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Chemical and phase composition of Enceladus: Insights from Cassini data

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Abstract

Compositional information obtained with Cassini instruments during Enceladus and Saturn's E ring flybys is used to constrain chemical and phase (minerals, ices, clathrates, organics, liquids) composition of the moon's interior. The Enceladus' plume emits cometary-type (NH_3, HCN, CH_4) likely primordial gases together with aqueously formed species (Na salts, silica and H_2). This could indicate aqueous-assistant differentiation of the comet-like moon with preservation of some primordial icy materials. Although the compositional data do not provide unequivocal evidence for a present liquid water reservoir that supply plume components, aqueous sources are possible.

1. Cassini chemical data

The compositional data have been obtained with the ultraviolet (UVIS), visible and near-IR spectrometers on surface and plume materials [1-3]; the Ion and Neutral Mass Spectrometer (INMS) on plume species [4,5]; and the Cosmic Dust Analyzer (CDA) on plume, Saturn's E ring, and stream particles [6-9]. The surface composition is dominated by water ice with possible traces of CO_2 and organic species [3]. Solid and gas plume emissions and E-ring grains are also dominated by H_2O. The plume gas composition is best characterized by the INMS data obtained with the low-speed E7 Enceladus flyby [5]. The high-speed sampling E5 data probably reflect impact dissociation of macromolecular organic species [4,5] which might also be the origin for species detected with CDA in the E-ring the plume grains [6]. INMS data suggest that H_2 is present in the plume gas [5]. The mass 28 species remain unresolved in INMS data; CO and N_2 are the likely candidates with upper limits set by INMS [5] and UVIS [2] data. Solid plume emissions are dominated by salt-bearing (chlorides and carbonates/bicarbonates of Na and K) icy gains [8], and the Saturnian stream particles primarily consist of silica [9].

2. Bulk and core compositions

The density of Enceladus (1.6 g/cm^3), the presence of HCN, NH_3, CH_4, and CO_2 in plume gases, the D/H isotopic ratio in these gases [4], and the occurrence of macromolecular organic matter in plume emissions suggest Enceladus' bulk composition more similar to that of the solar photosphere (except H and He) than CI carbonaceous chondrites. The abundances of major plume volatiles listed above (especially NH_3 and CH_4) are similar to those in comets. Comets could be compositional analogs of the moon. Despite this analogy, salts, silica and H_2 (if it is present) in the moon's emissions indicate aqueous alteration of rocks (dissolution, hydration, oxidation) in moon's history.

The low upper limit for N_2 in plume gases (0.5 % [2]), a preservation of typical cometary components and the low K/Na ratio in salt-bearing icy grains [7] indicate low-temperature ($T < 273$ K) water-rock interactions. This implies a low amount of accreted ^{26}Al and a formation of Enceladus at least several Ma after the Ca-Al-rich inclusions (CAIs), in agreement with recent formation models for the Saturnian system [10].

The low-temperature rock alteration is in agreement with the global shape of Enceladus which is not consistent with hydrostatic equilibrium [11,12]. The shape suggests that the rocky core has never reached temperature high enough to relax core topography. In this condition, a large porosity may have persisted in the organic-rich and hydrated core, leading to core density as low as ~1.7 g/cm^3. Depending on the core density, the ice shell may be as thin as ~13 km.

The low-temperature alteration of rocks of solar composition implies that CM2 carbonaceous chondrites could be used as a proxy for secondary mineralogy of the core. The major minerals are likely to be phyllosilicates (serpentine, saponite, cronstedtite), sulfides (troilite, tochilinite, pyrrhotite, pentlandite), magnetite and carbonates. Many of these phases are modelled to be present in the altered core [13]. CO_2 from melted ices converts to carbonate/bicarbonate species at alkaline conditions created by rock alteration. The organic fraction could consist of altered cometary-type C-H-O-N compounds [14] and may contain the insoluble polymer abundant in carbonaceous chondrites. Water-soluble and condensed light organic species (oils) and high-solubility Na salts could concentrate at the ice-core boundary along with NH_3 and methanol (also detected in the plume [4,5]) that strongly decrease melting temperature of ice. Both organic and water liquids could decouple the core from the icy shell and favour tidal heating.

2. Liquids and solids in the icy shell

Although NH_3-rich brine pockets are stable in the locally warmed surface ices, the plume gas composition is not consistent with degassing solely of aqueous fluids. The abundances of plume volatiles do not reveal a negative correlation with solubility in water. High-solubility NH_3 and HCN have almost the same comet-like content in the plume as low-solubility CH_4. Species reactive in aqueous fluids (HCN, NH_3) are not depleted compared to cometary abundances and the supposed reaction products are not detected. The INMS upper limit for H_2 (3.4 % [5]) in the plume is not consistent with complete dissolution of H_2 in water at pressures that characterize the shell. However, the plume gas composition agrees with sublimation of warmed water ice that contains volatiles trapped in mixed clathrate hydrates, small brine pockets and structural defects.

In contrast, H_2, salts and silica in the moon’s emissions indicate aqueous chemical processes. They alone do not prove present liquid water sources of the plume because salt and silica grains and $H_2(g)$ could be imbedded in ice through rapid freezing of earlier aqueous fluids. It is currently unclear how sublimation could produce the observed emission of ice particles, therefore plume salts could originate from current water solutions [7,8].

The occurrence of likely primordial volatiles (e.g. HCN, NH_3, CH_4, CH_3OH) together with aqueously processed compounds indicates compositional heterogeneity that should reflect mechanisms and scales of differentiation and later tidally-driven processes. In one possible scenario, salts and organic compounds could be concentrated in frozen dikes. In another pathway, these impurities could also be abundant in upper shell layers reflecting a rapid freezing of early oceanic water after sinking of a primordial icy-rocky shell. These scenarios suggest incomplete melting of primordial ices. Salts are abundant at the bottom of the shell and could be partially dissolved in liquid water.

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