All Comets are Somewhat Hyperactive and the Implications Thereof

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Received 2021 January 21; revised 2021 March 5; accepted 2021 March 19; published 2021 May 10

Abstract
We critically examine what hyperactivity on a comet entails, fully develop the A’Hearn Model for Hyperactivity based on the analyses of data collected for the Deep Impact encounter of comet 103P/Hartley 2, describe manifestations of hyperactivity suggested on many, if not all, comets, and give implications of hyperactivity for future cometary exploration. The A’Hearn model requires a highly volatile ice reservoir within a comet to undergo sublimation, escape the nucleus, and drive out less volatile ices along its path to the surface. Once in the coma, the less volatile ice eventually sublimates, creating a secondary source of that gas in the coma, which is generally displaced anti-sunward and not distributed symmetrically about the nucleus. The secondary source of gas increases the total production of the less volatile species in the coma, sometimes well above that expected if the total surface was undergoing sublimation. We argue that based on the simple assumptions of the A’Hearn model and the fact that several comets display one or more of the characteristics of hyperactivity detailed here, it is probable that nearly all comets experience some degree of hyperactivity. Of significance, the ice that is brought from deep within the nucleus into the coma via the process described by the A’Hearn model is the least thermally altered and is thus the most pristine ice in the comet. Therefore, it behooves future mission teams to consider cryogenically sampling coma ice, rather than or in addition to attempting a direct nucleus sample, for a better understanding of the unaltered ices and conditions present in the protoplanetary disk.

Unified Astronomy Thesaurus concepts: Comets (280); Comet origins (2203); Comet volatiles (2162); Comae (271); Dirty snowball model (388)

1. Introduction
Four apparitions before 46P/Wirtanen’s 2018 December 16 close approach to Earth inspired the Mike A’Hearn Symposium in 2019 August, the comet was extensively observed in support of ESA’s Rosetta mission (e.g., Schulz & Schwenk 1996; Böehnhardt et al. 1997) as Wirtanen was, prior to a launch delay, Rosetta’s initial target (ESA 1994). After updating the nucleus size, Rickman & Jorda (1998) determined that Wirtanen was extremely active, suggesting that a very high fraction of its surface was outgassing. After ruling out a very low-albedo (<2%), Rickman & Jorda (1998) explored the range of potential physical causes of Wirtanen’s “hyper-activity,” as they termed it, including internal energy sources (i.e., amorphous-crystalline phase transitions) and external sublimation from expelled grains up to large fragments that might have broken off from the nucleus (e.g., Benkhoff & Boice 1996).

Integrating many previous observations, Groussin & Lamy (2003) confirmed that Wirtanen’s active fraction was nearly 100% at perihelion, indicating that the comet produces more water than can be explained by sublimation even if it occurs over its entire nucleus (see A’Hearn et al. 1995). Subsequently, three additional Jupiter family comets: 41P/Tuttle–Giacobini–Kresá (Combi et al. 2019), 45P/Honda–Mrkos–Pajdusakova (Lamy et al. 1999), and 103P/Hartley 2 (Groussin et al. 2004) were also recognized as similarly hyperactive. All four of these hyperactive comets, including Wirtanen, are notably small with nucleus sizes of order 1 km in diameter. The Oort cloud comet, C/1996 B2 Hyakutake, also shows evidence of being highly active (Lisse et al. 1999). These same five comets (plus 73P/Schwassmann–Wachmann 3, which is fragmented) still stand out as unusually active even in the most recent compilations of activity (Combi et al. 2019; Lis et al. 2019).

After the Deep Impact prime mission successfully carried out its impact experiment at comet 9P/Tempel 1 (A’Hearn et al. 2005), Principal Investigator Mike A’Hearn proposed an extended mission to fly by comet Hartley 2, one of these known hyperactive comets. As discussed below, Hartley 2 was not always the target for the extended mission, yet as a hyperactive comet, Hartley 2 was consistently recognized as scientifically the most intriguing object among the possible candidates. The Hartley 2 flyby’s unprecedented set of images and spectral maps of water, ice, and CO₂ provided unequivocal evidence on the origin of Hartley 2’s hyperactivity (A’Hearn et al. 2011). As described by A’Hearn et al. for the first time, water–ice grains were observed around the nucleus in images (Figure 1) and CO₂ outgassing from the smaller end of the bilobed nucleus was seen to be highly correlated with the water ice (Figure 2). This strongly suggests that the sublimation of CO₂ was responsible for dragging water ice into the coma, providing a substantial secondary source of water activity. Here we explore the implications of this A’Hearn Model for Hyperactivity for all comets, not just those that are small and highly active.

2. 103P/Hartley 2: The Prototype
Scientifically, Hartley 2 was always considered to be the best target for Deep Impact’s extended mission. In October 2003, more than a year before Deep Impact’s launch, Mike A’Hearn articulated that his goal for the extended mission was to fly past an additional comet after Tempel 1. Given the expected fuel reserves and assuming no changes to the primary mission, at least two comets, 85P/Boethin and 103P/Hartley 2, were accessible. Hartley 2 was favored for many reasons. Its total activity was comparable to Tempel 1, but the encounter would
be closer to the Sun so gas emissions would be twice as bright. Hartley 2 also had a favorable geometry with respect to Earth for the targeted apparition, an inferred CO$_2$ abundance of $\sim$4% as compared with water based upon HST measurements of the CO Cameron bands (Weaver et al. 1994) and, most critically, a well-known orbit. Boethin provided a much shorter flight time. However, Boethin had only been observed during two previous apparitions (its discovery in 1975 and 1986), was not observable during its 1997 apparition, and therefore the nongravitational effects and consequently the precise orbital characteristics of Boethin were unknown. Based on these uncertainties, prior to the prime mission at Tempel 1, Hartley 2 was chosen as the target for Deep Impact’s extended mission, with Boethin serving as a backup.

When the Deep Impact eXtended Investigation (DIXI) was formally proposed as a Mission of Opportunity (MO) in the 2006 Discovery call, the shorter mission time and therefore lower cost prevailed and a 2008 December flyby of Boethin (mission length of 3.4 yr) was targeted with Hartley 2 relegated to the backup target (5.2 yr mission). To assure a reliable encounter, an intensive observing campaign was planned to provide an early recovery of Boethin. A second mission of opportunity to use the Deep Impact spacecraft was also proposed at the same time. The Extrasolar Planet Observations and Characterization (EPOCh) project, which would operate during cruise phases, took advantage of the out of focus telescope on Deep Impact to make photometric measurements of bright stars with known exoplanets (e.g., Ballard et al. 2010). In addition, it was proposed to observe Earth as a remote object at visible and infrared wavelengths. Both extended mission concepts were selected and, at NASA’s direction, were merged into a single project named EPOXI (EPOCh + DIXI).

However, to be viable under the existing fuel margins, the trajectory to Boethin needed to be defined before a 2007 December Earth gravity assist. Despite extensive searches with all available major telescopes, Boethin was not recovered, not even later at its 2008 perihelion, having presumably disintegrated (Meech et al. 2013). Consequently, in 2007 November, EPOXI was re-targeted to Hartley 2 as originally preferred. Unfortunately, the initial trajectory, which included 3 Earth gravity assists, would have resulted in an encounter geometry with a phase angle that was too low and thus temperatures too high for continuous operation of the infrared spectrometer. Thus, while value morphologic and color data could be collected at Hartley 2, compositional data of the nucleus, or most critically of the coma, would have been sporadic at best. Recognizing the significant science value of the IR spectrometer, the JPL mission designers (Min-Kun Chung, in particular) were able to identify a new trajectory by adding two additional distant Earth gravity assists that arrived at Hartley 2 at a phase angle of 86 (versus 70) degrees allowing the IR spectrometer to fully operate. Remarkably, after all these changes to the Deep Impact extended mission, the efforts by the entire team starting before launch allowed the fully functioning Deep Impact spacecraft to arrive at Hartley 2 on 2010 November 4 and, just as Mike A’Hearn always wanted, acquire a unique set of data that led to the unraveling of the mystery of hyperactive comets.

3. The A’Hearn Model for Hyperactivity

The A’Hearn Model for Hyperactivity combines measurements of past apparitions of Hartley 2, which showed high activity for a small comet, with spatially resolved flyby observations of Hartley 2 to explain the phenomena of comets with very large active fractions. While Hartley 2 provides the best spatial and temporal data to develop a model for hyperactivity, as discussed below, this new understanding is applicable to any comet.

The principal observations from the Deep Impact flyby of Hartley 2 that support the model are:

1. Hartley 2’s surface is not covered in water ice;
2. There are no large fragments breaking off of the nucleus;
3. Images readily display bright grains in the coma;
4. Spectral maps show a spatial correlation between CO$_2$ and water ice concentrated around the small lobe of the nucleus; and
5. The two lobes of the nucleus are connected by a smooth water-rich waist that likely includes the fallback of ice-rich grains.

Incorporating these notable properties of Hartley 2 into a self-consistent model, Mike A’Hearn formulated a process to fit these details together (Figure 3). Dubbed here as the A’Hearn Model for Hyperactivity, a reservoir of ice more volatile than water sublimates in the interior of the comet and escapes the nucleus also dragging water–ice grains on its path. Some of the ice particles move too slowly to escape the gravitational pull from the nucleus and therefore fall back to the surface and accumulate at gravitational lows, like the waist area on Hartley 2. After entering the coma, the faster-moving icy grains (on the order of 0.1–0.5 m s$^{-1}$, Protopapa et al. 2014; Kelley et al. 2015) are pushed tailward by pressure from the solar wind prior to completely sublimating. This tailward accumulation of small grains with high surface areas provides a second, extended,
source of water in the coma predominantly distributed in the anti-sunward direction, thus inflating the sublimation rate from the surface alone and creating a cometary system that appears to be hyperactive.

After the formation of the initial hyperactivity model, additional analysis of the Hartley 2 data led to more detailed results that corroborated and expanded the concept. One of the first in-depth investigations considered if Hartley 2’s surface was covered in water ice. Color data suggested not (Figure 4). Not only was this confirmed by 1–5 \( \mu \)m spectral imaging, but relative strengths of ice absorptions at 2 and 3 \( \mu \)m revealed that what ice was present on the surface was 10–50 \( \mu \)m in size (Sunshine et al. 2011). These relatively small ice patches were preferentially located along the terminator rather than globally distributed, suggesting that they were likely depositional frosts. These results from Hartley 2 are consistent with what was determined at the less active Tempel 1, namely that surface ice on comets is very localized with grains on the order of tens of microns in size (Sunshine et al. 2006). Thus, this small quantity of surface ice is not nearly abundant enough to supply the overproduction of water in the coma of hyperactive comets. In addition, the distribution of ice on the surface is not correlated with the jets of material flowing from the nucleus, therefore the outgassing in jets cannot be driven by the surface ice patches or reservoirs just under the surface at those locations.

Surprisingly, when Deep Impact arrived at Hartley 2, it was visibly clear that the comet was engulfed in a particle swarm, however, there were no large plates or fragments of the nucleus that had broken off. The active process proved to be much less dramatic than a fragmenting event. After thorough spectral analysis of the many concentrations of visible jets driving material into the coma, it was found that Hartley 2’s interior water–ice grains are small, on the order of 1 micron in size, and preferentially propelled out of the small lobe of the comet as is CO\(_2\) gas (Protopapa et al. 2014). This ice has similar properties as those originating from depth and excavated at Tempel 1 (Sunshine et al. 2007). From this, it was inferred that Hartley 2’s small ice grain population is expelled from depths larger than the thermal wave propagates and likely is more pristine than the surface ice. A separate population of larger particles also exists in the coma of Hartley 2, but their photometric properties are not well constrained, and it is unclear how they are released from the nucleus (Hermalyn et al. 2013; Kelley et al. 2015).

In addition to the large number of visible ice particles in the coma of Hartley 2, the comet has an average to above average abundance of CO\(_2\) with respect to water (A’Hearn et al. 2012), whereas its CO abundance is nearly negligible (Weaver et al. 2011). With the high cadence spectral data acquired during the Deep Impact flyby, frequent measurements of its CO\(_2\) were acquired. The CO\(_2\) abundance ranges between 10% and 20% depending on the rotational phase and coma location being sampled (A’Hearn et al. 2011; Feaga et al. 2011). Furthermore, when viewing the near nucleus environment, the CO\(_2\) distribution in the coma is coincident with the highest concentrations of water ice, not correlated to the water vapor enhancements, and predominantly located in the coma off the small lobe of the comet. At the other abundance extreme is CO, measured at...
0.15%–0.45% relative to water using HST (Weaver et al. 2011). If subsurface ice requires a driver more volatile than water to drag it out of the nucleus, CO$_2$ and/or CO, the top two abundant volatiles in addition to water found in most comets (Bockelée-Morvan et al. 2004), are the most likely candidates. Due to the spatial correlation between the water ice and the CO$_2$ enhancements in the coma emanating from the nucleus, and the fact that Hartley 2 has very little CO, CO$_2$ is identified as the primary driver of activity (A’Hearn et al. 2011). In Hartley 2’s case, the A’Hearn hyperactivity model implies that there is a subsurface reservoir of CO$_2$ that sublimates and propels the solid phase water ice it encounters on its path out of the nucleus.

Another striking feature of Hartley 2 is the smooth waist that connects the two lobes of the nucleus. As a gravitational low, it was hypothesized that the region accumulates a mixture of somewhat processed dirty grains and icy aggregates from fallback (A’Hearn et al. 2011). The distinct spatial enhancement of water vapor seen in the infrared compositional maps directly emanating from the waist (see Figure 2) is consistent with water sublimating from an ice-rich component of the accumulated material. As part of the A’Hearn model, some of the icy grains entrained by CO$_2$ that do not have the velocity to escape the gravity of the nucleus will eventually deposit in the gravitational low at the waist. This deposited material is rich in water, susceptible to solar insolation, warmed by the nearby dirty grains, and readily sublimates contributing to the coma enhancement of water over the waist. The hyperactivity of the comet enables this sedimentary process of cyclic deposition, which was not envisioned before for comets. For Hartley 2, the mass movement of grains was due to strong jetting, but there is evidence of seasonally driven mass movement occurring on 67P/Churyumov–Gerasimenko (CG), where material was transported from the southern to the northern hemisphere (Fornasier et al. 2016; Keller et al. 2017). The redeposited...
grains, regardless of their origin (nucleus interior for Hartley 2 and hemispherical surface for CG) and cause of movement (expelled with other more volatile sublimating gases for Hartley 2 and seasonal insolation for CG), are thermally altered and therefore fractionated in the process.

A global coordinated observing campaign was also designed for the Hartley 2 flyby as part of the extended mission (Meech et al. 2011), allowing the fundamental results from the close-in, spatially resolved, spacecraft data to provide context for the much larger spatial scales of the remote sensing data. In large fields of view, Hartley 2 displays an asymmetric, anti-sunward spatial distribution of water and its dissociation products OH and H (Dello Russo et al. 2011; Meech et al. 2011; Mumma et al. 2011; Kawakita et al. 2013; Knight & Schleicher 2013; Combi et al. 2011) as well as an asymmetric and offset rotational temperature profile for the water (Bonev et al. 2013). This asymmetry in gas species is opposite the typical sunward direction in which most ambient surface/near-surface water vapor readily sublimes under solar insolation and outgasses from the nucleus, and the anti-sunward offset peak in rotational temperature implies an excess in energy potentially from vapor released from icy grains (Bonev et al. 2013). With the A’Hearn model, the anti-sunward water vapor and associated byproducts are directly tied to the population of subsurface ice released from the nucleus with other more volatile gases.

Since acquisition, the HRI-IR data from Hartley 2 have also continued to be examined to improve the calibration. During the flyby, data were acquired at 1/2 to 1 hr increments to map the distribution of volatiles in the coma as the comet rotated (A’Hearn et al. 2011; Feaga et al. 2011). Recalibration of these data has facilitated new analyses. In particular, L. M. Feaga et al. (2021, in preparation) have been able to separate the two distinct sources of Hartley 2’s water at two different points in the comet’s rotation. In one case the water abundance map is symmetric reflecting a nucleus source while in the other, the water abundance map is highly asymmetric in the anti-sunward direction reflecting a higher proportion of coma ice sublimation (Figure 5). These maps confirm, with unprecedented clarity, the two water sources that are at the center of the A’Hearn Model. Similar anti-sunward distributions of volatiles in remote sensing data from other comets can now be explained by observations from Hartley 2.

By integrating all the observations of Hartley 2, the A’Hearn Model for Hyperactivity identifies icy grains in the coma as the secondary source of water and explains their origin. While water is the most abundant volatile in most comets, the model requires ice more volatile than water, in a reservoir below the depth of the thermal wave penetration. Once in the coma, the ice collects anti-sunward due to radiation pressure and ultimately sublimes, contributing to the total water vapor measured in the coma, which can rival that produced directly from sublimation of the nucleus. This hyperactivity model does not require a specific volatile driver, but rather only one more volatile than water. Notably, the A’Hearn Model for Hyperactivity does not necessarily require the equivalent active fraction of a nucleus to be greater than 100% nor set a minimum active fraction. Although comets with large active fractions most likely contain icy grains in their coma, this process may be occurring on all comets to one degree or another.

**Figure 5.** Hartley 2 has two distinct sources of water vapor, sublimation from the nucleus and from icy grains in the coma, which explains the comet’s hyperactivity. Maps of relative abundance of water vapor in the coma derived from infrared data acquired by Deep Impact’s HRI-IR spectrometer at two different times and nuclear rotations at 2 (left) and 6.5 (right) hours after closest approach capture differing proportions of these two components. In both cases, the unresolved nucleus is located by black crosses and the Sun is to the right. The map on the left is dominated by a symmetric source of water sublimating directly from the nucleus. In contrast, the map on the right is asymmetric and is dominated by sublimation from icy grains pushed in the anti-sunward direction (Data available from the Planetary Data System: Year 2010/DOY 308/HRI-IR scans 4000700 and 4001600; McLaughlin et al. 2014). From L. M. Feaga et al. (2021, in preparation).
4. The Importance of Hyperactivity for All Comets

While it is clear the A’Hearn Model for Hyperactivity applies to a small number of highly active comets, the same processes revealed by this small population of comets must also occur to some degree on, and affect, all comets, even those with lower activity. Cumulative results from observations of individual comets and large cometary surveys provide increasing evidence that one or more of the processes seen at Hartley 2 manifests on many comets.

Fundamentally, the basis of the A’Hearn model is the process of entraining ice in the gas phase escape of volatiles from the nucleus. To understand how similar processes might occur on lower activity comets, one can first examine those for which water ice has been detected. Ice has been detected in the comae of several comets ranging in size from those similar to Hartley 2 up to the 60 ± 20 km diameter C/1995 O1 (Hale-Bopp; Davies et al. 1997; Lellouch et al. 1998; Fernández 2002), revealing no apparent size dependence. In some cases, e.g., 1P/Halley, C/2002 T7 (LINEAR), C/2011 L4 (PANSTARRS), and C/2013 US10 (Catalina) (Krasnopolsky et al. 1986; Kawakita et al. 2004; Yang et al. 2014; Protopapa et al. 2018, respectively), ice in the coma seems to be released in a steady state process. However, for other comets including 17P/Holmes and P/2010 H2 Vales, ice was detected in the coma following outbursts that resulted in the coma brightening by several orders of magnitude (Yang et al. 2009; Jewitt & Kim 2020). In these outbursts, ice grains must also be entrained in gas in a similar, but more instantaneous, process to the A’Hearn model from Hartley 2. In addition to detection of water ice in these comae, spectral analyses provide constraints on the size of the icy grains. Unlike surface ice deposits observed on cometary nuclei (Sunshine et al. 2006; Raponi et al. 2016), which have moderate size grains of order 10–100 μm, icy grains seen in many cometary comae are often more fine-grained, of order 1 μm (Kawakita et al. 2004; Yang et al. 2009, 2014; Protopapa et al. 2014, 2018; Jewitt & Kim 2020). Such fine-grained ice was also inferred in the ejecta of Tempel 1 suggesting they represent the unprocessed interior (Sunshine et al. 2007). The remarkable grain size similarities suggestive of analogous processes occurring in the interior of all of these comets are fully consistent with the A’Hearn model that the ice is dragged from depth with volatile gases.

Given the widespread evidence of water ice in cometary comae that appears to result from a basic process, sublimating gas entraining ice grains, it seems likely that this process is common to all comets to some degree and that some ice, below detectability limits, is likely to be present in all comae. This implies that all comets have two sources of water contributing to their total water production, albeit in varying degrees. For example, while no direct detection of water ice was made in comets C/2007 W1 (Boattini) and C/2009 P1 (Garradd), both showed strong asymmetric excesses in their coma water distribution and sublimation of icy grains was invoked to explain this phenomenon (Villanueva et al. 2011, 2012). However, in the absence of direct detection of water-ice grains internal variations in nuclear sources could also result in such asymmetries. Nevertheless, the A’Hearn model does appear to be quite applicable to C/2009 P1 (Garradd) as the comet is very abundant in CO (Paganini et al. 2012; Feaga et al. 2014), one of the most volatile cometary ices, which could easily drag water ice from deep within the nucleus to the coma as it is released. On the other hand, it would be difficult to detect bimodal sources of water on a relatively inactive and highly seasonal comet like 67P/Churyumov–Gerasimenko (active fraction <6%; Combi et al. 2019), where despite being in orbit Rosetta detected ice in the coma only in localized jets (Agarwal et al. 2017).

Variability in the relative proportions of the two water sources adds to the complexity of establishing a set of representative abundances for any comet. The source rates are also affected by heliocentric distance, which dictates the ability of a volatile to reach its sublimation temperature. In addition, diurnal variations due to cometary rotation likely affect the gas, and therefore ice, production. This strongly implies that cataloging and comparing production rates of volatiles as ratios relative to water, as is traditionally done, is suspect. However, it is possible to assess the relative contributions of the two water sources by examining differences in spatial asymmetry over time, as coma derived water would be offset from the nucleus in the anti-sunward direction due to radiation pressure as seen at Hartley 2 (Kelley et al. 2013; Knight & Schleicher 2013). In fact, DiSanti et al. (2014) investigated the two sources of water, direct sublimation from the nucleus and sublimation from icy grains, for C/2009 P1 (Garradd) and estimated 25%–30% of the water detected in their data could be due to an extended icy grain source.

While H2O ice was delivered to the coma via CO2 outgassing in Hartley 2, an analogous process should similarly occur with any combination of high volatility gases driving lower volatility ice grains. Under this model, the sublimation of more volatile gases occurs at lower temperatures than the sublimation temperature of less volatile grains maintaining them in their ice phase and inhibiting their sublimation. Particularly beyond the water snow line where comets are known to exhibit CO and CO2 activity (e.g., Ootsubo et al. 2012), one could extrapolate from the A’Hearn model and expect comets where, for example, CO or CH4 propels CO2 ice grains or CO drives CH4 ice grains creating secondary sources in the coma. As in comets that are hyperactive in water, such complex activity would enhance the production rate of the less volatile gas. Such nonwater ice hyperactivity may be particularly likely for dynamically new comets, which have yet to deplete their original complement of highly volatile gases.

With the significant amount of mass movement indicated by the A’Hearn model, thermally altered material is expected on the surface. This thermally processed ice leads to fractionation and suggests cometary surfaces are more evolved. On the other hand, ices propelled from the interior that collect in the coma are likely the least fractionated cometary grains. As proposed by Lis et al. (2019), this could explain why hyperactive comets seem to be the most similar to the Earth’s water in D/H ratios than other comets.

5. Conclusions and Implications for Future Cometary Sample Missions

Based on the significant and consistent evidence from the data analysis associated with the Deep Impact encounter with Hartley 2, the A’Hearn Model for Hyperactivity on comets articulates a complex system of volatile sublimation, ice grain ejection, and deposition on comets. The accumulation of ice grains with high surface areas in the anti-sunward direction due to solar wind pressure creates a second, non-nuclear source for water, which explains how some comets like Hartley 2 and Wirtanen are able to produce more water than is possible given the size of their nuclei. Hartley 2 is not hyperactive in water because it has a larger than normal reservoir of water, but rather...
because it has a substantial amount of CO₂ that delivers water ice into the coma. Under the A’Hearn model, the re-accumulation of the slower grains entrained in more volatile gases suggests for the first time the concept and a mechanism for sedimentary processes on comets.

In extending the A’Hearn model to all comets, it is envisioned that all comets are likely a bit hyper, i.e., with bimodal sources of water. In most comets, ice grains in the coma may be a smaller proportion of the water emission than in hyperactive comets. Nonetheless, the processes outlined in the A’Hearn model, that icy grains can be dragged from the interior by colder more volatile gases are generalizable to all comets. In particular, it is not only water and CO₂ but any pair of volatiles that can result in less volatile ices in cometary comae. Furthermore, comets that were once envisioned as simple spherical dirty snowballs (Whipple 1950), have proven to be much more complex systems, with highly nonspherical shapes (H2: Thomas et al. 2013 and CG: Preusker et al. 2015), evolving rotational periods (e.g., Mueller & Ferrin 1996) exquisite morphological variations (El-Maarry et al. 2015), strong seasonal effects (Keller et al. 2017), and now a bimodal source of coma gases.

From the evidence and implications presented here, it is clear that to sample the most pristine and unfractinated ices in a comet, akin to original ice grains from formation, we are best served by that to sample the most pristine and unfractinated ices in a comet, akin to original ice grains from formation, we are best served by

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The authors thank the two anonymous reviewers and the editor for their helpful and supportive comments. Many of the concepts in this paper were stimulated by early discussions with Mike A’Hearn, whose legacy inspires us still.

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