THE EFFECT OF RADIOGENIC HEATING ON THE ACCRETION OF COMET 67P/CHURYUMOV-GERASIMENKO.

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Introduction: Radiogenic heating has played a major role in the evolution of small bodies in the early solar system [1,2]. Given the fact that short-lived nuclides such as ^{26}Al and ^{60}Fe were present in these bodies, they may have constituted a major heat source for metamorphism, melting, and differentiation in asteroids [3]. The influence of radiogenic heating has also been explored in comets. It was found that these bodies had to accrete over several Myr before reaching their final sizes to retain their amorphous ice, assuming they agglomerated from this solid phase [4,5]. The nitrogen deficiency observed in these bodies could result as well from the internal heating engendered by the decay of ^{26}Al and ^{60}Fe present in the refractory phase [6]. Meanwhile, formation delays of several Myr after the formation of Ca-Al-rich Inclusions (CAIs) in the protosolar nebula (PSN) have been invoked to maintain the presence of carbon monoxide in comets with sizes similar to that of Hale-Bopp [6,7].

Here, we investigate how heat generated by the radioactive decay of ^{26}Al and ^{60}Fe influences the formation of comet 67P/Churyumov-Gerasimenko (67P/C-G), as a function of its accretion time and size of parent body. To do so, we use a thermal evolution model that includes various phase transitions, heat transfer in the ice-dust matrix, and gas diffusion throughout the porous material and on thermodynamic parameters derived from *Rosetta* observations. Two possibilities are considered: either, to account for its bilobate shape, 67P/C-G was assembled from two primordial ~2 kilometer-sized planetesimals, or it results from the disruption of a larger parent body with a size corresponding to that of comet Hale-Bopp (~70 km). To fully preserve its volatile content, we find that 67P/G-G must have formed between ~1 and 7 Myr after the CAIs in the PSN, depending on i) the primordial size of its parent body and ii) the composition of the icy material considered (amorphous ice or clathrates and crystalline ice). Our calculations of the impact of radiogenic heating on 67P/C-G's composition are consistent with both comet accretion from primordial rubble piles and from debris issued from the disruption of a Hale-Bopp-like body.

Model and parameters: We use the one-dimensional thermal evolution model presented in [8]. In this model, the nucleus consists of a sphere made of a porous mixture of water ice and other volatile molecules (in both gas and solid states), along with dust grains in specified proportions. The model describes heat transmission, latent heat exchanges, all possible water ice structures and phase changes, sublimation/recondensation of volatiles in the nucleus, gas diffusion, gas trapping or release by clathrate formation or dissociation, as well as gas and dust release and mantle formation at the nucleus surface. The model computes the time evolution of the temperature distribution by solving the heat diffusion equation, which includes now an extra source term due to radiogenic heating, in addition to those depicted in [8].

Our computations have been conducted under the assumption that 67P/C-G results from the merging of two lobes originally formed separately. We postulated that these lobes originated from the disruption of larger bodies [9]. Consequently, we adopted a generic Hale-Bopp-like size for the body under consideration. Two distinct ice compositions, based on the current literature, have been investigated:

- *Mixed model*. The icy phase is made of pure solid water distributed half as pure crystalline ice and half in clathrate form [10]. Clathrate destabilization is simulated without any volatile inclusion in the cages; the latter does not affect the energetics of the destabilization process.
- *Amorphous model*. The icy phase of the nucleus is exclusively made of pure amorphous water ice [11].

Results: We have considered that the icy matrix made of clathrate and pure crystalline ice starts to devolatilize at temperatures higher than 47 K in the mixed model, which is the average clathrate formation temperature found in the PSN to match the volatile content of 67P/C-G [10]. In the amorphous model, the icy matrix starts to devolatilize at temperatures higher than 130 K, corresponding to the crystallization temperature of amorphous water [11]. The vastly different devolatilization temperatures imply that comets made from amorphous icy grains allow shorter formation delays than those made from crystalline ices and clathrates in the PSN to preserve their volatile budget.

Figure 1 represents the extent of the devolatilized region as a function of the formation delay within bodies with a radius of 35 km. For the sake of clarity, we defined a non-dimensional radius *r**, corresponding to the value of *r*/*R* with *R* the total radius of the object. The figure shows that a Hale-Bopp sized body must start its accretion at least ~4.6 and 4.9 Myr after CAIs formation for dust-to-ice ratios of 1 and 4, respectively, to fully preserve its volatile content in the case of the amorphous model. On the other hand, the accretion must start at least 6.4 and 6.9 Myr after CAIs formation for dust-to-ice ratios of 1 and 4, respectively, in the case of the mixed model.

Conclusion: We find that 67P/C-G's measured composition can be explained via its agglomeration from debris resulting from the disruption of a larger body having a Hale-Bopp size, provided that the accretion of this body is delayed to 4.6-6.9 Myr after the formation of CAIs.

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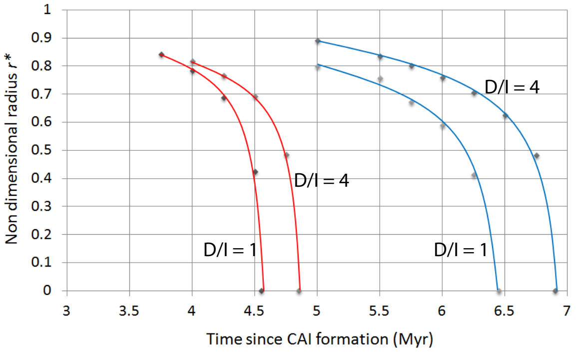

Figure 1. Extent of the devolatilized region (between 0 and *r**) within a body with a radius of 35 km as a function of its formation delay (D/I stands for dust-to-ice ratio). The red and blue curves correspond to the amorphous and mixed models, respectively.