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Agglomeration of 67P/Churyumov-Gerasimenko from clathrates and crystalline ices

O. Mousis (1), T. Ronnet (1), J. I. Lunine (2), P. Wurz (3), K. Mandt (4), P. Vernazza (1), A. Luspay-Kuti (4), F. Pauzat (5), Y. Ellinger (5), G. Danger (6), and L. D'Hendecourt (6).
(1) Aix Marseille Université, CNRS, LAM, UMR 7326, 13388, Marseille, France (olivier.mousis@lam.fr), (2) Department of Astronomy, Cornell University, Ithaca, NY 14853, USA, (3) Physikalisches Institut, University of Bern, Sidlerstrasse 5, CH-3012 Bern, Switzerland, (4) Johns Hopkins University Applied Physics Laboratory, Laurel, MD, USA, (5) Sorbonne Université, Laboratoire de chimie Théorique (LCT) Paris, France, (6) Aix-Marseille Université, PIIM UMR-CNRS 7345, F-13397 Marseille, France.

Abstract

The origin of cometary volatiles remains a major open question in planetary science. Comets may have either agglomerated from crystalline ices condensed in the protosolar nebula (PSN) or from amorphous ice originating from the molecular cloud and interstellar medium (Klinger 1980; Bar-Nun and Laufer 2003; Bar-Nun et al. 2007; Mumma & Charnley 2011; Rubin et al. 2015; Mousis et al. 2016a; Marty et al. 2017). Here, based on the recent argon, krypton and xenon measurements performed by the ROSINA instrument aboard the European Space Agency's *Rosetta* spacecraft in the coma of 67P/Churyumov-Gerasimenko (67P/C-G), we show that these noble gas relative abundances can be explained if the comet's building blocks formed from a mixture of gas and H_2O grains resulting from the annealing of pristine amorphous ice (i.e., originating from the presolar cloud) in the PSN. In this scenario, the different volatiles released during the amorphous-to-crystalline ice phase transition would have been subsequently trapped at lower temperatures in hydrate or clathrate forms by the crystalline water ice generated by the transition (see Figure 1). Once crystalline water completely consumed by clathration in the ∼25–80 K range, the volatiles remaining in the gas phase would have formed pure condensates at lower temperatures. The formation of clathrates and pure condensates to explain the noble gas relative abundances is consistent with an interstellar origin for the molecular oxygen detected in 67P/C-G (Bieler et al. 2015; Mousis et al. 2016b; Mousis et al. 2018), and with the measured molecular nitrogen depletion in comets (Rubin et al. 2015).

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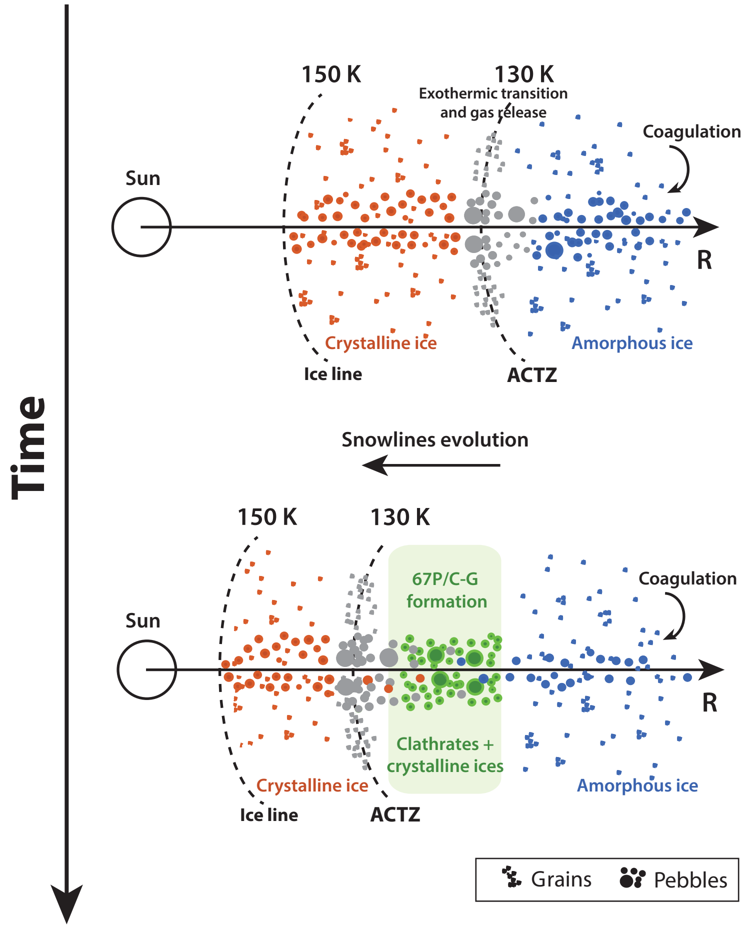

Figure 1: Illustration of the formation conditions of the ice grains precursors of 67P/C-G beyond the ice line during the cooling of the PSN. *Blue particles:* grains/pebbles made from pristine amorphous ice coming from ISM. *Red particles:* grains/pebbles made exclusively from crystalline ice condensed at the location of the ice line in the PSN. *Grey particles:* grains/pebbles made from crystalline ice resulting from the amorphous-to-crystalline transition at the location of the ACTZ line. *Green particles:* grains/pebbles incorporating clathrates and crystalline ices. *Top panel*: Snapshot of the distribution of grains/pebbles around the different snowlines at a given epoch of the PSN evolution. Small grains coagulate into pebbles which rapidly settle to the midplane and drift inward, thereby allowing pristine material originating from the outer portions of the PSN to be processed in the inner regions. Pebbles made of amorphous water ice crystallize at the ACTZ line and release the adsorbed volatiles as vapors during their inward motion. Crystalline ice also forms from the condensation of water vapor at the ice line which moves inward as the PSN cools down. *Bottom panel*: Snapshot of the distribution of grains/pebbles around the different snowlines at a later epoch of the PSN evolution. The snowlines have continued their drift inwards the PSN and clathrates formed at the surface of grains/pebbles that crystallized from pristine amorphous material at earlier times when the ACTZ line was present at these now cooler locations. With time, these regions of the disk cooled enough to favor the condensation of the most volatile species because the water budget was insufficient to form clathrates. 67P/C-G agglomerated from a mixture of clathrates and pure condensates formed in these regions.