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Sources of ^{40}Ar and N_2 for Enceladus' plumes

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Abstract

Recently the Cassini Ion and Neutral Mass Spectrometer (INMS) team has reported the probable detection of ^{40}Ar [1, 2]. Since ^{40}Ar is produced by the decay of ^{40}K, where in Enceladus does ^{40}Ar originate? For satellite models with the core composed of rock (i.e., all the nonvolatile species) in the center, and the ice above it containing water and all the volatiles, there is no choice but for the ^{40}Ar to originate in the core rock. Since ^{40}Ar in these models is essentially immobile in solid rock, it is difficult to explain how it would diffuse out and reach the surface, in the absence of magmatic or volcanic processes to transport core material to the surface. However, the relatively recent realization that the satellites could have undergone hydrothermal activity at various times in their histories provides a way around this problem. Also, the models have become more complex and require coupling between thermophysical and chemical modeling [3] as has been done in the case of meteorite parent bodies [e.g., 4, 5].

Most likely Enceladus is differentiated [6, 7] and the composition of its geysers [1, 2] indicates that the chemical environment offered moderately high temperatures, similar to those found in hydrothermal regions on Earth [6, 8]. One possible scenario explaining warm temperatures in Enceladus assumes early accretion involving heat from ^{26}Al decay [7, 9]. Under such conditions Enceladus would have undergone early hydrothermal processing similar to meteorite parent bodies. Meteoritic records as well as modeling of the hydrogeochemistry for Enceladus (using chondritic composition for the rock phase) [10] indicate that a large part of the potassium could be leached, significantly lowering its abundance in the core and changing the spatial distribution of that long-term heat source. The amount of potassium that entered solution is a function of the hydrogechemical conditions (temperature, pH, redox conditions], which are not known for Enceladus but may be assessed by comparison with the literature that addresses the evolution of the parent bodies of CI and CM chondrites.

If potassium minerals dissolved in the internal ocean then the heat from ^{40}K decay helped to warm the water. The ^{40}Ar produced during this early period probably escaped to the surface. However, as the ocean slowly froze and ice crystallized, a large part of the dissolved species were excluded from the ice. The remaining 'ocean' became increasingly 'salty' and occupied a decreasing volume between the bottom of the ice and the top of the core. In this model most of the observed ^{40}Ar could be created in this brine layer as a result of ^{40}K decay. This layer may be liquid because the supersaturated solution has a freezing point depressed to as low as 190 K. However, it is not clear at this stage if such a liquid layer was present throughout Enceladus' history. The solubility of Ar in water is relatively high (0.1 g per kg of pure water at 0 C, 0.5 at 30 C; three times more soluble than N_2). Solubility is inversely dependent upon temperature and decreases if other dissolved species are present (e.g., the solubility of Ar in seawater is ~20% less than in pure water). If this liquid layer is sufficiently large today, it could be the main ^{40}Ar reservoir. ^{40}Ar will build up slowly in any such reservoir because the ^{40}K half-life is ~1.3 x 10^9 years. Thus, the tapping of the ^{40}Ar reservoir must be relatively recent. In fact, Waite et al. [2] argue that at the present rate of ^{40}Ar discharge, Enceladus' total ^{40}Ar production would be exhausted in 10 My.

Not far below the suggested ^{40}Ar reservoir is the region where N_2 may have been created. Matson et al. [6] suggested that the N_2 in the plumes is formed by the thermal decomposition of water borne NH_3 in cracks in the surface region of the core. The envisioned analogs are the Earth's oce-

anic ridges where seawater percolates downward to depth and is heated to relatively high temperatures. In Enceladus when the water descended deep enough in the cracks to reach a high enough temperature, the decomposition of ammonia would take place and N_2 and H_2 formed. (Since clay minerals and other catalysts may have been present at the reaction sites, the exact temperatures at which this decomposition took place are not known.) The heated water rose and carried N_2 out of the core, directly into the aqueous layer reservoir, and then it eventually reached the surface. However, this model does not specify when these reactions took place, so it could not be inferred whether the N_2 is recently formed or was created billions of years ago and stored to be released later. The latest INMS observation finds that "NH_3 is present in the plume with a mixing ratio of 0.8%" [2]. This shows that the decomposition of (presumably primordial) ammonia did not go to completion. With ammonia still available, it is possible that N_2 is still being produced today if interior temperatures remain high.

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