Chemical and Physical Aging of Comets

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Abstract. Aging effects for comet nuclei encompass both chemical and physical changes to the nucleus which may be manifested as a change in the level of and type of activity that the nucleus experiences. Recent observations have shown the importance of the amorphous to crystalline water ice phase transition in comet nuclei for controlling activity at large distances, and for altering the porosity and volatile distribution in the interior of comets. Evidence for secular changes in activity levels or differences between dynamical classes of comets which have spent different amounts of time in the inner solar system must be decoupled from expected primordial differences between comets. Long-term observational programs by several groups have demonstrated that the effects of aging are detectable. This paper will discuss the expected primordial comet differences, the expected physical and chemical effects of aging, the techniques for observing differences in activity levels, and will present summaries of results of several observing programs.

Key words: comets – formation – aging

1. Introduction

“Aging” of comet nuclei concerns the effects on the nucleus since the time of its formation which serve to alter the nucleus either chemically or physically, and which can be manifested as causing a change in the type or level of activity. There have been several reviews of aging – a field which encompasses many topics (including secular fading (Kresák, 1991; Whipple, 1991), lost comets, splitting (Sekanina, 1982), outbursts (Hughes, 1991), differences between short-period and Oort comet activity (Meech, 1991), thermal evolution (Rickman, 1991) and irradiation of the surface in the Oort cloud (Strazzulla & Johnson, 1991)). This paper will focus on the interior changes to the nucleus as a comet ages, and the implications for the expected change in activity from the observational point of view. This paper will provide an updated summary of the topic of aging in the context of distinguishing aging effects from primordial differences between groups of comets. Aging will be discussed in terms of formation scenarios and looking for activity and physical differences between comet classes (*e.g.* short-period, long-period, Centaurs and Edgeworth-Kuiper Belt objects), as well as specialized observing techniques for making these observations.

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1.1. Formation of Comets

Recent dynamical models of small body evolution and sophisticated models of accretion and growth of planetesimals in the outer solar system are refining our understanding of the early solar system. Dynamical evidence suggests that the short-period (SP) comets must have had a low-inclination source in the trans-Neptunian region (Duncan *et al.*, 1988), whereas the long-period (LP) and dynamically new (DN) comets formed at smaller heliocentric distances, r, and were perturbed outwards (Fernández & Ip, 1981). As the nebula collapsed, solid particles settled to the midplane. They may have undergone processing (*e.g.* shock-induced sublimation and volatile recondensation) of their icy mantles as they fell (Lunine *et al.*, 1991). Weidenschilling (1997) has shown that the planetesimals grew by collisional coagulation until they were big enough to decouple from the turbulence between the particle layer and the gas. This decoupling occurred when the planetesimals were 10 to 100's of meters in sizes. Comets formed in this manner should be compact at the sub-m scale, but have voids and fractal-like structure at larger sizes. In addition because collisions were caused by differential radial velocities induced by gas drag, a single comet nucleus may have incorporated planetesimals from different heliocentric distances.

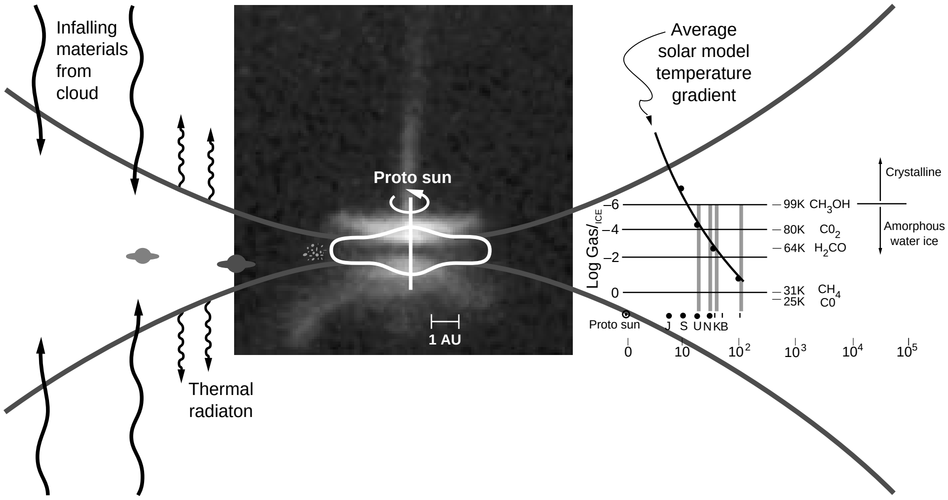

Figure 1. Schemiatic of collapse of the solar nebula superimposed on an HST image of the protostellar disk, HH-30 (C. Burrows, STScI). In-falling solar nebula material is shock heated during infal, sublimating volatiles found on interstellar grains. The volatiles recondense at nebular ambient temperatures. An average temperature gradient versus heliocentric distance [AU] is shown at the right of the figure. The region of probable LP comet formation is the Uranus-Neptune zone (indicated by the grey verticle lines) and that of the SP/KB comet in the 30-100 AU region.

Although this phase of comet formation cannot be observed directly, we can observe nucleus size distributions and comet nuclei sub-structure (through splitting, and inhomogeneities). Collisions probably played a large role in altering the size distributions of the trans-Neptunian objects (Farinella & Davis, 1996; Davis & Farinella, 1997), helping transport the SP comets into the inner solar system. The Centaurs probably represent the transition objects between the trans-Neptunian and SP comet populations (Stern & Campins, 1996). Figure **??** depicts an overview of the comet formation process.

2. Aging Effects

The aging or evolutionary effects that a comet nucleus will experience can be divided into 4 primary areas: the *pre-cometary phase*, where the interstellar material is altered prior to incorporation into the nucleus, the *accretion phase* during nucleus formation, the *Oort Cloud phase* – the phase where the comet is stored for long periods at large distances from the sun, and the *active phase*.

2.1. Pre-Solar Nebula

The pre-cursor cometary material, the interstellar grains, is stored in cold quiescent molecular clouds ($T = 10K$, $n = 10^3$ cm^{-3}) and in warm, dense protostellar regions ($T = 100K$, $n = 10^6$ cm^{-3}). The inventory of species detected to date in the ISM is very similar to those found in comets (Ehrenfreund *et al.*, 1997; from ISO observations), leading to the suggestion that much of the interstellar material is incorporated unaltered into comets.

Observations of recent bright comets have shown that there is evidence for preservation of an interstellar ice component within nuclei, yet at the same time the cometary material has undergone processing during its formation. Measurements of the D/H ratio in P/Halley (Balsiger *et al.*, 1995; Eberhardt *et al.*, 1995), in C/1996 B2 Hyakutake (Bockelee-Morvan, *et al.*, 1998) and in C/1995 O1 Hale-Bopp (Meier, *et al.*, 1998a,b) show an enrichment by a factor of ten in water compared to the protosolar ratio. The enrichment is a result of ion-molecule and grain-surface reactions in molecular clouds. Laboratory experiments have shown that this ratio cannot have been re-equilibrated in the solar nebula (Laufer, *et al.*, 1998).

The mantles of interstellar grains also undergo significant processing in the molecular clouds from bombardment by cosmic rays. The ions lose energy by ionization of the target material and breaking chemical bonds in the target, and they can also cause sputtering from the surface (Strazzulla and Johnson, 1991). This will create both non-volatile material and highly reactive radicals.

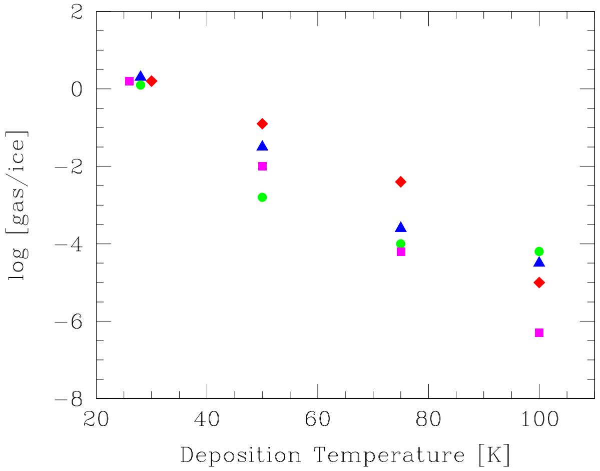

Figure 2. Total amounts of trapped gases in water ice versus deposition for ◇ CH_4; △ CO; ◯ N_2; and □ Ar. Figure after Bar-Nun & Kleinfeld, 1989.

2.2. Accretion Phase

The laboratory studies of volatiles condensed at low temperatures in comparison to the abundances of volatiles in recent comets has shown that interstellar grains were altered prior to incorporation into comets (Bar-Nun & Owen, 1998). ISO observations have shown a relatively high abundance of CO (ranging from a few to 45%) and CO_2 ($\approx$ 15%) relative to water in icy grain mantles (Whittet, *et al.*, 1996). When water-ice condenses at temperatures below 100K, it condenses in the amorphous form and has the ability to trap gases as high as 3.3 times the amount of the ice (Laufer, *et al.*, 1987). Upon heating, the gases are released in distinct temperature regimes in response to the restructuring of the ices (between 50-125K due to annealing). Beginning near 120K and peaking at 137K, gases are released as the ice undergoes an exothermic amorphous to crystalline phase transition. The amount of gas which can be trapped is a very strong function of the condensation temperature: H_2 and D_2 can only be trapped below 20K, Ne only below 24K, and many other light gases may be trapped only up to 100K (see Figure **??**).

The CO abundance in P/Halley relative to water was 7%, suggesting formation in a region near 50K, and for C/1996 B2 Hyakutake a formation temperature near 63K was suggested (Bar-Nun & Owen, 1998). These CO abundances are much lower than seen in the solid component of molecular clouds, suggesting that grains underwent processing in the nebula – possibly sublimation and recondensation during infall. Likewise, if grains had been formed in cold clouds below 24K, then we would expect to see large amount of H_2, D_2 and Ne in comets and this is not detected.

2.3. Storage in the Oort Cloud

Comets may be stored for billions of years in the Oort cloud or the distant outer solar system before passing close to the sun and entering the active phase. During this time galactic cosmic ray irradiation can create a thin stable cohesive crust which will have some tensile strength to a depth of 10 g cm^{-2} (Strazzulla & Johnson, 1991). In addition radicals will form in the upper few meters of the comet surface causing chemical alteration (to $\approx$ 300 g cm^{-2}). Finally, the upper layers will be depleted in volatile material (to $\approx$ 100 g cm^{-2}). Figure **??** summarizes the stages of evolution that a comet may undergo.

In addition to the radiation damage to the surface, Stern & Shull (1988) have shown that up to 20% of the Oort cloud comets will have been heated to at least 30K to a depth of 20-60m from the passage of luminous stars, and that most comets may have been heated as high as 45K to a depth of 1m from stochastic supernovae events. This may result in volatile depletion in the upper layers. Likewise, gardening from interstellar grain impacts will also alter the upper few cm of the surface (Stern, 1986).

Evolution of meteorites provides evidence of an early heat source in the solar system, and it is likely that the radionuclide ^{26}Al was responsible for radiogenic heating of large bodies. Prialnik *et al.*, (1987) have examined the role of this radionuclide in the possible evolution of cometary interiors. Models showed that because there is evidence for amorphous ice in comets (*e.g.* from its direct detection in C/1995 O1 Hale-Bopp (Davies *et al.*, 1997); and inferences from activity at large r (see section 4.1)), comet interiors cannot have been heated above 137K. This places limits on the abundance of ^{26}Al and timescales from chondrule formation to final comet formation to allow the ^{26}Al to decay by 2 orders of magnitude from the abundance seen in the Allende meteorite. The heating from ^{26}Al would occur during 10^5-10^8 years and would raise temperatures between 20-120K, depending on the nucleus size (the larger nuclei would be less efficient at cooling). Whereas it would be expected that a pure ice nucleus would either be all crystalline or all amorphous – depending on size, the effect of refractory material would be to quench the conversion, leaving a crystalline core with an amorphous mantle.

The situation regarding heating in Edgeworth-Kuiper belt objects may be somewhat different because of their large sizes. Depending on their conductivity, porosity and size, their interiors may have undergone complete changes (*e.g.* crystallization and melting in the core), resulting in a layered structure with a weak devolatilized region below the surface (Prialnik, 1998a).

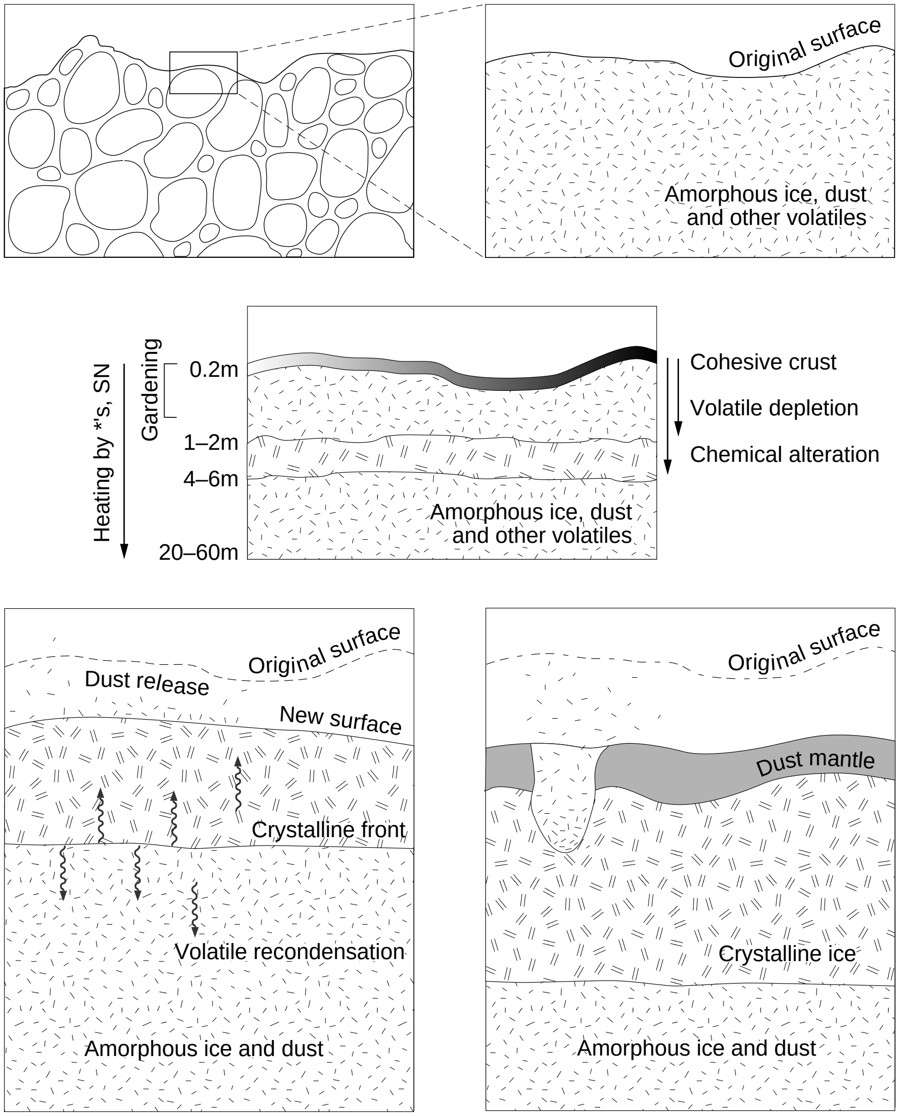

Figure 3. Diagram showing the sequence of aging processes in the upper layers of a comet nucleus from (a) the pristine state, consisting of primordial planetesimals (upper left, enlargement – upper right), (b) to the alterations it undergoes while stored in the Oort cloud including a possible crystalline core caused by radioactive heating from ^{26}Al (central diagram) to (c) the changes in the surface during the active phase (lower left) and (d) near the end of its evolution as a dust mantle builds up (lower right).

Table 1. Important temperatures for comet physics.

T[K]	Process	T[K]	Process
5	H_2 sublimation	64	H_2CO sublimation
22	N_2 sublimation	80	CO_2 sublimation
24	O_2 sublimation	80	amorphous H_2O ice anneals
25	CO sublimation	80-90	slow crystallization can begin
25	excess frozen-in gas sublimates	99	CH_3OH sublimation
31	CH_4 sublimation	120	amorphous H_2O ice anneals
35	amorphous H_2O ice anneals	137	amorphous-cubic ice phase change
42	C_2H_4 sublimation	160	cubic-hexagonal ice phase change
57	C_2H_2, H_2S sublimation	180	crystalline ice sublimation

2.4. The Active Phase of Comets

During the active phase, when the comet passes within the inner solar system and experiences significant solar insolation, we get considerable evolution of the interior and surface of the comet. The upper few meters of the surface of a comet making its way into the inner solar system for the first time will both be depleted in volatile material, and may have highly volatile radicals created due to the chemical processing from galactic cosmic rays. Just below this layer, which will be removed during the first passage, will be a layer of "pristine" amorphous ice.

On the first passage through the inner solar system, the solar insolation will cause the crystallization of the amorphous ice from the surface inward at much lower temperatures than would be expected for water ice sublimation (see Table **??**). In contrast to sublimation of crystalline ice, which proceeds from the surface, this process occurs deep below the surface as the crystallization front propagates inward. During crystallization the trapped gases are released and will flow both toward the interior and toward the surface through the porous material (see Figure **??**). This was seen experimentally in the KOSI experiements (Grün *et al.*, 1991). Much of the released CO_2 will recondense on the icy mantles of grains (Yamamoto & Sirano, 1998), causing sintering between grains, thus increasing the nucleus tensile strength. This will reduce the porosity of the nucleus, and increase the thermal conductivity. In the case of low porosity, the gas will not be able to freely escape and pressure can build leading to outbursts (Prialnik, *et al.*, 1993).

The gas released during the amorphous to crystalline transformation cannot immediately rise to the surface, and it may accumulate in pockets through dynamic percolation through the pores. The largest vapor pressures will be found at the crystalline–amorphous boundary. When the pressure exceeds a critical value, the crystalline layer shatters, and an outburst or jet occurs (Prialnik & Bar-Nun, 1987). For a periodic comet made of pure ice, this process will not procede continuously, but may procede in spurts. The presence of dust in the icy matrix will quench the process, preventing a runaway crystallization, and the process can only begin again after the crystalline layer is eroded as the ice sublimates near perihelion (Prialnik & Bar-Nun, 1992).

The phase transition and subsequent gas release is sensitive to the physical properties of the nucleus (density, porosity, thermal conductivity), its chemical properties (mass fraction of volatiles, dust to mass ratio) as well as the orbital evolution of the comet. The release of gasses will affect the physical properties of the nucleus: changing the porosity, redistributing volatiles, and allowing for selective loss of more volatile materials. A dust mantle will form on the surface, which may erode during periods of high activity, and which will be a function of orbital evolution. One might expect to observe secular fading as a dust mantle builds up on the surface, inhibiting sublimation, and this would imply that there would be a difference in the fractional surface area active as the mantle builds up (see Figure **??**).

Kührt and Keller (1994) have reviewed the problems that models of dust mantle formation have encountered. Early mantle models that consisted of layers of permeable, non-interacting dust were unable to sustain the mantle near perihelion. However, observations of P/Halley from the Giotto spacecraft clearly showed the nucleus to be heavily mantled, with only 10% of the surface active (Keller, *et al.*, 1987). Likewise, estimates of the fractional areas active in SP comet nuclei (A'Hearn *et al.*, 1995) from comparison of Q[OH] to the surface area indicate that most comets have small active areas. Kührt and Keller have shown that without including cohesive forces, the vapor pressure dominates the gravitational pressure of the mantle near perihelion, and the mantle will not stay in place. Kührt and Keller found that the crust/mantle thickness depended on the orbit, obliquity and conductivity of the refractory layer; however, the thermal properties of the layer had a dominant effect on its growth. Crusts/mantles were found to reach maximum thicknesses of a few m in their models. Likewise, the vapor pressure under the mantle strongly depended on the mantle heat conductivity and porosity. As the dust mantle grows, it will insulate the nucleus and the erosion of the surface will slow. As a consequence, a thinner crystalline layer may be maintained beneath the dust crust.

2.5. Expected Observable Consequences of Aging

It is important to be able to separate the effects of aging from primordial differences between the comets. For example, the trans-Neptunian objects which evolve into the SP comets formed in-situ at larger distances than the DN and LP comets. Because of the greater ability of amorphous water ice to trap gases at lower temperatures (see Figure **??**), the trans-Neptunian icy bodies may contain up to 2 orders of magnitude more trapped gases than the DN and LP comets, and would be expected to be very active on their first passage through the inner solar system. Based on the previous discussion, the following might be observable as evolutionary and primordial effects:

- Onset of crystallization in a new comet observed as activity at large r pre-perihelion
- Secular fading of light curves as volatiles are lost and dust mantle builds up (although the mantle will erode at each perihelion passage)
- More uniform activity in new comets – with larger available surface area for sublimation due to lack of mantling
- Jets and outbursts will be more likely for comets which have passed through the inner solar system previously
- Difference in the amount of outgassing between LP, DN and SP comets
- Primordial differences in nucleus size distributions
- Because the mantle/crust stores heat, it can cause a lag in interior heating and maximum vapor pressure which can cause perihelion brightness asymmetries. Comets having made many passages may get brighter post-perihelion (depending on comet obliquity, rotation rate etc).

However, because of the complexity of thermal and structural changes the nucleus undergoes, it is likely that detailed thermal models should be calculated for particular comets to fully understand their light curve behavior.

3. Techniques for Observing Changes in Activity

One of the common requirements for the ability to detect many of the evolutionary processes is the ability to observe bare nuclei and to detect activity at large r. This often requires a long-term observing program with a standard set of equipment / filters, and in addition owing to the intrinsic faintness of the nuclei, and low surface brightnesses of the dust comae at large r, it requires large telescope apertures.

3.1. Broadband Photometry – Observing the Dust

Observations of distant comets out to scientifically interesting distances (*e.g.* the onset or cessation of activity) can be very challenging. To follow the evolution of activity in comets at large distances from the sun, the m_R filter is best because it avoids significant contamination from gas bands as the comet nears the sun, and because the peak efficiency of the CCD and scattered light from the comet dust occurs in this bandpass. Detection of low surface brightness comae at large distances is especially difficult. The observations require that the CCD detector can be flattened to high accuracy. This can be achieved by dithering the images making up the total integration so that the images can be used as flat fields. The observations must be planned carefully so that the expected path of the comet does not overlap any bright (*i.e.* m < 21) field stars. For very distant comets, faint background galaxies become the most challenging source of “noise” which needs to be removed. This can be done by creating deep masks of the background objects to be scaled and subtracted off individual frames under similar seeing conditions.

3.2. Limits on Outgassing

When spectroscopy is not available for placing limits on the presence of molecules, very sensitive limits on the amount of dust removed from the nucleus from outgassing, Q [kg s^{-1}], may be made from broad band azimuthally averaged surface brightness profiles (Meech & Weaver, 1995). The difference in the surface brightness profiles between comparison stars and the comet can give upper limits to any flux contributed by a possible dust coma, F. This flux may be written as:

$$\mathrm{F} = \left[\frac{S_\odot \pi \phi}{2r^2\Delta^2}\right]\left[\frac{a_{gr}^2 p_v}{v_{gr}}\right] Q(0)$$

where $S_\odot$ is the solar flux through the bandpass [W m^{-2}], ϕ the projected size of the aperture [m], a_{gr} [m] the grain radius, p_v the grain albedo, v_{gr} [m s^{-1}] the grain velocity, and r is in AU and Δ in m. The terms between the left brackets are known parameters, whereas assumptions must be made for the terms between the right brackets. This can place dust production limits 1-2 orders of magnitude more sensitive than other methods which compare the outer wings of the surface brightness profiles since the highest signal to noise is near the core.

4. Evidence for Aging

4.1. Comparison of Long-Term Light Curves

A long-term program of observation of the activity level of approximately 50 comets as a function of heliocentric distance has been undertaken over the last decade using the facilties on Mauna Kea, the National Optical Astronomy Observatories and the Hubble Space Telescope. This program has the advantage over previous summaries of long-term visual and photographic programs both in the standardization of equipment used, the band pass and measurement aperture, as well as its ability to go faint – pursuing comets until only the bare nuclei are observed. Of the short-period comets in the program, P/Halley was the brightest and showed the most activity as a function of distance. The post-perihelion light curve of P/Halley is compared to the post-perihelion light curves of 6 dynamically new comets in Figure **??**.

The post-perihelion light curve of P/Halley was characterized by a gradual fading, followed by a steeper fading near $r = 10$ AU as the activity from sublimation of crystalline water ice ceased. The increase in brightness near $r = 14$ AU has been explained as a release of gas and dust brought on by the onset of crystallization in the amorphous ice several tens of meters below the surface (Prialnik and Bar-Nun, 1992). In contrast the DN and LP comets tended to

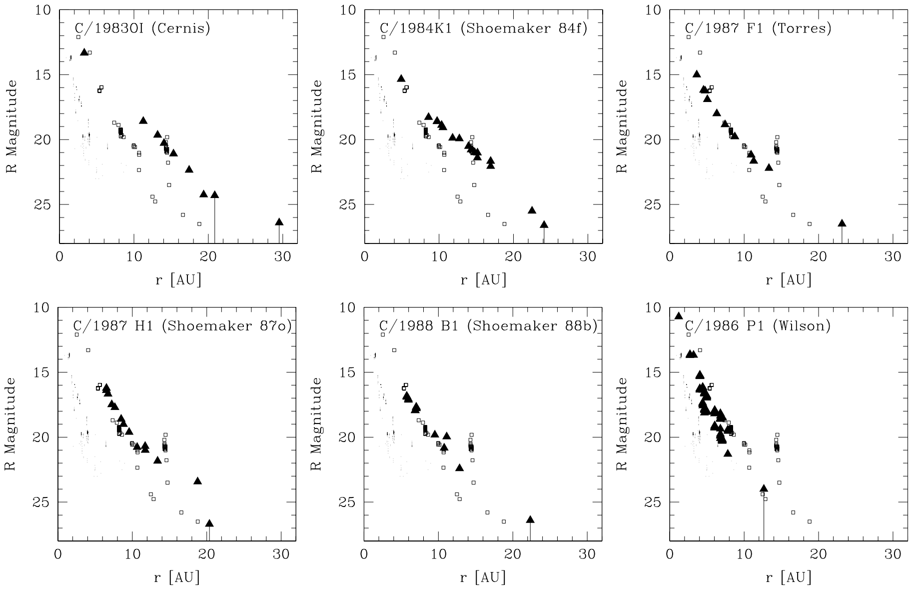

Figure 4. Comparison of the post-perihelion lightcurves of 6 Oort and long-period comets with that of P/Halley (small squares), and the Jupiter family SP comets (dots) showing the large difference in activity levels. The verticle lines attached to some of the LP and DN data points represent upper limits to the brightness as obtained from HST and the ground, and probably are good limits for the nucleus brightness.

fade much more slowly, in particular, not exhibiting the sharp down turn near 10 AU or earlier that comet P/Halley and the SP comets do.

It could be interpreted that one possible explanation for the excess activity in the DN comets is because they have unusually large nuclei. Observations made in our long-term program combined with nucleus sizes summarized in Meech *et al.* (1998) and shown in Figure **??** suggest that this is not the case. With the limited data that exist, it is clear that the SP and LP comets do not have widely differing size distributions. This suggests that the activity level differences may be evidence of the different underlying causes (*e.g.* sublimation from crystalline ice versus the amorphous ice phase transition).

Further evidence of the amorphous to crystalline ice phase transition has been modelled in comets which exhibit activity at large r. Chiron's dust coma was discovered at $r = 11.8$ AU (Meech & Belton, 1990). The brightness peaked near $r = 12$ AU (see Figure **??**) and slowly faded as it approached perihelion. An examination of historical lightcurve showed another period of brightening near $r = 17.5$ AU. Prialnik *et al.* (1995) have shown that the lightcurve behavior can be reproduced with a model assuming an amorphous ice nucleus with 60% dust fraction, where the activity is driven by crystallization. This not only reproduces the sporadic brightening which began near aphelion, but also the thermal mea-

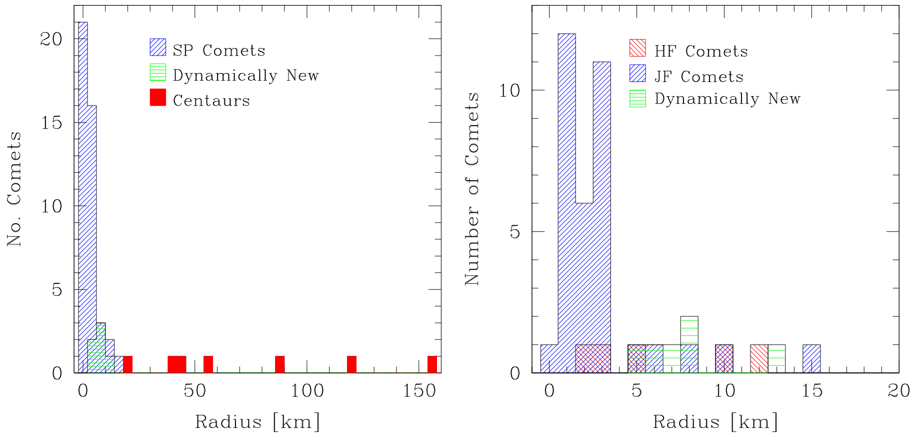

Figure 5. Comparison of the size distributions of SP, DN comets and Centaurs (left) and broken down into Halley-family (HF), Jupiter-family (JF) and DN comets (right).

surements and limits on CO and CN production at its peak brightness. While it is likely that Chiron is a transition object from the trans-Neptunian region to the inner solar system, because the perihelion distance is so large, this level of activity could be sustained for a long time since. The surface may be significantly "aged" because it doesn't get refreshed from removal of the crystalline layer by sublimation since the comet never gets close enough to the sun.

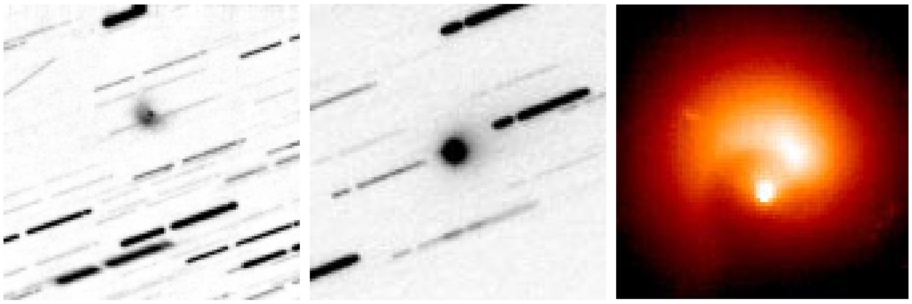

Figure 6. Comparison of [a] the outburst of P/Halley (left) at $r = 14.3$ AU on 02/15/91 (FOV = 1.6′; 9.3×10^5 km), [b] the coma on P/Chiron (center) at $r = 9.3$ AU on 02/20/93 (FOV=2.5′; 9.1×10^5 km), and [c] the coma of C/1995 O1 Hale-Bopp (right) seen from HST about 60 hours after a large outburst of dust at $r = 6.49$ AU on 09/26/95 (FOV = 10″; 4.7×10^4 km). Image courtesy of H. Weaver). The large heliocentric distance activity may be related to amorphous – crystalline ice transitions.

Comet C/1995 O1 Hale-Bopp's unusual brightness allowed it to be observed at radio wavelengths over a wide range of distances from shortly after discovery (Biver, *et al.*, 1998). The production of CO was very high at $r = 6.7$ AU, rising moderately fast until 3 AU. Water activity rose steeply during this period and surpassed the production of CO near $r = 3.5$ AU. This behavior – both the extensive activity at large r, the large CO production near $r = 7$ AU and its leveling off near 3 AU can be explained with amorphous ice phase transition models (Prialnik, 1998b). While C/1995 O1 Hale-Bopp is not a dynamically new LP comet, it is probably dynamically young (Bailey, *et al.*, 1996). This was confirmed with the model calculations which required that there could only be a thin ($\approx < 1$ m thick) dust mantle on the surface in order to match the gas production rates. Since the comet is known to be very dusty, this implies that it has not made many close solar passages to have built up a thick mantle. The model predicted a rise in gas production (CO) from the phase transition between $r =$ 10-6 AU, which was seen.

These three examples show the evolutionary differences expected in the activity of relatively young objects (*e.g.* P/Chiron and C/1995 O1 Hale-Bopp) and a more evolved object (P/Halley).

4.2. Narrowband Photometry

A'Hearn *et al.* (1995) have undertaken a twenty year study of the abundances and dust production rates in 85 comets using narrowband photoetectric photometry. Their sample included 39 Jupiter-family comets, 8 Halley-family comets, 8 dynamically new comets and 27 long-period comets. In their study, they measured the molecular production rates for C_2, C_3, OH, NH, CN and estimated the dust production rates. While overall, they found that most comets were similar in chemical composition, there was a group of comets which were depleted in the carbon chain molecules (C_2 and C_3). As shown in Figure **??**, the depletion is strongly correlated with dynamical age, as described by the Tisserand invariant. Only Jupiter-family comets are depleted, however, not all Jupiter family comets show the depletion. A'Hearn *et al.* argue that this is attributed to a primordial rather than an evolutionary difference. If this were an evolutionary difference there should be a correlation with dynamical age among other comet classes which was not seen. Likewise, no correlation was seen between the carbon-chain depletion and active fractional area of the nucleus, yet the active fractional area was correlated with dynamical age. A'Hearn *et al.* suggest that some process in the solar nebula may have preferentially produced or destroyed the carbon chain molecules at the distance of the Edgeworth-Kuiper Belt, the source region for the Jupiter-family comets.

A'Hearn's data set also showed that there was a clear trend of active area versus the dynamical age shown in Figure **??**. This could either be interpreted as evidence that the nuclei of the dynamically older comets are smaller (primordial condition), or that a smaller fraction of their surfaces are active (evolutionary effect). Work on obtaining the nucleus sizes for inactive comets suggests that the latter is correct, and that we are seeing the effects of aging.

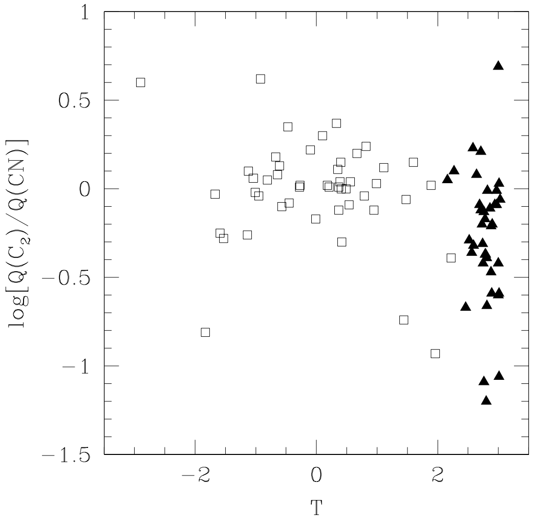

Figure 7. Ratio of Q(C$_2$)/Q(CN) versus the Tisserand invariant, *T*, an indicator of cometary dynamical age. Data are from A'Hearn *et al.* (1995).

5. Conclusions

Chemical and physical changes may occur on the precursor comet nucleus material (interstellar grains) prior to and during its accretion in comets. Changes can also occur from radiation processing and radionucleide heating while stored in the Oort cloud and Edgeworth-Kuiper belt, and during the comets' active phase.

Processing of interstellar grains in the molecular cloud was seen from the high cometary D/H ratos, whereas solar nebula processing is seen from the relatively low CO abundance compred to ISO observations of ice grains in the ISM. The fading of LP and DN lightcurves, the high gas/water ratios and the ice grains (amorphous) see in comet Hale-Bopp support the idea of recondensation of volatiles in the solar nebula. Models of the activity at large distances suggest that the primary driver of large *r* activity is due to the amorphous to crystalline ice phase transition. This leads to irreversible aging effects. During the active phase, there is evidence for further aging with dust manteling, outbursts, jets and loss of active area. These effects are beginning to be distinguished from primordial differences such as size distributions and C$_2$ and C$_3$ abundances between dynamical classes.

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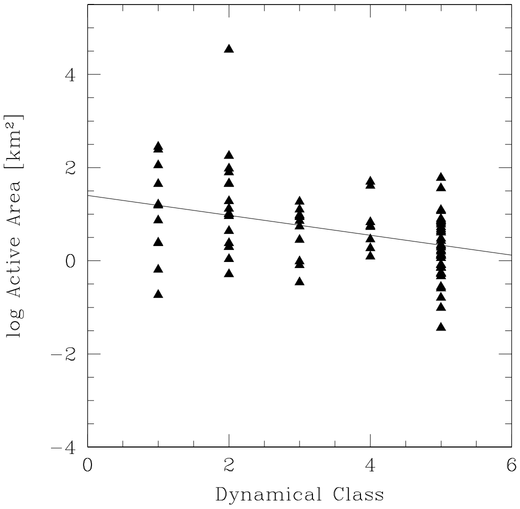

Figure 8. Log of the active area [km^2] versus dynamical age or class: 1 = dynamically new, 2 = young long-period comet, 3 = old long-period comet, 4 = Halley family, 5 = Jupiter family. Data are from A'Hearn *et al.* (1995).

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References

A'Hearn, M. F, R. L. Millis, D. G. Schleicher, D. J. Osip and P. V Birch: 1995, *Icarus* **118**, 223
Bailey, M. E. *et al.*: 1996, *Mon. Not. R. Astron. Soc.* **281**, 916
Balsiger, H., K. Altwegg, and J. Geiss: 1995, *J. Geophys. Res.* **100**, 5827
Bar-Nun, A and I. Kleinfeld: 1989, *Icarus* **80**, 243
Bar-Nun, A. and T. Owen: 1998, in *Solar System Ices*, ed.: B. Schmitt et al., Kluwer, The Netherlands, 353
Biver, N.: 1998, *Earth, Moon, Planets* , submitted
Bockelee-Morvan, *et al.*: 1998, *Icarus* **133**, 147
Davies, J. K. *et al.*: 1997, *Icarus* **127**, 238
Davis, D. R. and P. Farinella: 1997, *Icarus* **125**, 50
Duncan, M. F., T. Quinn and S. Tremaine: 1988, *Astrophys. J.* **328**, L69
Eberhardt, P., M. Reber, D. Krankowsky and R. R. Hodges: 1995, *Astron. Astrophys.* **302**, 301
Ehrenfreund, P. *et al.*: 1997, *Icarus* **130**, 1
Farinella, P. and D. R. Davis: 1996, *Science* **273**, 938
Fernández, J. A. and W.-H. Ip: 1981, *Icarus* **47**, 470

Grün, E. *et al.* : 1991, in *Comets in the Post-Halley Era*, ed.: R. L. Newburn, et al., Kluwer, Netherlands, 277

Hughes, D. W.: 1991, in *Comets in the Post-Halley Era*, ed.: R. L. Newburn, et al, Kluwer, Netherlands, 825

Keller, H. U.: 1987, *Astron. Astrophys.* **187**, 807

Kresák, L.: 1991, in *Comets in the Post-Halley Era*, ed.: R. L. Newburn, et al., Kluwer, Netherlands, 607

Kührt, E. and H. U. Keller: 1994, *Icarus* **109**, 121

Laufer, D., E. Kochavi and A. Bar-Nun: 1987, *Phys. Rev B* **36**, 9219

Laufer, D., G. Notesco, T. Owen and A. Bar-Nun: 1998, *Icarus* , in press

Lunine, J. I, S. Engel, B. Rizk and M. Horanyi: 1991, *Icarus* **94**, 333

Meech, K. J.: 1991, in *Comets in the Post-Halley Era*, ed.: R. L. Newburn, et al., Kluwer, Netherlands, 629

Meech, K. J. and M. J. S. Belton: 1990, *Astron. J.* **100**, 1323

Meech, K. J. and H. A. Weaver: 1995, *Earth, Moon, Planets* **72**, 119

Meech, K. J., O. R. Hainaut and B. G. Marsden: 1999, *Icarus* , in prep.

Meier, R., *et al.*: 1998a, *Science* **279**, 842

Meier, R., *et al.*: 1998b, *Science* **279**, 1707

Prialnik, D.: 1998a, *Earth, Moon, Planets* , submitted

Prialnik, D.: 1998b, *Proc. of the MBOSS Meeting, 11/98* , submitted

Prialnik, D. and A. Bar-Nun: 1987, *Astrophys. J.* **313**, 893

Prialnik, D. and A. Bar-Nun: 1992, *Astron. Astrophys.* **258**, L9

Prialnik, D., A. Bar-Nun and M. Podolak: 1987, *Astrophys. J.* **319**, 993

Prialnik, D., N. Brosch and D. Ianovici: 1995, *Mon. Not. R. Astron. Soc.* **276**, 1148

Prialnik, D. *et al.*: 1993, *Icarus* **106**, 499

Rickman, H.: 1991, in *Comets in the Post-Halley Era*, ed.: R. L. Newburn, et al., Kluwer, Netherlands, 733

Sekanina, Z.: 1982, in *Comets*, ed.: L. L. Wilkening, Univ. AZ Press, Tucson, 251

Stern, S. A.: 1986, *Icarus* **68**, 276

Stern, A. and H. Campins: 1996, *Nature* **382**, 507

Stern, S. A. and M. Shull: 1988, *Nature* **332**, 407

Strazzulla, G. and R. E. Johnson: Comets in the Post-Halley Era, in *1991*, ed.: R. L. Newburn, et al., Kluwer, The Netherlands, 243

Weidenschilling, S. J.: 1997, *Icarus* **127**, 290

Whipple, F. L.: 1991, in *Comets in the Post-Halley Era*, ed.: R. L. Newburn, et al., Kluwer, Netherlands, 1259

Whittet, D. C. B. *et al.*: 1996, *Astron. Astrophys.* **315**, L357

Yamamoto, T. and S. Sirono: 1998, in *Cometary Nuclei in Space and Time*, ed.: M. F. A'Hearn, ASP Conf. Series, , submitted