013: Comets and the Outer Solar System

013.1 Comets in Detail

Comet Tails

A comet is a ball of frozen gas and ice with some dust mixed in. Comets have been referred to as ‘dirty snowballs.’ They originate far from the Sun and follow highly elliptical orbits.

The characteristic tail of a comet is formed by the action of sunlight. While they are farther from the Sun than the planet Mars, comets are simply balls of frozen gas and dust and do not have tails. Closer to the Sun, the gas evaporates and the dust that was held together by the frozen gas is released. The Solar wind pushes these materials away from the Sun to form tails. Notice that the tail leads the comet on its trip away from the Sun.

The Ion Tail consists of atoms that have gained or lost electrons and consists of straight streamers. It forms first and can be as long as the size of the Earth’s orbit.

The Dust Tail is usually fuzzy looking and is curved because the individual dust particles are taking up their own separate orbits around the Sun. It forms closer to the Sun.
Parts of a Comet

<table>
<thead>
<tr>
<th>Nucleus</th>
<th>The 'dirty snowball'</th>
<th>a few kilometers across</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coma</td>
<td>Vaporizing gas and dust</td>
<td>as large as the planet Jupiter</td>
</tr>
<tr>
<td>Ion Tail</td>
<td>Atoms with electrons missing</td>
<td>as large as the Earth’s orbit</td>
</tr>
<tr>
<td>Dust Tail</td>
<td>rock fragments</td>
<td>Forms close to the Sun</td>
</tr>
</tbody>
</table>

Examples

Here is an image of the Comet Hale Bopp taken in Joshua Tree National Park by Wally Pacholka on April 7, 1997. Notice the ion tail and the dust tail.

![Image of Comet Hale Bopp](image)

As we saw earlier, in module 10.5, The Stardust spacecraft flew into the coma of a relatively new comet, Wild-2 in 2004, and took this picture of the nucleus while collecting dust samples for return to earth:

![Image of Wild-2 nucleus](image)

The short exposure, on the left, shows an object that is not too different from the moons of the outer planets. The surface includes cliffs and craters, indicating a fairly strong outer crust. Wild-2 is a new comet that has only made about five Sun passes so far and it does not approach the Sun very closely, so its surface has not yet been modified. Older comets, such as Halley’s Comet, have nuclei that look very different, as we saw in module 10.5.
The longer exposure, on the right, shows the jets of gas that are forming the coma of the comet.
013.2 Meteor Showers

Language Lesson

<table>
<thead>
<tr>
<th>Before it hits the atmosphere it is a</th>
<th>Meteoroid</th>
</tr>
</thead>
<tbody>
<tr>
<td>Passing through the atmosphere it is a</td>
<td>Meteor</td>
</tr>
<tr>
<td>Once it has landed, it is a</td>
<td>Meteorite</td>
</tr>
</tbody>
</table>

Meteor Showers occur when the Earth passes through the orbit of a shattered comet. The point in the sky where the shower seems to come from is called the radiant and indicates the direction of the Earth’s motion when it encounters the cloud.

Because the Earth is always moving in the same direction in space when it passes through a given comet orbit, the radiant is always the same. Thus, meteor showers are named after the constellation that contains their radiant.

Because a given comet orbit is always encountered at the same point along the Earth’s orbit, each meteor shower always happens at the same time of the year.

Examples

The Lyrid shower seems to come out of the constellation Lyra and peaks in April. This year it is the night of April 21-22, 2008 and will not be very visible because it coincides with a full moon. The comet that gave rise to this shower was comet 18611 (Thatcher).

The best known meteor shower is probably the Leonid shower, which peaks in November and has its radiant in the constellation Leo. This year its peak is the morning of November 17, 2008.
013.3 The Origin of Comets

Long Period Comets and the Oort Cloud

Some comets arrive near the sun on trajectories that will not bring them back again for millions of years. These long period comets come from random directions, not just in the plane of the solar system. A somewhat arbitrary definition of a long-period comet is that its orbital period is greater than 200 years.

In 1950, Jan Hendrick Oort was trying to explain how a solar system that is billions of years old can still have comets when each comet is destroyed after only a few orbits past the Sun. His answer was that there is a very large reservoir of potential comet nuclei in a cloud at the far fringe of the Solar System. The cloud supplies new comets as fast as the old ones are destroyed.

The question that Oort considered was not new and neither was his answer. Both had been discussed by Ernst Öpik in 1932 and probably by others before that. However, we tend to name things after the last person to present them rather than the first, so the cloud has come to be called the Oort Cloud.

When the paths of long-period comets are traced backward in time, it is found that they have fallen in from about 50,000 astronomical units out. Since they come in random directions, the cloud appears to be spherical. At the present time it is somewhat speculative because there are almost no direct observations of Oort cloud objects.
Short Period Comets and the Kuiper Belt

Comets that have periods that bring them back near the Sun in less than 200 years are referred to as short period comets. Many of these objects have orbits that are approximately in the same plane as the orbits of the major planets. The Kuiper Belt is a reasonable candidate for the origin of many of these comets. Unlike the Oort cloud, we have begun to observe large numbers of Kuiper Belt objects, so it has become a well-tested concept.

Unlike the Oort Cloud, the Kuiper Belt is of limited extent. The limits are determined by orbital resonances with Neptune. At the inner edge of the main belt are objects whose orbital periods are in a 3:2 relation to the orbital period of Neptune. The outer edge is defined by objects whose orbital periods are just twice the orbital period of Neptune. This Main Kuiper Belt goes from 39.5au at its inner edge to about 48au at its outer edge. The fully extended Kuiper Belt extends a bit farther, from 30au to 55 au.

Yet another variation on the Kuiper Belt is the region that is largely uninfluenced by the gravity of Neptune. That region extends from 42 to 48au and is called the Classical Kuiper Belt. About 2/3 of the thousand or so Kuiper Belt objects found so far are in that region.

Trans Neptunian Objects

As the number of objects discovered has increased, new classes of objects have been defined and named. Here is a partial list:

* TNOs or Trans-Neptunian Objects — Objects beyond the orbit of Neptune.
* KBOs or Kuiper Belt Objects — objects in the extended Kuiper Belt
* SDOs or Scattered Disc Objects — objects beyond the Kuiper Belt out to about 100au.
* Plutinos — About 200 objects in the same type of orbit as Pluto. These objects orbit the Sun twice for every three times that Neptune does. They are said to be in 3:2 resonance with Neptune.
* Cubewanos — Objects in the Classical Kuiper Belt. Named after the first such object, 1992QB1.
**Planemos** — Planetary Mass Objects. These are large enough to be spherical but are not necessarily in orbit around the Sun or any other star. They include possible ‘rogue planets’ that drift between the stars entirely on their own.

**Examples**

Most of these objects are in the main Kuiper Belt and the Scattered Disk. The one exception is Sedna, which has a highly elliptical orbit with its perihelion at 76au and its aphelion at 975au. It was discovered in 2003 while it was approaching perihelion. It is regarded as an inner Oort cloud object.

All of these objects were found in essentially the same way that Pluto was found by Clyde Tombaugh in 1930. The method is to take pictures of the same part of the sky at different times and then switch back and forth between the two pictures with all of the star images lined up so that they do not change. Any object that is not a star will move from one picture to the next and will be seen to be jumping back and forth as the images are alternated.

Tombaugh used a mechanical device called a ‘blink comparator’ with a flipping mirror to alternate images. The rapid discovery of other Trans Neptunian objects came only after telescopes using Charge Coupled Devices (CCDs) came into common use. The resulting digital images made it possible for computers to search for the few faint images that were changing position. The discovery
picture of Sedna

with Sedna at the center of the green ring, shows just how faint these images are.
013.4 The Transition from Kuiper Belt to Oort Cloud

Our current picture of the region beyond the Kuiper Belt is shown in this picture:

The Inner Oort Cloud is a wide toroidal shaped region from 50 to 20,000au that starts where the Kuiper Belt stops. The innermost part of this region, out to about 100au is often referred to as the Scattered Disk. Sedna, with its highly elliptical orbit that reaches almost 1000au is regarded as a visitor from the Inner Oort Cloud.
013.5 Beyond the Oort Cloud

The Oort cloud reaches out about one light-year, about a quarter of the way to the nearest star. The assumption until recently has been that the space between the Oort clouds of neighboring stars is mostly empty. However, that might not be true.

Our current theory of how the Solar System formed suggests that there may be many planetary mass objects scattered throughout interstellar space. Direct observation of these objects is difficult but a few large, relatively hot ones have been spotted in the star-forming regions of the Orion Nebula.

If rogue planets do exist and are as common as we now suspect, many of them are likely to be similar to the ice planets of the Kuiper Belt and would make ideal base camps for interstellar expeditions at some far future time.
014: Formation of the Solar System

014.1 The Solar Nebula

The Sun is a Typical Star

We will discuss stars in detail later. Our Sun is a typical middle-aged, medium temperature star. Its system of planets also appears to be fairly typical although we have only been able to study a few hundred planets of nearby stars.

Astronomers cannot test their ideas about the formation of the Solar System by trying to create stars and planetary systems in the laboratory. However, Nature has provided something that is almost as good: thousands of examples of stars and planetary systems that are forming now.

Interstellar Clouds and Star Clusters

Our solar system began as a slowly rotating cloud of gas and dust. Every part of the cloud is attracted to every other part by gravity, so the cloud becomes smaller until it looks like this example:

Here the cloud is dense enough to hide the stars behind it. At this stage, the cloud is usually referred to as a globule. The particular globule that led to the formation of our own Sun and Solar System is called the Solar Nebula.
Globules often come in bunches as in Thackeray’s Globules shown here:

These collections of globules come from the fragmentation of larger clouds and eventually lead to clusters of stars. An extreme example of a large cloud fragmenting and forming many stars is NGC604.

Over 200 stars have formed within this cloud, which is 1500 light years across. These clusters of stars remain long after the original cloud has vanished. A familiar cluster that still shows wisps of the original cloud is the Pleiades often called the seven sisters. Actually they really are sister stars but there are about 400 of them.

The closest star cluster to us forms most of the pattern that we know as the Big Dipper. All but the end stars of the Dipper belong to a single cluster that is moving through space together and passing very near our Sun.
Rotation

The original Solar Nebula was rotating very slowly. As it collapsed, it rotated faster.

The material that formed the Sun collapsed at the center. In order to collapse, it had to transfer some of its rotation to the rest of the cloud, which condensed into a rotating disk. The planets condensed out of this rotating disk.

As a result, the planets rotate around the Sun in the same direction that the Sun rotates and in the equatorial plane of the Sun.

Because they condensed out of the rotating disk, most of the planets rotate on their axes in this same sense — counterclockwise when viewed from above the Earth’s North Pole.
014.2 The Protostar Stage

When the collapsing Solar Nebula reached a density that light could not penetrate, the heat from compressing the cloud became trapped and the central temperature began to rise rapidly.

Where the material thins out enough for light to escape, we see the apparent surface or *photosphere* of the new *protostar* or, in this case, the *proto-Sun*.

Examples of Protostars Forming Now

Although protostar surface temperatures are low, their surface areas are very large, so they can be extremely bright. Shining entirely from the gravitational energy released by its collapse, a protostar can be a thousand times brighter than our Sun. Most of that energy comes out at light wavelengths too long for our eyes to see, so we have to look for them with infrared telescopes. Here is a collection of protostars (the reddish dots) in the R Corona Australis star-forming
region, 500 light-years from our Sun.

The picture is actually made in infra-red light by the University of Hawaii 88 inch telescope. The colors are "false" because our eyes are not sensitive to any of the wavelengths being detected by the telescope.

Here are protostars forming 1000 light years away in the Serpens Region, again in an infra-red picture:

Here is the Elephant’s Trunk Nebula in the constellation Cepheus seen in
ordinary light. The tip of the trunk is over on the right.

The nebula looks very different when viewed by the Spitzer Space Telescope in infrared light. The bright reddish objects in this picture are protostars.
014.3 Condensation of the Planets

Once the protoSun formed, any ices that had formed earlier vaporized in the hot inner region. Only rock and iron grains survived there and gradually collected into larger objects that eventually became the terrestrial planets. Since all of the water ice and frozen gases had been driven away from this region by the heat, these proto-terrestrial planets would have been completely without water and without atmospheres.

Farther out in the Solar Nebula, the original icy fragments were collapsing into a few miniature Solar Nebulae, each forming into a miniature Solar System with a large central object and smaller objects condensing out of a disk around it. These were the beginnings of the Jovian planets.
014.4 Jupiter Loses the Race

The Tau-Tauri Wind

In the early Solar System, the Sun and the Jovian planets were essentially similar objects, each large enough to grow still larger by collecting gas from the Nebula. Each with a rising central temperature.

The Sun won the race. When it began the final collapse that would raise its central temperature into the range needed to ignite the nuclear fusion reaction that powers stars, its outer layers blew off.

The result is called a *Tau Tauri wind*, named after the first protostar that was seen to be in that stage of its evolution. The Tau-Tauri wind blew all of the remaining gas out of the solar system so that Jupiter and the other Jovian planets could not grow any larger and would never become stars.

0.0.1 Binary Star Systems

Half of the stars in the sky are actually binary or even higher multiple systems. In these cases the ‘Jovian planets’ managed to grow fast enough to ignite before all of the gas was blown away by a Tau Tauri wind. Why they made it while Jupiter failed is not exactly known.

It was once thought that binary star systems would not be able to form Earth-like planets. Nature has shown us by example that this idea was wrong. Here is what we think is now happening in the newly formed binary star system...
HD113766, 424 light years away from us.

The brown ring in this artist’s image represents dusty material detected in this system. It is thought to be enough to form a terrestrial planet at exactly the right distance from its sun to have liquid water. The white ring represents icy material, also detected around this star that could be a possible source of that water. A few billion years from now, that system could host an Earthlike planet. The implication is that many binary star systems could have Earthlike planets.

That is particularly interesting because the closest star system to us is a trinary system (Alpha Centauri) that includes a near-twin of our own Sun.
014.5 The Fates of Dirty Snowballs

Unstable Orbits

Out beyond where the terrestrial planets were forming, a large number of icy objects — dirty snowballs — condensed out among the Jovian planets and in the region beyond Neptune. These objects saw a changing gravitational field because of the gravity of the giant Jovian planets. There are very few stable orbits in such a changing field, so all of these objects were ejected from that part of the solar system, some moving outward and some falling inward.
The Origin of the Oort Cloud

The outward-bound icy objects were sent in all directions on trajectories that took them far from the Sun, where they formed a spherical cloud of ejected material, the Oort Cloud.

An interesting prediction of this model is that some icy objects would have been sent out at escape velocity from the Solar System and are now wandering the space between the stars along with icy objects from the formation of other stars. That argument is one of several reasons that interstellar space might not be all that empty.

The Rain of Comets

The inward-bound icy objects found themselves in a very busy part of the Solar System with newly formed precursors to the present terrestrial planets. These proto-planets were massive enough to sweep up the icy objects. It is thought that all of the water and atmospheric gases on Earth and the other terrestrial planets came from this early "rain of comets."

In addition to water and bits of rock, comets also contain a variety of hydrocarbon compounds that are precursors to organic molecules. Thus, the rain of comets also supplied the building blocks and possibly the initial food supply for living things.

Pluto and the Origin of The Kuiper Belt

The icy objects that formed just beyond Neptune had stable orbits and remained there to become the Kuiper Belt. In 1951, Gerard Kuiper noted that such a belt of icy objects would be left in that region. However, at the time that he was working, Pluto was thought to be a full-fledged planet with about the mass of Earth. Such a planet in Pluto’s elliptical orbit would have completely disrupted the orbits of any objects in that region, so he predicted that no such objects would be found.

The newly adopted definition of a planet requires that it must have cleared the neighborhood of its orbit. Kuiper was correct in predicting that an Earth-mass Pluto would have cleared its neighborhood of most objects. Actually, Pluto has only 1/500 the mass of the Earth and has obviously not cleared the neighborhood of its orbit, so it is no longer regarded as a planet.