PUBLISHED: 04 JANUARY 2017 | VOLUME: 1 | ARTICLE NUMBER: 0018

The ice content of Kuiper belt objects

To the Editor — Rosetta has measured the bulk density of non-volatiles in a primitive Solar System object for the first time[1]. Models of Pluto and Charon[2] assume rock densities ranging from 2,770 to 3,260 kg m^{-3} and a hydrocarbons-to-silicates mass ratio $h/s = 0.2$. However this value, first suggested for comet 1P/Halley[3], is biased by a low dust-to-ices ratio that was later refined to larger values[4], implying larger h/s ratios as well. Soft hydrogenated carbon alloys[5] (the best terrestrial analogues of hydrocarbons in the protosolar nebula) have a bulk density similar to ices, so that the low bulk density of Kuiper belt objects (KBOs) can be due either to abundant ices or to hydrocarbons.

The composition of comet 67P/Churyumov–Gerasimenko (67P) was fixed[1] by the volume abundances c_1 of Fe-sulfides (bulk density $\rho_1 = 4{,}600$ kg m^{-3}), c_2 of Mg and Fe olivines and pyroxenes ($\rho_2 = 3{,}200$ kg m^{-3}), c_3 of hydrocarbons[5] ($\rho_3 = 1{,}200$ kg m^{-3}), and c_4 of ices ($\rho_4 = 917$ kg m^{-3}). The volume abundances depend on the ice porosity and on the pristine composition (between the solar and CI-chondritic end-cases[1]) in the pebbles forming comets and KBOs, and provide $h/s = (c_3\rho_3)/(c_2\rho_2) \gg 0.2$ (Table 1).

We assume that the non-volatiles in comets and KBOs have a similar composition, which is fixed by the ratios c_2/c_1 and c_3/c_1 provided by Rosetta (Table 1). This is consistent with the elemental C/Fe ratio in 67P[6] and in 1P/Halley[3], with a possible origin of comets as fragments of KBOs, or with a probable common origin of comets and KBOs from similar pebbles[7]. Comets and KBOs differ instead in the abundance and composition of ices, which depend on their distance from the Sun during accretion and on their evolution.

Here we infer the ice abundance c_4 in KBOs, where the lithostatic pressure eliminates all the voids among the pebbles following gravitational collapse[7] and the subsequent evolution. Therefore the average KBO bulk density is

$$\begin{aligned}\rho_{\mathrm{KBO}} &= c_1\rho_1 + c_2\rho_2 + c_3\rho_3 + c_4\rho_4 \\ &= c_1\rho_5 + (1 - c_1/c_5)\rho_4\end{aligned} \qquad (1)$$

where $\rho_5 = \rho_1 + (c_2/c_1)\rho_2 + (c_3/c_1)\rho_3$ and $c_5 = 1 / (1 + c_2/c_1 + c_3/c_1)$ allow us to relate ρ_{KBO} to the ratios c_2/c_1 and c_3/c_1 only. Equation 1 provides c_1, and the constraint $c_1 < c_5$ provides the maximum possible values $\rho_{\max} = c_5\rho_5$ of ρ_{KBO} (Table 1), which are close to the bulk densities of Pluto[8] (1,860 kg m^{-3}), Charon[8] (1,700 kg m^{-3}), and Triton[9] (2,060 kg m^{-3}). This fact shows that the ice content in these KBOs is necessarily low.

We validate this conclusion by computing the non-volatiles-to-ices mass ratios $\delta = (c_1\rho_5)/(c_4\rho_4)$ (Table 1), which are systematically larger than the value $\delta = 1.5$ obtained by Pluto's models[2], and imply a water content lower than in CI-chondrites[2]. The largest ice volume abundances are obtained for the CI-chondritic composition, and provide $c_4 = 24\%$ on average in KBOs. The dominant frost observed on the surfaces of Pluto and Charon[10] confirms a complete differentiation (also occurring during the largest impacts), storing all the ices in surface layers[2,8,10] of thickness of about 95 and 80 km for Pluto and Charon, respectively, which envelope a thick mantle of hydrocarbons surrounding a smaller silicate nucleus. The icy surface layer of Triton is even thinner, 55 km at most. The C/Fe ratio in 67P[6], close to the solar end-case, confirms a dominant abundance of hydrocarbons[1] and suggests an ice content in Pluto even lower than in 67P. ❐

Table 1 | The volume abundances of sulfides (c_1), silicates (c_2) and hydrocarbons (c_3); the ice volume abundances c_{4P}, c_{4C} and c_{4T}; and the non-volatiles-to-ices mass ratios δ_P, δ_C and δ_T, in Pluto, Charon and Triton, respectively, for the end-cases of CI-chondritic and solar composition, and for compact and porous ices in the pebbles which accreted into KBOs.

Parameter	Compact ices CI-chondritic	Porous ices CI-chondritic	Compact ices Solar end-case	Porous ices Solar end-case
c_2/c_1	4	4	5	5
c_3/c_1	7	6	14	12
c_5	1/12	1/11	1/20	1/18
ρ_5 (kg m^{-3})	25,800	24,600	37,400	35,000
$\rho_{\max}$ (kg m^{-3})	2,150	2,236	1,870	1,944
h/s	0.66	0.56	1.05	0.90
c_{4P}	0.23	0.28	0.01	0.08
c_{4C}	0.35	0.40	0.18	0.24
c_{4T}	0.08	0.13	0.00	0.00
δ_P	7.76	6.12	192	23.7
δ_C	4.32	3.74	9.42	6.77
δ_T	28.5	16.2	∞	∞

The ratios c_2/c_1 and c_3/c_1 are extracted from Rosetta data[1].

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Acknowledgements

Rosetta is an ESA mission with contribution from its member states and NASA. Rosetta's Philae lander is provided by a consortium led by DLR, MPS, CNES and ASI. We thank the Rosetta Science Ground Segment at ESAC, the Rosetta Mission Operations Center at ESOC and the Rosetta Project at ESTEC for their outstanding work enabling the science return of the Rosetta Mission.

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