Implications of cometary water: Deep Impact, Stardust and Hayabusa

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ABSTRACT

Three recent *in situ* spacecraft missions have explored comets or asteroids, producing data in conflict with the standard comet paradigm, the Whipple Dirty Snowball Model (DSM). We have developed an alternative Wet Comet Model (WCM) which proposes that comets undergo an irreversible phase change to a wet comet when they enter within Mars orbit. The WCM may explain some of the observational discrepancies seen by Deep Impact, Stardust and Hayabusa. In particular, it accurately predicted Deep Impact observation of organics, biominerals, and meltwater temperatures. Predictions concerning Stardust's returned cometary dust particles have yet to be falsified, but if comets are largely composed of the silicates seen by Stardust, there may be a cometary explanation for Itokawa's low density rubble-pile observed by Hayabusa.

Keywords: Comet, liquid water, astrobiology, orbital dynamics, geysers, Deep Impact, Stardust, Hayabusa

1. INTRODUCTION

After three photographic flyby missions to comets in the past 20 years–P/Halley, P/Wild2 and P/Borrelly–this past year has seen two (or possibly three if Itokawa be an extinct comet) *in situ* measurements capable of testing current comet models–Deep Impact, Stardust and Hayabusa. While the analysis is still ongoing, it is apparent that the current comet model must be revised to incorporate these findings. We have developed (1; 2) a wet comet model (WCM) that predicts that comets undergo an irreversible phase change when they first pass within Mars orbit (2 AU) and melt. That is, the Whipple Dusty Snowball Model (DSM) may accurately describe comets in the Oort Cloud before they make their first pass through the inner solar system, but once they melt, their morphology, their dynamics, their dust production, their heat flux, all change irreversibly. Since the WCM is novel, we review it briefly.

Comets are thought to have formed by gravitational settling of proto-solar nebular dust, out beyond the orbit of Pluto in the Oort cloud (3; 4). The relatively low density of ice and dust would mean that average comet sizes never get beyond 10's of kilometers, and thus gravitational settling and differentiation that has occurred for the planets would not have taken place. The breakup of comet Shoemaker-Levy-9 (SL9) in the gravitational pull of Jupiter, supports the contention that comets are fluffy, dirty snowballs with densities far less than water, and relatively homogeneous in composition (5; 6). Other indirect evidence from meteoritic fireballs (7), cometary splitting (8), and dust impacts on spacecraft, seem to support a mean density much less than that of water ice. The formation of fluffy agglomerates in the Oort cloud suggests that comets would also be at tens of Kelvin temperatures which would make liquid water extremely unlikely outside the orbit of Jupiter.

Since the equilibrium blackbody temperature for an object at Earth orbit is above the melting point of water, 300K, several regulatory mechanisms have usually been invoked that enable comets to remain frozen as they circle the Sun and retreat back into the deep freeze of trans-Jupiter space, including insulating blankets of porous dust, ablative cooling, a high-albedo, and a natural "heat pump" that radiates heat away from the comet(9). These mechanisms have been rendered unlikely by all four cometary flybys with their detailed photographs of the surface. That is, images of P/Halley, P/Borrelly, P/Wild-2, and P/Tempel-1 show black objects (albedo < 0.03) emitting jets of steam from a crusty surface at temperatures 300-400K, jets which seemingly remain

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fixed in location, even over several passes of the comet, whereas no sublimation wind is seen for the remaining 70-80% of the comet's surface.

Without a reliable way to shed the heat, it seems likely that comets have local regions of meltwater (1), and in fact high pressure geysers that can support local meltwater have been invoked to explain P/Borrelly (10). Subsequently meltwater reduces the albedo, plugs the pores, reduces sublimation cooling, and increases conductive heat transport from the surface, producing positive feedback melting until substantial amounts of liquid water are present. The liquid water then affects the spin, non-gravitational forces, dust production, tail geometry, fragmentation probability, and ultimately senescence and extinction of the comet. Thus the dusty snowball undergoes an irreversible, non-linear, positive feedback conversion to a wet comet, and evolves in a quite different fashion than a dusty snowball.

Therefore the WCM predicts that a comet would begin life as a roughly spherical, dusty snowball deflected from the Oort cloud, which upon entering within Mars orbit, melts to form a dark crust, since water plus anhydrous dust produces concrete. Geysers, either before or after melting, spin up the comet until the Rayleigh-Taylor instability causes heat to flow inward, melt, and displace high density mud toward the equator. But mass transport to the equator lowers the spinrate until the R-T goes stable again, and the meltrate decreases. Therefore water acts as a speed regulator such that a wet comet will henceforth spin at the critical spinrate for the R-T instability within the comet. The adolescence of a wet comet is stormy because the crust is thin, the resulting heat flux is high, and the critical spinrate (which depends on density and the location of the R-T unstable region) is at its highest. Thus mechanical failure of the thin crust is at its maximum probability in young wet comets, which if it occurs, would remove an equatorial band of material. The resulting apple-core profile converts the spin axis to the axis with the smallest moment of inertia, which is unstable against a spin flip facilitated by a liquid interior, ultimately resulting in a low spinrate, prolate tumbler as most comets are observed to be. Subsequently in mature wet comets, the R-T instability heats the interior and empties the now rigid crust of volatiles leaving behind an empty eggshell. As the shell heats up (lacking a cooling mechanism) it dries and loses mechanical strength, eventually collapsing into a rubble pile or a rubble stream. If CI carbonaceous chondrites are taken as the final end of cometary evolution (11)), then WCM also explains the composition of the Orgeuil meteorite, a grainy, extremely heterogeneous matrix cemented with water soluble salts.

Unlike the WCM, the DSM attempts to remain consistent with flyby photographs by hypothesizing the existence of a very fluffy dust coating of the comet, insulating the ice while reflecting the heat. Geysers were interpreted to be phase changes of dissolved gasses in amorphous ice kept far below the melting point, requiring the thinnest of "burnt toast" layers to focus the gas into jets. Accordingly, the Deep Impact mission was conceived as an impactor that would penetrate beneath this insulating layer and excavate pristine ice for remote observation (12). Stardust was proposed as a sample-and-return mission that would determine composition and isotopic composition of the dust captured in a flyby of the coma, while Hayabusa was an ambitious Japanese sample-and-return mission scooping up material from the surface of an asteroid. All three missions would provide *in situ* measurements beyond the capabilities of photon remote sensing. Therefore they had the potential to discriminate between DSM or WCM, or even falsify both. In this paper, we consider the predictions of the two theories, the comet observations, and potential issues for the Rosetta rendezvous with comet 67P/Churyumov-Gerasimenko in 2014.

In section 2, we discuss the predictions of the two models, and the observations. In section 3 we discuss refinements of the two theories in response to the recent observations. We discuss the consequences of the WCM for the Rosetta mission as well as NASA's Mars exploration initiative, and we Conclude.

2. PREDICTIONS AND OBSERVATIONS

2.1. Deep Impact

2.1.1. Our WCM Predictions

The mission to send an 370 kg impactor into a P/Temple-1 (See figure 1) at hyperkinetic velocity of 10 km/s was expected to excavate a crater some 20 meters deep from the icy matrix below the roughly meter-thick crust. We predicted 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/m^3, making the size of the excavated crater much smaller than expected.

Likewise, the amount of vaporized ejecta will be less on account of the lower volatility of dust. On the other hand, such an excavation may trigger the formation of a water-geyser on the comet, if the impact is sufficiently close to the equator. But should the impact occur near the pole of the comet, which is likely 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.

2.1.2. The DSM and Observations

The DI excavation did not behave as was expected (13). About the only thing that was within 50% of prediction was the mass of dust lifted by the impact (14).

DSM comets were thought to be amorphous ice with built-in energy due to strained bonds, so as to provide the explosive jetting observed. The impact was expected to shock and trigger a larger volume of ice to phase change than the simple kinetic energy calculation might suggest. In addition, hypervolatiles trapped in the amorphous ice of the Oort cloud might boil out, particularly CO, which might have a dramatic rise by a factor of 300 (15). None of this was observed, rather the coma brightened as if it were a normal, 90 minute outburst (16; 17), suggesting that the surface material excavated was no different than interior, outburst material in either chemical or isotopic composition (18). The volatiles observed were typical of Oort cloud comets, slightly depleted in acetylene and ethane, and showed no change post-impact, interpreted to mean that material excavated had already be thermally modified (19). The WCM predicted little if any amorphous ice near the surface, with jetting and coma gases controlled by water vapor so that should the impactor penetrate a gas geyser rather than a water geyser, gas evolution would look like a normal outburst.

DSM comet dust was thought to be in the 1-100 micron range resembling fine sand, a size range previously detected by satellite impacts. The big surprise was that the dust cloud lifted by the impact was submicron silicates in the ejecta fan, with gas-levitated amorphous carbon / coarse silicates (pyroxenes, olivines) in the ejecta core (20; 21; 22). The conclusion that the submicron dust only present for 26 hours after impact must have been produced from loose agglomerates that fragmented under impact. Not only is the dust very fluffy, but it must be very fragile as well. The WCM did not predict submicron silicates either, though it correctly predicted a carbonaceous, large silicate geyser core. In the next section we refine the WCM to explain the submicron signature as well.

The DSM comet invokes a mantle of fluffy dust to insulate the ice, which seems incompatible with picture-perfect, round, flat-bottomed impact craters. They are similar to the depressions observed on P/Wild-2 and P/Borrelly, which are likened to hypervelocity impacts into porous, resin-coated sand (23), which is not compatible with a low density, low rigidity, thick dusty surface. The WCM, however, readily interprets this as a consequence of a several meter thick rigid crust overlaying a low density core, which is also consistent with modeling of the ejecta "curtain" (24).

The DSM predicted a 60m diameter crater from Deep Impact, which should be easily resolved by the High Resolution Imager on the flyby craft (12). The inability of the HRI to see the crater even 13 seconds after impact (24) was blamed on dust obscuration. The WCM predicted that a thin crust could be penetrated by the impactor, which would produce an anomalously small crater, which perhaps could more easily be obscured by lifted dust.

The DSM predicted that hypervelocity impacts into dust would produce an intense flash, likely to be seen from Earth. Actual light intensity was very subdued, about 1/10000 of the scaling from lab projectiles hitting pumice (25), perhaps due to high porosity, ice content, projectile tunnelling so that the crater walls blocked the light. The WCM adds the possiblity that punch-through of the crater floor would also remove the hottest, self-luminous material from view.

The DSM would predict that infra-red spectra should detect the presence of proto-solar nebula (PSN) grains. Instead, IR spectra observed phyllosilicate clays and carbonates (26), two minerals generally associated with biology and liquid water. After discussing possible mixing of the PSN that might redistribute clays made near the Sun into Oort cloud comets, the possibility of a liquid water layer on the comet is advanced, along with an alternative model theorizing localized melting in an impact crater. We consider these observations the best evidence to date for the WCM and point out that the DSM is incompatible with water in any shape or form. In addition, the time to form substantial amounts of phyllosilicates would seem to militate against a transient, impact-produced water source.

The DSM would predict sublimation cooling at least near jets, but the sunlit side of the comet was between 260K-326K, mostly around 280K (±6K systematic calibration error), suggesting low thermal mass and no sublimation cooling (24). The identification of 30 micron ice grains, thermally decoupled from the hotter 94% dust grains, also suggests that water vapor is recondensing on the surface, but the bulk of the water vapor is being released elsewhere, presumably geysers (27). The WCM requires geysers, while the DSM grudgingly permits their existence, since geysers undermine the stability of the DSM (10). More significanly, the WCM predicts an equatorial swath of near 277K temperatures due to liquid water circulation, which is broadly consistent with the ∼290K band observed (24), if we allow some thermal insulation provided by the crust.

The DSM predicted that much of the ejecta should consist of dust and ice grains, which would subsequently vaporize and contribute to the coma gases. The lack of hypervolatiles suggested that the excavated region has already been thermally modified, the presence of phyllosilicates suggests it has even melted. Thus the small amount of <5 micron ice crystals observed (28; 26) fits neither a thermally processed nor a pristine comet picture. It suggests a heterogenous excavation, yet the consistency of other constituents with typical outbursts would imply a homogeneous excavation. The temperature was measured to be well above the melting point of ice, so some thermal gradient must also exist. These mutually exclusive options might be understood in the WCM as the penetration of the impactor into the vapor chamber of a gas geyser, and the subsequent dislocation of cold ice grains in the more pristine interior or the flash freezing of liquid water by rapid boiling. In other words, the WCM support a highly heterogenous comet structure that can simultaneously provide ice grains, submicron dust grains, water, gas and organic volatiles.

Finally, the DSM predicts a fluffy, homogeneous average density less than that of ice. The calculation of 600 (+400,-300) kg/m^3 (24) is broadly consistent, though somewhat more dense than the estimates from crater formation. The calculation is based on modelling the crater ejecta as a gravitationally bound system not taking into account the gaseous acceleration observed by (21), which would raise the calculated density. The WCM, however, predicted that the 41 hour spin period implies an average density of 20 kg/m^3 if the (spherical) comet is marginally Rayleigh-Taylor unstable.

2.2. Stardust

2.2.1. Our WCM prediction

The Stardust mission collected dust from Comet P/Wild-2 in aerogels, designed to trap the grains without vaporizing them. Since Wild-2 is a short period comet, we predicted water geysers on P/Wild-2 with relatively large dust grains (>10 micron). At much lower density, there may even be evidence of CHON grains in the form of biogenic carbon. In any case, we predicted the ratio of large to small dust grains $d > 1/d < 1$ microns will be much greater than that expected from sublimation winds, as well as the percentage of CHON grains.

2.2.2. The DSM and Observations

The DSM predicted that cometary dust particles would be similar to CI chondrites, consisting of submicron-sized grains levitated by sublimating ice. Only a few press releases on Stardust particles have emerged to date, with the surprising finding that crystalline olivines have been recovered, two photos being displayed. Since these require temperatures in excess of 1400K to form, the assumption is that the Sun produced these particles in the early history of the PSN, which were subsequently carried out to the Oort cloud and accreted to the comet. Alternatively, they may have formed at a nearby star and migrated to the Oort cloud, the isotopic composition should differentiate. The size distribution discussed in the press releases also exceeded expectations, with more than a million particles greater than 1 micron, 45 particles greater than 10 micron, 10 greater than 100 micron, and 1 almost a millimeter. Though the anecdotal size distribution does not fit a typical power law spectra (29), it is clearly enhanced in larger radii particles, as the WCM predicts.

3. REFINEMENTS TO THE WCM

Although we made no predictions for the Hayabusa mission to asteroid Itokawa, or the Cassini mission to Enceladus, both returned data that can refine the WCM. But first we address some of the discrepancies with the Deep Impact observations.

3.1. Deep Impact Discrepancies

The submicron dust lifted by the impactor was not expected by the WCM, since we had assumed that all the crust of an old, Jupiter family comet had been extensively water modified, cementing the grains together. However, the submicron silicates were observed only in the cratering cone of backsplashed surface material, not in the central core of carbonaceous particles. Therefore it seems possible that the outer crust of a water modified comet has a regolith layer much as asteroids do, and as long as the comet does not spin too quickly, the regolith will remain gravitationally bound. Sublimation winds would lift these particles, but the WCM assumes there is a compact crust some distance below this regolith that completely seals the gases in, allowing only periodic geysers to remove the pressure. Because of the weak gravity, lack of disturbing winds, dehydration of the cement, and continual bombardment by micrometeroids, regolith will continue to thicken and distribute into low spots in the gravitational potential. Deep Impact was thought to have struck in the vicinity of an old crater, which would be an ideal location for such fine regolith. And the central core of carbonaceous material was the expected WCM signature of a water-modified crust.

The average density of the comet was unexpectedly high compared to the spinrate. Since theory suggests that on average, geysers will spin up a comet, and ground based observations were consistent with geysers that activate at dawn and go dormant at dusk, it seemed unlikely that P/Tempel-1 would be spinning so slowly unless there were an internal governor limiting the process. The WCM predicted that mass transfer from the interior of the comet to the equator was just such a brake, which would maintain the comet at the R-T marginal instability spinrate. Therefore the 41 hour period of P/Tempel-1 corresponds to a spherical, homogeneous comet of density 2% that of water, whereas Deep Impact calculated a density 60% of water. However the WCM does not predict a homogeneous comet, but one with a thick crust, which need not be R-T unstable, since it plays no part in the transfer of mass, only the fluids in the interior of the comet. Therefore for a 41 hour period, if 98% of the spherical comet mass were in the crust, R-T would be marginally unstable on the interior. In addition, if we account for a prolate tumbler, then the required density increases (or equivalently the mass fraction in the crust decreases), since the centripetal acceleration is increased at the expense of gravitational attraction. Without a solid model of P/Tempel-1 to integrate, we can only estimate that these two corrections suggest that almost 90% of the pristine material has been transferred to the crust, and that P/Tempel-1 is closer to senescence than previously thought. This implication is weakly consistent with the observed depeletion of hypervolatiles and presence of phyllosilicates, but there are no other indications that is running out of water.

Finally we comment on an outstanding question not yet addressed by the Deep Impact team: the parent source of the CHON emissions. The DSM predicts it will be in relatively simple organics, abiotically present in large molecular clouds and the PSN. The WCM predicts it will be complex biogenic organics which are also responsible for the observed kerogens and amorphous carbon. The mystery peak observed in the excavation plume by the IR spectrometer (24), was interpreted to be acetonitrile, the simplest compound that approximated the signature. This tentative identification is neither simple nor complex enough for either model. We would encourage the team to attempt fits to more complex biogenic materials in the expectation that this will solve the mystery. For having argued that Mars-crossing comets can melt, we further argue that Earth-crossing comets can become liquid water incubators if they are infected with life. It is commonly thought that meteoritic events, such as the Yucatan peninsula event, are capable of propelling large amounts of water into space, which would be expected to form a dust lane along the Earth orbit that may contain algae or bacterial spores. Lyophilization is a well known technique for preserving bacteria that involves cold temperatures and vacuum, almost identical to this process. And if previous comets were infected, with subsequent disintegration of the comet, then all the cometary dust lanes will be filled with spores as well. Accordingly if even one infection has occurred in the past, it seems probable that future infections are not just likely, but inevitable. If this be the case, then the water-processed crust of wet comets should be cemented with biogenic organics whose subsequent exposure to sunlight leads to the low-albedo kerogens observed on all comet flybys.

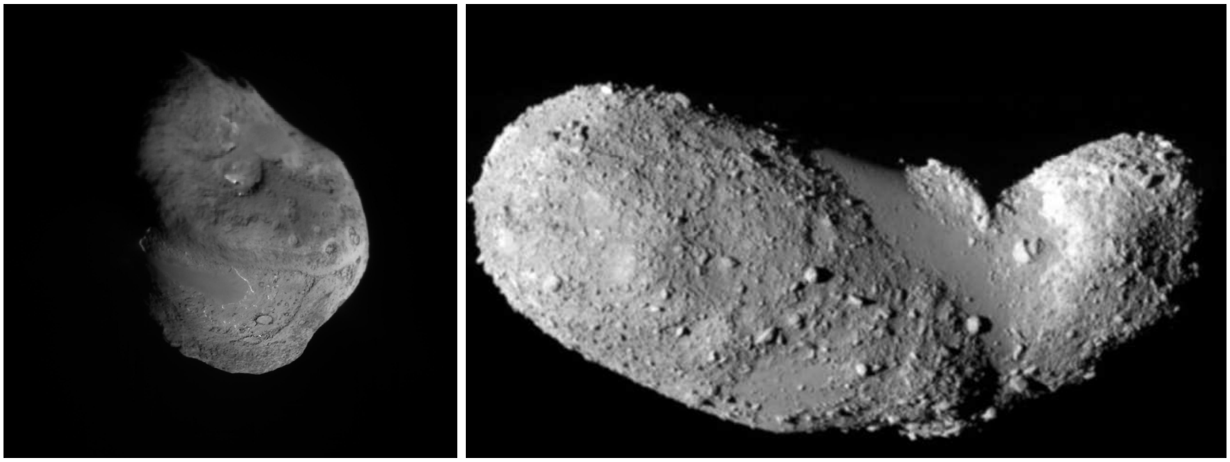

Figure 1. Left: Comet Tempel-1, courtesy NASA/JPL/UMD. Right: Asteroid Itokawa, courtesy JAXA/ISAS.

3.2. Hayabusa

The Hayabusa mission to asteroid Itokawa (30), did not discover an extinct comet, at least, not by surface composition (31; 32), however it did find a rubble pile with a density of 1900 kg/m^3, in a peculiar, bent prolate configuration that is not gravitationally relaxed see Figure 1 (33). That is, had the rubble pile been produced by tidal disruption or impact, it would be natural to find it in a compact, roughly spherical, minimum energy state, instead, Itokawa, like many comets, was prolate with small shear strength. In addition, the rubble observed at different spatial scales followed a power law size distribution with a weak enhancement at 25 meter length scale (34; 35).

While the composition resembles S-class asteroids or LL chondrites, unlike comets with their black, carbonaceous exteriors, they do resemble the two large silicate grains collected by Stardust. Another possible origin for cometary silicates might be the dust trails left by rubble pile asteroids. Likewise, the WCM predicts the final collapse of a dead comet into a rubble pile much like Itokawa. The layered crust of comet should produce rubble piles with just such a peak in the size distribution, where the boulders seen edge on will preferentially display the uniform thickness of the crust.

Finally, lessons learned by Hayabusa's attempted landing on Itokawa (36) will be instructive for the future Rosetta mission to an equally low mass object.

3.3. Rosetta

With Rosetta's rendezvous with 67P/Churyumov-Gerasimenko still 8 years distant, we hope to refine this prediction several more times. (37) 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 (R_1/R_2=1.17), inhomogeneous comet would be somewhat higher, closer to 200 kg/m^3. This is just slightly more dense than the typical comet (38) suggesting that 67P/C-G is a young and potentially water-rich target.

Rosetta will undoubtedly have to land at the poles, to 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 perhelion 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.

Finally, the high heat capacity of water will permit 67P/C-G to remain liquid to further heliocentric radii than its melting point on the way in. Rosetta will track the comet on its way out, and may even be able to record magnetic signatures in any liquids that might be circulating below the surface. In a very concrete sense, the presence of liquid water and living organisms out beyond Mars will expand the biosphere by five orders of magnitude, and perhaps permit the seeding of life on the moons of Jupiter and beyond (now that Titan is thought to have a liquid water ocean).

4. CONCLUSIONS

The WCM has survived the scrutiny of three *in situ* missions to nearby comets and asteroids. The discovery of phyllosilicates in P/Tempel-1 is a particularly compelling observation in support of the WCM. We found the slow spinrate of P/Tempel-1 combined with the relatively high density of 600 kg/m^3 the hardest to explain with the WCM, but otherwise saw many confirmations of the theory. Stardust will continue to release results, but preliminary evidence for unusually large dust grains is consistent with the WCM prediction of water geysers. Hayabusa found a S-type rubble-pile asteroid with some features in common with the WCM, and may be another source of the unexpected silicates found in P/Wild-2 by Stardust. Finally we conclude that Rosetta has the opportunity to confirm (or falsify) many aspects of the WCM on a comet that is young, spinning rapidly, and should be quite wet.

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