WET COMET MODEL: ROSETTA REDUX

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ABSTRACT

The wet-comet model (WCM) of the structure and composition of comets was developed in 2005 to replace the "dirty-snowball" model (DSM) of Fred Whipple, because the first comet flybys of P/Halley "armada" revealed a very different landscape. Subsequent flybys of P/Borrelly, P/Wild-2, P/Hartley, P/Tempel-1 have confirmed and refined the model, so that we confidently predicted that the Rosetta mission would encounter a prolate, tumbling, concrete-encrusted, black comet: P/Churyumov-Gerasimenko. Unfortunately, the Philae lander team was preparing for a DSM and the anchors bounced off the concrete surface, but the orbiter has returned spectacular pictures of every crevice, which confirm and extend the WCM yet a sixth time. We report of what we predicted, what was observed, and several unexpected results from the ROSETTA mission.

1. INTRODUCTION

The study of comets has been a journey that brought most surprising results. We began in 2004 with a physics problem–can comets possess liquid water in the vacuum of space despite the need for 6mbar of pressure to achieve this phase of matter? The solution—a pressure vessel—became clear once the question was asked, as we wrote in 2004 and 2005[1,2] discovering that water explains all the peculiar properties of Jupiter-class comets travelling in from Jupiter's orbit. This wet-comet model (WCM) applies particularly to periodic, or short-period comets that have made multiple passes by the Sun, while non-periodic or long-period comets like Hale-Bopp have probably never been warm enough to melt previously, and so they fit the Whipple "dirty-snowball" model (DSM) better. This difference explains the sharp contrast between new, dry, "dusty" comets and old, wet, "muddy" comets.

In 2006 we published a prediction that NASA's Deep Impact mission would create a big splash,[3] but were disappointed–the spacecraft team targeted the hot, dry subsolar region, rather than the cooler liquid water pools. But even then, we predicted the high speed copper bolide would "punch through" the concrete crust to produce an anomalously small crater, which mystified the mission planners and the betting pool alike. JASA's Hayabusa mission was supposed to visit an asteroid, but Itokawa revealed itself as something else, a loose aggregate rubble pile, which we interpreted as an uninfected dehydrated comet—the exception that proves the rule. Finally NASA's Stardust returned material from a comet: clays, amino acids, cubanite, and something we did not expect—a forsterite sand grain. Yet this unexpected grain proved that in their long journeys comets do vacuum up the detritus of space and can likewise be infected the same way.

In 2007, after exhausting all of our comet encounters (until Rosetta), we looked at where comets go, and how they prepare for the journey.[4] In 2008, we argued that infected comets are more ancient than the Earth, filling the galaxy with information that bootstrapped life on Earth some 3.8 billion years ago.[5] In 2011 we addressed the Origin-of-life (OOL) that filled the galaxy with infected comets, arguing that the inter-connected network of comets holds more information than the mere multiplicity of comets, i.e., permutations rather than combinations can explain the information of OOL.[6–8] In 2012 we looked inward, examining the nanometer-size magnetites that fill infected comets, arguing that they are biological machines for harvesting energy and magnetic field.[9] In 2013 we brought the large and small together, showing how magnetic fields permit information addition, how biology "violates" the 2nd law of thermodynamics. In 2015 we looked at another attribute of magnetic fields, how they break the homogeneous, isotropic symmetry of the Big Bang to produce carbon, nitrogen and oxygen and abundant primordial comets that may account for the dark matter portion of galactic mass.[10]

Now in this paper, we take a look back at the wet-comet model, and see how it holds up to all the new data from the Rosetta mission. Unlike previous flybys with their few hours of data, the Rosetta mission has

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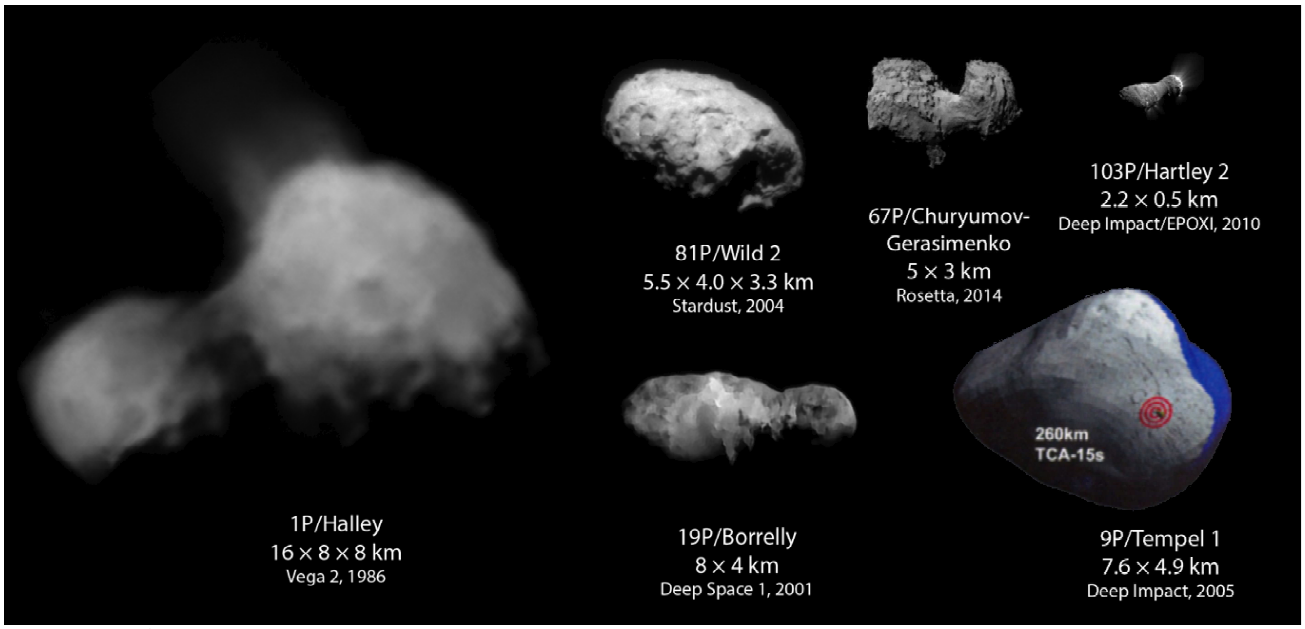

Figure 1. All comet nuclei imaged by spacecraft flybys at common scale with a preponderance of prolate dumbbells.

returned over a year of continuous cometary weather, as comet 67P/Churyumov-Gerasimenko approached and then receded from perihelion.

In section 2, we summarize the 2005 WCM as developed from pre-Halley telescopic, and post-Halley flyby data. In section 3 we address the collective observations of four more flybys: P/Borrelly, P/Wild-2, P/Tempel-1, and P/Hartley-2 as well as the surprising results from Hayabusa's sample-and-return to asteroid Itokawa. In section 4 we discuss an elemental abundance argument why CI meteorites are extinct comets showing evidence of water processing. In section 5 we look at some of the early data from the Rosetta mission, and compare it to the WCM. Finally, in section 6 we conclude with predictions for future comets.

2. WET COMET MODEL IN 2005

In our 2005 paper,[2] we detailed the steps taking a pristine, new, dusty comet to a old, wet comet, summing it up with the following description of a cometary life cycle:

> The comet begins its life as a gravitational and/or diffusion limited growth in the Oort cloud, one lightyear from the Sun. Millenia of cosmic rays convert an outer centimeter or so of ice into a tarry, low volatile goo. Passing stars or gamma ray bursts provide the delta-V for a comet to begin its long journey into the inner solar system. When it passes the orbit of Jupiter, it begins to outgas and by the time it has reached Earth orbit, it has active gas geysers. As it gains angular momentum, it reaches critical [spin] period and begins to form water under the surface. Either the loss of water or a catastrophic shedding of this first crust cause the comet to become prolate and switch rotation axes, but generally avoid breaking up. Then there begins a period of crustal metamorphosis into set concrete, fixing both the diameter and prolate dimensions of the comet. Subsequently geysers become water geysers, providing high thrust, and reducing the apogee in from the Oort cloud. Only ten or so meters of fluffy snow are melted on this first orbit, leaving behind a roughly 1 meter thick crust. On subsequent orbits, the comet does not change its shape, but water geysers continue to empty the comet, thickening the crust, and hollowing out the icy interior with large vapor pockets. The thickening crust cause successive orbits to be less active, but eventually all the ice is gone, and the comet goes extinct. It survives only a short time, however, before a chance collision destroys the hollow egg-shell crust, leaving behind a trail of debris, and CI chondritic meteors.

This model predicted that all comets should be prolate tumblers probably with apple-core profiles when they lose their equatorial belt and flip axes. Of all imaged comet nuclei, 5/6 are prolate, while 4/6 are "dumbbell" shaped (See Fig. 1). We used this model to explain 10 post-Halley comet puzzlers, which we list:

- Low Albedo–explained as a result of water processing bringing non-volatiles to surface, and kerogenizing carbon compounds.
- Tangential Dust Velocity in Collimated Jets–explained as a direct consequence of water geysers subsequently flash boiling some distance above the surface.
- Abnormal Aphelia [highly diffused]–explained as a consequence of water-geyser delta-V imparted near perihelia.
- Slow Spinrates [compared to asteroids]–explained as increase in moment of inertia due to water moving from center to skin of comet.
- Prolate Propensity [all nuclei have been prolate tumblers]–explained as a consequence of equatorial erosion to apple-core shape changes the moment of inertia, followed by a spin flip to the stable rotation axis mediated by liquid water.
- Distance Dependence [not the expected r^{-4} power-law, symmetric about perihelion]–explained as a consequence of liquid water's high latent heat, high heat of fusion, and active heat transport.
- Active Area [limited to a few active geysers]–explained as a near-complete resurfacing of the comet with water-tight concrete.
- Short vs Long Period [short period Jupiter-class comets are dominantly gas emitters, long are dust emitters]–explained as water processing of dust clumps and retains it, whereas dry comets entrain anhydrous dust in sublimation flow as expected.
- Outburst Occurrences [often outside Mars orbit]–explained as the latent heat of water causing the release of pockets of liquid.
- Extinct Asteroids [lack of extinct comets on asteroidal orbits]–explained as the fragility of dried out "egg-shell" comets would self-destruct and not clutter up the asteroid belt.
- Carbonaceous Chondrites [chondritic, high-water content, water-soluble salts]–we explain as the rubble left over from a fragile, egg-shell comet, now become a rubble stream.

We then made predictions for three upcoming cometary missions, which we quote verbatim.

> With the recent launch of two comet rendezvous missions, Rosetta landing gently and Deep Impact rather more violently, as well as the imminent return of the Stardust comet sample-and-return mission, we make predictions based on the wet comet theory.
>
> **Stardust**... our prediction is that they will consist of larger than 10 micron dust clusters, perhaps with evidence of accompanying ice due to the higher viscosity of water-geysers. At much lower density, there may even be evidence of CHON grains in the form of microbial life, though we expect the controversial claim will hinder the identification as such. In any case, we predict the ratio of siliceous dust $d > 1$ to $d < 1$ microns will be much greater than expected from geyser wind speeds, as well as the percentage of CHON grains...
>
> **Deep Impact**...We predict that the crust of P/Temple-1 will be far more than a meter thick, and that the mean density of the material will be more than 2000 kg/m3, making the size of the excavated crater much smaller than expected...given the desire to hit the center of the highly prolate comet, the crust may indeed be only a few meters deep. If the vapor chamber of a gas geyser has extended to the pole, by analogy with P/Borrelly, then the impact may be spectacular in a different way. A hole in the thin crust and a transit across the vapor chamber will be followed by an impact on the icy core some distance in. The resulting overpressure may remove all the thin crust above the geyser, lifting a cloud of debris away from the comet...
>
> **Rosetta**...Our prediction is that the comet will indeed be found to have a 100 kg/m3 average density, but that the surface will be found to be far more dense than expected. The anchors and

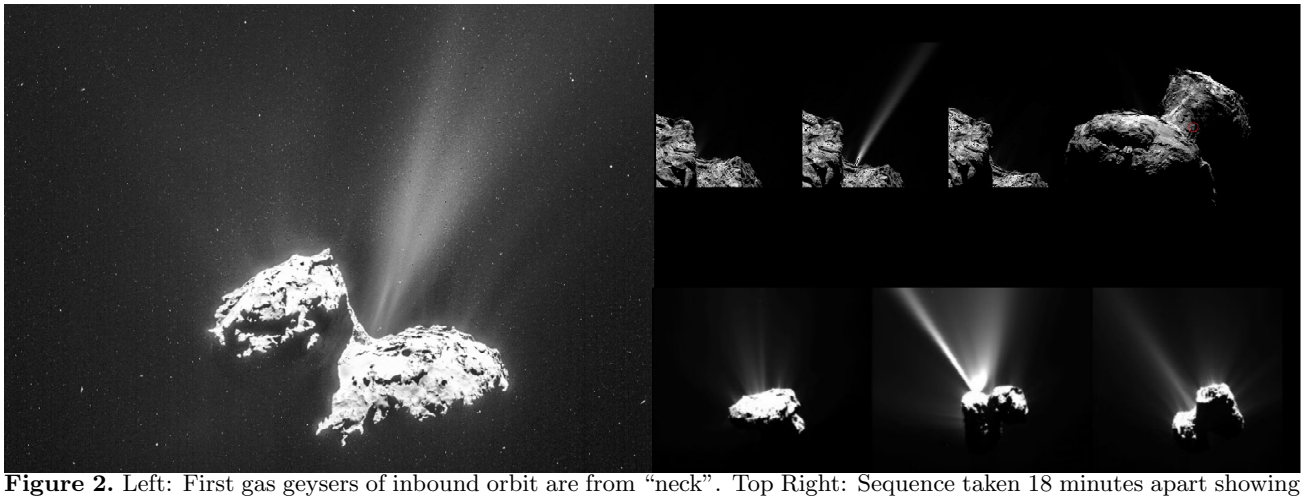

Figure 2. Left: First gas geysers of inbound orbit are from "neck". Top Right: Sequence taken 18 minutes apart showing transient "neck" geyser. Bottom Right: Sequence taken near perihelion showing water geysers from "head".

> drill will work as expected, though they may have some difficulty penetrating to any depth. The expectation that ice and snow will be found below the surface, however, will be dashed as the 20cm drill encounters only more siliceous crust. Seismic profiles will be quite exceptional, due to a much more rigidcrust than expected, as well as its hollow character. Cameras will record a surface, which will be in many ways similar to the three previous comet flybys (four, if Deep Impact is successful). The magnetic field results will be the biggest surprise of the mission, and we predict a surprisingly large dipole moment.

How did we do?

Well, Stardust returned good-sized grains, as predicted, though we did not expect forsterite sand grains. Deep Impact drilled a very small hole in the comet as predicted, and the gaseous geyser that formed was extremely dusty, with large tangential accelerations consistent with flash boiling. But having chosen the hot subsolar point, the eruption was drier than hoped.[3]

As predicted, Rosetta encountered a much tougher crust than expected, and to my disappointment, the harpoons did not hold, so the lander ended up sideways and unable to drill. And according to Auster et al.,[11] the magnetic fields were too weak to measure, so those two predictions failed. On the other hand, the thermal inertia meant that gas production peaked 14 days after perihelion, and provided delta-V to change the orbit—unexpectedly inward.[12]

3. WET COMET MODEL IN 2006

In 2006 we examined the results of Deep Impact, Stardust and the surprises of Itokawa. While our hopes for incontrovertible water signatures in the first encounter and living microbes in the second encounter were dashed, we had made no predictions for JASA's mission to an asteroid. But Hayabusa instead discovered an extinct comet, for Itokawa was a rubble pile with curiously high proportion of 2m thick boulders unlike any known asteroid, but precisely our description of a dried-out comet with a uniform, now pulverized, crust. We still had 8 more years to wait for Rosetta, so we refined our prediction that comet 67P/Churyumov-Gerasimenko was young, thin-skinned, with an average density of 200kg/m^3 based on its relatively fast rotation rate.[7]

> ... estimates that the comet is 4 km in diameter with a period of about 9.2 hours. Interpreting this as the R-T instability threshold for a homogeneous spherical comet predicts a lower limit of D=130 kg/m^3, which for a prolate (R1/R2=1.17), inhomogeneous comet would be somewhat higher, closer to 200 kg/m^3. This is just slightly more dense than the typical comet suggesting that 67P/C-G is a young and potentially water-rich target. Rosetta will undoubtedly have to land at the poles, to

Table 1. Telescopic differences between comets and asteroids.

Telescope observed	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	sector bndry
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
Spacecraft observed	Itokawa	Long-period	Short-period
1. Temperature	30 C	<0 C (subl.)	0 C / 100 C
2. Crust	rock	unknown	rigid
3. Geysers	none	few	polar
4. Cratering	some	unknown	weird
5. Density	2	1	0.5-0.6
6. Geology	2m rubble	unknown	resurfaced
7. Albedo	0.3	0.5	0.03
8. Outgassing	none	diatomic	organic

avoid being spun off the equator. Being young, the crust will be relatively thin, especially at the poles, perhaps as thin as half a meter. The 1.2AU perihelion is quite close with a large heat input, so Rosetta should observe some spectacular water geysers from the equator, gas geysers closer to the poles. The surface will be black, of course, but depending on the youth of the comet, there may be patches of eroding crust exposing actively photosynthesizing (pigmented) regions.

Indeed, the attempted landing on 67P/Churyumov-Gerasimenko was closer to the pole. The geysers were observed, with what we interpret as water geysers near the equator, but gas geysers near the poles (or "neck"), see figure 2. Note how the jets from the poles are linear, they can be traced with a straightedge, whereas the jets forming over the "head" or equator show a bend in direction, some 100 meters above the comet, which would not occur if the jets were pure gas expanding into a vacuum. The crust over "neck" was thin to almost nonexistent, showing bare ice, which may account for its low thermal inertia as well.[13] The average density was $\sim$400kg/m^3, and it was a prolate tumbler.[14] Despite the surface having low albedo$\sim$0.06, it was spectroscopically more reddish than black, with intriguing patches of what we take to be green interspersed among them (if we stretch the saturation as in figure 3).[15]

4. WET COMET MODEL IN 2011

While waiting for the much-anticipated Rosetta mission, we compared the data on asteroids, long-period comets, and short-period comets, showing that short-period comets are the most evolved of structures, consistent with water processing and subsequent loss of angular momentum. We also examined the elemental abundance ratios of CI carbonaceous chondrites to support that argument that these reflect a wet-comet model. To our surprise, they also show a fingerprint of living organisms that have modified the elemental abundances. The following tables summarize the findings.

The progression from spherical, rocky, old, unresurfaced asteroids to prolate, crusty, new, resurfaced comets is unmistakable. If the shape changes so dramatically, as does the density, the spin axes and the surface, it strongly suggests evolution, rather than some sort of formation process in the Oort cloud that designed short-period comets for special missions, nor could the albedo change cannot simply be due to cosmic rays, or there would be no differences among the categories. Even the spin rates vary considerably, with older comets spinning slowly despite their jet activity, which does not fit a random walk through angular momentum space. Only

Table 2. Log Elemental atomic abundances of carbonaceous Chondrites

1:Atom	2:*Uni.	3:*SS	4:*CC	5:+CC	6:*CC/U	7:*CC/SS	8:*CC/Si	9:+CC/Si	**CG/Si
C	7.29	6.59	6.82	7.4	-0.47	0.23	1.22	-0.11	
N	6.21	6.06	6.06	6.25	-0.15	0.00	0.4	-1.26	
O	8.61	6.95	7	8.39	-1.61	0.05	1.4	0.88	
F	2.52	2.62	4.87	4.43	2.35	2.25	-0.73	-3.08	
Na	6.58	4.44	4.14	6.27	-2.44	-0.30	-1.46	-1.24	-1.68
Mg	7.90	5.66	5.60	7.53	-2.30	-0.06	0	0.02	
Al	6.74	4.55	4.47	6.43	-2.27	-0.08	-1.13	-1.08	
Si	7.90	5.71	5.60	7.51	-2.30	-0.11	0	0	
P	5.75	3.55	3.55	5.4	-2.20	0.00	-2.05	-2.11	
S	7.31	5.30	5.40	7.16	-1.91	0.10	-0.2	-0.35	
Cl	5.25	3.57	2.67	5.23	-2.58	-0.90	-2.93	-2.28	
K	5.46	3.21	3.09	5.06	-2.37	-0.12	-2.51	-2.45	-2.66
Ca	6.64	4.44	4.44	6.29	-2.20	0.00	-1.16	-1.22	-1.79
Fe	5.50	5.47	7.80	7.45	2.30	2.34	2.2	-0.06	
Ni	4.21	4.33	6.54	6.20	2.34	2.21	0.94	-1.32	
N/P	0.46	2.51	2.51	0.850					
O/S	1.3	1.65	1.6	1.230					
F/Cl	-2.73	-0.95	2.2	-0.8					
Na/K	1.12	1.23	1.05	1.21					0.98
Mg/Ca	1.26	1.22	1.16	1.24					
Fe/Ni	1.29	1.14	1.26	1.25					

After *Winter,[19] +Asplund et al.,[20] **Wurz et al.[21]

the WCM posits a mechanism that explains all these features naturally. While the language is guarded—"subsurface fluidization models and mass loss through the ejection of large chunks"–it would seem that Rosetta found support for the WCM.[16] In a similar guarded tone, Hassig et al write of outgassing that "... show large fluctuations in composition in a heterogeneous coma that has diurnal and possibly seasonal variations in the major outgassing species: water, carbon monoxide, and carbon dioxide. These results indicate a complex coma-nucleus relationship where seasonal variations may be driven by temperature differences just below the comet surface." This heterogeneity is not expected from a dust-coated insulated comet, but would be a characteristic of wet, high-thermal conductivity, black concrete, which again is weak support for the WCM.

In other papers, we tie many of these features to life–explaining the low albedo as a direct result of cyano-bacterial activity, or the organics in the outgassing as consequences of living matter. But much of the argument hinges on the identification of carbonaceous chondrites with extinct comets, which display spectacular fossils.[17, 18] The following table makes the identification of CC with comets even stronger.

We take ratios of Carbonaceous Chondrites (CC) with Universe (U) abundances, with Solar System (SS) abundances, and with Silicon, since Si is neither a volatile nor a water-soluble mineral. Additionally, we tabulate ratios of pairs of elements that appear in the same column of the periodic table because they have similar chemical properties, where N/P, O/S, F/Cl, Na/K, Mg/Ca are examples of such pairs. In the literature, the CC data is often used to fill-in for either SS or U abundances when spectroscopic data is lacking, which may account for the occasional identical abundances. Unfortunately different authors normalize SS and U differently, so we list the CC abundances given by Winter,[19] by Asplund,[20] and by Wurz.[21] Asplund appears to be quite different from both Wurz and Winter, so in what follows we use the more recent Winter results, but include the Asplund value for reference.

The elements C, N, O, F, P, S, and Ca all show some enhancement in CC compared to Solar System whereas Na, Cl show clear depletions. Borderline cases include Mg, Al, and K. Likewise, the most obvious chemical pair to show an enhancement from SS to CC is F and Cl, where Fluorine is not just conserved but concentrated in CC, while Chlorine is expelled.

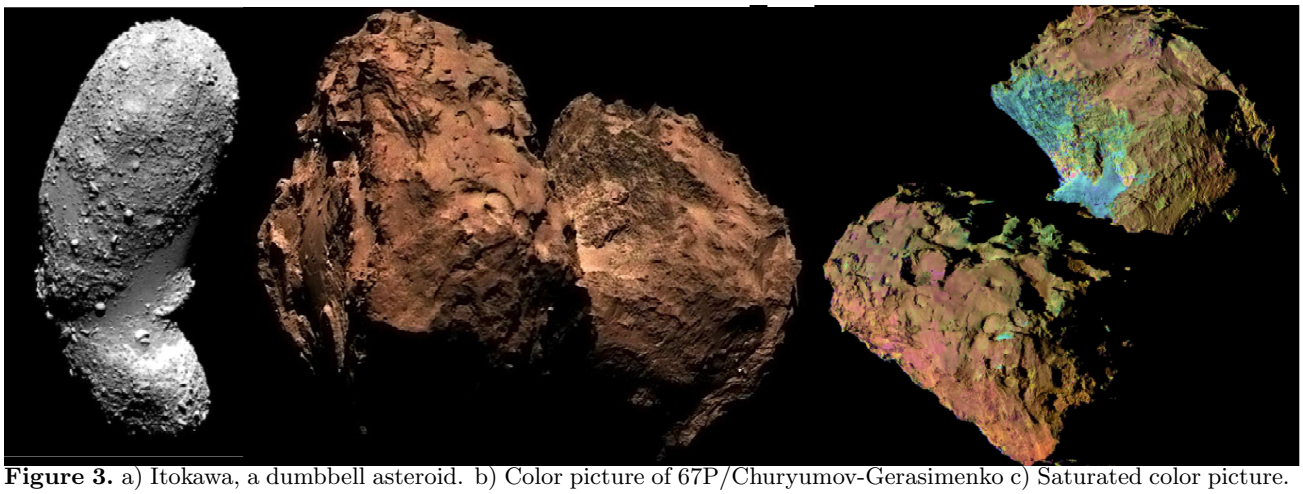

Figure 3. a) Itokawa, a dumbbell asteroid. b) Color picture of 67P/Churyumov-Gerasimenko c) Saturated color picture.

Since the CNO elements are expected to exist in the proto-solar nebula in their most stable forms CO, CO_2, N_2, and H_2O, all of which are highly volatile, if they are enhanced with respect to Silicon, then they are somehow transformed to be chemically less volatile or mobile than Silicon (which life accomplishes by making polymers) and/or comets are depleted in Si at formation. But if comets are depleted in Si, they are enriched in Fe so their formation by condensation is not straightforward. Likewise, the trend in chemical pairs from SS to to CC abundances is generally toward enhancement of the lighter element, which is characteristic of fractionation by vaporization, whereas non-volatile pairs seemly are identical to solar system abundances. But two pairs stand out: F/Cl is enhanced far more than fractionation would explain, and Na/K is depleted, despite the non-volatility of Na. We attribute both of these effects to the solubility of NaCl in water, and the removal of water from the comet, where the simple sublimation of ice would not achieve the removal of NaCl from comets. The Na/K change is smaller than F/Cl but still significant, the depletion being larger than the error bars. This is strange because K is a more soluble ion than Na, and should have had the greater depletion if it is due to water leaching. We attribute this anomalous reduction in the Na/K ratio to the tendency for life to sequester K and excrete Na ions.

How did we do?

Wurz et al.[21] used solar wind sputtered ions to find the composition of the surface of 67P/Churyumov-Gerasimenko. They compare the observed Na/K ratio to planets and photospheres concluding that it is closest to CC, validating the common assumption and our prediction that CC are extinct comets. Wurz et al also showed that the sputtered ions from the "neck" or polar region of the comet were predominantly from water ice. So unlike the geysers, this part of the comet seemingly had no outer crust.

5. ROSETTA EARLY RESULTS

What new things did the Rosetta mission tell us?

Unfortunately the botched landing of the Philae probe meant that we did not get the drill cores, the organics, the seismology that we were hoping for. One organic spectra was produced with three new complex organics from the surface, which corroborates our claim that most short-period comets have been colonized by cyanobacteria.[4, 22, 23]

The radio signals from the lander passed through the comet and was used to estimate a 75-85% porous but homogeneous "dirty snow" interior, which we believe validates our estimate of 200kg/m3=80% porous ice calculation..[24] It is also gratifying to read that they too equate comet 67P/C-G with CC.

The closeup pictures from the lander reveal that the regolith is not unprocessed dust from a DSM sublimation, but granular with blocks up to 5m in size, very similar to Itokawa (see figure 3), and characteristic of water-cemented dust that has been subsequently dehydrated and pulverized by micrometeors, as predicted by the WCM.[3, 25]

The bouncing of the Philae probe provided data on the rigidity of the crust in two places–bounce 1 and final resting spot. The first bounce gave a rigidity of 1 kPa and thickness 20cm under a thin layer of dust, but with a more rigid basement layer. The final resting place was just plain hard–no upper limit given.[26] The softest, silty soils have a rigidity of about 50kPa, so the first bounce was on a soft foam mattress, so this matches the DSM better than the WCM, on the other hand, the final resting place sounds more like WCM.

The values for magnetic moment were somewhat disappointing, with Auster et al reporting <2nT fields in the surface,[11] unlike the magnetite-rich material of CC Orgueil we expected.[8]

Our original discussion of cavities or caverns excavated under the concrete crust,[2] seems validated by the discovery of sinkholes,[27] which we did not predict because we thought the rotation rate would be very close to the R-T instability rate, which produces zero gravity at the equator. On the other hand, poleward of the equator, the direction of gravity is down, and sinkholes were found in these areas. So this is a weak validation of WCM.

No nitrogen has ever been observed spectroscopically, but the Rosetta mass spectrometer was able to detect N2 at a N2/CO ratio ∼0.04 that of the solar system value, which they suggest is due to condensation onto the comet from proto-solar gases at <30K,[28] consistent with observations of extra-solar planetary nebulae.[29] Likewise, Altwegg et al.[30] find a D/H ratio 3X higher than Earth, which is consistent with primordial comets as well. Strictly speaking, this is not part of the WCM, but if 67P/C-G were partially derived from primordial comets, we would interpret both as a consequence of a magnetized Big Bang nucleosynthesis (MBBN), in which N/CNO abundances are about 0.04 of the total, and D/H in this range.[10]

6. CONCLUSIONS

The WCM has held up better than perhaps expected, with Rosetta discovering a concrete-clad, rigid, prolate, low-albedo, tumbling comet with composition most similar to carbonaceous chondrites, and gas geysers from the poles. The WCM also predicted high magnetic field strength and lower densities than observed, but these may simply be sampling bias of both the CC collected on Earth, and the portions of 67P/C-G that were analyzed. There were observations that were not predicted, but support WCM as well: the sinkholes near the poles, the exposed ice near the poles, and the granular nature of the regolith. Then there were observations that support extensions to the WCM: organics on the surface that result from colonization of water by cyanobacteria, color changes on the comet consistent with cyanobacteria, high D/H ratios and low N/CO ratios consistent with MBBN and primordial comet contributions.

But the comparison with DSM is not nearly so sanguine. If the previous five flybys had not already destroyed its high-albedo, spherical, dusty sublimation wind model, the Rosetta pictures have confirmed the utter failure of a sublimation wind driven coma. We think it is high time to revise the standard comet models used to estimate the coma and magnetosphere of short-period comets.

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REFERENCES

1. R. B. Hoover, E. V. Pikuta, N. C. Wickramasinghe, M. K. Wallis, and R. B. Sheldon, "Astrobiology of comets," in *Instruments, Methods, and Missions for Astrobiology VI*, R. B. Hoover, G. V. Levin, and A. Y. Rozanov, eds., *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **5555**, pp. 93–106, Nov. 2004.
2. R. B. Sheldon and R. B. Hoover, "Evidence for liquid water on comets," in *Instruments, Methods, and Missions for Astrobiology VII*, R. B. Hoover, G. V. Levin, A. Y. Rozanov, and G. R. Gladstone, eds., *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **5906**, pp. 127–145, Sept. 2005.
3. R. B. Sheldon and R. B. Hoover, "Implications of cometary water: Deep impact, stardust and hayabusa," in *Instruments, Methods, and Missions for Astrobiology IX*, R. B. Hoover, G. V. Levin, and A. Y. Rozanov, eds., *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **6309**, pp. 6309–0L, Proc. of SPIE, (Bellingham, WA), 2006.

4. R. B. Sheldon and R. B. Hoover, "The cometary biosphere," in *Instruments, Methods, and Missions for Astrobiology X*, R. B. Hoover, G. V. Levin, and A. Y. Rozanov, eds., *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **6694**, pp. 6694–0H, Proc. of SPIE, (Bellingham, WA), Oct. 2007.
5. R. B. Sheldon and R. B. Hoover, "Cosmological evolution: Spatial relativity and the speed of life," in *Instruments, Methods, and Missions for Astrobiology XI*, R. B. Hoover, G. V. Levin, and A. Y. Rozanov, eds., *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **7097**, pp. 7097–41, Proc. of SPIE, (Bellingham, WA), Aug. 2008.
6. R. B. Sheldon and R. B. Hoover, "More evidence for liquid water on comets," in *Instruments, Methods, and Missions for Astrobiology XIV*, *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **8152**, Sept. 2011.
7. R. B. Sheldon, "The cometary biosphere and the origin of life," in *Instruments, Methods, and Missions for Astrobiology XIV*, R. B. Hoover, G. V. Levin, and A. Y. Rozanov, eds., *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **8152**, pp. 8152–42, Proc. of SPIE, (Bellingham, WA), Sept. 2011.
8. R. B. Sheldon and R. Hoover, "Carbonaceous chondrites as bioengineered comets," in *Instruments, Methods, and Missions for Astrobiology XV*, *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **8521**, Oct. 2012.
9. R. B. Sheldon, "Comets, information, and the origin of life," in *Genesis–In The Beginning: Precursors of Life, Chemical Models and Early Biological Evolution*, J. Seckbach, ed., *COLE* **22**, pp. 363–386, Springer, 2012.
10. R. B. Sheldon, "Big bang nucleosynthesis, comets and life," in *Instruments, Methods, and Missions for Astrobiology XVII*, R. B. Hoover, G. V. Levin, A. Y. Rozanov, and C. Wickramasinghe, eds., *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **9606**, pp. 9606–27, Proc. of SPIE, (Bellingham, WA), 2015.
11. H.-U. Auster, I. Apathy, G. Berghofer, K.-H. Fornacon, A. Remizov, C. Carr, C. Güttler, G. Haerendel, P. Heinisch, D. Hercik, M. Hilchenbach, E. Kührt, W. Magnes, U. Motschmann, I. Richter, C. T. Russell, A. Przyklenk, K. Schwingenschuh, H. Sierks, and K.-H. Glassmeier, "The nonmagnetic nucleus of comet 67P/Churyumov-Gerasimenko," *Science* **349**, p. 015102, July 2015.
12. J.-L. Bertaux, M. R. Combi, E. Quémerais, and W. Schmidt, "The water production rate of Rosetta target Comet 67P/Churyumov-Gerasimenko near perihelion in 1996, 2002 and 2009 from Lyman α observations with SWAN/SOHO," *Planetary and Space Science* **91**, pp. 14–19, Feb. 2014.
13. S. Gulkis, M. Allen, P. von Allmen, G. Beaudin, N. Biver, D. Bockelée-Morvan, M. Choukroun, J. Crovisier, B. J. R. Davidsson, P. Encrenaz, T. Encrenaz, M. Frerking, P. Hartogh, M. Hofstadter, W.-H. Ip, M. Janssen, C. Jarchow, S. Keihm, S. Lee, E. Lellouch, C. Leyrat, L. Rezac, F. P. Schloerb, and T. Spilker, "Subsurface properties and early activity of comet 67P/Churyumov-Gerasimenko," *Science* **347**, p. aaa0709, Jan. 2015.
14. H. Sierks, C. Barbieri, P. L. Lamy, R. Rodrigo, D. Koschny, H. Rickman, H. U. Keller, J. Agarwal, M. F. A'Hearn, F. Angrilli, A.-T. Auger, M. A. Barucci, J.-L. Bertaux, I. Bertini, S. Besse, D. Bodewits, C. Capanna, G. Cremonese, V. Da Deppo, B. Davidsson, S. Debei, M. De Cecco, F. Ferri, S. Fornasier, M. Fulle, R. Gaskell, L. Giacomini, O. Groussin, P. Gutierrez-Marques, P. J. Gutiérrez, C. Güttler, N. Hoekzema, S. F. Hviid, W.-H. Ip, L. Jorda, J. Knollenberg, G. Kovacs, J. R. Kramm, E. Kührt, M. Küppers, F. La Forgia, L. M. Lara, M. Lazzarin, C. Leyrat, J. J. Lopez Moreno, S. Magrin, S. Marchi, F. Marzari, M. Massironi, H. Michalik, R. Moissl, S. Mottola, G. Naletto, N. Oklay, M. Pajola, M. Pertile, F. Preusker, L. Sabau, F. Scholten, C. Snodgrass, N. Thomas, C. Tubiana, J.-B. Vincent, K.-P. Wenzel, M. Zaccariotto, and M. Pätzold, "On the nucleus structure and activity of comet 67P/Churyumov-Gerasimenko," *Science* **347**, p. aaa1044, Jan. 2015.
15. F. Capaccioni, A. Coradini, G. Filacchione, S. Erard, G. Arnold, P. Drossart, M. C. De Sanctis, D. Bockelee-Morvan, M. T. Capria, F. Tosi, C. Leyrat, B. Schmitt, E. Quirico, P. Cerroni, V. Mennella, A. Raponi, M. Ciarniello, T. McCord, L. Moroz, E. Palomba, E. Ammannito, M. A. Barucci, G. Bellucci, J. Benkhoff, J. P. Bibring, A. Blanco, M. Blecka, R. Carlson, U. Carsenty, L. Colangeli, M. Combes, M. Combi, J. Crovisier, T. Encrenaz, C. Federico, U. Fink, S. Fonti, W. H. Ip, P. Irwin, R. Jaumann, E. Kuehrt, Y. Langevin, G. Magni, S. Mottola, V. Orofino, P. Palumbo, G. Piccioni, U. Schade, F. Taylor, D. Tiphene, G. P. Tozzi, P. Beck, N. Biver, L. Bonal, J.-P. Combe, D. Despan, E. Flamini, S. Fornasier, A. Frigeri, D. Grassi, M. Gudipati, A. Longobardo, K. Markus, F. Merlin, R. Orosei, G. Rinaldi, K. Stephan, M. Cartacci, A. Cicchetti, S. Giuppi, Y. Hello, F. Henry, S. Jacquinod, R. Noschese, G. Peter, R. Politi, J. M. Reess, and A. Semery, "The organic-rich surface of comet 67P/Churyumov-Gerasimenko as seen by VIRTIS/Rosetta," *Science* **347**, p. aaa0628, Jan. 2015.
16. N. Thomas, H. Sierks, C. Barbieri, P. L. Lamy, R. Rodrigo, H. Rickman, D. Koschny, H. U. Keller, J. Agarwal, M. F. A'Hearn, F. Angrilli, A.-T. Auger, M. A. Barucci, J.-L. Bertaux, I. Bertini, S. Besse, D. Bodewits, G. Cremonese, V. Da Deppo, B. Davidsson, M. De Cecco, S. Debei, M. R. El-Maarry, F. Ferri, S. Fornasier, M. Fulle, L. Giacomini, O. Groussin, P. J. Gutierrez, C. Güttler, S. F. Hviid, W.-H. Ip, L. Jorda, J. Knollenberg, J.-R. Kramm, E. Kührt, M. Küppers, F. La Forgia, L. M. Lara, M. Lazzarin, J. J. L. Moreno, S. Magrin, S. Marchi, F. Marzari, M. Massironi, H. Michalik, R. Moissl, S. Mottola, G. Naletto, N. Oklay, M. Pajola, A. Pommerol, F. Preusker, L. Sabau, F. Scholten, C. Snodgrass, C. Tubiana, J.-B. Vincent, and K.-P. Wenzel, "The morphological diversity of comet 67P/Churyumov-Gerasimenko," *Science* **347**, p. aaa0440, Jan. 2015.

17. R. B. Hoover, "Fossils of cyanobacteria in ci1 carbonaceous meteorites," *J. of Cosmology* **13**(3), 2011.
18. R. B. Hoover, "Microfossils, biomolecules and biominerals in carbonaceous meteorites: implications to the origin of life," in *Instruments,Methods,and Missions for Astrobiology XVI*, *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **8521**, p. 6, Nov. 2012.
19. M. Winter, *WebElements: the home of the periodic table*, The University of Sheffield, http://www.webelements.com/, 2011.
20. M. Asplund, N. Grevesse, A. J. Sauval, and P. Scott, "The Chemical Composition of the Sun," *Annual Reviews of Astronomy and Astrophysics* **47**, pp. 481–522, Sept. 2009.
21. P. Wurz, M. Rubin, and K. A. et al., "Solar wind sputtering of dust on the surface of 67p/churyumov-gerasimenko," *Astr. Astrophys.* **15**, pp. 1–9, june 2015.
22. F. Goesmann, H. Rosenbauer, J. H. Bredehöft, M. Cabane, P. Ehrenfreund, T. Gautier, C. Giri, H. Krüger, L. Le Roy, A. J. MacDermott, S. McKenna-Lawlor, U. J. Meierhenrich, G. M. M. Caro, F. Raulin, R. Roll, A. Steele, H. Steininger, R. Sternberg, C. Szopa, W. Thiemann, and S. Ulamec, "Organic compounds on comet 67P/Churyumov-Gerasimenko revealed by COSAC mass spectrometry," *Science* **349**, p. 020689, July 2015.
23. I. P. Wright, S. Sheridan, S. J. Barber, G. H. Morgan, D. J. Andrews, and A. D. Morse, "CHO-bearing organic compounds at the surface of 67P/Churyumov-Gerasimenko revealed by Ptolemy," *Science* **349**, p. 020673, July 2015.
24. W. Kofman, A. Herique, Y. Barbin, J.-P. Barriot, V. Ciarletti, S. Clifford, P. Edenhofer, C. Elachi, C. Eyraud, J.-P. Goutail, E. Heggy, L. Jorda, J. Lasue, A.-C. Levasseur-Regourd, E. Nielsen, P. Pasquero, F. Preusker, P. Puget, D. Plettemeier, Y. Rogez, H. Sierks, C. Statz, H. Svedhem, I. Williams, S. Zine, and J. Van Zyl, "Properties of the 67P/Churyumov-Gerasimenko interior revealed by CONSERT radar," *Science* **349**, p. 020639, July 2015.
25. S. Mottola, G. Arnold, H.-G. Grothues, R. Jaumann, H. Michaelis, G. Neukum, J.-P. Bibring, S. E. Schröder, M. Hamm, K. A. Otto, I. Pelivan, G. Proffe, F. Scholten, D. Tirsch, M. Kreslavsky, E. Remetean, F. Souvannavong, and B. Dolives, "The structure of the regolith on 67P/Churyumov-Gerasimenko from ROLIS descent imaging," *Science* **349**, p. 020232, July 2015.
26. J. Biele, S. Ulamec, M. Maibaum, R. Roll, L. Witte, E. Jurado, P. Muñoz, W. Arnold, H.-U. Auster, C. Casas, C. Faber, C. Fantinati, F. Finke, H.-H. Fischer, K. Geurts, C. Güttler, P. Heinisch, A. Herique, S. Hviid, G. Kargl, M. Knapmeyer, J. Knollenberg, W. Kofman, N. Kömle, E. Kührt, V. Lommatsch, S. Mottola, R. Pardo de Santayana, E. Remetean, F. Scholten, K. J. Seidensticker, H. Sierks, and T. Spohn, "The landing(s) of Philae and inferences about comet surface mechanical properties," *Science* **349**, p. 019816, July 2015.
27. J.-B. Vincent, D. Bodewits, S. Besse, H. Sierks, C. Barbieri, P. Lamy, R. Rodrigo, D. Koschny, H. Rickman, H. U. Keller, J. Agarwal, M. F. A'Hearn, A.-T. Auger, M. A. Barucci, J.-L. Bertaux, I. Bertini, C. Capanna, G. Cremonese, V. da Deppo, B. Davidsson, S. Debei, M. de Cecco, M. R. El-Maarry, F. Ferri, S. Fornasier, M. Fulle, R. Gaskell, L. Giacomini, O. Groussin, A. Guilbert-Lepoutre, P. Gutierrez-Marques, P. J. Gutiérrez, C. Güttler, N. Hoekzema, S. Höfner, S. F. Hviid, W.-H. Ip, L. Jorda, J. Knollenberg, G. Kovacs, R. Kramm, E. Kührt, M. Küppers, F. La Forgia, L. M. Lara, M. Lazzarin, V. Lee, C. Leyrat, Z.-Y. Lin, J. J. Lopez Moreno, S. Lowry, S. Magrin, L. Maquet, S. Marchi, F. Marzari, M. Massironi, H. Michalik, R. Moissl, S. Mottola, G. Naletto, N. Oklay, M. Pajola, F. Preusker, F. Scholten, N. Thomas, I. Toth, and C. Tubiana, "Large heterogeneities in comet 67P as revealed by active pits from sinkhole collapse," *Nature* **523**, pp. 63–66, July 2015.
28. M. Rubin, K. Altwegg, H. Balsiger, A. Bar-Nun, J.-J. Berthelier, A. Bieler, P. Bochsler, C. Briois, U. Calmonte, M. Combi, J. De Keyser, F. Dhooghe, P. Eberhardt, B. Fiethe, S. A. Fuselier, S. Gasc, T. I. Gombosi, K. C. Hansen, M. Hässig, A. Jäckel, E. Kopp, A. Korth, L. Le Roy, U. Mall, B. Marty, O. Mousis, T. Owen, H. Rème, T. Sémon, C.-Y. Tzou, J. H. Waite, and P. Wurz, "Molecular nitrogen in comet 67P/Churyumov-Gerasimenko indicates a low formation temperature," *Science* **348**, pp. 232–235, Apr. 2015.
29. M. Hogerheijde, V. Salinas, E. Bergin, I. Cleeves, C. Brinch, C. Dominik, C. Dullemond, and E. van Dishoeck, "Cold water and ammonia vapor in the disks around TW Hya and HD100546," *IAU General Assembly* **22**, p. 56838, Aug. 2015.
30. K. Altwegg, H. Balsiger, A. Bar-Nun, J. J. Berthelier, A. Bieler, P. Bochsler, C. Briois, U. Calmonte, M. Combi, J. De Keyser, P. Eberhardt, B. Fiethe, S. Fuselier, S. Gasc, T. I. Gombosi, K. C. Hansen, M. Hässig, A. Jäckel, E. Kopp, A. Korth, L. LeRoy, U. Mall, B. Marty, O. Mousis, E. Neefs, T. Owen, H. Rème, M. Rubin, T. Sémon, C.-Y. Tzou, H. Waite, and P. Wurz, "67P/Churyumov-Gerasimenko, a Jupiter family comet with a high D/H ratio," *Science* **347**, p. 1261952, Jan. 2015.