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Cometary Origin and Evolution

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Abstract.

The earliest stages of collapse of our solar nebula are not subject to direct observational constraints, although we are beginning to get information about protoplanetary dust disks during the planet forming eras. Lacking direct observational constraints on our own solar nebula, cometary nuclei can give us some information from this early era. Comet nucleus size distributions may preserve a record of the outer nebula mass distribution in the late states of planetary formation, as well as a record of collisional evolution. The rate of proto-planetary growth and scattering as a function of heliocentric distance depended on the size and mass distribution of the km-sized planetesimals that have survived as today's comets, their nebular surface density and their velocity distributions. Likewise, comparisons of the development and cessation of activity as a function of heliocentric distance for comets originating in different regions of the outer solar nebula can help us understand the volatile distribution and physical processes in the outer nebula and the planet formation environment. Observations of recent bright comets have shown that there is evidence of a preservation of an interstellar ice / dust component within nuclei, yet at the same time the cometary material has undergone processing during its formation.

1. Introduction

Over the past quarter century theorists have been developing increasingly sophisticated models of solar system formation. The discoveries of extrasolar planetary systems which look significantly different from our solar system – with massive hot Jupiters close to the star, and distant non-circular planetary orbits – have forced new approaches to understanding planet formation. While extrasolar planets are placing new constraints on planetary system formation models in general, the rich field of discoveries of small bodies in our own outer solar system is providing a wealth of constraints which will help us understand the formation of our solar system.

2. Formation of Comets

Comets formed in the outer solar nebula out of interstellar material which was probably altered to some extent before its incorporation into the cometesimals. The pre-cursor cometary material, the interstellar grains, was 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 mantles of interstellar grains underwent significant processing in the molecular clouds from bombardment by cosmic rays and UV photolysis (in the cold clouds). The cosmic ray ions lost energy by ionization of the grain target material, by breaking chemical bonds in the target, and from surface sputtering (Strazzulla & Johnson 1991). This can create both non-volatile material and highly reactive radicals.

Dynamical studies have identified several likely regions for comet formation. This is important because it implies different physical and chemical environments for formation. Duncan *et al.* (1988) found that the short-period (SP) comets must have had a low-inclination source in the trans-Neptunian region. The long-period (LP) comets and the dynamically new comets, on the other hand, formed at smaller heliocentric distances and were perturbed outwards through random interactions with the giant planets (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 of solar nebula grains 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 size. Comets formed in this manner should be compact at the sub-meter 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 shows a schematic diagram of our protoplanetary nebula at the time of its collapse. Planetesimal accumulation which lead to comet formation probably occurred from the Uranus-Neptune region ($r \sim$ 20-30 AU) out to the region of the Kuiper belt ($r \sim$ 30-50 AU).

After some of the icy interstellar grain components were sublimated as the infalling material was heated, the gases would have re-condensed on the cold grain cores. Laboratory studies have shown that when water ice 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.

As shown in Figure 1 strong temperature gradients were expected in the 20-50 AU comet formation region, thus comets should have formed with different amounts of trapped volatile materials. This primordial difference could be reflected in differences in behavior as the comets are heated by the sun since the outgassing will be controlled both by annealing of amorphous ice as well as by the quantity of trapped higher volatility materials.

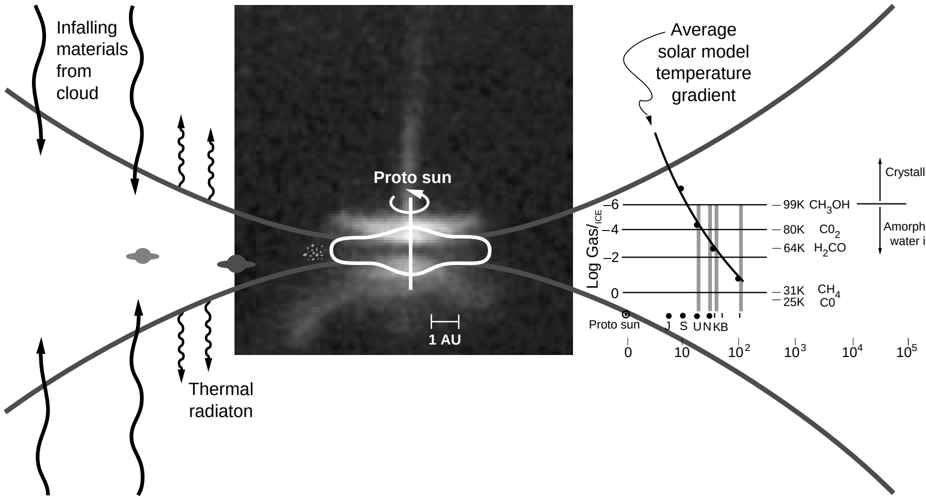

Figure 1. Schematic of collapse of the solar nebula superimposed on an HST image of the protostellar disk, HH-30 (C. Burrows, STScI). In-falling solar nebula material is shock heated during infall, sublimating volatiles found on interstellar grains. The volatiles recondense at nebular ambient temperatures. 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-Kuiper Belt comets in the 30-100 AU region.

3. Evolutionary Processes

Using the differences in observed comet chemical composition and physical characteristics to infer properties of the early solar nebula must be done with caution because there are many evolutionary processes which will alter the comet over the age of the solar system.

3.1. 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 2 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

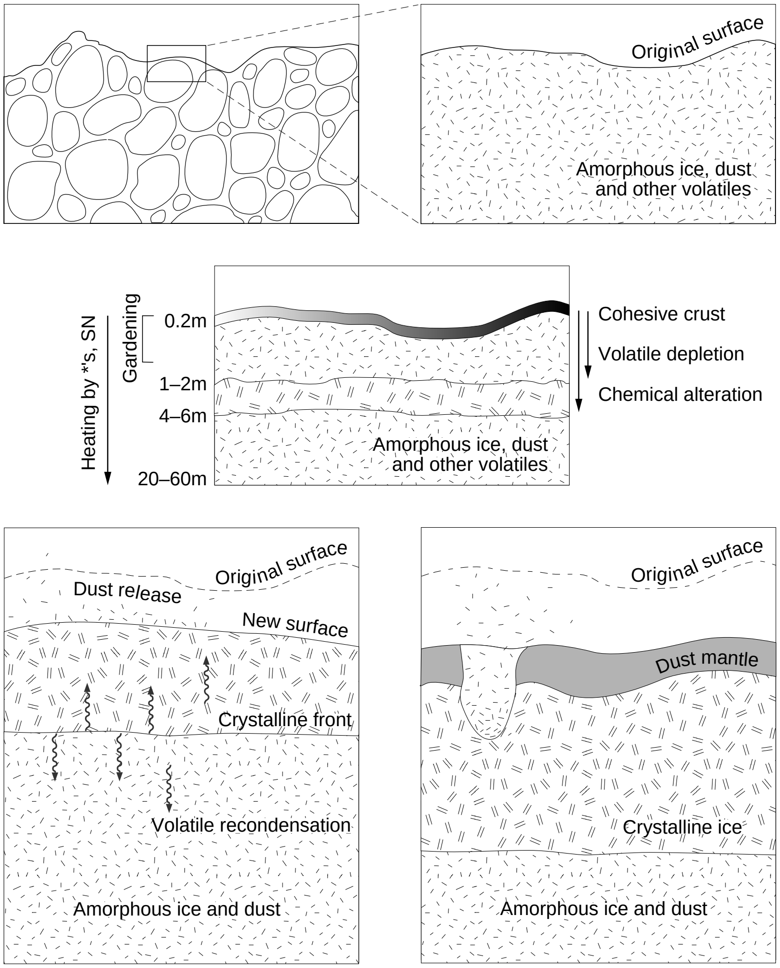

Figure 2. Diagram showing the sequence of aging processes in the upper layers of a comet nucleus from (a) the pristine state, consisting of primordial planetesimals (upper left, enlargement – upper right), (b) to the alterations it undergoes while stored in the Oort cloud including a possible crystalline 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).

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; ^{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 (Davies *et al.* 1997), comet interiors cannot have been heated above 137K. This places limits on the abundance of ^{26}Al and heating timescales. 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. Larger comet nuclei, such as Kuiper belt objects may have undergone complete phase changes (*e.g.* crystallization and melting in the core), depending on their conductivity, porosity and size. This could result in a layered structure with a weak devolatilized region below the surface (Prialnik 2000).

3.2. Active Cometary Phases

During the active phase, when the comet passes within the inner solar system and experiences significant solar insolation, the comet's surface and sub-surface layers (up to a few meters in depth) will be both 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 ($T \sim 180$ K). During crystallization the trapped gases are released and will flow both toward the interior and toward the surface through the porous material (see Figure 2). Much of the released CO_2 will recondense on the icy mantles of grains (Yamamoto & Sirano 2000), causing sintering between grains, thus increasing the nucleus tensile strength. This will reduce the porosity of the nucleus, and increase the thermal conductivity. The released gases cannot immediately rise to the surface, and they may accumulate in pockets via dynamic percolation through pores. 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 proceed continuously, but may proceed 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 and redistributing volatiles. 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 2).

4. Observational Evidence from Comets

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 LP and dynamically new comets (DN; *e.g.* on their first passage through the inner solar system from the Oort cloud). Because of the ability of amorphous water ice to trap gases at lower temperatures, 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 mantles build 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.

4.1. Processing & Preservation of Interstellar Material

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

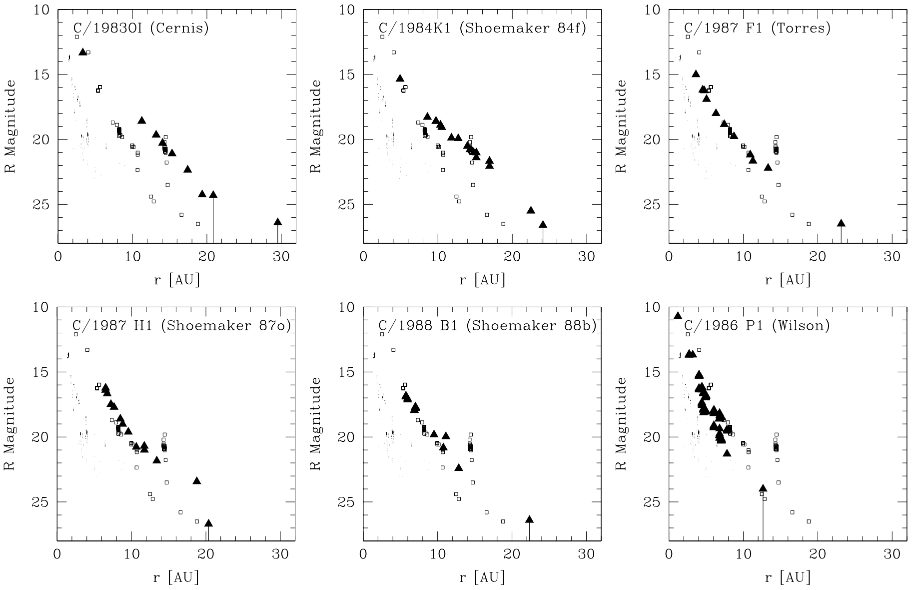

Figure 3. Comparison of the post-perihelion lightcurves of 6 DN and long-period comets (filled triangles) with that of P/Halley (small squares), and the Jupiter family SP comets (dots) showing the large difference in activity levels. The verticle lines attached to some of the LP and DN data points represent upper limits to the brightness as obtained from HST and the ground, and probably are good limits for the nucleus brightness.

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.* 1999).

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). 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.

4.2. Evolution During the Active Phases

Long-term observation of the dust coma evolution in comets over a range of heliocentric distances can be measured through broad-band photometry to very faint limiting magnitudes. This can be used to infer volatile processes in the nucleus and be used to compare comets of different dynamical classes to search for primordial differences. 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. The post-perihelion light curve of P/Halley is compared to the post-perihelion light curves of 6 dynamically new comets in Figure 3.

In Figure 3 it is clear that the DN and LP comets are much brighter at any given r than are the SP comets, including P/Halley, which is the brightest of the sample of SP comets shown. For the comets shown in the figure, the greater brightness is due to the presence of coma, indicative of sustained activity at large r. 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 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 (2000). 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).

5. Conclusions

Comets formed from planetesimals which may have come from a large range of heliocentric distances in the outer solar nebula, and the particular r at which the cometesimals formed may have a significant effect on the physical properties and chemical composition of the comet. 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.

Continued physical and dynamical observations of comets, in comparison to exciting characterization of the physical properties of extrasolar dust disks will bring us closer to an understanding of the planetary formation processes.

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