More Evidence for Liquid Water on Comets

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ABSTRACT

It has been seven years since we presented evidence for liquid water on comets and the wet comet theory that comets melt and undergo an irreversible phase change on their first passage through the inner solar system. Since then there have been three more comet flybys and analysis on returned cometary material. We review the wet comet model and discuss the new data, showing that the model not only has been further vindicated, but explains several more independent observations. Not only do comets show evidence of some melting, they show evidence of complete melting.

1. INTRODUCTION

Whipple Dirty Snowball Model There are many differences between long and short period comets which Whipple's model does not explain, and even between comets and asteroids which do not have easy explanations. In Table 1 we list some of the strange properties of comets which the Whipple model does not address.

The old paradigm of comets was developed primarily by the late Fred Whipple, who suggested that the dust and gas of telescopically observed comets could be explained if they were an amalgam of ices and dust formed out of the left-overs of the proto-solar nebula now found out beyond the orbit of Pluto in what is known as the Oort Cloud. Since these ices have never been close to the Sun or any star, they are composed of CO, CO_2, CH_4 and H_20 ice grains loosely cementing together interstellar dust. The Oort cloud objects, with mean radii of 1 lightyear from the Sun, are very loosely bound to the gravitational well of the Sun, and can experience significant perturbations by passing stars, which occur regularly whenever the Sun in its orbit about the galactic center passes through the plane of the galaxy. In addition, events such as nearby magnetar gamma ray bursts can heat a layer of ice several centimeters below the surface and blow off chunks of ice that supply enough delta-v to send the comet into the inner solar system.

As a pristine comet enters within the orbit of Jupiter, the CO ice will begin to evaporate, and within the orbit of Mars, the H_2O will begin to evaporate forming a tail. These "long-period" comets have apogees out beyond the orbit of Pluto, and typically are very bright, very dusty, and very large. According to Whipple's model they have rather high albedo, reflecting most of the sunlight that falls on them, and their outgassing keeps their surface cool. Gravitational interactions with Jupiter, the largest gravitational cross-section planet in the solar system, can trap their aphelion, causing them to have 5-6 year orbits with aphelion near Jupiter's orbit. These Jovian or "short-period" comets not only are periodic but they typically are smaller, have less dust and are not as bright. There is a third category of Kuiper-belt objects that have aphelia near the orbit of Neptune, which may include comets such as Halley's comet with periods of 75 years.

Review of Wet Comet Model In our earlier papers on comets, Hoover et al. 2004, Sheldon & Hoover 2005, 2006 and 2007 (HEA04, SH05, SH06 and SH07) we presented evidence that comets must go through a phase transition as they enter the orbit of Mars. The outgassing of comets provide random torques that spin the comet up. At low spin rates, the Rayleigh-Taylor instability causes the comet to act as a refrigerator. The gravity vector points down, and the Sun's radiant heat is applied at the top of the atmosphere. Since heat rises, the heat does not penetrate in toward the comet. But as the comet rotates to point away from the Sun, the atmosphere radiates to the cold night sky and colder gas sinks down. Thus heat is pumped out of the comet.

But as the spin rate increases and exceeds the local force of gravity so that a pebble will just barely lift off the equator, then the Rayleigh-Taylor instability begins to operate in heat-pump mode. The gravity vector points upward, and as the sun-facing side applies heat at the top of the atmosphere, the heat convects toward

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Figure 1. Left: Long-period comet Hale-Bopp with dust and plasma tails. Medium-period comet 2P/Halley. Short-period comet 109P/Swift-Tuttle.

Table 1. Telescopic differences between comets and asteroids.

Metric	Asteroids	Long-period	Short-period
1. Rotation Period	hours	hours	days
2. Tails	none	dust+gas	mostly gas
3. Aspect ratio	spherical	spherical	prolate
4. Plasma tail shed	none	rare	at sector boundary
5. Precession	gyroscopic	unknown	zero
6. Radial diffusion	none	small	huge
7. Time lag of coma	none	symmetric	asymmetric
8. Tensile strength	high	very low	sporadic

the comet via convection cells. The night side, however, is stabilized because as the atmosphere cools at the top, the gravity vector points away from the comet, keeping the colder air away from the surface. This phase change rapidly heats the surface of the comet and begins to sublime the gases. Soon a thick layer of dust lies on top of the ice. Now if by chance a melting event occurs, perhaps due to clear ice containing a black pebble that provides a pressure vessel capable of holding the 6 millibars of pressure needed for liquid water, then water will wet the dust, clogging the pores and hydrating the anhydrous minerals in the dust. Just as Portland cement sends out fingers of hydrated minerals to form an interlocking web of crystals, so the dust on the surface of the comet will begin to form a crust. The crust interferes with the subliming wind, raises pressure, lowers the albedo, absorbs more heat from the Sun, all of which permit more liquid water. More water means more wetting of dust, and the system has a strong positive feedback.

We would expect that all through this time the comet is spinning faster, so there may be catastrophic loss of these pieces of crust, leading to rapid erosion of the equator of the comet. This gradually changes the profile of the comet from a sphere to a prolate "apple-core" shape. The prolate shape is no longer stable to spinning about its smallest moment of inertia, and this instigates a spin-flip to a prolate tumbler. Either because of this spin-flip, or perhaps the wetting process advanced faster than the spin rate, at some point the entire region crusts over, forming a single, self-reinforcing belt of relatively high tensile strength material. From this point onward, the crust is not lost by "lifting off" the surface, which allows the crust to grow wider in latitude as water collects behind the crustal band. Soon the entire comet is "crusted over" and from this point on, the volume of the comet is fixed. This is the irreversible phase change that occurs to a comet as it passes from Whipple dusty snowball, to black encrusted dumbbell.

Now the changes to the comet are occurring deep within the crust. The ices melt, forming water which then drains into the equatorial region. This changes the moment of inertia of the comet, causing the comet to undergo a spin-flip to a prolate-tumbler as well as to slow down like an ice-skater throwing out her arms. If the spin rate drops below the Rayleigh-Taylor critical speed, the water moves toward the center of the comet, and the surface of the comet cools. But this process speeds the comet up, turning on the Rayleigh-Taylor instability again. So the Rayleigh-Taylor instability controls the rotation speed of the comet to keep it right at the critical value. As cracks in the crust form, the comet has geysers that carry out water and mud from the interior. The mud may make geysers self-healing, though telescopic observations show persistence of geyser fields for multiple orbits. However, because it is mud, dust is less prevalent in the telescopic coma, and the mud accretes an ever-thickening band of concrete at the equator–which for a prolate tumbler, is at the ends. This makes the poles the thinnest crust, and where non-self-healing steam geysers might form.

As the comet passes by perihelion and escapes past the orbit of Mars, the water eventually freezes, ready to restart the process on the next perihelion pass. The refreezing, however, occurs at much greater distances from the Sun than the melting, providing an asymmetric coma with respect to orbital distance. However the refreezing can also be local, since the night side of comets can be quite cold. Thus it would be expected that many freeze-thaw cycles would process the rock in the comet leaving it finely grained, as well as fractionate the water into ice and brines. The presence of liquid water also acts to lower the moment of inertia of the comet as well as damp out any nutations due to external torques from the geysers. The net result is a gradual slowing down of the comet as the interior is hollowed out but without changing its spin-axis in space.

Telescopic Evidence for Wet Comet Model This model then explains each of the tabulated differences between asteroids, long-period comets and short-period comets. Comets are seen to rotate slower than asteroids because of this Rayleigh-Taylor rotation governor. Short-period comets are much older than long-period, and hence have become more hollowed out, and therefore slower rotating.

The tails of long period comets are dusty because they are subliming dirty snow, whereas the tails of short-period comets have had their dust emissions scrubbed with water, so that the tails are far less dusty.

Asteroids collapse under gravitational attraction, and the minimum energy surface is a sphere. Long-period comets likewise are a gravitationally accreted ice and dust ball. Short-period comets, however, have been processed by heat, concrete, and centripetal force, and are therefore prolate tumblers.

The plasma tail from long-period comets does not normally “shed” because as the magnetic fields of the solar wind impinge on the comet, the low conductivity of the comet present a small impedance to the solar wind, and little if any plasma tail develops. The short-period comet, however, has a liquid brine conductor whose motion through a magetic field induces one of its own. As a consequence the plasma tail gets “hung up” on the comet, and when the comet passes through a magnetic sector boundary, all the draped magnetic field is peeled off, causing the plasma tail to appear to “shed”.

Asteroids are rigid bodies, so torques will cause them to precess or even nutate as they rotate. Long period comets begin to spin up as they approach the Sun, and appear to precess as well, if that can be determined telescopically from asymmetric coma. Short-period comets, however, do not precess or nutate at all, but maintain the same spin axis in inertial space. This is possible because the liquid acts as a nutation damper, keeping the comet in its lowest moment-of-inertia spin axis.

A plot of aphelia show asteroids have a 4AU density bump that decreases outward in both radial directions. This is indicative of diffusion from a source. However, comets do not appear to be diffusing from an Oort cloud source, but show nearly constant density between Mars and Pluto as soon as their perihelia get within the orbit of Mars. This indicates a very rapid diffusion, or alternately a very rapid acceleration of comets at their perihelia location. This is consistent with melting of water at the orbit of Mars, and the superior thrust of a geyser over a sublimation driven wind.

The coma on the inbound leg is often offset from the outbound leg, where the inbound coma only forms near the orbit of Mars, whereas the coma of the outbound leg persists out to the orbit of Jupiter. This indicates a very large heat capacity, capable of continuing geyser activity with decreasing solar activity. Liquid water, of course, has one of the highest heat capacities known.

The tensile strength of asteroids is about that of rock, whereas long-period comets seem to break up easily, often on their first orbit around the sun. Short-period comets, on the other hand, make many perihelia passes of much smaller radii than long-period comets without disrupting. A plot of radial distance at breakup indicate no perceivable pattern. This is consistent with liquid water appearing for the first time on a long-period comet, and

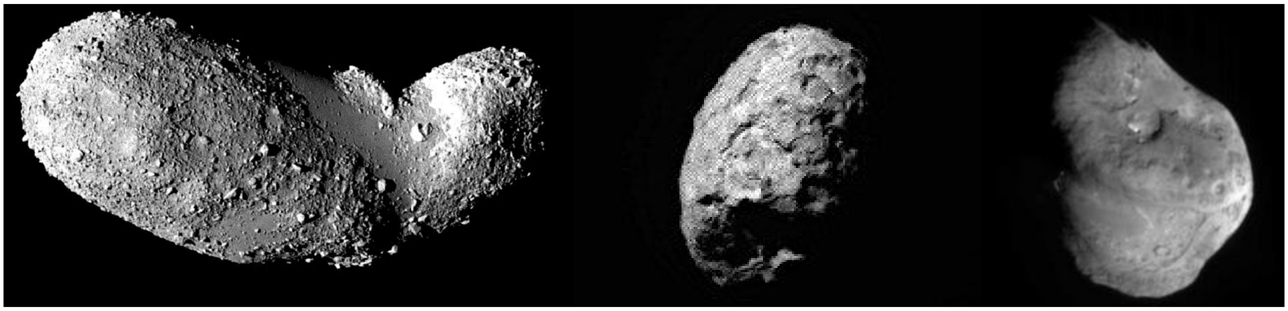

Figure 2. Left: Hayabusa images of asteroid Itokawa. Middle: Stardust images of Wild2. Right: Deep Impact images of Tempel1. Photos courtesy JASA and NASA.

Table 2. Spacecraft flyby observations of comets.

Metric	Itokawa	Long-period	Short-period
Temperature	30 C	<0 C	0 C / 100 C
Crust	rock	unknown	rigid
Geysers	none	few	polar
Cratering	some	unknown	weird
Density	2	1	0.6
Geology	2 m rubble	unknown	resurfacing
Albedo	0.3	0.5	0.03
Outgassing	none	diatomic	organic

like the failure of the Columbia shuttle wings, the water penetrates the comet and destabilizes it. Short period comets, on the other hand, have had their tensile strength raised by being coated in a layer of concrete.

So as discussed in SH05, SH06 and SH07, the wet-comet model is capable of explaining many of the anomalies between asteroids, long-period comets, and short-period comets.

Satellite Evidence for Wet Comet Model The advent of the space age, and the ability to conduct comet flybys has completely transformed the understanding of comets, bringing a new set of questions. However, nearly all the observations have supported the wet comet model, and a few were predicted before the measurements were made.

All the comet flybys showed temperatures above the freezing point of water. A few places on the comet were above the boiling point of water at 1 atmosphere. This contradicted the Whipple model, and supports the wet comet model. A modified Whipple model suggests that the dust does not get blown off by the subliming wind, but forms a thick blanket of low thermal conductivity around the comet which can support temperatures higher than melting temperatures. However this is not supported either, because temperature maps show much of the comet at the same temperature, 0C. This can only occur if the comet has high thermal conductivity, which the dust blanket cannot, but in fact, liquid water is an ideal thermal conductor.

All the comet flybys showed a thick crust that could support craters and spires without collapsing, which neither dust nor snow could support, and which rock could not be shaped. Concrete of the wet comet theory, however, has all these capabilities.

All the comet flybys showed the presence of water geysers in addition to steam geysers, which the wet comet model predicts but are disallowed by the Whipple model. The difference in shape of the two geysers, is that as water enters the vacuum, it boils and obtains a transverse velocity. Gas has an opening cone consistent with a nozzle, but beyond its fixed cone shape, does not develop a substantial transverse velocity. It is also probably true that dust "clusters" are not possible in a steam geyser which can only transport preexisting dust grains through a compression/decompression cycle that would destroy the fluffy consistency of the dust. A water geyser, however, would transport mud grains that subsequently boil and generate fluffy dust.

All the flybys showed craters, which as we earlier argued, are evidence of a rigid crust. But in addition, the craters record the history of the body. Asteroid cratering is normally rather complete, consistent with the age of the asteroids. Comets show cratering as well as resurfacing events, which is consistent with a liquid interior rather than a solid.

It has been known that asteroids are principally silicon-based rock, and therefore have densities between 2 and 3 grams/mL. Comets, being mixtures of ice and dust, were thought to have densities closer to 1, accounting for the loose aggregation of the mixture. However flybys that attempted to measure the density either with gravitational perturbation on the spacecraft, or by observing the parabolic trajectory of dust emitted from a geyser or crater estimated the density to be considerably less than 1.0, closer to two-thirds. This is not consistent with the cratering observations, and suggests that the comet is inhomogeneous, with higher density on the surface than the interior. While low values can be consistent with the Whipple model, an inhomogeneity is not, but is predicted by the wet comet model.

The sample-and-return to stony asteroid Itokawa, revealed a very un-asteroidal object that did not look like any of the previously photographed asteroids. The asteroid was essentially without craters, and consisted of an asymmetric rubble pile, strangely in the same prolate shape of comets. Close examination of the rubble using a spatial Fourier transform showed a preponderance of 2 meter dimensions. We interpret this as an extinct comet, where the 2-meter thick shell of concrete was formed as the water evaporated from the comet, and subsequent drying caused it to collapse in upon itself, maintaining the same prolate shape. This is consistent with the man-made crater in Tempel1 which confounded all expectations, looking neither like an asteroid nor like a icy snowball, but like a thin crust overlaying a hollow interior.

But it was the last two items observed by all the flybys that convince us we need to take the wet comet model even further.

All the comet flybys revealed that the surface had extremely low albedo, darker than dirty snow, darker than asteroidal rock, as dark as coal soot. This exceeds both the Whipple model and asteroidal materials, even the water-wetted materials suggested by the wet comet model. But if we additionally hypothesize that wet comets can grow cyanobacteria, then the dark color is a consequence of ultraviolet light darkened polysaccharides exuded by bacteria, similar to the dry valleys of Antarctica. This same polysaccharide material will condition the concrete and give it additional strength. Since life needs water, this is also support for the wet comet model.

Even more significantly, all the comet flybys recorded organic material outgassing from the comet. It has been known since telescopic observations that cyanogen was emitted from comets (which caused a panic during the Halley flyby of 1910), but it had been argued that these were abiotic carbon compounds perhaps generated as the outgassed molecules fragmented under ultraviolet light. The flybys, however, revealed unambiguous organic signatures, from phyllosilicates to aldehydes, the comets contain compounds that can only be produced by life, and then only from short-period comets rather than pristine long-period comets.

These results have all been documented in SH05, SH06 and SH07, and in particular, the Deep Impact data have been very illuminating.

2. NEW EVIDENCES FOR LIQUID WATER

Since 2007 we have had two additionally flybys:comet 103P/Hartley-2 and Tempel-1 by the Deep Impact spacecraft. Despite the hope that photographs of a fifth comet would reveal new surprises, the pictures were disappointingly similar to Borrelly and Tempel–a low-albedo, prolate tumbler with polar jets. However since these are precisely the predictions of the wet comet model, we are encouraged that our model explains five out of five flybys, or 100% success rate. The real test, however, will come with the 2014 Rosetta mission that lands on a comet. We have predicted that the rotation rate of Comet 67P/Churyumov-Gerasimenko is consistent with a young, very wet comet that has lost less than 10% of its volatiles.

Another piece of evidence comes from the continuing analysis of the Stardust sample-and-return mission. They have reported recovery of a crystal of cubanite, which can only from in the presence of water at less than 210C.[6] This is strong support that comets both have water, and have it at relatively low temperatures.

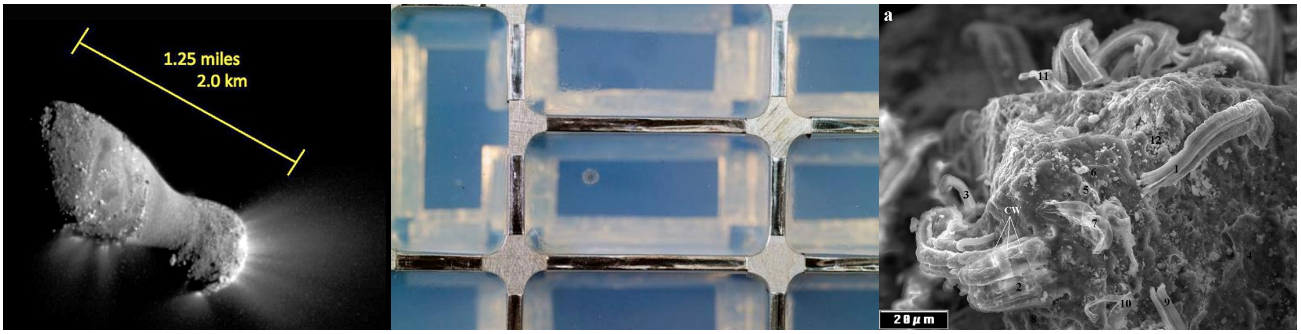

Figure 3. Left: Image of comet 103P/Hartley-2; Middle: crystal of cubanite returned by Stardust; Right: interior of carbonaceous meteorite as imaged by a scanning electron microscope. Photos courtesy NASA.

Table 3. Logarithmic Elemental abundances (by atoms) of carbonaceous meteorites

Element	Universe	Solar System	Carb Chon	CC/Univ	CC/U/Si	CC/Sun	CC/S/Si
C	7.29	6.59	6.82	-0.47	1.83	0.23	0.34
N	6.21	6.06	6.06	-0.15	2.15	0.00	0.11
O	8.61	6.95	7	-1.61	0.69	0.05	0.16
F	2.52	2.62	4.87	2.35	4.65	2.25	2.36
Na	6.58	4.44	4.14	-2.44	-0.14	-0.30	-0.19
Mg	7.90	5.66	5.60	-2.30	0.00	-0.06	0.05
Al	6.74	4.55	4.47	-2.27	0.03	-0.08	0.03
Si	7.90	5.71	5.60	-2.30	0.00	-0.11	0.00
P	5.75	3.55	3.55	-2.20	0.10	0.00	0.11
S	7.31	5.30	5.40	-1.91	0.39	0.10	0.21
Cl	5.25	3.57	2.67	-2.58	-0.28	-0.90	-0.79
K	5.46	3.21	3.09	-2.37	-0.07	-0.12	-0.01
Ca	6.64	4.44	4.44	-2.20	0.10	0.00	0.11
Fe	5.50	5.47	7.80	2.30	4.60	2.34	2.45
Ni	4.21	4.33	6.54	2.34	4.64	2.21	2.32

The third piece of evidence comes from carbonaceous chondrites. It is commonly thought that these represent remnants of extinct comets that have entered the Earth's atmosphere. Not only do they possess a great deal of water and carbon, but they are often observed to fall while the Earth is passing through a rubble stream left along a known comet trajectory. In March of 2011, Hoover published details of microfossils found on several carbonaceous chondrites that pre-existed before their meteoritic reentry.[7] This suggests that life is growing on comets, which can only be possible if they contain liquid water.

There has been some debate, however, whether sufficient liquid water exists on comets. It is known that the carbonaceous chondrites show extensive aqueous alteration, but perhaps this was merely local. In this paper we argue that this aqueous alteration encompasses the entire parent body of the carbonaceous chondrite.

In Table 3, we list the elemental abundances of the universe, the solar system (for which the Sun is the most important contributor), and the carbonaceous meteorites.[8] We know the carbonaceous chondrites are extraterrestrial because of their very unique isotopic composition that is clearly not from Earth. Therefore the simplest model is that they are either composed of the same material that formed the Sun–the protosolar nebula–or they represent even older material that predates the Sun–the universe. By taking a ratio with these two sources, we can determine which source better fits the composition of comets, and whether there has been substantial chemical alteration of the comet. Because meteorites do not have any substantial noble gases or gaseous hydrogen, we follow standard practice in doing a second normalization by dividing by the Silicon ratio, since it is neither volatile nor soluble in water.

From examination of Table 3, we see that the elemental ratios of CC/Universe have a wider spread (from -2.58 to 2.34) than the ratio of CC/Sun (-0.9 to 2.34) so we argue that a proto-solar nebula remains the best fit to the origin of comets. Examining the last column, where we normalize these abundance ratios to that of Silicon, we group them into "enhancements" and "depletions".

The elements C, N, O, F, P, S, and Ca all show some enhancement whereas Na, Cl show depletions. Borderline cases that may or may not show enhancement or depletion include Mg, Al, and K. We note several things about this division. First, the group C, N, O are expected to exist in the proto-solar nebula in their most stable forms CO, CO_2, N_2, and H_2O, which are all highly volatile. If they are enhanced with respect to Silicon, then they are somehow transformed to be chemically less volatile or mobile than Silicon.

A second observation is that both Na/K are alkaline elements found in the same column of the periodic table, so that their chemistry is very similar. Nevertheless, Na is depleted and K is nearly conserved. Likewise, Ca and Mg are similar in chemistry to Na and K, yet they are even more enhanced. The biggest difference between similar pairs of elements is that between F and Cl, where Fluorine is not just conserved but concentrated, while Chlorine is expelled.

Therefore a simple explanation of the chemistry of comets cannot capture all the chemical fractionation we observe. No combination of heat or cold can provide this sort of separation.

A discussion of systems biology, however, provides a very significant clue, where in 2007 Williams writes, *In essence, organisms at all times had to accumulate certain elements while rejecting others. Central to accumulation were C, N, H, P, S, K, Mg and Fe while, as ions, Na, Cl, Ca and other heavy metals were largely rejected.*[9] Every ion that Williams identifies as critical to life has been enhanced (or nearly enhanced) in carbonaceous meteorites, and two out of the three life-rejected ions have been depleted. It would appear that the peculiar fractionation of carbonaceous meteorites is somehow related to life. Now Williams is referring to the Earth, and so his rejected ions may not be in cells, but they are still present on the Earth, which is not depleted in these elements. In comets, however, there is continual loss of material in geysers. We can understand how life may have fractionated comets by polymerizing the essential volatile elements and sequestering them so that they were not lost to geysers or sublimation, but how would the mere rejection by cells cause the depletion of Na and Cl?

We think this can be explained by the wet comet theory. As the comet rotated, it warmed on the sunward side and cooled on the night side, so that there would have been a freeze-thaw cycle on the timescale of the comet rotation period. Young comets rotate rather quickly, but old comets that have lost most of their interior ice would rotate very slowly, with the 41 hour rotation rate of Tempel-1 being typical. Accordingly, there is ample time for freeze-thaw cycles to dominate the ice. Now when salty water freezes, the ice is relatively salt-free while the brine becomes saltier. So if a comet partially froze and then formed a liquid geyser, the geyser would be preferentially losing salty brine, depleting the soluble minerals. The most soluble minerals, as observed both in the ocean and the Dead Sea, are Na, K, Cl, and would account for their depletion. But if life is sequestering K but rejecting Na, then one would expect a disparity to arise between these alkaline ions, favoring K.

Why would this disparity not exist between Ca and Mg? Because of their less soluble nature than K and Na. As has been known since 1849,[10, 11] when sea water evaporates, the dissolved salts come out of solution in a distinct order. The first to precipitate after losing about 50% of the original water are carbonates, principally calcium and calcium-magnesium carbonates followed by sulfates at 80%, and finally by chlorides after 90% of the water is lost. Since calcium carbonate precipitates first, the biological sequestering of Mg does not deplete the Ca ion even in salty brines.

To recap, biology sequesters K and Mg inside cell membranes and expels Ca and Na and Cl to the brine. Adhesion of the cells to solid materials keeps them preferentially out of the brine, and therefore geysers will preferentially expel those ions found in the brine. As the brine gets more concentrated due to freeze-thaw cycles, calcium carbonate precipitates out of the brine, which means that geysers deplete only Na, despite their equal abundance in the proto-solar nebula.

3. CONCLUSIONS

The wet comet model provides a very comprehensive explanation of all telescopic and spacecraft flyby observations of comets. Since its formulation in 2004, it has made several predictions that have subsequently been confirmed by Deep Impact and Stardust mission. Recent observations of comet Hartley-2 and returned cometary dust containing cubanite have only confirmed the model. We have analyzed the well-known elemental fractionation of carbonaceous meteorites and shown that they are also in agreement with the wet comet model, demonstrating that the parent body of carbonaceous meteorites has undergone a global fractionation process involving liquid water. The discovery of microfossils in these same carbonaceous meteorites, therefore is evidence that the entire parent body was available for life.

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