Evidence for Liquid Water on Comets

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ABSTRACT

The electron-microscope analysis of the Orgeuil carbonaceous chondrite, thought to be the extinct core of a comet, shows many archaen microfossils adapted for both cold and hot liquid water environments. Since water is a prerequisite for life, its presence on a comet would have important implications for interplanetary cross-contamination of the planets as well as strongly impact the dynamics and evolution of a comet. Therefore we develop a wet comet model to explore the consequences of liquid water on Mars-crossing comets and hypothesize that all the periodic comets, such as P/Halley, P/Wild-2, and P/Borrelly show signs of significant liquid water processing. The wet comet model is shown to be compatible with observation, as well as provide significantly better explanations for well-known cometary anomalies. Finally, the model predicts that the results of both Rosetta and Deep Impact missions will deviate from expectations.

Keywords: Comet, liquid water, astrobiology, orbital dynamics, geysers, Deep Impact, Rosetta, splitting, tensile strength

1. INTRODUCTION

Comets are thought to have formed by gravitational settling of proto-solar nebular dust, out beyond the orbit of Pluto in the Oort cloud.[1,2] 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.[3,4] Other indirect evidence from meteoritic fireballs,[5] cometary splitting,[6] 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 approximately the mean temperature of the Earth, 300K, one might suspect that water ice on comets may easily melt as the comet crosses the Earth orbit. Several regulatory mechanisms have been invoked that may mitigate this thermal input, enabling 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 whereby a cold sublimation wind cools the surface, a high-albedo, and a natural "heat pump" that radiates heat away from the comet.[7] Several of these mechanisms have been rendered unlikely by the three cometary spacecraft flybys with their detailed photographs of the surface, to which we add several instabilities that may upset the delicate refrigeration cycle. That is, images of P/Halley, P/Borrelly, and P/Wild-2 (and P/Tempel-1) show black objects (albedo < 0.03) with a relatively thick crust emitting jets of steam from a surface at temperatures 300-400K, jets which seemingly remain 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.

Therefore, without a reliable way to shed the excess heat absorbed, it seems likely that comets may have local regions of meltwater,[8] much as glaciers or the Antarctic can support localized melting. Alternatively, high pressure geysers that can support local meltwater have been invoked to explain P/Borrelly.[9] In addition, we argue that meltwater produces a positive feedback effect causing greater melting, until substantial amounts

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of liquid water can be found on a comet. Should this occur, it would cause dynamical changes in cometary spin, orbital non-gravitational forces, dust production, tail geometry, fragmentation probability, and ultimately senescence and extinction. (Note that this mechanism is entirely separate from the "liquid center" theory,[10] with much smaller quantities of liquid water.) If CI carbonaceous chondrites, such as Orgeuil, are taken as the final end of cometary evolution[11]), then this model should also be compatible with the analysis of the Orgeuil meteorite, that is, a grainy, extremely heterogeneous matrix cemented with water soluble salts.

While we would prefer an inductive presentation of the model, drawing compelling inferences of the ubiquitous presence of liquid water, space constrains us to a deductive approach, presenting the model and demonstrating that its consequences are consistent with observations. While the inductive approach might show that this hypothesis has the greater explanatory power, the deductive approach will at least show consistency with the data. Accordingly, we develop the model in Section 2, and address several contradictory inferences in Section 3. In Section 4 we assemble a short list of puzzles for Whipple's "Dirty Snowball" paradigm,[12, 13] demonstrating how liquid water can resolve the paradoxes. In Section 5 we make predictions for future comet missions Rosetta and Deep Impact.

2. WET COMET MODEL

The wet comet model is in substantial agreement with the standard, dirty snowball model of Whipple concerning the formation and distribution of pristine comets. Where we differ is in the subsequent evolution of a comet once it makes a trans-Jupiter pass into the inner solar system. At first, as in the Whipple paradigm, the inbound comet maintains its cold interior by ablative cooling. As the thermal forcing increases with $1/r^2$, however, the comet undergoes a rapid, irreversible transition in average surface temperature, akin to a phase transition, whereby the heat input to the interior of the comet melts the ice, differentiates the water from the dust, and permanently modifies the crust. Only a complete disruption of the crust, say, by splitting of the comet, could undo this phase change to the surface and permit the Whipple-type ablative cooling to restart. Barring such catastrophic events, the subsequent evolution of the comet is entirely dictated by this low-albedo, low-porosity crust, and the consequent continued differentiation of the comet.

Since this phase transition is relatively fast, being driven by positive feedback mechanisms, it is nearly impossible to predict its exact timing with the information available to ground-based observations. However, the model will predict the properties before and after such a phase transition, as well as the forcing conditions that favor such a transition. As a consequence, long and short period comets are distinguishable by more than their apogee distance, but also by whether they have undergone the phase transition to a wet comet. Finally, cometary debris, whether dust or CI meteorites, should arise almost entirely from the final stages of a wet comet evolution, rather than the more infrequent disruption of an undifferentiated, pristine long-period comet.

As we discuss later, there are significant differences between non-spinning, or slowly spinning comets and fast rotators. Since our model depends on this difference, we must first argue why both types of comets undergo the same temperature phase transition and result in identical end states. Therefore, we first address the spinup of slow spinners, and argue for their evolution to a fast rotator. Then we consider fast rotators and the subsequent evolution of both initial sets as wet comets.

2.1. Dynamic Evolution of a Slow Spinner

The equilibrium temperature of a comet has been well discussed in the literature,[14] depending on heat input, visible and infrared albedo, dust-modification of the incoming heat flux, latent heat of the ices in the comet, insulation by a porous non-volatile mantle, conductivity of the ice, snow and mantle, and possible heterogeneities of all the above. We summarize all these variables into two simplified models: the homogeneous, or average temperature model[15]; and the heterogenous, or geyser model.[9] By considering parameter regimes not discussed in these models, we attempt to show their instability to perturbations, and therefore, their dynamic evolution to a fast rotator.

We begin with the simple homogeneous model, where the average surface temperature, T, is given by the reradiated heat equals the heat input less the heat dissipation, averaged over the comet period, P[15, 16]:

$$\sigma T^4 = \frac{1}{P} \int_0^P [(1-A)F_o - \phi(t)]dt \tag{1}$$

where ϕ is the power lost by dissipative processes such as the heat of vaporization or the internal energy of the sublimation wind. Now the surface temperature has no thermal latency, and the solar input is relatively steady on the timescale of one period, P, so the surface temperature will fluctuate with the rotation, and be non-linearly dependent on the dissipation, ϕ. From elementary physics, we can distinguish four components of the heat dissipation: convection, conduction, radiation and phase change. Since the left hand side already takes into account the radiative cooling, we can rewrite the equation as:

$$\sigma T^4 = \frac{1}{P} \int_0^P [(1-A)F_o - \phi(t)_{CONV} - \phi(t)_{COND} - \phi(t)_{H0}]dt \tag{2}$$

Now the convective dissipation loss, or heat lost to the outgassing vaporization wind, is by far the dominant heat loss term on the surface. Should the surface become less porous, and the convective term diminish, then the temperature will rise to a new equilibrium.

In the limit that the surface becomes a nearly impervious seal, suggested by the spacecraft observations of three comets, then the dissipative heat term, ϕ, can only be directed inward. The pressure produced by the phase change to a subliming gas will drive the gas into the interior of the porous comet, where the large surface area at low temperature act as a sorption pump for vapor. This reversal of the convective wind will carry heat into the interior of the comet until the rise in temperature of the interior produces a vapor pressure equal to that imposed at the surface, taking into account temperature gradients and resistivity of the porous matrix. That is, not only does the temperature show a scale length from the surface, but the pressure does as well. We model the combination of conduction and convection for a layer below the surface as:

$$F_{IN}(r) = \kappa \Delta T + m(r) \Delta T \tag{3}$$

where $m(r)$ is the product of heat capacity and mass flow of the convective wind into the comet. Since both the heat input and the mass flow diminish as we drop below the surface, we adopt powerlaws in r for both. Solving for the temperature gradient then gives:

$$\frac{dT}{dr} = \frac{F_0 r^a}{\kappa + m_0 r^b} \tag{4}$$

where m_0 includes the heat capacity as well.

Depending on the size of the mass flux, the temperature gradient has a weak slope, r^{a-b}, at the surface where the convective term dominates, falling to a steeper slope, r^a, in the interior where conduction dominates. Defining the distance from the surface to the transition in slope as the "thickness" of the heat-affected comet layer, we see that the effective heat capacity of a comet is much smaller than that of the entire comet. We also note that increased heat input, say, at the subsolar point, thickens the layer as it increases the surface temperature, and that thicker layers support higher subsurface pressure.

On a slow rotator, the gravity vector always points inward, so that the heating of the surface during the day remains Rayleigh-Taylor stable. At night, however, the surface cools rapidly by radiation, causing the gas trapped under the surface to go Rayleigh-Taylor unstable, so that at least over some outer region of the comet the conductive wind reverses direction yet again, carrying heat from the interior to the outer layers. This day-night convection cycle has important consequences for the porosity and evolution of the comet.

First, during the day, the inward convective wind terminates as the vapor recondenses on cold grains in the interior. This tends to fill in the voids between the grains and decrease the porosity, which in turn, increases the pressure gradient, reduces the convection wind and increases the temperature gradient. As in sorption pumps, decreasing porosity creates greater condensation at the restriction ultimately shutting off the convection flow so that all the heat flux is carried by conduction and phase change of ice to vapor with consequent rapid pressure increase. Therefore no matter what the actual form of the convective heat flux, it goes rapidly to zero at some interior point of the comet, producing a sharply defined inner boundary.

Second, during the night, the outward convective wind terminates at the cold outer surface, driven not only by condensation and reduced pressure, but also by the Rayleigh-Taylor instability. Again this tends to drive down the porosity of the surface and reduce the efficiency of the sublimation cooling, should any gas be percolating through the surface. Subsequent daytime heating of this treated surface will result in lower temperature gradients (solid ice having a higher thermal conductivity than snow), higher thermal flux, and higher pressures at the surface.

Third, the day-night reversal of convection winds will process the ice grains, moving ice to the periphery, and forming a closed vapor chamber of increased porosity and weakened tensile strength under a cap of ice. This vapor chamber will tend toward higher pressure and higher pressure differences with each day-night cycle, as the "sorption pump" loses capacity both due to rising average temperatures, less ability to absorb heat by vaporization, and flatter temperature-pressure gradients. At some point, one would expect the daytime pressure to exceed the strength of the outer cap, and the entire vapor content of the chamber will vent in a geyser-like event carrying the now-uncemented dust with it. *Yelle et al.*[9] give the parameters for the venting of such a system, to which we add the probable erosion of the outer icecap by sublimation and inevitable collapse of the chamber and cessation of the geyser.

Now the thickness of this layer, based only on the heat conduction of fluffy snow, is estimated by Klinger to be $d = (\kappa P/\pi \rho c_v)^{1/2}$, comes to about 13 cm for rotation period, $P = 10$ hours. Including the convective transport will increase this thickness, perhaps to double this value. Since the mass loss of the comet corresponds to about 0.2 cm/hour, this suggests that 6-12 comet "days" are sufficient to remove all the material in a layer, giving the lifetime of a single geyser. The subsequent erosion would expose the inner, low-porosity ice boundary as the new outer surface. Since this layer already is of low porosity, one would expect the same process to begin anew but with higher final pressure before venting. Such a sequence of venting and subsistence may cause a quasi-periodic brightness variation of cometary coma, which may be misinterpreted as a slow rotation rate variation, hence the possible confusion determining Halley's rotation rate.[15]

Therefore whether one adopts the "ice-crack" model of Yelle, or the post-Halley "crusty snowball" model,[15] it would seem that fissures and venting of high pressure gas are an inevitable result on comets. That is, sublimation and mass loss of a comet are a dynamically unstable process, both spatially and temporally, resulting in uneven venting and geysers. As a consequence, the net angular momentum of a comet is not constant, but a random walk through momentum space, with a preponderance of comets gaining angular momentum in this process.[17]

We note also that the greater heat load at the subsolar latitude (as measured from the spin axis pole) would lead to thicker layers and larger geysers, as well as more significant erosion of the cometary surface. These largest geysers would then provide torques both parallel and perpendicular to the spin axis, such that their reaction force would tend to drive the comet spin axis more perpendicular to the sun-comet line, even as the comet spun up. Therefore the dynamical evolution of angular momentum would seem to drive a pristine comet toward rapid spin with the spin axis oriented roughly perpendicular to the orbit plane. When the comet spins fast enough for a pebble to lift off the equator, a whole new instability appears, irreversibly driving the comet to a new temperature equilibrium, which we discuss next.

2.2. Phase Transition of a Fast Rotator

For a spherical, homogeneous comet, the gravitational acceleration depends only on the mass of the sphere below point r, or $\mathbf{g_m} = -(4/3)G\pi r^3 D/r^2$, where D is the density, and G is the gravitational constant. Using cylindrical coordinates, $r^2 = \rho^2 + z^2$, we can write the centripetal acceleration as $\mathbf{g_c} = \omega^2 \rho$. Then the effective gravity is the sum of these two vectors, which in the equatorial spin plane ($z = 0$) can be written:

$$g = (\omega^2 - \frac{4}{3}\pi G D)\rho \tag{5}$$

For $z \neq 0$ the two components are not collinear, and must be added vectorially. The critical period occurs when the effective g given in equation 5 is zero. For periods shorter (angular speed faster) than this, the effective gravity points outward at the equator, rather than inward. Similar formulas apply to right-circular cylinders and ellipsoids, whose critical period increases linearly with aspect ratio.

Now the Rayleigh-Taylor instability occurs when a denser fluid overlays less dense fluid. Since hotter fluids generally are less dense, this is equivalent to saying that a temperature gradient (hot to cold) is oppositely directed to a gravity gradient. When a slow rotator is heated on the surface on the dayside, the temperature and gravity gradients are parallel, and the fluid is RT-stable. However when a warm comet is cooled on the surface on the nightside, this becomes RT-unstable. Even in a nearly non-rotating comet, this simple relation becomes more complex, since the cosine dependence of the sunlit side can cause the temperature gradients to be non-radial. Likewise, rotation of the comet complicates this simple result. First, it causes the gravity vector to be non-radial apart from the poles and the equator. Second, it also brings heat around to the nightside, increasing the RT-instability there. Third, if the period is shorter than critical, it drives the dayside equator regions RT-unstable, and the nightside equator regions RT-stable.

Therefore as a barely rotating comet begins to speed up, at first the night-side cooling is enhanced as the RT-instability is amplified by the heat rotated around from the dayside. This reduces the average temperature of the comet. Then as the comet continues to accelerate through the critical period, the RT instability is suppressed on the nightside and enhanced on the dayside, causing a phase transition in the mean temperature as it makes a rapid jump to higher temperature. Further increase in spin rate will continue to increase the mean temperature as the RT-unstable equatorial regions widen to encompass more of the cometary surface. This discontinuous jump in the mean temperature does more than this, it also flags an important change in differentiation, or separation of cometary components.

2.2.1. Rayleigh-Taylor Enhanced Heat Flux

Returning to equation 2, we see that RT-driven convection dominates the flow of heat into the comet, and that this mass flow has essentially no ceiling. That is, it is not pressure driven, but a bubble of hot gas will continue to rise as long as it retains its heat. Since the effective gravity vectors starting near the poles move inward toward the center and then outward at the equator, a bubble of hot gas heated at the equator can conceivably rise toward the center then up at the poles. Conversely, a dust grain at the pole could conceivably sink all the way to the equator. That is, the temperature gradients produced by the convective flows can themselves contribute to the RT-instability, so that an entire gravity "fieldline" will be potentially unstable if its footpoint in the equator is at elevated temperature. With a continuous source of heat near the equator, the comet will remain RT-unstable as long as any cooler ice or fluid is found in the interior or poles. The convection cells set up by this gravitationally driven RT-instability do more than move fluid, they also move embedded dust grains to the surface. This causes non-reversible differentiation of the comet, as a layer of non-volatile dust builds up on the surface. Not only does this dust reduce the porosity of the crust, but it contributes to its tensile strength, and therefore the maximum pressure sustainable by an equatorial geyser.

2.2.2. Water Geysers

Returning to the geyser model,[9] we see that this RT-instability affects only two aspects: the heat conduction κ, (actually, microscopic convection in the crust), and the thickness of the outer crust. Since the heat input is given by their ratio, increasing both by the same amount has no qualitative effect on the solution. Making these extrapolations to the model, we note that the cavity temperature is proportional to the pressure, which is in turn, proportional to α, the vent area divided by the solar collection area. Therefore, as the geyser removes gas, the uncemented dust will collect around the vent, with the likely occurrence that the vent becomes restricted. This reduction in α will cause an increase in both temperature and pressure, which for values of $\alpha < 10^{-5}$, (a 1cm^2 vent in $3 \times 3m^2$ collection field), will permit liquid water to form, assuming of course, that it doesn't completely fracture the crust.

As soon as liquid water forms, it will condense on the cold walls of the geyser, run down to the crust, and cement the dust grains together. Depending on the pressure fluctuations in the chamber, it may even form a fog that condenses near the vent, thereby strengthening the crust of the geyser and/or restricting the vent further. Liquid soaked crust will conduct heat even faster, so that the system may "runaway" until either the vent opens up, or becomes completely clogged. Since this is another positive feedback mechanism, we would expect equatorial geysers to regularly get plugged up and generate liquid water.

Liquid water introduces yet another irreversible phase change to the comet. Unlike vapor, it can carry soluble salts to the surface. Since the geyser model has a nearly constant 320K temperature crust, this water evaporates quickly leaving behind water soluble crystals in the interstitials between dust grains, cementing them together. Water also dissolves colloidal particles, such as micron-sized dust, and its viscosity can carry even larger grains in an active flow. Using a typical 50:50 water to dust ratio typical of the coma as reflective of the cometary interior, then when the geyser spikes in pressure producing water, great drops of mud begin to rain on the crust, rapidly plugging the vent and producing an interior pond. Since the heat cannot be further removed by venting gas, the heat absorbed by this mudpacked crust goes either into the evaporation of water percolating through the crust, or into the further melting of ice. The water, like the vapor above it, is RT-unstable once it has warmed above 279K, so the heat is rapidly drawn into the interior of the comet, where it continues to rain muddy drops.

Surface tension will draw the water away from its source, so we would expect a larger area of the exterior comet surface to be water-logged than immediately over the geyser. This would increase the heat flux over a wider region, and may result in a pond expanding in area as it finds a new equilibrium. Eventually the growing sediment thickens the crust sufficiently to restrict the heat flow, and a new equilibrium is reached with an ice-covered pond that nearly melts in the daytime, and freezes at night. Above this pond the vapor remains RT-unstable, and continues to conduct heat into the interior of the comet, as well as provide an icy wind to keep the surface of the pond frozen.

Of course, if the comet were on its outbound leg, the pond could freeze entirely, whereas on the inbound leg, we might imagine the pond growing deeper and deeper, as the rainy season continues. Although the effective gravity is small, the accumulation of water near the surface will put the crust under tensile stress. Small cracks will probably be self-healing, as the escaping water freezes by rapid boiling, and the sediment is carried into the vent. However, this doesn't preclude large areas failing under tension, at which point the pond would empty in a spectacular water geyser.

Water geysers may be indistinguishable from steam geysers seen at a distance. However they would differ in several important ways from steam. Viscosity and mass keep the fluid from having as high an initial velocity as a steam geyser, though subsequent heating and acceleration in the coma may erase this deficit at telescopic distances of 100km or more. Like a rocket engine, a water geyser may have the same energy input as a vapor geyser (the vapor above the water providing a constant pressure), but a much larger thrust and therefore a much larger torque on the comet. The sudden drop in pressure as the water exits the geyser will cause flash boiling of the water, producing gas and ice/dust grains with substantial tangential acceleration. The higher viscosity of water will support much larger dust grains in the geyser, which when intermixed with flash frozen ice, may produce fluffy conglomerates. The later sublimation of the ices will then provide a continuous gas source much farther out from the comet and more collimated than in a pure gas geyser. All these differences will cause substantial changes in the gas/dust ratio of the two kinds of geysers, and may account for the variability of the observed ratios.

2.2.3. Mass Fractionation

We should take stock of what this water geyser has done to the mass distribution of the comet. It has removed ice and snow from the interior, and deposited it at the surface, putting the most dense material at the largest radial distances, thereby increasing the moment of inertia. Like an iceskater who flings out her arms at the end of a twirl, this increase in inertial moment will slow down the comet. But a slower spin will drop the comet below criticality, and not only will the RT-instability cease and the mean temperature of the comet drop, but the water will slosh back to the center of the comet and freeze, where it will no longer brake the comet spin. On the other hand, while a geyser is active, it will provide a thrust or net torque that should on average, spin up the comet. In practice, we expect that liquid water provides the critical feedback, keeping the comet just over the edge of RT-instability, but not too high, or else the shift in mass will shut it back down. Therefore water has a dual role, not only a positive feedback in a geyser, but a negative feedback on the comet spin period.

Now the water-formed equatorial crust is cast like wet cement, neither plastic nor ablative, so a dry comet, once it transitions to a wet comet, no longer shrinks infinitesimally by ablation, but only by catastrophic shedding of its crust. Meanwhile, the interior of a comet is becoming less dense, as vapor chambers replace the dirty snow matrix. As a consequence, our calculation of RT-instability assuming a homogeneous comet no longer apply, and in fact, the interior of a comet can become RT-unstable, even if the crust is not. This is because the true density of the interior continues to decrease, whereas the total mass and average density remain unchanged. That is, a pebble may never lift off the equator, but the water under the crust could be churning with RT-driven convection. This also means the crust may be much stronger than supposed under compression rather than tension, even while the interior of the comet continues to melt.

2.2.4. Cometary Erosion

Ablative erosion would tend to smooth out features or surface structure, keeping a spherical comet nearly spherical. In contrast, the RT instability increases the equatorial erosion rate such that a spherical comet will very rapidly evolve toward a prolate shape. Details may differ, but we suggest a potential scenario to illustrate this asymmetric erosion.

Although ablation would not be a major mass loss for water-treated equatorial crust, sunlight would continue to erode "dry" regions of the comet. The boundary between polar ablative crust and equatorial cemented crust should be quite dramatic. One might expect mesas and perhaps undercutting of the mesa face that could lead to catastrophic failure of large sections of water modified crust. Of course, simple overpressure from increasing vapor pressure could also lead to large sections of crust separating from the comet.

If the fragmentation occurs at slow enough speed, it may not achieve escape velocity and may generate multiple collisions between the fragments and the surface, effectively sandblasting the surface and removing all the fragile crust regions. Should such large erosion events occur, the majority of the mass loss will be at the RT-unstable equatorial regions, leaving the comet with an apple-core profile.

In addition, we argue that this equatorial erosion may proceed faster than the estimated ablative velocity of some 2 mm/hr at Earth orbit, or perhaps 10 m for a single revolution about the sun. This limit assumes that all the eroded ice is vaporized by solar heat flux, but greater erosion rates than this are possible if the heat is directed into the interior of the comet, and chunks of ice are released from the surface. Since we have argued that the RT-instability follows the gravitational field lines, it shows exactly this divergence of fieldlines from the RT-unstable equator fanning outward toward the poles.

Whatever the exact mechanism of such a catastrophic erosion event, the cycle of geysers and pools would be expected to begin anew, once more concentrated near the equator. Except this time the z-axis is no longer the axis of the largest moment of inertia, having lost a belt of equatorial material, and geyser torques would be expected to cause the comet to precess and nutate. Once liquid water reoccurred, if indeed it had all been lost in the event, it would provide a very efficient nutation damper, forcing the comet into a rotation about its largest moment axis. That is, water will transport momentum effectively among the axes and allow the axis of rotation to switch to the more stable tumbling rotation of a prolate object. This would be expected to happen very quickly, perhaps in as little as a few cometary days. Although the rotation axis remains fixed in inertial space, the comet itself would reorient so that former polar regions would now be equatorial, and the equator has become the pole. Regions of crust that had been under compression, will now be under tension, and conceivably the entire comet could split during this transition.

The slight increase in centripetal force (and RT-instability) can be seen in this simple-minded calculation. Assuming a spherical comet of radius 1.414 R has eroded to resemble a right-circular cylinder that is 2R high and 1R in diameter, then the ratio of the moments of inertia (tumbling versus spinning) is 7/6, and the new angular velocity will be $\omega_2 = (6/7)\omega_1$. A point on the equator (cylinder vertex) after the flip will have a centripetal force $\omega_2^2 r_2 = \sqrt{2}(6/7)^2\omega_1^2 r_1$ greater than a point on the equator before the flip, or a 4% increase. Though in general, larger (and more unstable) aspect ratios actually reduce the centripetal force after the flip due to the much slower rotation. The key point being that spherical comets would be expected to become prolate and rapidly swap their rotation axes due to the presence of liquid water.

Would further erosion produce another round of axis swapping? Possibly, though we might imagine that once sufficient water processing of the crust had occurred, the cometary shape is "set in concrete" and further catastrophic shedding is unlikely; the comet will maintain its prolate shape and fixed rotation axis until extinction.

2.3. Magnetohydrodynamic Forces

The presence of liquid water on the comet also introduces other non-gravitational forces beyond the geyser torques. Since the water will have dissolved salts, as is evident both in the visible light scattering by Na I and the analysis of CI chondrites, it becomes a weakly ionized plasma. Thus water currents also carry electrical currents that can produce magnetic fields. The liquid water ocean of Europa was detected in this manner from magnetometer measurements aboard the Galileo spacecraft. Unlike magnetic fields of the ion tail, which also responds to the solar wind, water-induced magnetic fields will provide a body force to the comet nucleus, or a potentially measurable non-gravitational force. The mass loss of a Halley type comet is thought to be approximately 64,000 kg/s, and if this is ejected through a single geyser with a 250 m/s velocity (not observed on Halley, though possibly on Borrelly), it would have a net thrust of 16 Mega-Newtons, whereas a Jupiter-family comet with lower mass loss would be perhaps 1 MN. This is obviously an upper limit both because multiple geysers have been observed on all spacecraft flybys providing partially counteracting thrusts, and lower geyser velocities are inferred from direct observation. For magnetic effects to be important, they should be at least a substantial fraction of the geyser forces. In the spirit of this paper, we provide an order-of-magnitude estimate for this effect.

2.3.1. Solar Wind Thrust

Regardless of whether the water circulates in many localized ponds, or possesses a global circulation in a subsurface equatorial "ocean", the effect observed from a few comet radii away would be a dipole magnetic field. This magnetic field would trap ions and electrons in the near vicinity of the comet, but more importantly, repel solar wind ions and electrons. It would then be an obstacle, or barrier to the solar wind, and the deflection of this wind would provide a body force to the comet. Even should the water in the comet be stationary, the solar wind magnetic field will cause it to circulate in a fashion that opposes the field as a consequence of Lenz's law.

Therefore to estimate the magnetohydrodynamic (MHD) drag, one need only estimate the size of the cometary magnetic obstacle, and the momentum flux of the solar wind. Since Giotto observed the location of the cometopause, the boundary between solar wind ions and cometary ions, we can confidently take this to be about 10,000 km for Halley-type comets. Then given a typical solar wind density of 3/cc travelling at 400 km/s, we get an order of magnitude 1 nPa pressure. Applying that to a circular obstruction of radius 10,000 km, gives a force of 0.3 MN, a not insubstantial fraction of geyser forces.

The Giotto spacecraft detected a nearly absent magnetic field strength inside the cometopause, however, implying that the cometopause is formed by the neutral atmosphere rather than the plasma, so that momentum transfer to the cometary neutrals would not be transmitted to the comet. Given that the cometary dipole field is a very small fraction of the volume energy, how much momentum could be transferred through this high-beta, weakly ionized system? This is difficult to estimate, so the following is an order-of-magnitude guess.

First, we estimate the magnetic field needed to keep a water group ion magnetized, by calculating the gyroradius of 1000 km, or 0.1 radius of the cavity. Using the measured 300K temperature, only 0.07 nT of field would keep water ions magnetized. Therefore a field much smaller than is measurable could in fact confine the plasma.

Data from the Giotto mission show a 1-2 nT field from 10,000-5,000 km from the nucleus, with no data recorded for closest approach. Assuming a 5 km dipole radius on the comet, this gives a maximum dipole strength of $2 \times 10^{-9} = D(5000/5)^3$, or 1 T. Clearly this is too large, and demonstrates that the Giotto magnetometer really could not be made sensitive enough to detect Halley's magnetic field. Therefore we estimate an upper limit, the maximum size of Halley's dipole that could still escape detection.

But is the vacuum dipole the best approximation for the magnetic field parent body? A dipole field can induce a ring current in the surrounding plasma, which would inflate a much larger magnetic field than the parent dipole alone, much as Jupiter's vacuum magnetosphere is only 35 R_J in radius, whereas the observed magnetosphere can be up over 150 R_J. Of course, by Lenz's law, the interior field of the ring current must oppose the central magnet, and if the ring current strength grows too large, it will eject, or be repelled by the central magnet. From these considerations, one might estimate the ring current to have no more flux than the central nucleus, but spread out in a larger radius, which when viewed exterior to the ring current, would be almost a doubling of the flux. Using Jupiter and Earth as a guide, we estimate a radius of the ring current at 3 times the parent body radius. With these numbers we estimate the maximum strength of Halley's undiscovered dipole to be, $1nT \cdot (5000/20)^3 = 16mT$, which may still be too large by several orders of magnitude. Continuing this upper limit argument, such a field would drop to 0.07 nT in a distance of 1.2×10^4 km, persisting and magnetizing the plasma within the entire cometosphere volume. If we use a more believable 0.016 mT field, the magnetization of water ions would extend out to at least 1200km, perhaps as far as 4000km before the gyroradius was the size of the magnetosphere, constituting some 15% of the area, and 6% of the volume.

Finally, the momentum coupling of the neutrals with the solar wind ions would reflect those neutrals travelling upstream, directing them downtail. This would constitute a neutral wind through the magnetosphere, which could couple to the plasma, and hence to the magnetic field and finally the comet.

Is this an upper limit on the MHD force, or a lower limit? As far as solar wind deflection goes, this is an upper limit, as if the solar wind were absorbed by the cometary magnetosphere rather than merely deflected. However, the cometary magnetosphere is not empty, but filled with ions, neutrals and charged dust. These particles also exchange momentum, not with the solar wind only, but with the solar photon flux as well. Given a solar constant of 1.4kW/m^2 at Earth orbit, and dividing by the speed of light, gives 4500 nPa of light pressure compared to 1 nPa of solar wind pressure. Assuming that as little as 1% of the light is absorbed by the trapped dusty plasma, gives an estimate of 10 MN thrust that also provides drag on the magnetospheric plasma. Therefore it would be premature to dismiss all momentum transfer to the comet before more exact calculations of the drag are performed.

2.4. Magnetic Forces

Since the solar wind is blowing away from the Sun at speeds always greater than the comet, this thrust would tend to slow down the comet on its inbound leg, speed it up on the outbound leg, and do neither at perihelion. Unfortunately, this is precisely the behavior of sun-pointed geysers, so one is unable to distinguish the two types of thrust on purely orbital considerations. Although the relative velocity on the inbound leg is greater than the relative velocity outbound, this would primarily affect only the solar wind momentum transfer, the solar photon momentum flux is indifferent to the relative velocity. In fact, if the cometary magnetosphere is compressed on the inbound leg by the solar wind pressure and expanded on the outbound leg due to reduced pressure and higher water content, it may even provide a larger cross-section to photon flux, and hence experience a net acceleration out of the solar system. MHD forces, then, could provide a net loss to long period comets which are not incorporated in the present models.

Yet another way in which melting can produce magnetic fields, is based on the observation that more than 5% of a CI carbonaceous chondrite consists of magnetite grains. Since these grains are 0.1-10 microns, they are inherently magnetized. If we consider the effect of liquid lubrication on the magnetite grains, it should be clear that they will have very low coercivity while wet, but high remanence when dried in the outer crust, or refrozen, producing a cometary analogue of sedimentary remnant magnetism, which should then persist on its journey out of the solar system.

It is difficult to estimate the strength of such magnetization, depending on the degree of magnetic alignment of the dispersed magnetite grains, but we can again find an upper limit from pure alignment. If magnetite comprises 5% of the mass of a CI chondrite corresponding to the water-modified crust of a comet, and the crust has a density of 3000kg/m^3, then we have magnetization of magnetite, $M = 90Am^2/kg * 0.05 * 3000kg/m^3 = 13kA/m$. Converting to Teslas, we have $B = \mu_0 M = 1.7mT$. Likewise, a lower limit can be had from the observation that the freshly fallen Orgeuil meteorite would deflect a compass needle held nearby. Since the iron content of Orgeuil is miniscule, we attribute this to the magnetite grains, suggesting a field at least equal in magnitude to the Earth's 0.03 mT surface field.

Since the rotation of the comet in any external field (such as that produced by a ring current) would cause a torque on these magnetite grains, we would expect any permanent magnet moment to align with the spin axis of the comet as its minimum energy state. Thus there should be a coalignment of convection induced currents, ring currents and magnetite fields so as to produce an amplified magnetic moment signal.

We also note that the magnetorestrictive effect of magnetic grains trapped in a matrix (frozen water, or cemented crust) is highly temperature dependent, with magnetite showing a peak at 300K. Therefore a comet undergoing heating by the Sun can experience a thermal shock much greater than the coefficient of thermal expansion alone would predict. We speculate that comet splitting several AU from the Sun might be caused by crustal fracturing in this fashion.

2.4.1. Auroral Heating

The continual drag of plasma downtail, like the Earth, would require a return of comet dipole fieldlines from the plasmatail back to the comet. The particle acceleration and currents produced by this field line circulation at Earth drive the aurora, but at a comet, may drive currents through the cometary surface. The resistance of the surface of a comet will be critical in determining how much if any Joule heating is deposited, which may seem miniscule compared to the kW/m^2. However, if the heat is deposited a meter or so beneath the surface on the nightside, it may have larger effect than its magnitude suggests. That is, it modifies the heat budget such that a comet at large radial distances, even to the orbit of Jupiter, may remain melted and have liquid water outbursts. Therefore to the list of heat sources which include radioactive heating and solar photon input, we should also add MHD driven Joule heating.

2.5. Cometary Lifecycle

To sum up the model, then we describe a cometary lifecycle. 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 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 doesn't change it's 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.

3. REPLIES TO SOME OBJECTIONS

Several features in this scenario sketched above seem to contradict accepted wisdom and support for the dirty snowball theory. We address a few of these items.

3.1. Low Tensile Strength

Two pieces of information have been used to infer the tensile strength of comets. First is the observation of comet breakup as they orbit the sun, giving a solar tidal force estimate on tensile strength. This observation is inconclusive, since comets seem to break up at many radial distances, even where solar tidal forces are negligible. However, this calculation has been given new life by the breakup of Comet Shoemaker-Levy-9, which was observed after it had made a close encounter with Jupiter and broke into 20+ pieces. The calculation of tidal stresses at Jupiter produces a 100-300 Pa estimate for the tensile strength.[3] A second line of argument uses the apparent height in the Earth's atmosphere for breakup of "fireballs", or meteors that end in a large explosion. Inferring that many of these meteors derive from comet debris trails, a 10-1000 Pa range for tensile strength is derived. This inferred low tensile strength would obviously not agree with the water-treated crust of the wet comet model, and the need for the crust to hold the geyser forces. Nor does this low tensile strength accord with the three comet flyby observations of pinnacles, cliffs, and geysers, all incompatible with low tensile strength materials.

We can reconcile these two sets of observations by invoking liquid water. Just as the tensile strength of the Columbia shuttle was much higher than that inferred from its breakup altitude, heterogeneity of the comets is also their undoing. A comet fragment which enters the Earth's atmosphere would produce superheated plasma and fluids that work their way between the grains to cause breakup. In addition, the presence of a fluid on the meteorite, which would be very RT-unstable during air-braking, permits many instabilities at the plasma-meteorite interface that can lead to premature breakup.

Likewise, the splitting of comets could be completely unrelated to tidal forces, but rather due to the presence of liquid water and/or magnetorestrictive materials deposited by liquid water in the brittle crust. In the case of Shoemaker-Levy-9, we suggest that magnetorestrictive stresses on a Jupiter flyby when the magnetic field abruptly rotated could have fractured the crust augmented by vapor pressure, which then subsequently separated by tidal forces. Therefore we argue that comets are generally of much higher tensile strength than estimated, due to their rigid outer crust, but also subject to much higher stresses than calculated previously, due to both magnetic forces and water vapor.

3.2. Temperature Equilibria Too Cold for Water

Another objection might be that effects we attribute to liquid water occur sometimes on comets whose equilibrium temperature is far below 273K. We discuss five possibilities that could retain liquid water out to large solar distances.

First, the spin of a comet changes the RT-stability of fluids on the dayside and nightside, which have the effect of changing the equilibrium temperature of the comet from that of a black body at similar distance. Second, the heat capacity of liquid water means that the temperature as a function of radial distance from the sun will show a large latency, with outbound legs remaining much warmer than expected from instantaneous thermal equilibrium. Third, the phase change from liquid water to ice releases the heat of formation, which adds a large amount of heat to the above thermal latency of liquid water. Fourth, the freezing of water in the surface crust may reduce the heat flow out of the comet by shutting down the RT-instability in the crust, such that liquid water may be retained in the interior for a longer periods. Fifth, MHD heating may convert magnetic stresses in the solar wind into localized heating on the comet, providing a heat source with a different radial profile than solar photon flux. To first order, a pure magnetic obstruction in the solar wind will expand as the solar wind pressure drops such that a constant force is obtained, and consequently a constant potential drop or MHD current driven through the comet.

Therefore we might expect liquid water to exist on comets beyond the orbit of Mars, and out outbound legs such as the 1991 outburst of P/Halley,[18] beyond the orbit of Jupiter.

3.3. Undifferentiated Comets

Several authors have argued that comets are undifferentiated, they are uniform mixtures of ice and dust. One piece of evidence is that new comets and old comets with very different levels of activity, do not segregate by composition of the comae or gas/dust ratios. Further, the comae of split comets is indistinguishable from the original comet, suggesting that the surface of newly fractured interior fragments must be ablating similarly to old primary comet surfaces. The wet comet model, however, would suggest that the old primary comet crust should have very different ablative properties from newly formed pieces, just as wet, short-period comets should look different from dry, long-period comets.

We are not entirely convinced that the coma data support an unchanging composition for split comets. However, we would suppose that a subtantial fraction of the gas production in a split comet comes from the spilled water, which is the same material involved in the original unsplit cometary geyser. Accordingly, the few days or weeks surrounding a comet splitting event should not show a remarkable change in gas composition. Eventually, however, the crust will demonstrate different response than the interior, if in fact a split comet is presenting pristine “dry” cometary ices to ablative solar flux. Rather than seeing a composition change in the gases, the wet comet model would predict that water geysers would be replaced with gas geysers, and the primary change observed would be an increase in gas production rate, and an increase in micron-sized dust production. Since both of these effects would be masked by the the gas production of spilled liquid, and the continuing fragmentation of shed crust, the signal would be hard to separate from the catastrophe of splitting itself. Accordingly, one might be tempted to conclude that no change had occurred, other than that of the catastrophic splitting itself.

Similarly, the difference between dry, gas geysers, and wet, water geysers would not be in the composition of the gas, nor even in the dust/gas ratios, which could conceivably depend more on the details of the individual comet. Instead, the differences might be seen in overall production rate, with gas geysers showing much more mass loss per unit solar flux than water geysers. Or in dust particle size, with gas geysers having much finer dust suspended than water geysers. Or in CHON gas production, with gas geysers showing a faster radial decay than water geysers which would eject rather large particulates that outgas at larger distances from the comet. Since all of these measures we predict will depend strongly on the size of the parent nucleus, there is no way to calibrate them for comets whose parent body has not been observed. That is, long-period comets are usually observed when they already have a coma, and whereas Hubble Space Telescope observations of the stellar, trans-Jupiter nucleus are possible, they are hard to schedule in advance. Hence the nuclear size of long-period comets and their albedo are simply not known as well as that of short period comets to make the above short/long period comet comparisons. That is, determining whether comets differentiate by the wet comet process, or remain dry, ablative and undifferentiated may not be possible with the current data sets, unless we can catch a comet "in the act" of converting from one dry to wet.

4. COMET CONUNDRUMS

The wet comet theory does have explanatory power for some well-known comet paradoxes. We have mentioned already how the wet comet theory addresses the paradox of low tensile strength "snow", and the highly structured, low albedo crust observed on three comet flybys. In addition, we list some other conundrums which may be explained with the wet comet theory.

4.1. Low Albedo

The albedo prediction before the Halley flyby was 0.7-0.3 for dirty snow, so Halley's 0.03 albedo came as a great surprise. Since this is blacker than almost everything but carbon soot, it immediately generated suggestions on how carbon containing volatiles could transform into carbon black. Although the general consensus is that organics at low temperature and exposed to energetic radiation would turn black, none of these black products have the albedo of carbon black. Nor is the terrestrial process that forms carbon black by partial burning at high temperature appropriate for ablative ice comets. Nor is it apparent how ablative processes thought to remove the surface layers could reproduce the carbon black layer, which presumably required years of radiation treatment. Yet all three comet flybys have found essentially the same low albedo surfaces, with no albedos anywhere suggestive of dirty snow.

The wet comet theory puts not volatiles, but water-treated dust on the surface of the comet. The cemented material is high in CHON grains observed in CI chondrites, and when exposed to 1 kW/m^2 solar fluxes, could be converted into keragens and carbon black. Since the wet comet theory predicts that the entire surface of a short period comet has been water-processed, ablation no longer would lift off this layer, and hence the layer is relatively old and has had time to convert CHON to keragen. The relatively ice-free, low-albedo, thick crust of a wet-comet would also be expected to have much higher temperatures than a thin, dry-comet layer overlaying ice, consistent with the 400K Vega observations of P/Halley, or the SWIR observations of P/Borrelly[19] thus providing a rapid carbonization of the surface CHON materials.

By the same token, long period or pristine comets would not have such low albedos. Nor would their gas production rate be limited by the thick crust. Therefore estimates of the size of Comets West, Hale-Bopp or Kohoutek should not use the same mass loss and albedo values as P/Halley, P/Wild-2, or P/Borrelly, rather, they should use perhaps the original Whipple estimates. Since the product of albedo and area gives the stellar telescopic cross section, or the mass loss and active area give the effective radius, using the wrong albedo or active area would make it appear that long-period comets were far larger than actual. Allowing for these differences may bring both classes of comets back into the same size and mass range, permitting a single explanation of their origin, or perhaps, a younger estimate for the age of short-period comets.

4.2. Tangential Dust Velocity in Collimated Jets

When Giotto made it's night-side pass of P/Halley, one of the surprising discoveries was a great deal of dust on the wrong side of the comet. Since P/Halley, and later P/Borrelly, showed such strong jetting of dust and gas from dayside geysers, the problem arose of how to account for the tangential velocities of dust that would bring it to the nightside.

The wet-comet theory posits two types of geysers; gas geysers, which occur in non-RT regions, where the vent is at the "top"; and water geysers, which occur in RT-regions, where the vent is at the "bottom" of the effective gravity well. Clearly the P/Borrelly geyser was gas, since it occurred at the North pole of the spinning comet. Likewise, the P/Halley geysers observed by Giotto were not at the pole, and may have been water geysers. Thus the Halley jets could contain liquid water, which upon boiling, would acquire a tangential velocity for dust and flash-frozen water, that may account for the nightside dust encountered. Preliminary results from the Deep Impact mission also seem to imply a large tangential velocity for the artificially created geyser, suggesting liquid water escape.

4.3. Abnormal Aphelia

The Oort cloud origin of comets is a well entrenched part of the standard model, with various suggestions as to the disturbances that diffuse the perihelia into the inner solar system.[20] However, solving the MonteCarlo diffusive transport of cometary aphelia produces a power law dependence that is not observed, but rather a flat, or nearly gradient-free dependence is observed.[21]

Further, random orbital disturbances will favor aphelion, if only because the comets spend most of their time at these large distances, so for example, Oort's hypothesis was that passing stars would generate the gravitational perturbations needed. Now as orbital theory predicts and the MonteCarlo results indicate, perturbations at aphelion will diffuse perihelion only, they do not change aphelion appreciably. Yet a plot of aphelion versus perihelion for all comets whose orbital elements can be reliably measured, demonstrate that diffusion of aphelia occurs most rapidly for those comets whose perihelia lie in a belt between 0.5-3.5 AU.[22] This correlation cannot be understood if orbital perturbations are thought to be random.

Both these observations may be explained by the wet-comet theory. Nearly all the comets that went into the data set were those observed at Earth, meaning that they had come within 5 AU of the sun, and had developed extensive comae. Wet-comet theory would suggest that nearly all of them should have produced liquid water, which would have greatly increased the non-gravitational perturbations of the orbit. Perturbations at perihelion affect primarily aphelion, so the correlation between strong aphelion diffusion and perihelia in the "water belt" region of 0.5-3.5 AU is to be expected. This means that a major contribution to orbital diffusion is not random, but correlated to orbital position, and therefore calculations based on mainly aphelia perturbations are undoubtedly underestimates of the true diffusion rate. Thus the nearly absent radial gradient in perihelia are consistent with a much higher radial diffusion rate than predicted by random perturbation theory.

4.4. Slow Spinrates

Another feature of comets that appear anomalous is their slow spinrate. The spinrate of comets was first determined from observations of asymmetric coma,[23] later by telescopic observations of the light curve from the bare nucleus when the comet was far from the sun and did not have a coma, and finally from in situ observations of spacecraft flybys. All three of these methods are consistent in calculating a spinrates substantially less than that of small asteroids that have the same diameters. This observation comes despite the fact that the theory of jetting on non-spherical comets suggest that comets should spin up, gaining angular momentum, rather than spin down.[17] One important work which takes into account the asymmetric shape of the comets, suggest that the cometary spin rate is right on the edge of the RT-instability, if one assumes comets have mean densities of 100 kg/m^3.[24]

As we detailed above, the wet-comet theory predicts that liquid water acts as a speed governor, by first providing a substantial increase in thrust to a geyser, and then by slowing the comet by internally transferring mass to the equator. A wet comet continues to have an average density of 100 kg/m^3, not because it is a homogeneous fluffy snow matrix, but because the interior has been hollowed out, leaving a rigid crust with extensive vapor pockets.

4.5. Prolate Propensity

All the data on short-period comets support the theory that comets are prolate rather than oblate objects, more cigar-shaped than spherical or pancake shaped.[25] However, non-rigid to semi-rigid, spinning spherical objects will tend toward oblate, as is evidenced by Jupiter, the Earth and the Sun, since this reduces the angular energy while maintaining the angular momentum. That is, internal forces, such as tidal friction or plate tectonics, can lose angular energy by radiation into space, but they cannot reduce the angular momentum. Thus spinning spherical objects would be expected to evolve into oblate objects to minimize their energy. Fluffy snow is not thought to be a highly rigid material, especially not when warmed by the sun at perihelion. However, not only are all short period comets found to possess spin, they are found to be prolate, which is a higher energy state than oblate.

In the standard ablation model, the increased insolation at the subsolar point can produce a prolate shape, if the rotation axis is quasi-perpendicular. *Jewitt et al*[25] calculate a sublimation timescale ($500 < \tau < 65,000$ years) to preferentially erode a comet from spherical into the observed prolate shape. However, they assume that the rotation axis of a subliming prolate comet remains on an unstable axis for this process to work. Again, this would require a high rigidity of the cometary material, as well as an absence of geyser torques, that are hard to understand.

The wet comet theory suggests that the localization of the RT-instability to the equatorial regions provides an asymmetrical erosion to the comet far exceeding the ablation rate, that produces this prolate shape in as short at time as a single orbit. Furthermore, the theory suggests that the cometary surface is rapidly metamorphosed by liquid water into a cosmic version of portland cement, fixing this prolate shape on its first orbit, which, barring catastrophic events, will remain for the entire future of the comet.

4.6. Distance Dependence

The standard model of ablative erosion of cometary ices gives a very simple relationship between solar photon flux and mass loss rate. Since the optically thin coma has a brightness proportional to mass, the standard model also predicts a simple $1/\mathrm{r}^4$ dependence of the brightness of comets, arising from the product of mass loss ($1/\mathrm{r}^2$) and coma-scattered light ($1/\mathrm{r}^2$).[26] In contrast, both short-period and long period comets show obvious deviations from this expected power-law brightness dependence on radius,[27] usually with a steeper (softer) power law after perihelion. In addition, the standard ablative model has a low thermal latency time, suggesting that brightness should be symmetric about perihelion. In contrast, many comets show strong asymmetries with an estimated 2 day latency for Comet West 1976 VI.[6]

The wet comet theory has large thermal latencies from several sources. At the short, 2-day timescale is the thermal latency of the conductivity of the thick crust modified by the RT-instability. At the longer, several month timescale is the thermal latency heat retention due to the high heat capacitance of liquid water. And on a several-year timescale is the thermal latency of the liquid-solid refreezing of the deep interior of the comet. All of these come to play in the deviation from $1/\mathrm{r}^4$ law.

A long-period comet, such as Comet West, would be expected to behave classically (1/r4) until it transitioned to a wet comet. If we take the splitting just before perihelion on Feb 21, 1976 as the transition from dry to wet, then Comet West should behave differently outbound. After taking into account the brightness increase after splitting, we see this effect in the steeper (softer) power law for the outbound leg. We also infer that this may explain the steeper than $1/\mathrm{r}^4$ brightness curves for outbound legs of Comets Bennett, Bradfield 1980, Bradfield 1974, and Kobayashi-Berger-Milon. Note that both West and KBM had steeper than $1/\mathrm{r}^4$ dependence after splitting, suggesting that the dry-to-wet transition may be correlated to this event.

As we argued earlier, wet comets should outgas less for a given heat input, since more of the heat is redirected into the melting of water. Since this heat-redirection is controlled by the RT-instability, which is itself driven by the product of thermal and gravitational gradients, one would expect that the suppression of gas output weakens with radial distance, producing a gentler (harder) radial dependence law, or opposite to what is observed. However, if we argue that the heat input to a comet is primarily controlled, not by the RT-instability, but by the heat conductance through the crust, then the wet comet has an increasingly thick crust on its outbound leg. Since the dust deposition in the crust is a function of the melting, and hence a function of heat input, then the total heat into the comet as a function of radius would be a product of photon flux ($1/\mathrm{r}^2$), and the relative crustal deposition rate ($1/\mathrm{r}^n$), producing the observed steeper (softer) radial brightness dependence. Note also that wet comets that have thinner crusts, such as recently transitioned long-period comets (West 1976, Bradfield 1974), will have a much larger relative crustal thickening giving steeper radial dependence than older comets (P/Encke) with already thick crusts.

4.7. Active Area

One of the puzzles in the pre-spacecraft era was the relationship between mass loss and nucleus size. Estimates of heat input into the nucleus gave much higher mass loss rates than observed. One solution was to use a very high albedo, to reflect most of the incident radiation. Instead, spacecraft revealed an extremely low albedo object, but one which was dominated by jets, rather than uniform ablation. Why the uniform heat input should result in jets is not easily explained, nor why the assumption of non-uniform emission[9] should give excellent agreement with observations.

The wet comet theory suggests that the positive feedback of water treated crust should inevitably result in spatially non-uniform gas emission. That is, uniform ablative gas production should be unstable in regions of RT-unstable surface, converting rapidly to water geysers or trapped ponds. Although the model is not sufficiently detailed to predict the spatial inhomogeneity, we estimate that once water ponds form, lateral diffusion through porous crust will rapidly convert all available RT-unstable surface into water-treated crust, which provide a self-healing surface dotted with water-geysers. Rotation of spin axes complete the transformation of ablative crust to water-treated crust. At this point, the lateral heat and material transfer is greater than the radial heat transfer, erasing lateral thermal gradients, and increasing the scale size of the emissions. Then the gas emission rate will be controlled, not by the abundance of vents, but by the new heat balance maintained by conduction through the thickening crust. That is, as the temperature rises in the subsurface ponds on the inbound leg, new vents become active to release the excess interior vapor pressure. Likewise, as the heat input reduces on the outbound leg, vents seal over so as to maintain a relatively constant interior vapor pressure. Therefore the active area of a comet is determined not locally, but globally, as a consequence of a thick crust and an efficient means of lateral heat transfer.

4.8. Short vs Long Period

Over the past century, there have been many comparisons between the observations of long-period and short-period comets. Long period comets are thought to be brighter, dustier, and larger, with weaker tensile strength and a softer powerlaw radial dependence than the short-period comets. With the advent of spacecraft rendezvous, we may add higher albedo to the list of possible differences. These differences have led some to argue for a different possible origin for short period and long period comets, with perhaps a Kuiper-belt origin for short period, and an Oort-cloud origin for long period. Others would argue that a single origin in the Oort cloud is sufficient to explain all comets. Nevertheless, no theory predicts the systematic differences observed between the two sets of comets.

Wet comet theory agrees that there is likely a single origin of comets in the Oort cloud, but that inner solar system passes transform these pristine, dry comets into dark, wet comets. The theory correctly predicts that wet comets should be somewhat smaller, more prolate (having lost equatorial material), darker albedo (due to higher temperature on a thick crust), lower outgassing (thicker, stronger crust), having steeper powerlaw radial brightness dependence (thickening crust) with a higher tensile strength (thicker, cemented crust) than long-period dry comets. Further, the theory suggests that ablation lifts a smaller particulate dust than water-geysers, making dry comets appear to have more continuum light scattering for a given gas production rate than wet comets, hence appearing “dustier”.

At the moment, the theory cannot predict how many long-period comets may have transitioned to a wet comet crust on a previous orbit, though[28] suggests the appropriate cutoff might be aphelia $<$ 10,000 AU, or much further than the $\sim$20 AU division between short/long period comets. In general, however, the separation of the two types of comets should be distinct and separable, agreeing with the observations.

4.9. Outburst Occurrences

One of the great puzzles of comet observations, are the sudden flares in almost dormant comets, which can often increase the brightness by several magnitudes over a brief period. P/Schwassmann-Wachmann at $R > 5$ AU has had 100 flares in 50 years, one being an increase of 8 magnitudes. Long period comets have also been observed to flare, on both inbound and outbound legs.[29]

The outburst is probably not due to collisions, since both collisions are rarer than the occurrence frequency, and the comet appears to survive the flare without undue fragmentation. Nor can it be linked statistically to solar flares or enhanced radiation environment. Phase transitions of amorphous ice have been suggested, but they are hard to fit to short-period comets.

[18] has suggested liquid water outbursts, which have all the correct properties for such a flare. The water would rapidly boil to produce the sudden appearance of comae, and would just as rapidly diffuse away, leading to the rapid decay of the flare. Several mechanisms were proposed for the ejection of water, to which we add the draining of a water pond through a crack in the crust, perhaps with a vapor pocket above the pond providing the necessary pressure. Although the outbound leg of a cometary orbit could explain the existence of liquid water out to 5 AU, the nearly circular orbit of P/Schwassman-Wachmann I suggests other energy sources may be involved.

4.10. Extinct Asteroids

With the influx of comets from the Oort cloud, and the orbital capture by Jupiter into short period comets, estimated to be greater than 50%,[22] one might expect many "extinct comets" to exist on Earth-crossing orbits. And despite their low albedo, $A < 0.03$, programs such as NEAR and LINEAR are capable of detecting the several kilometer sizes of extinct comets. With a discovery rate of short period comets a little under 1/year[21] and the dynamic 400,000 year lifetime for comets to get ejected by Jupiter, there should be on the order of 10^5 extinct comets, unless some other dissipation process is occurring.

The wet comet theory suggests that once the comet has been spun up to the critical period, and all its water exhausted, it becomes a spinning egg shell, under nearly continuous tension. Much like pre-stressed concrete or safety glass, it would demonstrate a catastrophic failure mode. Should it have a collision, or a large fault failure, the shell would be expected to crack and disintegrate as the rotation axes move and the stress redistributes. Thus cometary cores would be expected to convert to rubble streams on a timescale much faster than loss due to orbital dynamics alone would suggest, leading to their apparent absence in the observational data.

4.11. Carbonaceous Chondrites

Having started with the assumption that CI chondrites were extinct comet cores, we now check to see if the wet comet theory still is in agreement with this assumption. The pieces of an extinct comet should be rubble with a thickness no more than the total dust thickness in a 5-10 km radius comet. With a 100 kg/m^3 density, and 50% volatiles, we estimate this maximum thickness as less than 500m. Certainly this upper limit is consistent with the smaller sizes of rubble observed in comet trails.

Likewise, this crustal material should show cementation by water soluble salts, homogeneous (non-sedimentary) macro-structure due to active convection, and extensive water-processing. It should also show temperature limited heat treatment (unlike lunar soils) due to the thermal regulation of water. If liquid water should percolate through the crust, one would also expect an absence of particles below a certain radius due to leaching. Finally, the presence of liquid water for months to years, permits the growth of life on a comet. Thus we would also expect microfossils. And indeed, whenever a researcher looks for microfossils on a carbonaceous chondrite, microfossils are found.

Having argued that Earth crossing comets can become liquid water incubators, we have not stated how life came to be in the comet in the first place. It is commonly thought that meteoritic events, such as the Yucatan peninsula event, are capable of propelling large amounts of water into space. The water would be expected to form a dust lane along the Earth orbit that may contain algae or bacterial spores, which would infect comets.

Therefore the possible infection of Mars or Europa by Earth microorganisms can no longer be considered speculative, but a real possibility. Carbonaceous chondrites have been recovered immediately after a meteor shower with frost covering them, showing that the interior of the comet is not sterilized upon entry of the atmosphere. Such a process could easily put viable organisms onto Martian ice caps. Considering the number of such chondrites hitting the Earth in the past century, it is almost certain that Mars has had many such events in the past 100 million years. Therefore it seems likely that Mars will be found to have not just similar, but identical species as are found here.

5. COMET RENDEZVOUS PREDICTIONS

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.

5.1. Stardust

The Stardust mission collected dust from Comet P/Wild-2 in silica colloid gels, designed to trap the grains without vaporizing them. Since Wild-2 is obviously a short period comet, we predict it will show the wet comet transformation we described above. Unlike P/Borelly, which had its main gas geyser at the pole, P/Wild-2 has a good chance for producing water geysers. If the grains make it back to the laboratory intact, 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 silicious 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.

5.2. Deep Impact

The mission to send an 370 kg impactor into a P/Temple-1 at hyperkinetic velocity of 10 km/s is expected to excavate a crater some 20 meters deep from the icy matrix below the roughly meter-thick crust. In addition to inferring composition of the comet from the size and shape of the crater, the mission hopes to observe the ejecta spectroscopically and determine the composition.

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/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. Ground-based telescopes will be disappointed by the show. 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 the geyser will probably take some time to form, and therefore will not be visible for the 13 minutes of spacecraft observation.

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. The resulting overpressure may remove all the thin crust above the geyser, lifting a cloud of debris away from the comet. Depending on the size of the vapor chamber and the thickness of its crust lid, the acceleration of crust may not reach escape velocity, and may even be difficult to observe in the 13 minute observation window.

Preliminary pictures from the mission indicate that the brighter than expected flash upon impact was consistent with higher temperatures and densities as the impacter encountered the crust. Looking backwards some 30 minutes after impact showed a plume with marked lateral expansion, consistent with a liquid water ejection and subsequent vaporization.

5.3. Rosetta

The Rosetta mission to rendezvous and land on a comet P/Churyumov-Gerasimenko. The mission will establish the density of the comet, based on the gravitational acceleration required to orbit the spacecraft. It will then land and attempt to anchor itself to the comet, so that a drill can be used to take subsurface samples.

Our prediction is that the comet will indeed be found to have a $\sim$100 kg/m^3 average density, but that the surface will be found to be far more dense than expected. The anchors and 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 silicious crust. Seismic profiles will be quite exceptional, due to a much more rigid crust 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.

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