To melt is not enough: Retention of volatile species through internal processing in icy bodies

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The outer Solar System hosts a vast population of small icy bodies, considered to be primitive remnants from the planet-formation epoch. Early thermal and collisional processes affected such planetesimals to varying degrees depending on the time scale and dynamics of early planet growth. Recent observations have revealed that many large ($>\sim$ 1000 km in diameter) transneptunian objects (TNOs) exhibit features of crystalline water ice in their surface spectra [1], as well as spectral features of more volatile ices, such as methane or hydrated ammonia [2]. These telltale observations should be accounted for when considering the alteration history and bulk processing of dwarf planets and their icy progeny. We will discuss preliminary calculations of early evolution scenarios for small icy-rocky bodies formed beyond the water-ice snow line. Such objects should also contain non-negligible fractions of pre-organic volatile compounds. The volatile composition and interior structure of these objects may change considerably due to internal heating and/or collisional modification prior to settling in their current (relatively quiescent) dynamical niches. Our initial model for the objects in question is that of a porous aggregate of various volatile compounds (as ices or trapped gases) and refractory silicate-metal solid grains, comprising the bulk matrix [3]. Chemical compositions for these objects are taken from existing simulations of chemical and dynamical evolution of disk material [4]. The key volatile species (e.g., H_2O, CO, CO_2, NH_3, CH_4, and CH_3OH) are also the most commonly observed in comets [5], which are remnants of such an early planetesimal population. Thermal and chemical internal evolution is examined self-consistently, as the abundances and locations of all species evolve, and we record mass ratios, temperatures, pressures, and porosity variations. The presence of volatile species in the interior can affect the overall heat balance and accompanied phase transitions [6,7]. Another important factor involving volatiles, mostly water ice, is the effect of shock- induced melting and vaporization on the fragmentation and flow regimes within the body, during massive collision events [8]. To explore the effects of collisions on the internal distributions of volatiles, we conduct 3D numerical simulations of collisions between porous icy bodies using the CTH shock-physics code [9]. The spatially heterogeneous effects of shock-induced heating, pore compaction, and bulk brecciation and redistribution of materials are used to estimate the post-impact re-equilibration of internal volatiles following collisions between similarly-sized bodies. We follow a long-term thermal evolution calculation ($>$ 700 Myr), through the bulk alteration of temperature, porosity and composition for icy dwarf planets ($>$1000 km in diameter). Some initial configurations result in a complex, differentiated structure, where the deep interior holds a few percent of water melt fraction, while there are shallower layers that can retain conditions for volatile-ice preservation (CO_2 and HCN, for this specific model). There exists a distinct separation between the warmer interior, which is much more compacted and hydrous, and the colder exterior, which is much more porous and stratified. If an evolved object, such as this, is subject to a massive collision, the effects of partial melting and porosity quenching may actually serve to trap more volatile species. We show that for massive collisions of icy bodies, the effect of melting may be grossly over-estimated, if extrapolated from that of cratering events. Interestingly, oblique impacts ($>$ 45 deg) will result in less than half of the volume experiencing pressures corresponding to water-ice melting. This means that the deep interior will not necessarily experience extreme alteration. Such an effect could even be more pronounced for porous or partially-differentiated objects. We focus on understanding the effects of different collision regimes (e.g., merging, disruption, hit-and-run, and graze-and-merge) on early volatile preservation. These regimes include potential moon-forming collisions between large TNOs. In the future, such results can be used to estimate the cumulative effects of multiple impacts. For that purpose, we need to understand the survival of water and more volatile species, as a function of their initial phases, objects' size and density (porosity), and the relative timing of collisional and thermo-chemical evolution.

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