The Comet's Tale Background

Comet's Tale Background Reading

Part I

Comets in History

Although the examples in our History section are few, humans in many cultures have been observing comets for a very long time. Oriental astronomers recorded comet sightings in ancient China, Arabic astronomers, Greeks, and Mayans were all fascinated by them. Your students may be interested to know that a Japanese boy named Matasaburou observed a comet in the 17th century, which he named the "tiger-tailed star."

Comets in Science

The development of western scientific thinking coincides rather closely with history and knowledge of comets. First there was wonder, followed by fear and apprehension. Some leaders no doubt used the appearance of a comet as a propaganda opportunity for their own ends, but unlike planetary movements, or eclipses, no one learned to predict when a comet would appear until the late 17th century. They were attributed to the whim of God or gods, and comets were often depicted as supernatural or god-sent omens of tragedies or miracles (1300, 1402).

But people went on observing, recording, and sharing information about comets. By the end of the Renaissance in Europe observers knew that not all comets looked the same, and people tried to define a morphology, a classification system based on the apparent differences in comet forms (1587). Classification by appearance, although a step toward systematizing knowledge, doesn't lead directly to physical understanding. With comets, differences in shape and color were eventually discovered to be due mostly to our viewing angle, and the comet's proximity to the Sun. If the earth and comet are situated differently, the same comet can look quite different from one periodic appearance to another, or even from observation to the next.

Newton and Halley

The next real progress was to show that comets obeyed the same natural laws as other bodies in the heavens, and this had to wait until someone--Sir Isaac Newton--determined what those laws were. Sir Edmund Halley, a close friend of Newton, tamed the mystery of comets and broke the prediction barrier. The popular recent theory of Kepler was that comets travel in straight lines. This seemed to allow for the way comets' tails changed orientation to point anti-sunward, but Newton's finding that heavenly bodies moved on closed, gravitationally bound orbits appealed to Halley. He might have thought: what if Kepler's straight paths were really parts of elliptical orbits? He began to wonder in 1703 whether a comet he had observed in 1682 had ever been seen before. Halley noted other comet sightings had occurred about every 76 years. Newton had demonstrated his laws of gravity and motion by using them to calculate the motions of familiar objects like the earth and moon, which have simple, nearly circular orbits. Both men had observed the comet of 1682* and had data on its position at various times. Using Newton's laws, Halley did some very difficult calculations, and discovered that a comet with an elliptical orbit and period of 76 years could account in detail for the sightings of 1607, 1531, and 1456.

The practice of actually checking a theory by comparing it with nature was still fairly new at the time! Halley predicted the next sighting of the comet, in 1758-1759. Although he did not live to see it, Comet Halley was named for him after it was first sighted on Christmas night of 1758. It is now easily the best known comet. There are still people living in 2000 C.E. who witnessed its spectacular appearance in 1910. The latest flyby in 1986 was less visible, but 2062 is coming...

Today

From the 1600's forward, western science was developing rapidly, and researchers created powerful tools of observation and calculation to describe the workings of nature. The investigation of comets went forward inexorably, using telescopes, photography, and today, multi-wavelength space instruments. The main highlights described in the student pages are:

- the origins of comets; how they came about, and where have they been before we see them.
- their composition and characteristics; what are they made of, how old is it, and what happens physically to produce the beautiful phenomena we see in the sky?
- their orbits; where one might look to find a comet, how their paths through space are determined.

Today, superstition about comets is much less common in our society, but the idea of "space rocks" as dangerous missiles has recently resurfaced. Are comets or meteors (they can have similar orbits) really a hazard after all? See our small investigation of one possibility in "Killer Comets?" The scientific search for evidence of a pre-historic impact and its result are now changing our vision of the Earth's history, climate, and future.

Comet Origins

Understanding the origin of comets means going back to the formation of the solar system. Comets probably formed soon after the sun, during the early stages of collapse and contraction in a cloud of gas and interstellar dust called a solar nebula. Formation of comets and asteroids was soon followed by the formation of the planets. Please take a few minutes to read this nice narrative on the formation of the solar system planets:

Nine Planets' Origin of the Solar System page:

http://seds.lpl.arizona.edu/nineplanets/nineplanets/origin.html

by Frank Crary, UC Boulder

--(Quoted in full)--

The Origin of the Solar System

by Frank Crary, CU Boulder

Here is a brief outline of the current theory of the events in the early history of the solar system:

1. A cloud of interstellar gas and/or dust (the "solar nebula") is disturbed and collapses under its own gravity. The disturbance could be, for example, the shock wave from a nearby supernova.
2. As the cloud collapses, it heats up and compresses in the center. It heats enough for the dust to vaporize. The initial collapse is supposed to take less than 100,000 years.
3. The center compresses enough to become a protostar and the rest of the gas orbits/flows around it. Most of that gas flows inward and adds to the mass of the forming star, but the gas is rotating. The centrifugal force from that prevents some of the gas from reaching the forming star. Instead, it forms an "accretion disk" around the star. The disk radiates away its energy and cools off.
4. First brake point. Depending on the details, the gas orbiting star/protostar may be unstable and start to compress under its own gravity. That produces a double star. If it doesn't ...
5. The gas cools off enough for the metal, rock and (far enough from the forming star) ice to condense out into tiny particles. (i.e. some of the gas turns back into dust). The metals condense almost as soon as the accretion disk forms (4.55-4.56 billion years ago according to isotope measurements of certain meteors); the rock condenses a bit later (between 4.4 and 4.55 billion years ago).
6. The dust particles collide with each other and form into larger particles. This goes on until the particles get to the size of boulders or small asteroids.
7. Run away growth. Once the larger of these particles get big enough to have a nontrivial gravity, their growth accelerates. Their gravity (even if it's very small) gives them an edge over smaller particles; it pulls in more, smaller particles, and very quickly, the large objects have accumulated all of the solid matter close to their own orbit. How big they get depends on their distance from the star and the density and composition of the protoplanetary nebula. In the solar system, the theories say that this is large asteroid to lunar size in the inner solar system, and one to fifteen times the Earth's size in the outer solar system. There would have been a big jump in size somewhere between the current orbits of Mars and Jupiter: the energy from the Sun would

have kept ice a vapor at closer distances, so the solid, accretable matter would become much more common beyond a critical distance from the Sun. The accretion of these "planetesimals" is believed to take a few hundred thousand to about twenty million years, with the outermost taking the longest to form.

8. Two things and the second brake point. How big were those protoplanets and how quickly did they form? At about this time, about 1 million years after the nebula cooled, the star would generate a very strong solar wind, which would sweep away all of the gas left in the protoplanetary nebula. If a protoplanet was large enough, soon enough, its gravity would pull in the nebular gas, and it would become a gas giant. If not, it would remain a rocky or icy body.
9. At this point, the solar system is composed only of solid, protoplanetary bodies and gas giants. The "planetesimals" would slowly collide with each other and become more massive.
10. Eventually, after ten to a hundred million years, you end up with ten or so planets, in stable orbits, and that's a solar system. These planets and their surfaces may be heavily modified by the last, big collision they experience (e.g. the largely metal composition of Mercury or the Moon).

Note: this was the theory of planetary formation as it stood before the discovery of extra-solar planets. The discoveries don't match what the theory predicted. That could be an observational bias (odd solar systems may be easier to detect from Earth) or problems with the theory (probably with subtle points, not the basic outline.)

--end quote--

Read between the lines of paragraphs 5, 6, & 7; metals are cooling and crystallizing, dust is accumulating into rocky material, and gases are freezing into ices, all depending on their distance from the sun and their mass. Comets are distinguished by being a mixture of ices and mixtures of carbon dust, silicate rock, and metals.

The Kuiper Belt and short period comets

Comets are mostly ice, with requires the lowest temperatures to freeze into a solid state. Thus, the oldest comets were probably those that formed at the outer edge of the proto-planetary disk. This region would be first area cool enough to freeze after the original ignition of the young star. The collection of objects outside the orbit of Neptune is known today as the Kuiper Belt. Kuiper Belt objects, thought to be the source of most short-period comets, are also thought to be some of the most primitive remaining objects in the solar system.

Forming the Oort Cloud: source of long period comets

Small objects (planetesimals) also formed in the inner solar system during the phase of "runaway growth" (paragraph 7). Many objects from the outer regions and a few of these inner objects were ejected from the system instead of becoming part of a larger planet. This happened by gravitational "scattering," whenever a planetesimal passed close to one of the giant planets without colliding or being captured in an orbit. The effect of gravity caused the two objects to "bounce" off each other. The result was that the tiny planetesimal would completely change direction, while the enormous planet was hardly affected-- something like bouncing a ping pong ball off a bowling ball.

Shape and size

A great many of these events occurred in the early solar system. Some of the ejected objects stayed in new, more distant orbits around the Sun, forming the Oort Cloud, more than 1000 times farther out than Pluto. It has been established that most of the comets in the Oort cloud come from about 50,000 AU away, and from many directions. This means the cloud is not an evenly filled sphere, but a spherical shell with some small thickness.

It makes sense that the cloud is a sphere centered on the Sun. The first small objects would have orbits of many angles and shapes and would approach large planets like Jupiter or Neptune from many different angles. So they would get scattered in every direction. If you could stand 50,000 AU from the sun, not even Jupiter could be distinguished from the Sun, and as one scientist put it, "it would look like the Sun was spitting out planetesimals."

Scientists have also observed that about half of the comets from the Oort Cloud have orbits that are what is called "retrograde." This means that while nearly everything in the solar system goes round in the same direction, because of the original solar nebula's rotation, half of the comets circulate the other way. This is taken as further proof that the Oort Cloud objects represent a set of random scattering events, which would result in an even spherical distribution.

Comet Composition: What's in a Comet, Anyway?

The content of comets can be investigated just like that of stars. Astronomers use spectroscopes, which separate different wavelengths of light from a single source. This allows them to look for the "signatures" of various elements and molecules in the resulting light spectrum. Of course meteorites also provide samples of the rocky and metallic parts of comets as well. The substances found in comets and their proportions are one things that helped scientists determine that comets were created early in the solar system.

The "dirty snowball" model of comets is easy to grasp, and remains fairly accurate. The main difference student need to understand is that the "snow" is not always composed of water. Besides water and carbon dioxide, other organic substances like formaldehyde and methane are frequently detected in comets by their spectral signatures in the light from the plasma tail and coma. These substances freeze at temperatures much lower than water. Talking about how cold it is in most of space (-270 degrees Celsius) may help students visualize this.

For more variations on the compositions of comets, see the Space Telescope Science Institute's "Amazing Space" module on comets:

http://amazing-space.stsci.edu/comets/lesson/make_nf.html

(requires ShockWave) This module links the compounds in the nucleus with the appearance of the ion plasma tails as well.

Going organic

The game and comet-making activity are good opportunities to introduce the general idea of organic materials. This term differs from the "organic" in "organic produce," and doesn't necessarily mean "about an organ" or even a living organism, as some students might think. When it comes up later in life sciences (if it hasn't already), they will have it from another context and hopefully some of the possible confusions will be avoided. An exercise to help students with the idea of organic substances is to have them find as many examples as they can in the picture that illustrates the glossary entry. It is not necessary to know the exact names of all molecules:

- CO2 in the bowl.
- Water in the bowl.
- Wooden spoon is made of many organic substances, including cellulose.
- Leather glove, and
- The boy himself are made of many organic materials
- Boy's shirt probably contains cotton, a plant fiber, which is yet another organic mixture.

Comets and life

The comet making activity is also a good time to reinforce the ideas from "Older Than Dirt." If you make comets, they will be mostly water and carbon dioxide. The reason the organics dominate is simple: the elements hydrogen, carbon, nitrogen and oxygen are some of the most common elements in the universe (aside from helium, which is a noble gas, and doesn't participate in chemical reactions). This is also what life is made of, so life is made of the most common stuff--also not surprising, when you think about it. Simple compounds like ammonia and CO2 (and even a few sugar-like molecules) were all present in the original solar nebula; these were all nature started with to make life.

Amazing, but this is part of what makes comets truly interesting today. The fact that the relative amounts of these various compounds can be observed in comets means we might one day have the list of ingredients and the relative amounts needed for life. Of course, some scientists are already working out the cooking instructions: the chemical transformations that took place along the way. These might have to do with the various
changes in climate conditions over the earth's history. In a way, each time a comet goes through perihelion inside the orbit of Jupiter, it undergoes a little bit of this aging and evolution, so even some comets are more "evolved" than others.

*Not to be confused with the great comet of 1680, a daylight comet with a seventy-degree tail.

Part II

Comet Anatomy and Characteristics

The Comet Characteristics section should help students bridge the gap between the comet as dirty snowball and the bright, but slow-moving "hairy star." Although Newton himself guessed that comets' tails were "formed of minute particles that emanated from the head under the influence of solar rays," deeper knowledge awaited better understanding of the near-sun environment, much of it in this century and even post-space age.

The power of the Sun's radiation and the solar wind are what make the difference--the comet absorbs energy, mainly in the form of radiation, but also from magnetic fields. To receive enough energy from the Sun to be visible, at least with a telescope, a comet's orbit must have a perihelion of less than 5 AU. This results from orbits that are either fairly eccentric ellipses, or open orbits that only visit the Sun once. Close to the Sun also means close to the earth, our observation site. Good thing for comet watchers that we aren't on Saturn!

The main effects come from the energy of the Sun's radiation, which sublimates, the ices and heats the resulting gas. The coma develops because gas molecules that have just "boiled" off the surface have the same original speed and direction of travel as the nucleus, and so seem to "cling" to it. The gas glows, as it absorbs sunlight, heats up, and emits a spectrum of visible light corresponding to its temperature. The dust, made of silica, carbon and trace minerals and metals, reflect sunlight. What happens to these two components, the gases and dust, is determined by the different ways they interact with the near-solar environment. The "Characteristics" lesson page has more about the appearance, size, and scale of the various features.

Plasma of ions + solar wind = plasma tail

Absorption of high-energy solar radiation (light) causes some molecules in the heated gas coma to *ionize*: they lose one or more of their negative electrons and become positively charged. This is where the solar wind comes in. Part of the solar wind is a magnetic field, which originates deep within the sun, and is carried outward by the protons and other positive ions escaping the solar atmosphere. The field is like the field of a bar magnet so large, that near the comet its field lines would look straight, like waves on a beach.

Because a magnetic field exerts a force on a charged particle, this solar field wave "breaks" over the comet, pulling on the ionized gas of the coma[1] It sweeps away the electrons, which are much lighter, and draws the heavier ions outward, into a long plasma tail (also called an ion tail) that points in the anti-sunward direction. Detailed pictures of ion tails show they are turbulent, like the wake of a small boat in a very strong current.

The hot ions swirl around in the magnetic field; the field speeds them up, and they release the energy as light, only to absorb more from the field. But the light from the plasma tail is still faint, so ion tails are often hard to see without a telescope. Astronomical photographers often use extended exposures to catch them. You can make a simulation of a comet with ion tails using the Amazing Space comet maker* referred to on Page I. Try putting in several volatile substances like methane and ammonia and see the resulting tails.

Solar dust broom

The sublimating of the comet ices also frees dust and rocky material. Dust particles in space are subject to actual pressure from the Sun's radiation. This radiation pressure, the same effect that makes those little solar radiometers in glass globes spin round, sweeps the dust away from the nucleus, also in an anti-sunward direction. The debris still has some momentum, and it continues to orbit the sun, but it is pushed away from the nucleus and is slowly left behind. The material forms a curved dust tail that can be very reflective. It may appear quite brilliant in the night sky when the comet is well separated from the sun in our field of view (like a full moon). It is the long, bright dust tail that is usually the most visible. Eventually this dusty debris spreads out along the comet orbit, and becomes the material of meteor showers. Most of this material is tiny or microscopic in size.

Since both types of tails point generally anti-sunward, and a comet's orbit may be oriented at almost any angle to the earth's orbit, whether a long tail is visible from earth is a matter of chance. If the comet is nearly on the other side of the sun, the tails will point away from (or towards) us, and be nearly invisible in the glare from the coma. So indeed, the different appearances of various comets, or even the same comet, can be deceiving.

Those looking for more about solar wind and the interplanetary environment may want to look at the reference desk of the NASA OSS Sun-Earth Connection Education Forum site at:

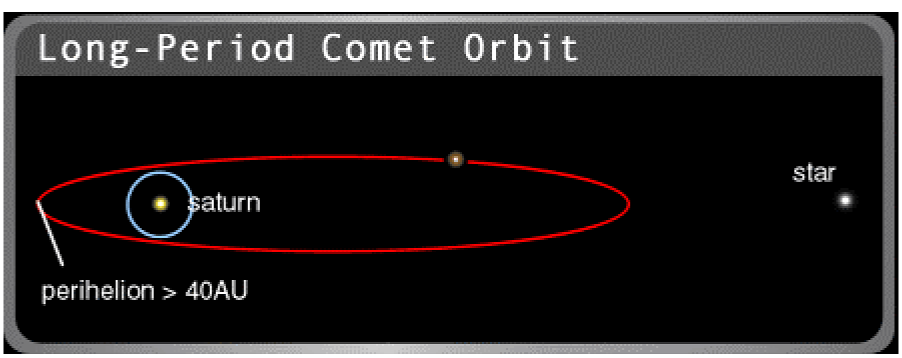
http://sunearth.ssl.berkeley.edu/educators/index.html

Orbits: Types and Evolution

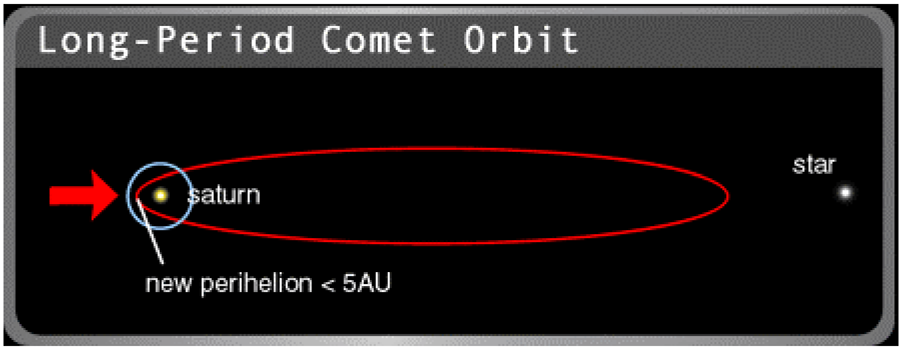
Once Halley and Newton figured out how the orbits of comets could be described, the next interesting question was why any comet has the orbit it has. As you saw in the Origins section, the formation of the Oort Cloud around the inner solar system put many comets into orbits where they no longer encounter large objects like Jupiter at close range, and are much farther from the sun than Pluto, even at perihelion. What caused the comets Oort originally studied to come close enough to the sun to observe? In other words, what changed their orbits?

Oort suggested that the gravity of passing stars might exert a gravitational pull on some comets, making their orbits longer and narrower. Stars pass each other within galaxies, although they also orbit around the galactic center. Another star passing by the Sun would be a relatively common event in the course of 4.5 billion years.

Unlike the "Origins" animation of Jupiter flinging comets outward, this cartoon shows lengthening an orbit by the pull of a distant, but extremely massive object: a passing star. The mass of the star makes up for the larger distance; its gravitational pull can both bring the comet outward and make its orbit flatter (more eccentric), like stretching a rubber band. When the star passes, the new orbit remains.

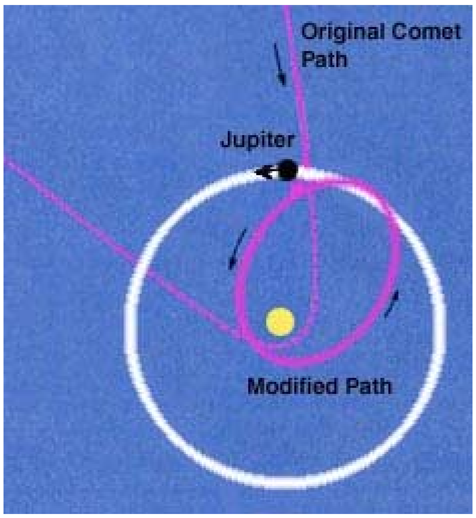


(distance to the star is <u>not</u> drawn to scale! The star would be at least 10 light years away.)

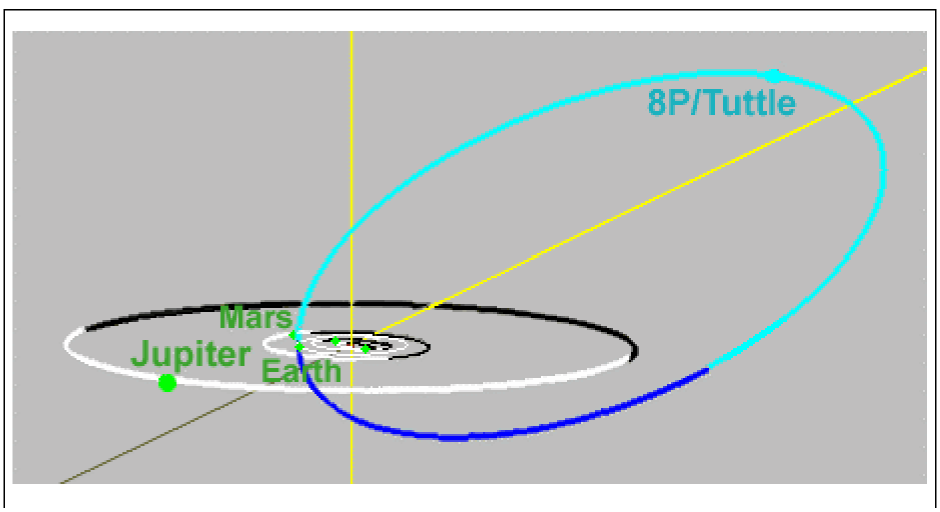


The more stretched-out an ellipse becomes, the closer the focus points are to the ends. This means the longer and flatter a comet's orbit becomes, the closer it is to the sun at its perihelion. If the orbit becomes narrow enough, the comet passes close enough to the sun, and becomes bright enough, to be observed with a telescope, binoculars, or the naked eye.

How do we get to observe short period comets, which start out in the Kuiper Belt? Objects in the Kuiper Belt have elliptical orbits too, and their paths may bring them inside the orbits of the giant planets. If a comet crosses a planet's orbit near where the planet happens to be, the planet can pull it into an orbit inside the solar system. This is like the way stars alter the orbits of long period comets, but on a much smaller scale. Note in the illustration at left that the comet's original (open) path would have brought it closer to the Sun, but only once! On the closed elliptical orbit, it will keep returning until its motion is perturbed again.



One thing about comets is that many travel in orbits at large angles to the ecliptic, the plane of the earth's orbit around the Sun. The ecliptic is used as a good approximation to the plane of the other planets, with the exception of Pluto, which is suspected of being a large Kuiper Belt object, rather than a true planet.[2]

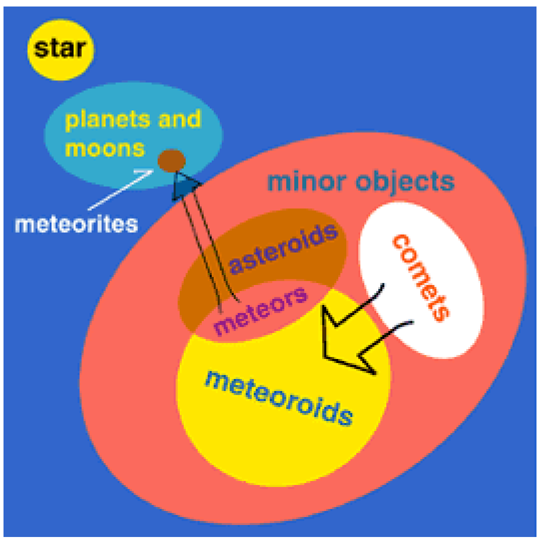


This diagram shows the orbit of comet Tuttle, which is in a plane almost perpendicular to the orbits of the planets and has its perihelion just inside Earth's orbit.

Comets, Meteoroids, Asteroids: the Interplanetary Zoo

It's common for students to have confusion about comets vs. asteroids, vs. meteors, meteoroids, and meteorites. The term meteor was probably coined to describe visible "shooting stars" long before the origin of meteors was known. Comets and asteroids both formed in the early development of the solar systems. Asteroids, most of which orbit between Mars and Jupiter, are thought to be a bit older. This is because metals, carbon, and silicon became solid at higher temperatures than the gases that make up most of comets, and so they solidified earlier (see also the section on the relative ages of Kuiper and Oort comets in Part I; the idea is the same.)

Comets are the main source of meteoroids, which they release as dust and rocky material near the Sun (this term is also used by some to denote any small body near the earth). Most of this material is the size of sand grains, or smaller. The Educator's Guide to Micrometeorites contains a good short summary on the relationships of all the "meteor" family of objects. The "ite" suffix in meteorite is common in names for terrestrial rocks like granite and calcite, as opposed to space objects, like meteoroids, which have the "oid" suffix.



Here is a diagram showing various kinds of objects in the solar system and their relationships as sets. The labeled groups are not scaled by mass or number, although there are certainly far more minor objects than stars, planets and moons. The group of "Comets" includes icy bodies in both the Kuiper Belt and Oort Cloud. The non-gaseous material that leaves comets enters the class of meteoroids. Both meteoroids and asteroids can contribute to the class of meteors (things that enter the atmosphere). Meteorites have become part of a planet like Earth, or a moon. Some astronomers even watch for meteorite impacts on our moon during meteor showers.