EPSC Abstracts
Vol. 6, EPSC-DPS2011-183-1, 2011
EPSC-DPS Joint Meeting 2011

On liquid phases in cometary nuclei

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Abstract

We predict the occurrence of aqueous and hydrocarbon liquid phases in subsurface regions of comet nuclei dependent on heliocentric distance. Microporosity and the formation of a stabilization layer in the near-surface are prerequisites for liquid phase formation. Characteristics favoring subsurface melting are discussed including pore-size distribution, chemical composition, rotation rate and diurnal heating/cooling effects. Subsurface melting is expected to produce wetted layers of considerable strength and associated topographical changes. An important feature of this wetted-layer model is the predicted compositional variation with depth within the layer. Gas-liquid transport within such melt zones can induce major cometary outbursts. Implications for the formation of liquid-water environments in small bodies within protoplanetary disks are discussed.

1. Introduction

Models describing the nature of cometary nuclei have tended to be based on the presence of amorphous ice containing trapped condensed volatiles, which on being heated escape from deep within the nucleus [1]. Cometary outbursts are generally explained by way of the rapid release of trapped gases caused by a sudden temperature increase when amorphous ice converts to crystalline ice in the 135-160 K temperature range [2]. Such idealized models overlook the complex physical and chemical characteristics of cometary nuclei especially the role of organic compounds as well as the fundamental importance of the nanoscale properties of matter.

2. Liquid phase formation

2.1 Factors influencing melting

We show from detailed considerations of the physical and chemical characteristics of comets that liquid phases can form and persist in near-surface regions of certain cometary nuclei. At low heliocentric distances (r = ~2 to ~3 AU) such liquid phases are predominantly aqueous-based whereas at larger r the liquid phases are increasingly hydrocarbon (HC) in nature. Heat flow into the surface is favored by high carbon content which reduces heat lost to space owing to its relatively low thermal emissivity (for amorphous carbon, ε = 0.5-0.7 at 10-15 µm) whilst also increasing bulk thermal conductivity. In the aqueous case, heat flow to the interior can exceed the rate at which ice is converted to water vapor that is then able to escape through a thin porous outer layer, thereby creating a stabilization crust and leading to continual melting of ice, capillary flow and consolidation of the subsurface region. Liquid-filled pores and subsurface consolidation within the melt zone dramatically enhance bulk thermal conductivity inducing further melting and collapse of larger interstices thereby stabilizing the crustal region and tending to level the overlying surface. Analogies are made with processes involving soil mechanics. Liquid phase formation is favored in the presence of solutes (e.g. H_2O/CH_3OH mixtures) which depress freezing point. Similar processes can occur with HCs which we now know comprise a wide variety of organic compound. For instance, the role of n-alkanes will be important in that they have relatively high melting points compared to branched, cyclic or unsaturated HCs, and also poor solubility in alcohols, aldehydes and organic acids. As a result complex mixtures of organic compounds will exist in both solid and liquid form over a wide temperature range and will undergo transport through capillary flow. In both the aqueous and HC cases, the pore size distribution of the surface region must lie largely in the sub-micron range for a stabilization crust to form.

The thickness of the stabilization region strongly depends on its microporosity. For instance for water ice at r = 2 AU, the crust is <1 cm in thickness if the average effective pore size is <0.5 µm. For strength, the interfacial surface tension between wetted particles must be sufficiently large as to exceed the total vapor pressure of escaping volatiles at the temperature of the near-surface: this condition can easily be met for water ice contained within a sufficiently microporous structure. Terrestrial soils exhibit analogous properties. Capillarity, for example, allows a dry surface to draw water to elevations several meters above the water table and in the process imparts considerable strength to the soil.

2.2 Effect of diurnal thermal cycling on composition

Liquid-filled reservoirs can form and remain for extended periods within the subsurface of slowly-rotating nuclei as a consequence of cyclic heating and cooling of the surface, with cooling on the night side leading to freeze fractionation and the gradual formation of a depth-composition gradient within the melt zone. The outer region tends to become depleted in solutes, including; dissolved gases such as CO and CO_2, volatile constituents such as CH_3OH and HCHO, and inorganic salts, each of which concentrate in subsurface reservoirs, and may then become supersaturated in the solute, or remain liquid at depressed temperatures through supercooling within a microporous structure. Given this compositional change *vs* depth, a much larger temperature drop can be maintained in the wetted subsurface than for a pure component such as for water alone, thus maintaining a greater heat flux to the interior and enhancing the degree of melting. Initial estimates indicate that, under favorable circumstances, the melt zone for water ice can extend to depths of 10-20 m for a comet nucleus having a rotation rate of 0.02-0.10 d^{-1}.

2.3 Further implications of melting

The melt zone acts as a relatively impermeable, dense layer possessing a physical strength much greater than that of unmodified cometary material as explained above. The diurnal melt-freeze cycle draws liquid towards the surface and creates void space below the melt zone leading to local subsidence and the formation of pits or flat-bottomed depressions (cf. surface features on Comet 81P/Wild). In addition to water vapor, other volatiles escape from within comet nuclei, the characteristic depth of which depends upon intrinsic volatility and hence chemical composition. Where melt zones occur, volatilization of compounds beneath the consolidated region will be inhibited by accumulated pressure and any heat flowing into the nucleus will encourage melting of species other than water-ice notably the organic fraction deeper within the nucleus. As comets recede from perihelion and cool, aqueous phases within melt zones freeze, creating capillary-size voids which are filled by other lower-melting-point material from greater depths drawing the liquid HC phase nearer to the surface. Conversely, where the warmer liquid phase is drawn deeper into the nucleus by capillary forces, heat transport to the interior is facilitated.

Cometary nuclei which do not experience water ice melting at r = 2-3 AU may still exhibit melting phenomena after perihelion passage when dust loss to the coma results in gradual erosion of the surface, lower and lower temperatures with increasing heliocentric distance, and ultimately excavation of the surface to a depth where organic compounds are exposed forming a HC melt zone with potential for trapping gases, etc. In a companion paper [3], we describe mechanisms involving liquid phases in promoting major outbursts of the comets 1P/Halley, 17P/Holmes and 29P/Schwassmann-Wachmann.

3. Summary and Conclusions

We have highlighted physical and chemical properties of cometary nuclei which favor local melting within the subsurface. Our model takes account of many characteristics not previously considered and demonstrates that both water ice and organic/hydrocarbon components will be subject to repetitive melting and freezing in a range of environments especially in cometary nuclei that rotate relatively slowly. This work has implications for the formation of liquid water in small bodies within protoplanetary disks.

Acknowledgements

We would like to thank Peter Hingley, librarian of the Royal Astronomical Society, for assistance in researching this paper.

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