Comets: Cosmic Wanderers

By: Walter Harris

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Comets and Physics

Comets are in many ways the quintessential scientific object in that they combine all the important elements that make science what it is. They are a combination of fundamental physics, applied understanding, universal building blocks, and social barometers.

Science is a human activity, and few physical objects embody the duality of the rational and irrational sides of humanity quite like comets do.

Today we are going to talk about comets from many perspectives including:

* History and Sociology.
* Basic Structure.
* Where they come from and what they are.
* What they tell us about the solar system and where we come from.
* How comets have and continue to shape the Earth and Solar System.

More Important Than You Think!

* Comets have played a critical role in our understanding of how the Sun and planets are organized.

* Comets give us with a view into the distant history of our solar system.

* Comets are the foundation upon which the planets were formed.

* Comets provide an astrophysical laboratory for the study of gasses, photo-chemistry, plasma physics, and the Sun.

* Comets have played a significant role (or not) in the development of life on Earth, including (possibly) being the source of terrestrial volatiles, the organic molecular basis of life, and (once and future) a major factor in global extinction. Humans and mammals owe their dominance on the world stage to a comet most likely, and life as whole owe Jupiter for keeping comets from wiping us all out.

* Comets have played a role in the evolution of mankind as well, both in directing our actions and in driving the development of our understanding of the solar system and the Earth's position in it.

Comets and Sociology

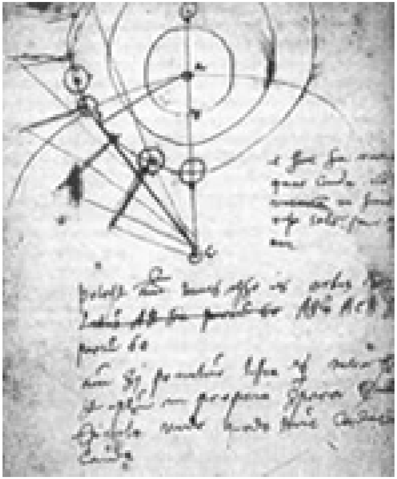
Comets have played a significant role in human history. This is perhaps because, in all of astronomy there are few phenomena that have inspired the kind of emotion and outright terror that comets have. They do, after all, have all the trappings of a divine message or an apocalyptic precursor; just the sort of sudden sign that the gods would send us just before (or during, or after) sending a big flood, destroying a harvest, or bringing a victory in battle.

Even the *historical description of a comet's arrival*, an '*apparition*', suggests something paranormal.

History *seems* to bear this (mistaken) idea out. Comets *do* always seem to appear at or near some significant historical event. The flaw in this reasoning is actually that there is *almost always something, somewhere that has just happened, is about to happen, or is going on!* Comets have been ascribed to everything from the *eruption of Mt. Vesuvius* to being a sign that Napoleon should invade Russia. A comet was prominent in the skies over London as the black plague was ravaging the city.

Our modern discoveries about the true nature of these objects haven't done much to quell the hysteria; we just find new ways to make fools of ourselves whenever they appear. During the *1910 comet Halley apparition*, snake oil salesmen used a report that the Earth would pass through the comet's tail to sell "comet pills" and gas masks to hysterical consumers. (Scientists had just discovered HCN (Cyanide Gas) in comets). Less amusing were the "*Trailing UFO*" rumors about comet Hale-Bopp that culminated in the Heaven's Gate cult's mass suicide in 1997.

A Move to a Modern View



Prior to the time of the great astronomer Tycho Brahe (in the mid 1500's), comets were believed (by Europeans) to be phenomena of the Earth's atmosphere. This fit with the religious dogma of the unchanging heavens. The first schism with this idea was brought about by Tycho, who observed that the bright comet in 1577 did not have a parallax, and therefore had to be very distant.

What Tycho didn't realize, and wouldn't have believed if told, was exactly how distant they actually were. The scale of comets and the solar system dwarfs anything that humans had considered to that time.

The first person to determine that they were small worlds orbiting the Sun was the astronomer Edmund Halley, who noticed that a prominent comet he saw in 1682 always seemed to appear on queue every 76 years. He speculated that this was actually the same object returning over and over again, and predicted that we would see it again in 1758. He had died by then, but Halley's comet did arrive on queue! The nature of these objects had been revealed.

Why Study Comets?

1) Comets are time machines:

Why? Because they are OLD, and have not changed in billions of years. When we have looked at the various planets and satellites in our solar system, we have always been observing the modified end state of these bodies.

2) Comets are experiments in basic physical processes:

The conditions that are found in the evaporated outflow of a comet are unique. They permit us to examine how the 'atmosphere' of escaping gas and dust evolves, including, when different gasses become prominent, photo-chemistry, plasma processes, and the scattering of sunlight. The dust grains blown off of comets as they evaporate are interesting because they are thought to be similar to material in vast clouds between stars (the Interstellar Medium).

3) Comets tell us about the Sun.

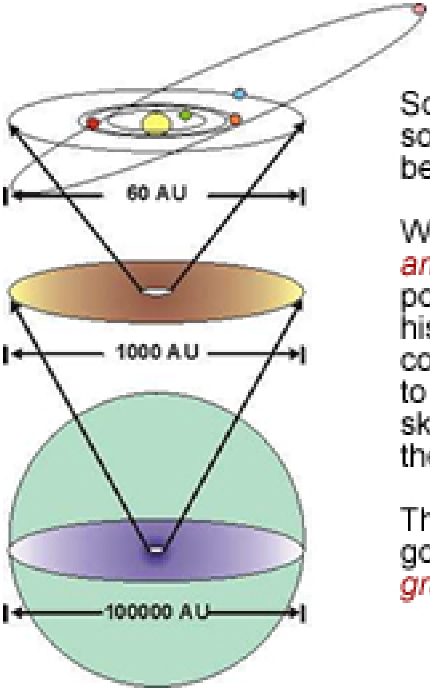
What we think of as a comet (the tail and head, etc.), is really all about the Sun. The Sun is what warms the surface and melts it. It is the Sun that breaks apart the molecules (e.g. H2O, CO, CO2, HCN, CS, etc.) that are evaporated from the surface. The Sun also io

But What are They Really?

Comets are in a class of what we call *cosmological objects*, building blocks for the manufacture of planets. They are the outer solar system analog to the asteroids, the planetesimal remnants of solar system formation. They form like snowballs, by grabbing material in the early *solar nebula* (what we call the cloud out of which the Solar System formed), slowly growing until they are accreted onto a larger body or planet. The leftovers of this process are what we see today. Occasionally one of these objects *finds itself in the inner solar system*, as close to, or closer than the Earth. As one can guess, this is an unhealthy place for an icy body, and *the comet begins to melt rapidly*.

Comets formed in the volatile *rich outer reaches of the solar system*, along with the giant planets. Their icy compostion has earned them the layman description '*Dirty Snowballs*'. Because there were always more ices and volatiles than rocks, there are probably *several hundred times more comets* than rocky asteroids!

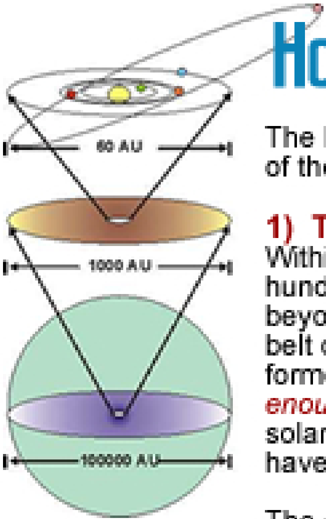
How do They Get Here?



So how to comets come to be present in the inner solar system in the first place? They are here because of the *law of averages*.

We discover new comets on a *more or less annual basis*. Extending that back through the post bombardment phase of the solar system's history, this tells you that *millions, if not billions*, of comets have already made the life ending journey to the Sun. And for every one that appears in our skies, *one or more have been lost to escape* from the solar system.

The mechanism driving this is the same one that got the comets where they are in the first place, *gravitational perturbation*.



How do They Get Here?

The location of comets in the modern solar system tells the tale of their history. There are *two primary reservoirs of comets.*

1) The Kuiper Belt: The Kuiper Belt is a new discovery. Within the last decade we have found that there are literally hundreds of thousands of icy objects in the Solar System just beyond the orbit of Pluto (at 40 AU). We believe that the Kuiper belt developed following the same slow accretion process that formed the planets as part of the solar nebula (but *without enough mass or time to produce a planet)*. With no large outer solar system bodies to deflect them, a significant fraction of them have survived to present day.

The size distribution of the Kuiper Belt objects ranges from 1-10 km objects up to possibly Pluto! Since the formation of the Solar System, objects in this region have changed little, and their composition is *representative of the region in the solar nebula beyond Pluto*. The distance range of the Kuiper Belt probably *extends out to about 500 AU from the Sun.*

Comets that come from the Kuiper Belt tend to be confined more easily to the inner solar system and are called "Short Period". These objects come back again and again.

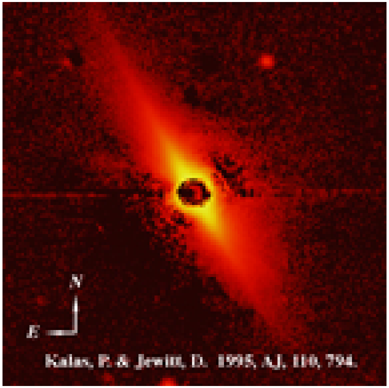
How do They Get Here?

2) The Oort Cloud: The Oort cloud (first proposed by Jan Oort in 1950) is the result of the *final phase of planet formation.* At the time the Sun began its life as a star, the outer solar system was still teeming with *planetesimals and protoplanets*. These objects could have only one of three fates:

* **Accretion onto the Jovian planets,**
* **Deflection into the inner solar system** to hit either the Sun or a proto-terrestrial planet (perhaps supplying it with water!)
* **Deflection beyond the solar system.**

The Oort Cloud is comprised of this *third group*, planetesimals from the Jovian planet forming regions *flung out into the void*, but not quite strongly enough for them to have been lost entirely. The scale of the Oort cloud is tremendous. At least *several billion, and possibly as many as a trillion* icy objects may exist out there in a roughly spherical distribution about *100,000 AU (1.6 Light Years!)* across.

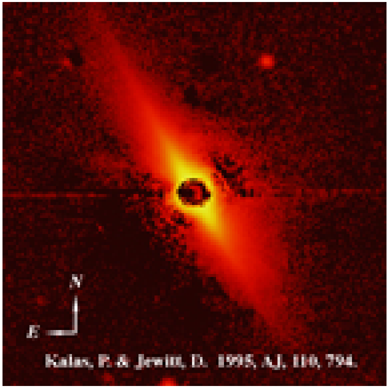
Surprisingly, this division of material means that *a comet in the Oort cloud actually formed closer to the Sun than a comet in the Kuiper belt.*



How do They Get Here?

Comets from the Oort cloud often have huge orbits that carry them beyond the edge of even the Kuiper Belt and have periods of 10's of thousands of years or more. We call Oort cloud comets "Long Period", and will typically only see them one time.

Kuiper Belt and Oort Cloud comets formed under very different conditions and *should be different both structurally and compositionally*. To date, however we have been unable to identify conclusively what those differences are. It's a major goal of cometary science.



Comets Revealed: So what makes a comet?

What we see when we look at a comet is the expansive cloud of gas, ions and dust around it, the comet itself is typically very small.

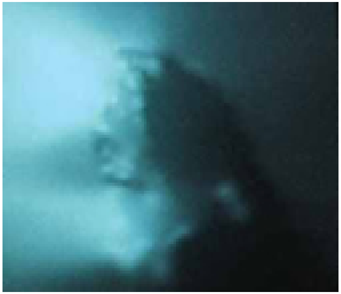
The largest modern comet was Hale-Bopp, which was between 20-40 km across.

Hale-Bopp, by itself, would not have been visible to the unaided eye, let alone observable over the skies of New York city!

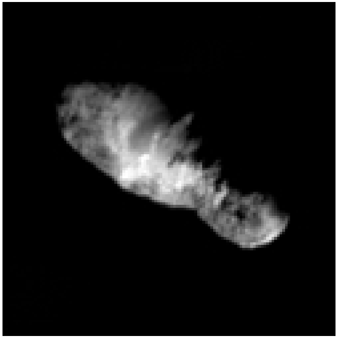
Comets Revealed: So what makes a comet?

We refer to the actual body of the comet as *the nucleus*. Most of what we know about comet nuclei comes from examining the material that comes off of it. *In only two cases have we actually observed the nucleus of a comet,* and that was P/Halley in 1986 with the Giotto spacecraft and then last year when Deep Space 1 flew by comet P/Borrelly.

Based on these images we conclude that comets are *irregular objects that are covered with dark tar like material.* They are *most active in small regions.* The differences between comet gas production rates are probably nothing more than differences in the size and number of these regions.



Comet Halley from Giotto



Comet Borrelly from DS1

Comets Revealed: So what makes a comet?

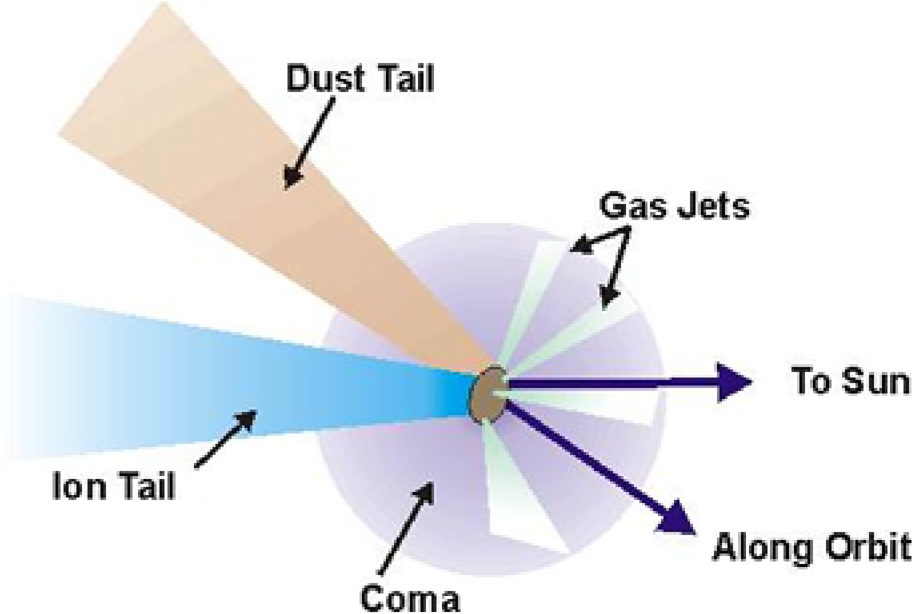
The internal structure of the nucleus is a mystery. There are **3 possibilities**. They could be *uniform mixtures of ice and rock*, just like the intermediate icy moons of Saturn.

They could have *differentiated* somehow into an *icy mantle surrounding a rocky core*. They could even be '*rubble piles*' of debris held together by weak gravitational forces.

Everything else in a comet we see had its *ultimate source from the nucleus*. The drawing below summarizes the structures we can see.

Comets Revealed: So what makes a comet?

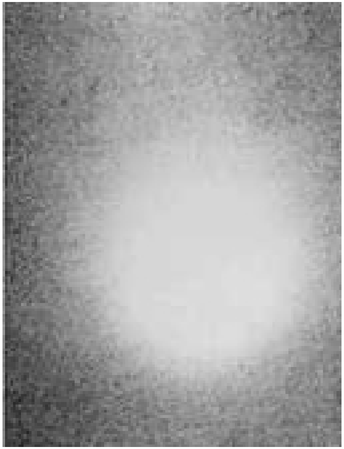
The three most prominent features are the '**Coma**', the '**Dust Tail**', and the '**Ion Tail**'.



The Coma

The coma is really just a general term for the *expanding shell of melted ices, atoms and molecules.* The angular size and shape of the coma depends on what gas you are looking at, and how long it survives before sunlight destroys it.

Water for example, is broken down by sunlight within 105 km of the nucleus, while *Hydrogen atoms survive out to distances >10 million km!*



The Coma

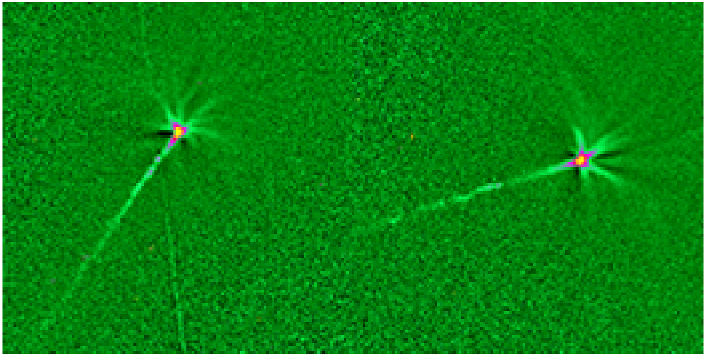
By looking at the comet with a *wavelength filter that separates colors*, we can *isolate* individual gasses from dust and each other in the coma. The example below shows the dust coma of Comet Hyakutake, dust and CN in the coma, and CN with the dust removed. Notice the differences?

Dust only **Dust + CN** **CN only**

When comets are at about *the distance of the asteroid belt or further*, the coma is dominated by production and chemistry of CO. Inside this distance, the *temperature becomes high enough for water to melt*, and the evaporation of water takes over. Up to *90%* of all gas produced from a comet is water.

Gas Jets

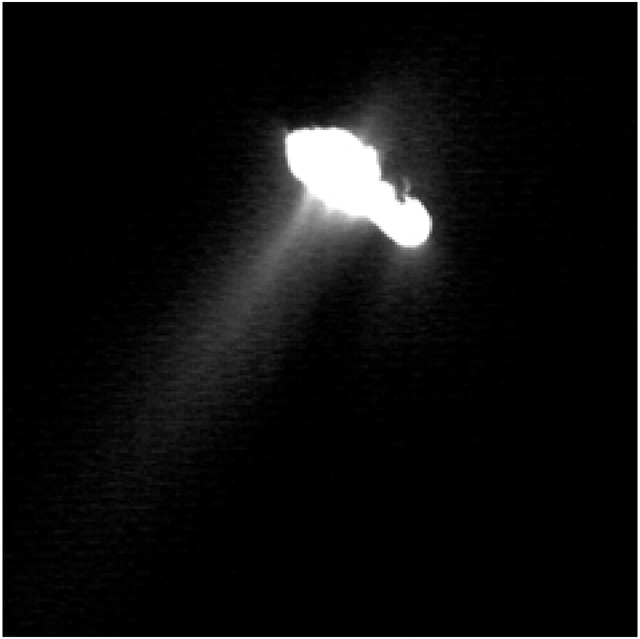
Buried beneath the fuzzy glare of the coma are the *active sectors of the nucleus*. They give off gas in **focused outflows** whenever sunlight shines on them. By using a technique called '*unsharp masking*', whereby we subtract off a slightly blurred version of an image of the coma, we isolate only the *small scale structure*. The image below shows what was lying underneath the dust coma picture of Hyakutake from above.



Notice how the *pattern of Jets faces toward the Sun* (opposite to the dust tail in both images) and changes with time? The changes are due to *rotation of the nucleus.*

Comet Borrelly

Below is an image of jets coming off of Comet Borrelley in December of year.
You can see that different comets have different jets.



The Tails

Comets have two types of tails that reveal very different things about both the nucleus and its environment.

The Dust Tail:

When gasses are evaporated from the surface of a comet, they *rapidly flow away into space*. As the amount of gas production increases the force of this outflow becomes greater. Eventually it becomes large enough to *carry away particles of dust along with it*. The more active the comet, the larger the grains can get. Some of these dust particles become co-orbital with the comet, and begin to spread out along its orbital path. The *heavy ones tend to stay very close to this path,* but the smaller grains are pushed off the orbital plane by solar radiation pressure (yes, light has 'pressure'!). The result is a splash of dust grains into a fan shape, with the *heaviest grains along the orbit, and the lightest lying closer to the anti-sunward direction.*

Above is an image of comet Hale-Bopp (top) with both tails (Dust toward bottom) and at bottom a representation of a meteor shower.

The Tails

While the dust tail of a comet is most prominent right near the nucleus, *the debris stretches all the way around the orbital plane*. This debris will often outlive the comet that produced it.

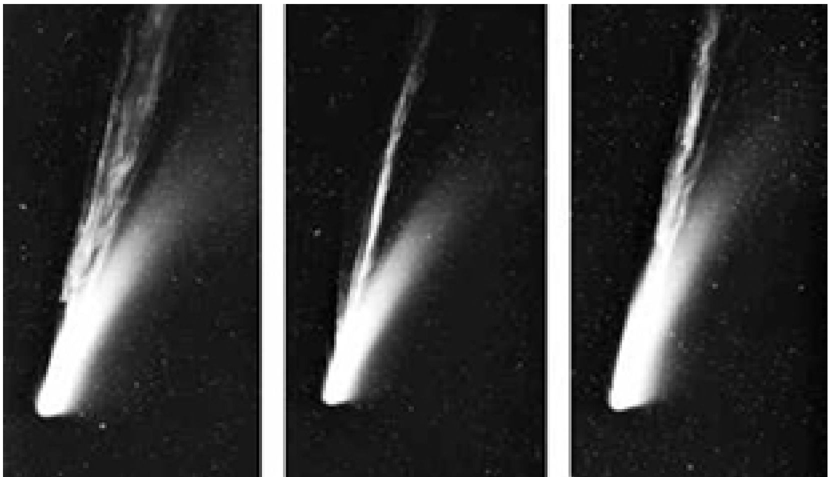
Occasionally the Earth *will pass through the orbit of a comet*, and when it does a shower of small dust particles will rain down into the atmosphere. We call these events '*Meteor Showers*'.

The annual '*Perseid*' (associated with comet 109P/Swift-Tuttle) and '*Leonid*' (associated with comet 55P/Temple-Tuttle) showers are examples of this. We name these showers after *the constellation they appear to emanate from*.

Above is an image of comet Hale-Bopp (top) with both tails (Dust toward bottom) and at bottom a representation of a meteor shower.

The Ion Tail

If you recall from our discussion of Io and the Io plasma torus, you will know that sunlight is capable of *stripping an electron off of a neutral atom or molecule*, giving it charge. The same thing can happen to gas produced produced from a comet. Unlike the Io plasma torus, which is shielded by Jupiter's magnetic field, ions in a comet are *exposed directly to the solar wind*. The solar wind has ***four important characteristics*** that are reflected in the observed interaction between it and the comet...



The Ion Tail

1) It carries a magnetic field with it. This means that when a comet neutral becomes an ion, it suddenly feels that field (just like at Io), and is '*picked up*'.

2) It is very fast. Typical expansion velocities in the coma are 1-10 km/sec, while the solar wind blows past at 1000 km/sec! The new Ions are *rapidly dragged out into a long anti-sunward streak* that can reach *100 million km in length*! This is what we call the Ion tail.

3) It is variable. The *velocity and density of the solar wind can change rapidly*. This is reflected in the structure of the ion tail as we move anti-sunward from the nucleus. Occasionally 'gusts' of the solar wind will hit the comet, triggering *distortions and disconnection events* in the ion tail.

4) It is patchy. The solar wind itself contains *streams and eddies*. These features of it are *reflected in the structure of the ion tail*. Often one will see filaments and streams in the tail.

By studying the characteristics of the ion tail, we are given an exquisite view of the intricacies of the solar outflow. It is this nature of comets that make them so useful for studying the Sun!

Evolution of a Comet

It should be pretty clear that the situation of repeated appearances and meltings is *not a stable one* for comets. In fact, *most of them are doomed*.

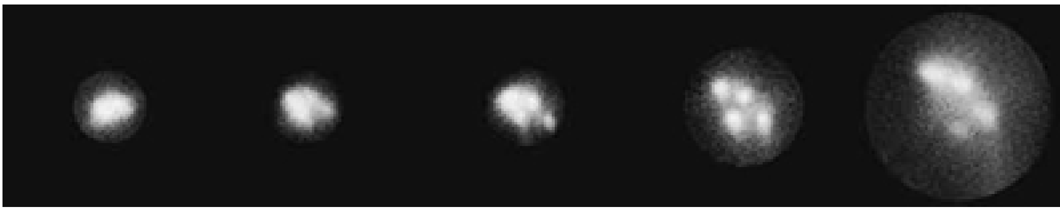
How much material is produced by comet? Well comet Hale-Bopp was observed to produce about 1031 molecules of water every second when it was closest to the Sun. That's 330,000 kg/second! Over about 6 months, Hale-Bopp gave off about something approaching 5 x 1012 kg; the equivalent of *a sphere of ice 1 km across*. Fortunately Hale-Bopp has a lot of ice to spare for now. The smallest estimate of Hale-Bopp's size (20 km in diameter) would have *a mass about 8000 x greater than what was lost!*

Still, all comets are destined to die. But how?

Do they evaporate away entirely?
Do the shatter into pieces and disintegrate?
Do they leave a rocky remnant that will orbit the Sun for the next several billion years?

Evolution of a Comet

Actually it is some combination of all of these. The fate of comets is ultimately tied up in *where they were produced, how close the get to the Sun*, and the i*nternal structure of their nucleus*.

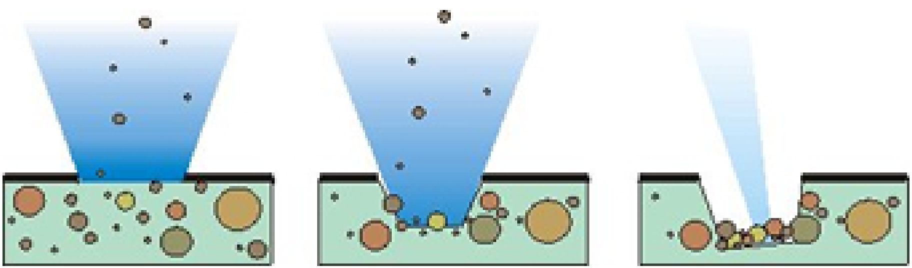


The view above is of the breakup of comet West in 1976. This object clearly was *an aggregate of smaller bodies* that finally could no longer hold together under the force of water evaporation.

Evolution of a Comet

Another possible end state is described by the **Carbonaceous Chondrite asteroids**, like Mathilde. It is possible that these objects are *dead comet nuclei,* where gas production has been stopped by either the *evaporation of all water* or a *thick mantle of dust* shielding the icy interior from further heating.

For those with a mantle, the dust layer chokes off further outgassing so that the comet becomes effectively '*dead*', although dormant may be the better term. These objects can suddenly burst back into activity under the right conditions. A mantle covered surface is most likely for comets that are *somewhat farther from the Sun*, where gas pressures are too low for large scale dust production, and solar heating is *less effective.*



One More Possibility…

Comets and asteroids share one other possible fate in the inner solar system, **accretion**. The presence of the planets (particularly Jupiter) have a continuing influence on these objects by *deflecting their orbits* and sometimes *just by being in the way*.

Much has been made of the significance of this for our planet, and over time we have accumulated considerable knowledge and the ability to (hopefully) identify any potential impactors.