.011 g, is ~10^3 larger than the surface gravity found on the typical JFC, with a corresponding V_{escape} of ~240 m s^{-1}, as opposed to V_{escape} ~1 m s^{-1} found for JFCs [1,2]. This implies that cometary geological structures can be much weaker, supported by powdery ice materials with bulk modulus ≥ 10^3 Pa [2,8], and that gas and dust particles of much lower velocities (i.e., larger sizes) can be emitted by comets given the ambient outgassing flow (on the order of 0.5 km s^{-1}). In contrast, it implies that the material emitted by the gas outflow from Enceladus (~1 km s^{-1}) is more fine grained, and that the cracks, vents, scarps, etc. found on Enceladus are due to relatively strong water ice with bulk modulus ≥ 10^6 Pa [3,9].

Rock/Ice Bulk Composition. The material that went into making up Enceladus was most likely derived from comets or comet-like KBO bodies. Both Enceladus and comets are dominated by water ice mixed with rock, CO_2 and organic carbonaceous species, plus some other trace materials. The bulk ratio of rock/(rock

+ ice) ~0.6 for Enceladus [3,10] is similar to the D/(D+G) ~0.5 found in the comae of comets [11].

Plumes and Jets. Enceladus' outgassing of material from a localized region is very similar to the behavior seen in JFCs. Since the dominant working fluid (H_2O), entraining gas outflow velocities (~1 km s^{-1}, set by the expansion of water gas from the solid or liquid into free space), mass outflow rates (~200 kg s^{-1}[12] and Fig. 1), and the gas-dust interaction lengths are all similar (km), we expect similar outflow velocity profiles for the gas and dust in the two systems. The energy budget for cometary emission is dominated by solar insolation. With $p_v = 0.04$, at 1 AU a typical 3 km radius Jupiter family comet absorbs 1 kW m^{-2} * π(3 km)^2 = 27 GW, and at 2 AU, it absorbs ~7 GW. The IR emission rate from the Enceladus SPT, driven by internal dynamical/tidal heating is ~6 GW [5]. The latent energy represented by the vaporization of 200 kg s^{-1} of water ice (ΔH_{vap} = 2.3 x 10^4 kJ kg^{-1}) is small, on the order of 0.5 GW. **Plume/Jet collimation** - evidence for significant plume collimation is found in Cassini observations, with $v_{bulk}/v_{thermal}$ ~ 1.5 – 2.0 at 18 – 35 km altitude [12]. Similar focusing was seen for the main jets of comet 19P/Borrelly by the DS-1 spacecraft up to 5 km above the ~1 km radius nucleus surface [13]. Yelle *et al.* [14] have argued that this requires a strong cometary subsurface pressure reservoir and a supersonic focusing mechanism for the Borrelly jets to retain coherence. It is difficult to reconcile this with other measures of the weakness of cometary material but it would be less of a problem for the deep source and stronger water ice found on Enceladus.

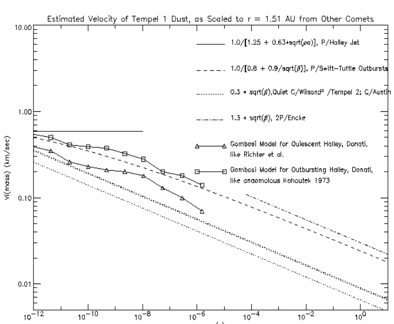

Figure 2 - A literature survey of V_{dust} vs. dust particle mass relations for cometary outflows. Even the most liberal would restrict the Enceladus icy plume particles capable of escaping to < 10 um [11,15].

Plume dust size sorting - assuming similar water gas sublimation driven dust entrainment physics in the Enceladus plume as for the cometry outgassing, we have V_{gas} ~ 0.5 km s^{-1}, and V_{dust} ~ 0.5 km s^{-1} $\beta^{-1/2}$ (where β = Surface Area/Volume for the dust grain; [15]). Only for particles less than 2 µm in size (~3x10^{-11} g) will V_{dust} > V_{escape} for Enceladus (Fig. 2); larger dust will fall back to the surface. Dust of less than few µm radius on escape trajectories is consistent with the the strong forward scattering signature of the plume dust [1], and with the particle masses detected by CDA [16]. 10 – 100 um water ice particles found on the surface from analysis of ISS and VIMS reflectance spectra are consistent with fallback of larger dust, originally emitted from the interior, onto the surface.

Plume/Jet Bulk Composition. Postberg *et al.* [16] report from CDA measurements that only 1% of the Enceladus plume is solid, and more than 90% of the solid mass is in water ice. The D/(D+G) ratio for the Enceladus plume is ~0.01, but ~0.5 for comets. (From the bulk rock/ice mass ratio, we would have expected 50% of the plume dust mass from water, and 50% from rock.) 5% of the solid particles show an ~ 1% concentration of NaCl and $NaHCO_3$, as expected for a liquid water ocean in equilibrium with a rocky core. Thus the composition of the plume does not reflect the bulk composition of Enceladus but that of a differentiated component. **Plume/Jet gas composition -** a rough estimate of the gas composition of Enceladus' outgassing is given by: 91% H_2O, 3.2% CO_2, 1.7% CH_4 ~1% (organics + N_2) [17]. For comets, the equivalent breakdown is ~85% H_2O, ~5% CO_2, 0.5-20% CO, and ~5% (organics [incl. CH_4] + NH_3). Ignoring the highly variable CO fraction of comets (very likely derived from a secondary source, like poly-H_2CO), the compositions are very similar – implying that he minor species must be dissolved in the Enceladus liquid ocean reservoir as well. The similarities includes **ammonia**, which is relatively common in cometary comae, at the 0.1 – 2% vs. water level. Current INMS limits on the ammonia abundance in the Enceladus plume gas is < 0.5% vs water [17]. (NH_3-rich water ice models requiring 10 – 100% NH_3 abundances, proposed in the pre-Cassini era to explain the apparent reprocessing of water ice at the low local temperatures found by the Voyagers, are clearly ruled out.) If missing, the lack of NH_3 gas in the plume can be easily explained if the plume vapor source is from a liquid ocean. NH_3 dissolves in water very stably, dues to its large dipole moment and hydrogen bonding ability (unlike, e.g., the detected plume hydrocarbon species), and should have a suppressed vapor pressure above the ocean.

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