A Predicted Dearth of Bulk Hypervolatile Ices in Small KBOs and Oort Cloud Comets. C.M. Lisse[a], G.R. Gladstone[b], J.K. Steckloff[c], L.A. Young[d], D.P. Cruikshank[e], S.A. Stern[d], J.T. Keane[f], O.M. Umurhan[e], J.W. Parker[d], R.P. Binzel[g], A.M. Earle[g], Y.J. Pendleton[e], S.A. Sandford[e], M. Horanyi[h], H.A. Weaver[a], A.F. Cheng[a], R.L. McNutt[a], M. El-Maarry[i], J.M. Moore[e], I. Linscott[j], B. Schmitt[k], J.J. Kavelaars[l], D.T. Britt[m], C.B. Olkin[d], W.M. Grundy[n] [a]JHU Applied Physics Laboratory, [b]SwRI San Antonio, [c]PSI, [d]SwRI Boulder, [e]NASA Ames Research Center, [f]Caltech, [g]MIT, [h]LASP, [i]Birkbeck Univ. London, [j]Stanford, [k]Université Grenoble Alpes, [l]NRC Herzberg Inst, [m]UCF, [n]Lowell Obs. *e-mail: carey.lisse@jhuapl.edu

Introduction. [1] presented state of the art saturation vapor pressure (P_{sat}) and gas production rate (Q_{gas}) curves for ices expected in Kuiper Belt Objects (KBOs) to determine which species could still be present-day abundant in 2014 MU_{69} (aka Arrokoth), given the 3σ upper limit for coma gas production of 10^{24} H atoms/sec from New Horizons (NH)/Alice instrument airglow observations [2,3; Fig. 1]. Assuming thermally driven sublimation over the age of the solar system, [1] went on to show that there could not be any deposits of bulk hypervolatile ice species (e.g., N_2/CO/CH_4) in any substantial abundance on the surface of MU69. Rather, Arrokoth should be covered with refractory H-bonded ice species such as CH_3OH, HCN, and H_2O that remain thermally stable against sublimation into space over Gyrs at local temperatures. This finding is consistent with the NH/LEISA and NH/MVIC findings of a surface uniformly rich in tholins, methanol ice and likely water ice [4].

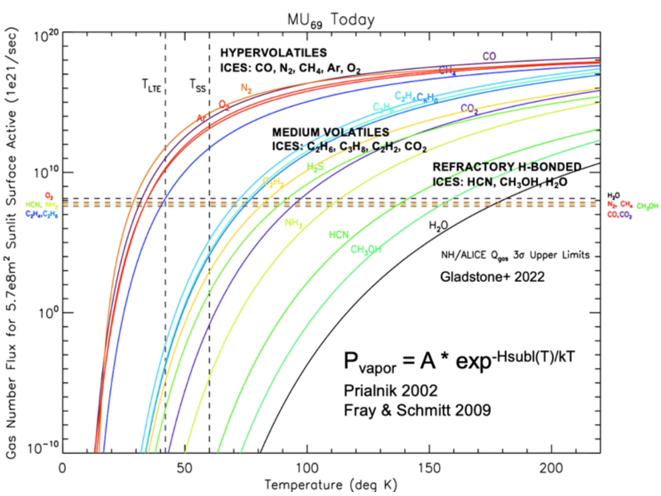

Figure 1 – Species specific 3-sigma Q_{gas} production upper limits for 2014 MU69, as determined by [3] (horizontal colored dashed lines). Also plotted are the gas production rates for different expected icy species found in comets and KBOs (colored curves), as well as the local equilibrium temperature at 45 au from the Sun for Arrokoth and its sub-solar (noon-time) temperature (vertical dashed lines). Hypervolatile species like N_2, CO, and CH_4 (red) violate the NH/Alice upper detection limits by 6-8 orders of magnitude.

Formation and condensation in molecular clouds, followed by loss after disk clearing. The hypervolatile ices can be identified as [5]'s small, apolar ices. Unable to bind well to dust grain surfaces, these apolar ice molecules form from gas-phase reactions and condense directly to ice in dense molecular clouds at extremely cold temperatures (~10-20 K), where thermal energy can be dominated by Van der Waals interactions. An important "Sublimative Epoch" of our early solar system was thus right after the so-called "disk clearing" time, when enough of the gas (>90%) was removed from the solar system's T-Tauri accretion disk for it to become optically thin to optical radiation out as far as the Kuiper Belt. Starting by 10 Myr after the beginning of the solar system [6], the direct insolation led to a sudden spike in local KBO surface temperatures from 10 – 20 K to the modern dayside/nightside surface temperatures of 60/30 K [7] and interior core temperatures of ~40K [1,8], and a wave of bulk hypervolatile ice sublimation and loss over the next ~10 – 30 Myr [9-11].

Consistency with Icy Planetesimal Observations. The predicted lack of bulk KBO hypervolatile ices is consistent with the dearth of substantial hypervolatile emission from end member objects 45P/HMP, 46P/Wirtanen, and 103P/Hartley 2 (small comets near the end of their lives emitting chunks of their cores, [12-14]; with the non-detection of any marked increase in hypervolatile emission seen from recently split comets 73P/SW3 [15] and 17P/Holmes [16]; and with very low levels of comet hypervolatile coma gas species vs water (CO at 0.5 – 25%, N_2 at 0.1 – 0.3 %, CH_4 at 0.2 – 1.0%, and [CO + CO2] at ~20% vs water, [17-20] – these are **sourced instead from interstitial impurities in cometary water and CO_2 phases** [11, 21].

Oort Cloud Stability. Bulk hypervolatile ices ***can*** remain stable over the age of the solar system ***beyond*** 100 AU from the Sun (Fig. 2). Thus Oort Cloud comets (OCCs), which spend > 99% of their orbit outside 100 AU, only sublimatively lose a small amount of their surface at each apparition (~0.5 m, [1,22]), and should be able to retain the bulk of their primordial hypervolatiles. However, only OCC C/2016 R2 [23,24] and perhaps the new ultradistant active comets such as C/2017 K2 PANSTARRS [25,26] are known to predominantly emit hypervolatiles. This handful of comets represents a negligible (~10^{-3}) fraction of all the known Oort Cloud comets.

C/2016 R2 thus represents an important example of an object outgassing just as one would expect if it was rich in nearly-pure N_2, CO, and CH_4 ice. The lack of water vapor production from R2 is very telling – for such an active comet, with $Q_{gas} \sim Q_{CO} = 10^{29}$ mol/sec, H_2O is ***always*** detected in a comet. Adopting the 1.1 x 10^{28} mol/sec water upper limit of [23], and using the observed Q_{CO} production rate of ~1.1 x 10^{29} mol/sec and the Q_{N2}/Q_{CO} ratio of ~8%, we see that Q_{CO}/Q_{H2O} > 10. This is at least 5 times higher than in any other comet, but as expected for a body with T

~ 20K set by sublimative cooling of CO and N_2 (Fig. 2). Further, the observed Q_{N2}/Q_{CO} ratio, indicative of the relative coma abundance of N_2 vs CO, is close to the solar N:C*N:O atomic abundance ratio product [27-29], as expected for a mix of PPD ices.

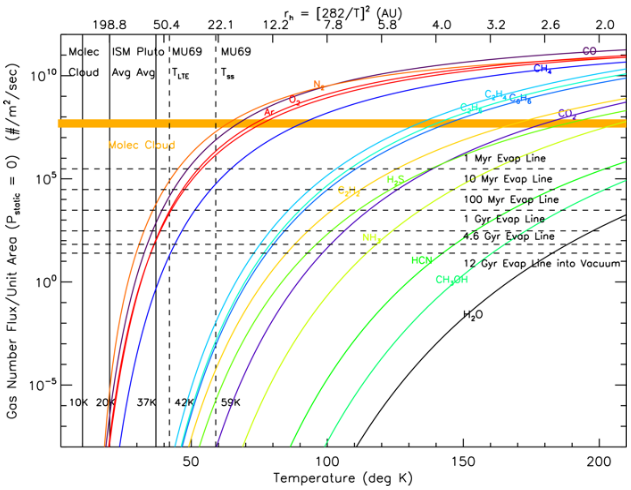

Figure 2 – Q_{gas} vs Temperature curves for species expected in comets and KBOs (colored curves). Horizontal lines: thermally driven outgassing rates at which an icy species is depleted at time ***t*** Myrs for an MU69-sized body. These rates are much slower than the loss rate of a piece of ice into free space, as they include the effects of an overlying lag layer with thermal diffusivity = $3x10^{-7}$ sec^2/m impeding the flow of heat and gas into free space from the interior [7-9]. Top axis: heliocentric distance from the Sun for a blackbody at local thermal equilibrium temperature T. From these curves and constraints, one can see that hypervolatile ices CO, N_2, and CH_4 are stable in cold, dense molecular clouds and in modern KBOs residing beyond ~100 AU from the Sun, but lost by ~20 Myr after MU69's formation.

Oort Cloud Emplacement. By the same arguments, Comet R2 must not have remained for long (< 40 Myr) after disk clearing in the giant planet/KB region of the solar system, otherwise it would have lost its bulk hypervolatiles. [1] thus concluded that R2 must have been created and scattered into the Oort Cloud within the first ~40 Myr of the solar system's existence.

Unlike the Kuiper Belt, which is at or near to the edge of the original PPD, the Oort Cloud is a later construct, formed of billions of icy planetesimals that were scattered out onto nearly parabolic, barely bound, ~million year orbits [30]. Most current models (e.g., [31-33]) favor populating the Oort Cloud around the time of the 2:1 Jupiter:Saturn giant planet orbital instability, at 100 - 1000 Myrs after the beginning of the solar system, via Neptune's scattering of planetesimals into the Cloud. Thus, with $t_{scattering} > t_{hypervolatile\ loss}$, we can expect that the large majority of Oort Cloud objects to have been depleted of bulk hypervolatile ices.

There will be exceptions to this rule. A few (< 1%) very extraordinary bodies, like R2, may have been quickly (in < 40 Myrs' time) inserted from the giant planet region. These few bodies, if as large as R2 (R_{nuc} ~15 km), can then endure thousands of orbits' worth (i.e., Gyrs) of hypervolatiles loss upon perihelion passage.

Implications and Observational Tests. The prediction that Oort Cloud comets should be depleted in majority species hypervolatiles has some important implications:

(1) Hypervolatile rich comets are rare, and thus abundant hypervolatiles will not be a general characteristic of all comets, despite the current high levels of interest expressed over the phenomenon of ultra-distant active comets like C/2017K2, C/2010 U3, and C/2014 UN271 [25,26].

(2) If the hypervolatile rich objects came from the lucky few primitive planetesimals scattered by the giant planets, then they must have been emplaced within ~40 Myr [7-9] and thus represent some of the first objects put into the Oort Cloud, as well as good measures of $CO/N_2/CH_4$ ratios in the proto-planetary disk.

(3) Obtaining quality frequency of hypervolatile rich Oort Cloud comets statistics (i.e., from $N_{Oort,\ hypervolatile\ rich}/N_{Oort,\ normal\ comet}$, *e.g.* [34], Fig. 3) can provide important constraints on models of early (< 40 Myr) versus later (0.1-2.0 Gyr) emplacement of objects into the Oort Cloud from the giant planet & Kuiper Belt regions of the solar system.

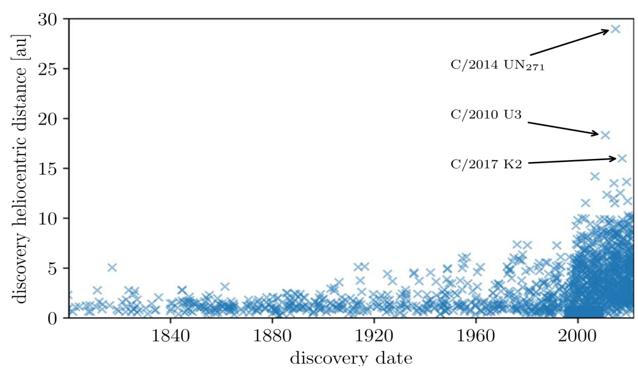

Figure 3 – Heliocentric distances at the time of discovery of all OCCs discovered since 1801 in the MPC database. A 10 AU cut-on in activity is consistent with activity driven by non-hypervolatile ices. After [34].

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