Will Deep Impact Make a Splash?

Robert B. Sheldon and Richard B. Hoover

Abstract

Recent cometary observations from spacecraft flybys support the hypothesis that short-period comets have been substantially modified by the presence of liquid water. Such a model can resolve many outstanding questions of cometary dynamics, as well as the differences between the flyby observations and the dirty snowball paradigm. It predicts that the Deep Impact mission, slated for a July 4, 2005 collision with Comet Tempel-1, will encounter a layered, heterogenous nucleus with subsurface liquid water capped by dense crust. Collision ejecta will include not only vaporized material, but liquid water and large pieces of crust. Since the water will immediately boil, the water vapor signature of Deep Impact may be one to two orders of magnitude larger than that expected from collisional vaporization alone.

I. Introduction

The standard “dirty snowball” model for the structure of cometary nuclei was first proposed by Whipple [1951] as a cohesive replacement for the “sand bank” model composed of loose, gravitationally bound icy grains. Since most comets, both historical and recent, are observed when the orbit of a comet brings the nucleus sufficiently close to the Sun to outgass and form a coma, the question naturally arises why comets should not completely melt or vaporize upon passage through the inner solar system, where blackbody equilibrium temperatures are above the melting point of water ice.

Several suggestions have been advanced for thermal modifications that would keep a comet cool based mainly on telescopic observations: a high albedo, an insulating dusty blankets, an outgassing sublimation wind, and a Rayleigh-Taylor driven “refrigeration” cycle. Subsequent satellite flybys have revealed that none of these mechanisms operate as expected, and indeed, the surfaces of comets are often far above the melting point of water ice. That is, the albedo was found to be as black as soot, the surface topography failed to find evidence for an insulating dust layer, little or no sublimation wind was observed from the cometary surface, and spin-rates too high for refrigeration were inferred.

Surprisingly, large and stable steam vents or geysers, were observed at every satellite flyby, leading to models of heat flow more similar to geysers than sublimation cooling (Yelle, 2004). Such geysers can operate in parameter regimes (small vent orifice, large heat input), where the internal pressure of the geyser permits liquid water or condensation to occur. We suggest that should this liquifaction event occur, irreversible changes to the structural materials of the geyser would also occur, including water-modified dust and cementation of the crust (Sheldon 2005). All these changes make the geyser more efficient—increasing the thermal input flux, strengthening the geyser vent, raising the pressure further—leading to a positive feedback runaway modification of the entire cometary surface.

In section two we discuss the feedback mechanism that we predict will differentiate short period comets to make them “wet”. In section three we predict the outcome of Deep Impact. In section four we discuss some anticipated objections to the hypothesis, before concluding in section five.

II. Thermal feedback mechanisms.

Albedo

To keep a comet frozen inside the orbit of Mars, would require a way to reduce the equilibrium temperature below that of a black body. The first, and most important approach used by the famous Skylab blanket and most manned missions is to increase the reflectivity by increasing the albedo. Additional effort is expended for space solar telescopes, such as SOHO or TRACE, which must stare at Sun, whereby radiation in the infrared is enhanced to shed heat, while absorption in the visible is minimized to reflect energy. Unfortunately for theorists, exactly the opposite was observed for cometary surfaces in the three satellite flybys.

Cometary surface albedo was measured to be about 0.03, or as black as carbon soot. Carbon, and carbon compounds, absorb energy very readily in both the visible and the UV, while providing little in the way of enhanced IR radiation (few rotational IR lines). Not only does carbonized surface heat up, but the elevated temperatures accelerate keratogenosis, or the conversion of simpler carbon compounds to black carbonaceous tar. Therefore once a highly reflective patch of high albedo comet begins to darken, it would be expected to accelerate its conversion to low albedo carbon black, providing a positive feedback instability.

Dust insulation

A second suggestion often made, is that as the ices sublimate away, the crust of a comet will be covered in a fluffy dust agglomerate that has excellent insulating properties. Such dust would have properties perhaps similar to lunar regolith, and would be expected to “soften” surface topography, perhaps even forming a levitated dusty plasma layer similyar to the moon. In contrast, satellite photos do not show this feature-blurring effect of a thick dust layer, and photographed surfaces are thought to be more consistent with a “burnt toast” or tarry consistency. The surface topography of pinnacles and cliffs is also inconsistent with an undisturbed dust blanket, or its hypothesized underlying dirty snow. Finally, the presence of jets on all comets observed by satellite indicate that substantial heat is making through the surface crust, and apparently in a rather inhomogeneous way. And the greater the inhomogeneities of surface topography and outgassing strength, the less likely that an insulating blanket will be formed, and the more likely it will be eroded away.

Sublimation wind

A third suggestion, inherent in the Whipple model, is that the radiant heat input to the comet is convectively cooled by a sublimation wind directed radially outward from the nucleus. The Halley flyby, as well as subsequent flybys, showed that the expansion of the steam jets was not consistent with a background sublimation wind. The jets also carried the majority of the cometary mass loss of the telescopically observed total mass loss from the comet. This suggests that just as the jets carry more mass, they also carry more heat. Accordingly, the ices near a jet and which feed it, must also be at substantially higher temperatures than Whipple envisioned. And the higher the temperature, the greater the pressure and the heat conduction inward, hence the necessity of a higher wind speed to remove the heat. The Whipple solution of a gentle sublimation breeze, therefore, seems to become unstable in the presence of high heat loading, evolving toward jets and geyser fields at substantially higher temperatures and pressures.

Spin and heat pumping

Although all of the above observations are empirical evidence of positive feedback in thermal modelling of a comet, the spin rate is direct theoretical evidence of positive feedback. At very low spin rates, the comet gravitational vector is toward the center of the comet, whereas the heat is applied to the surface. Since hot gas is more buoyant, the dayside remains stable against Rayleigh-Taylor (RT) convection. On the other hand, as the heated surface rotates into night, it radiatively cools faster than the conductive heat transport below the surface, and becomes RT-unstable. Cool gas will sink into the comet, and heated gas will rise. The onset of this “refrigeration” cycle is a rotation period shorter than the time for heat to conduct to the surface due to the strength of the radial thermal gradients near the terminator of the comet. Faster rotation leads to stronger radial gradients, and stronger RT-convective cooling.

At the equator, however, faster rotation also leads to a gravity-counteracting centrifugal acceleration that reduces the strength of the RT-interaction. When the comet is rotating fast enough to lift a pebble off the equator, then the effective gravity vector reverses, stabilizing the night side thermal gradients, and destabilizing the dayside. At this critical spin rate, the RT refrigerator runs backward and heat is now pumped into the interior of the comet, at least, in an equatorial belt.

This critical rotation rate depends upon at least two empirical factors: the density of the comet, and the structure of the comet. That is, centrifugal acceleration depends only on the distance from the rotation axis and the angular velocity^2, whereas the gravitational force is an integral of density * volume element / distance^2. For some cylindrically symmetric shapes, the volume element has the same units as the distance, and both centrifugal and gravitational accelerations are proportional to radius, so that one can define the critical period in terms of the density and an ellipsoidal "shape" factor.

Spacecraft flybys, however, have been unable to determine the gravitational attraction of the comet, and therefore unable to pinpoint its average density. Accordingly, estimates of the critical rotation rate are uncertain, with densities inferred indirectly from non-Keplerian orbits or tensile strength estimates, but span a range which includes the observed spin rates. In addition, if our hypothesis be correct and a comet differentiate into a dense shell around a vapor pocket and icy core, the resulting inhomogeneous structure may have an RT-unstable interior with an RT-stable exterior.

Since cometary jets can impart angular momentum to a comet, it is thought that on average a comet should spin up due to jet development. Therefore the first three instabilities that increase the heat load into a comet will also increase the angular momentum. So as a comet approaches the sun on its first journey within the orbit of Mars, we expect jets to first decrease the heat load by increasing refrigeration before abruptly increasing the heat load as it becomes a heat pump. This abrupt heat transition on the inbound leg, coupled to an increasing solar heat flux, we predict will cause an irreversible phase change of the comet from a long-period dirty snowball, to a short-period low albedo "wet" comet.

III. Wet Comet Phase Transition

We have submitted a paper on the dynamics of this phase transition (Sheldon et al. 2005) which we summarize briefly. The sudden jump in heat loading into the comet by the RT-instability may create stronger and stronger steam jets, which at sufficient size and pressure, will condense the steam into liquid. When this event occurs, water will modify the crustal materials by dissolving minerals and evaporating them at the surface so as to increase the tensile strength of the crust. It also increases the heat conduction of the crust, and hence the heat flow into the geyser cavity. Deposition of dust or mud at the geyser vent can also restrict the exhaust, leading to higher pressures and further condensation. Since each condensation event drives the geyser irreversibly in the same direction, this positive feedback will ultimately produce either rupture or "sealing" of the geyser, when it would become an enclosed pond. The pond is expected to spread through surface tension of water permeated dry crust, as well as by increased melting of internal ice and increased heat load of water-saturated crust. As a consequence, the entire equatorial region of the comet should rapidly become water-modified to a high tensile strength, high thermal conductivity, high density crust that no longer sublimates.

Since the radius of the comet is fixed, but geysers and heat input continue, subsequent evolution of the comet evacuates the subsurface region forming vapor pockets and possibly enclosed ponds. The amount of water expected at any time in these ponds has an upper limit based on the thermal heat flux needed to melt the icy core less the water expelled by a geyser. This is slightly greater than the estimated 2mm/hr erosion of dirty snow, since only the heat required to melt ice is necessary, not the heat required to vaporize ice. Based on the estimate for heat flux into a low albedo comet at Earth orbit, we expect perhaps 10 meters of snow to melt during a pass through the inner solar system, resulting in a water layer no more than a meter deep.

Therefore, when Deep Impact encounters Tempel-1, we expect it to penetrate through a meter of crustal material , transiting a large vapor chamber of tens of meters thick, and finally terminating in an snowy core, where its kinetic energy will vaporize ice. The resulting steam will not emerge in a jet from the crater as expected, but will pressurize the entire vapor chamber, resulting in the relatively slow motion lift-off of the approximately meter-thick crust over a substantial portion of the equatorial belt of the comet. Depending on the cometary latitude of the impact, the Cu bolide may intersect the shallow lake formed near the equator which would send shock waves ahead of the overpressure wave. In that case, a much larger crater would form in the crust, and perhaps less crust would be lifted off by the following vapor overpressure. In either case, liquid water would boil suddenly throughout the entire lake volume while simultaneously freezing. This would produce a very large plume of vapor and ice emerging from the crater. Since a 16 km/s impact of a 500 kg Cu bolide can boil approximately 28 tons of water, whereas a 50 cm deep lake that is 10 meters wide and 100 meters long will contain 500 tons of water, the presence of liquid water on the comet will amplify by a factor of 10 or 100 the expected water signature of the impact. And unlike a bolide vaporization, the spontaneous boiling caused by sudden pressure release will generate many particles of ice that will sublimate over a period of days, creating a cloud of light-scattering particles and significant visual brightening for several days.

IV. Anticipated Objections

One objection to such a heterogenous model for comets might come from the spontaneous splitting of comets, including the famous Shoemaker-Levy-9 comet that disintegrated as it passed Jupiter. Both methods calculate a tensile strength much too small to support the pressure needed to contain liquid water on a comet. However these calculations make two assumptions: that the tidal force is the major disrupting force that fractures a comet, and that the stresses are distributed isotropically throughout the comet. If, as we argue above, the comet is resurfaced unevenly by a high tensile strength material, it may locally confine water, but globally rupture due to tidal stresses. It is also possible that other stresses besides tidal forces can rupture the surface leading to subsequent disintegration of the comet. As we discuss in Sheldon et al (2005), magnetorestriction is a strong candidate for Jupiter’s magnetic disruption of Shoemaker-Levy-9. In any case, heterogeneity of a comet can result in globally weak tensile strength, but locally strong crust over geyser fields sufficient for confining liquid water.

Another objection is that comets which split have very similar gaseous emissions before splitting as after. This would suggest that whatever is coming off the differentiated cometary surface before splitting is very similar to the undifferentiated interior of a split comet. As we argue above, this result is not too surprising if the geysers that are active before the split, are also spilling their contents after the split, and therefore no dramatic compositional changes are expected during the time around the split.

A third objection might be the high altitude disintegration of meteors that arise from cometary dust trails, suggesting a low tensile strength material. But as was seen from the recent Space Shuttle accident, heterogenous material with gaps and fluids may disintegrate at much higher altitudes than more homogeneous materials. Likewise, the fluffy Brownlee particles recovered from the stratosphere may be not constituitive of comets, but produced in the water geysers from rapid boiling.

V. Conclusion

The presence of liquid water on short period comets due to positive feedback in the thermal budget will have a many important observable effects. We describe a potential scenario for Deep Impact, whereby water will greatly amplify the expected vapor signature of the collision. In addition, water will acts as a nutation damper, preventing comets from precessing or nutating as they rotate, and stabilizing the spin axis along the largest moment of inertia despite the perturbation of geyser forces. This naturally explains why most comets appear to be prolate and tumbling, since water enhances the equatorial erosion of a spherical comet into a prolate comet, and then promotes the swap of rotation axes into a tumbling motion. Water will amplify the thrust of equatorial geysers, providing much higher momentum transfer to the comet and accounting for non-gravitational forces. Water will provide larger particulates and ice grains to the coma, resulting in an extended source for molecular and atomic species. Water will provide a large thermal latency, making the cometary emissions asymmetric about closest approach. Water provides for spectacular splitting of comets, and the formation of meteoritic “fireballs”. Water provides for the circulation of dissolved ions, such as observed at Europa, introducing magnetic interactions along with thermal. Once a magnetic field is established, charged dust grains are electromagnetically attached to the nucleus, which changes the properties of the extended comae, and can potentially transmit momentum from the comae to the nucleus. But most importantly, the existence of water permits the presence of life, which if somehow transferred to a comet, would convert it to an interplanetary incubator.

REFERENCE

D. T. Britt, “The morphology and surface processes of Comet 19P/Borrelly” Icarus 167, 45-53 (2004).

B.J. Buratti et al. “Deep Space 1 photometry of the nucleus of Comet 19P/Borrelly”, Icarus 167, 16-29, (2004).

J. M. Greenberg, H. Mizutani and T. Yamamoto, “A new derivation of the tensile strength of cometary nuclei: application to comet Shoemaker-Levy 9”, Astron. Astrophys. 295, L35-38 (1995).

W. F. Huebner, ed. Physics and Chemistry of Comets, Springer Verlag, New York, 1990.

W.-H. Ip “Tidal Breakup of Comets”, in Celestial Mechanics and Dynamical Astronomy 2298-IA: 1-6 (2003).

D. C. Jewitt and K.J. Meech “Optical properties of cometary nuclei and a preliminary comparison with asteroids” Ap. J. 328, 974-986 (1988).

D. Jewitt, S. Sheppard and Y. Fernandez “143P/Kowal-Mrkos and the shapes of cometary nuclei”, Ap. J. 125, 3366-3377 (2003).

A.I. Neishtadt, D. J. Scheeres, V.V. Sidorenko and A. A. Vasiliev “Evolution of Comet Nucleus Rotation”, Icarus 157, 205-218 (2002).

J. Oberst et al. “The nucleus of Comet Borrelly: a study of morphology and surface brightness” Icarus 167, 70-79 (2004).

R. B. Sheldon, R. B. Hoover, M. Wallis, “A Wet Comet Theory”, submitted to SPIE proceedings, 2005.

L.A. Soderblom et al. “Imaging Borrelly”, Icarus, 167, 4-15, (2004).

L.A. Soderblom et al. “Short-wavelength infrared (1.3-2.6um) observations of the nucleus of Comet 19P/ Borrelly” Icarus 167, 100-112 (2004).

F. L. Whipple “A comet model II. “Physical relations for comets and meteors” Astrophys. J 113, 464-474 (1951).

L. L. Wilkening, ed. Comets, Univ. of Arizona Press, Tucson, 1982.

R. V. Yelle, L. A. Soderblom, and J. R. Jokipii, “Formation of jets in Comet 19/P Borrelly by subsurface geysers” Icarus, 167, 30-36 (2004).