PLANETARY SCIENCE RESEARCH
PSRD Discoveries

Hot Idea

posted February 14, 1997

1997 Apparition of Comet Hale-Bopp

Written by Karen J. Meech
Institute for Astronomy,
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Comets have both fascinated and frightened people throughout history, but few people outside the scientific community and a dedicated cadre of amateur observers pay attention to these celestial wanderers nowadays. This is largely due to our modern lifestyle in which the splendor of the night sky is rarely noticed. At any one time, there are a couple dozen comets which are accessible to astronomers and amateurs, but comets which can be appreciated by the general public are relatively rare. The unexpected discovery of comet C/1996 B2 (Hyakutake) provided excellent naked-eye observing opportunities during the spring of 1996, and another, comet C/1995 O1 (Hale-Bopp), may be even more spectacular this March and April.

In this issue of **PSR Discoveries**, we will discuss the importance of studying these small solar system bodies, including the historical development of cometary science, and will discuss the discovery and upcoming apparition of comet Hale-Bopp and how to best observe it.

Hot Idea Contents

Additional Resources

Ephemeris Generators - includes sources for downloading ephemeris and finder chart software, as well as computed ephemerides for the comet.

Comet Hale-Bopp HomePages - list of alternate web sites for comet Hale-Bopp information ranging from amateur level discussions to research observations from national and international observatories.

Institute for Astronomy, Univ. of Hawaii - includes current images obtained from telescopes on Maunakea, Hawai'i.

Honolulu's Bishop Museum Planetarium - includes information on programs and viewing opportunities in Hawai'i.

Making a Comet in the Classroom - hands-on activity (in The Why Files) created by Dennis Schatz, Pacific Science Center.

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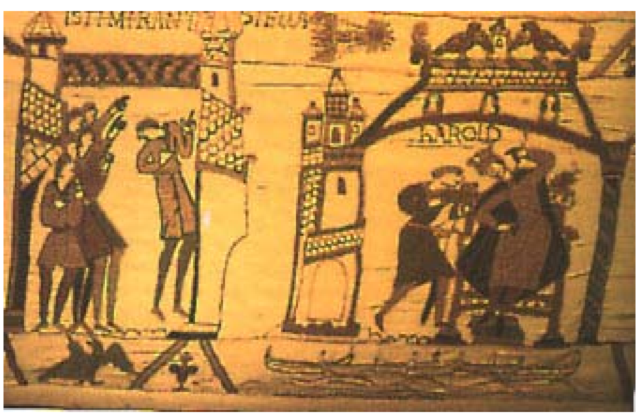
Historical Comet Observations by Karen Meech

To primitive man, a comet was something to be feared, a portent of an impending disaster. Because comets brighten relatively rapidly when they get close to the sun, and because bright comets (visible to the naked eye) are relatively rare, comets would appear in the sky suddenly and unexpectedly. In addition, near perihelion, comet tails can extend millions of kilometers in space (making them the largest objects in the solar system), thus depending on the geometry of the orbit, the tail can have a length projected against the sky which is a large fraction of the celestial sphere. In an era where the celestial realm was the realm of the gods, the sudden appearance of an unknown object which dominated the night sky was terrifying.

In the Greek Era, the nature of the comets was intensely debated, but the theme of fear was prevalent as seen in this cometary quote from the greatest Greek author of antiquity, Homer:

"[The helmut of Achilles shone] like the red star, that from his flaming hair shakes down disease, pestilence, and war" (*Iliad*, Bk. XIX, 11, 380-3).



One of the most familiar comets, Halley's comet, played a prominent role in history because of its large nucleus and therefore great brightness and longevity. In 1066 when King Harold was overthrown by William the Conquerer at the Battle of Hastings, the cause of the event seems to have been pegged on a celestial visitor as is shown by the appearance of Halley's comet in the Bayeux Tapestry (left) which chronicles the event. In 1456, on a return passage, Halley's comet was excommunicated as an agent of the devil by Pope Calixtus III, but it didn't do any good - the comet has continued to return! During this same apparition, while Turkish forces were laying seige to Belgrade, the comet was described as a fearsome celestial apparition "with a long tail like that of a dragon" which was perceived by some as being in the form of "a long sword advancing from the west ... " (Moore and Mason, 1984).

Great Comet of 1843

According to Chambers (1909), there are only a handful of comets which may be considered to be "remarkable". The list, reproduced below, comprises only 32 comets in the past 1000 years, indicating that we might expect an exceptional comet on average only 3 times per century. These remarkable comets are noteworthy for their extended visibility (including daytime visibility), and their exceptional brightness and spectacular features, which included reddish colors, multiple tails, jets and haloes.

This figure shows the Great Comet of 1843 as seen from Kent, England (Chambers, 1909). Because these comets appear suddenly and are seen by a multitude of people, nobody can be claimed as the discoverer. One of the most spectacular historical comets was the Great Comet of 1811 (Flaugergues) which was observed for an unprecedented 17 months. When discovered, it was 5th magnitude and over 2 AU from the sun. The maximum tail length was estimated to be 100 million miles. This comet attracted the attention of Napoleon as presaging his invasion of Russia, yet others wondered "what misfortune does it bring?" (Chambers, 1909).

Comets in History

Year	Comet name (if known)	Additional Comments
1066	Halley	Portent of Wm the Conqueror
1106	-	Widely visible in day - Europe & Orient
1145	Halley	Well documented by Chinese
1265	-	-
1378	-	-
1402	-	Comet visible in broad daylight
1456	Halley	Comet was excommunicated by the Pope!
1531	Halley	-
1556	Heller	-
1577	-	Observed by Tycho Brahe; tail 80 deg long
1607	Halley	-
1618	-	Tail 104 degrees
1661	-	6 degree tail & multiple nucleus structures
1680	Kirch	Max tail arc of 90 deg.
1682	Halley	Epoch of E. Halley's observations
1689	-	Discovered at sea, tail 68 deg
1729	Sarabat	Large perihelion distance
1744	De Cheseaux	Remarkable appearance with 6 tails
1759	Great Comet	Passed 0.07 AU from Earth
1769	Messier	Tail length exceeded 90 degrees
1811	Flaugergues	Unprecedented 17 mo. visibility

1823	Great Comet	Large sunward anti-tail
1835	Boguslawski	-
1843	Great Comet	Sungrazing comet
1858	Donati	Most beautiful comet on record
1861	Tebbutt	Daytime "auroral glow" reported
1874	Coggia	Unusual jet features
1880	Great S. Comet	Orbit resembles comet of 1843
1881	Great Comet	Only comet spectrum observed before 1907
1882	Great Comet	Orbit resembles comet of 1880
1887	Great S. Comet	Orbit resembles comet of 1843
1901	Great S. Comet	Brightness rivaled that of Sirius

Discovering The Nature of Comets

Comets were objects of much speculation among the early Greek astronomers, some of whom considered them to be planetary in nature, and others, such as Aristotle, considered them to be more of an atmospheric phenomena, such as meteors. The first real scientific facts known about comets were due to the observations of the great observer Tycho Brahe (1546-1601). Brahe made measurements of the position of the Great Comet of 1577 and determined from its parallax that it was a distant object, much farther away than the Moon, and therefore not an atmospheric phenomenon as many had believed. It was Edmond Halley (1656-1742) along with his contemporary Sir Isaac Newton (1643-1727) who contributed to the first physical understanding of the nature of comets. Halley's first experience with comets was with the spectacular appearance of the comet of 1680, and of the comet of 1682 (which was later to bear his name) and he became very interested in understanding how they moved. After observing these bright comets, Halley began contemplating the theory of gravitation with others at the Royal Society, but they needed a mathematical basis for their discussions. Halley approached his friend, Isaac Newton, the only man capable of working out the proof - and was surprised to learn that Newton had solved the problem many years earlier, but had lost his notes. At Halley's urging, Newton was convinced to re-work his calcuations, and Halley paid for their publication in the *Principia*. Using this, Halley was able to calculate comet orbits, and he noticed that the orbits of the comets of 1531, 1607 and 1682 looked very similar. He proposed that they were the same comet returning every 76 years, and that the comet would return in 1759. Although he died before the prediction could be verified, the comet was recovered on January 21, 1758, and it was named in honor of him (usually comets are named after their discoverers).

The next significant break-through in the fundamental understanding of the nature of comets came in 1950 with the appearance of 2 competing physical models for the comet nucleus. Lyttleton proposed the "Sandbank Model" which supposed that the comet was a loose swarm of ice and dust which developed the characteristic comet tail and coma as it was heated upon approaching the sun. In contrast, in attempt to explain the orbital behavior of periodic comet Encke, F. Whipple proposed that the comet was a solid nucleus composed of water ice and dust - a "dirty snowball". There were several pieces of evidence that suggested that the latter model was the correct one: (*i*) the survival of sungrazing comets is difficult to understand without a solid body; (*ii*) the radar echoes measured from comet Encke were interpreted as a return from a solid body; and (*iii*) the delay or advance of the perihelion passage date is best described as the result of a jet forces from localized outgassing from a solid body. Nevertheless, the Whipple comet model was not actually confirmed until the spacecraft encounters with comet Halley in 1986!

Both intense public interest in observing comets and fear over their apparitions has continued from the time of Halley and Newton. In the figure at the left the celebration of the discovery of a bright comet at Greenwich Observatory was published in *Punch* in 1906 (Chambers, 1909). At the same time people still feared comets as evidenced from the advertisements of comet pills to fend off the evils effects of the passage through comet Halley's tail in 1910, and the concern over the appearance of Biela's comet in 1872: "The fear which took possession of many citizens has not yet abated. The general expectation herabouts was that the comet would be heard from on Saturday night. As one result, the confessionals of the two Catholic churches here were crowded yesterday evening. As the night advanced there were many who insisted that they could detect a change in the atmosphere. The air, they said, was stifling..." (Chambers, 1909).

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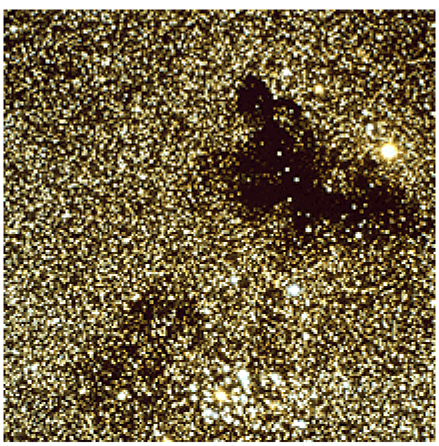
The Scientific Importance of Comets

by Karen Meech

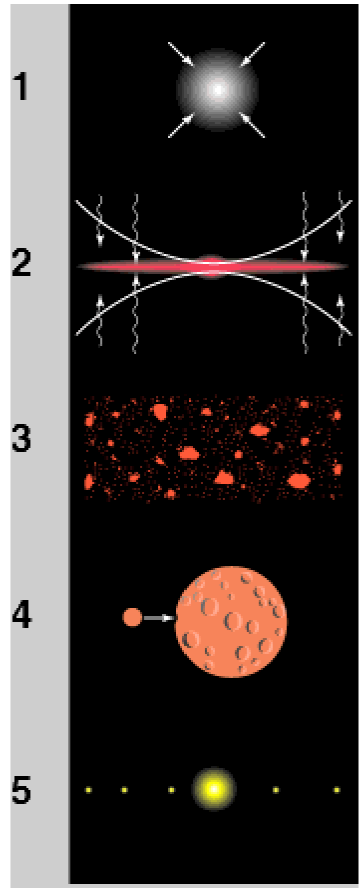
Solar System Formation

Comets are important scientifically because they represent the remnants from early in the era of the formation of our Solar System, and may provide clues to the physical and chemical conditions within the nebula out of which our Solar System formed. Comets are potentially our only direct samples of this early epoch in our history, and like the archaeologist who uses relics to piece together the chronology and structure of an ancient civilization, astronomers hope that by understanding the composition and physical structure of comets that we can constrain the models which describe the process of planet formation.

Our Solar System was formed approximately 4.55 billion years ago out of a molecular cloud - a large concentration of gas (roughly 75% hydrogen and 21-24% helium with trace amounts of other molecules) and dust grains. In addition to hydrogen (H) and helium (He), the interstellar medium (ISM) gas consists of a rich array of organic and inorganic molecules, some of which include: H_2O, CO, NH_3, CN, CO_2, OH, HCN, CH_3OH, H_2CO, CH_3C_2H, HNCO, CH_3CN etc. The dust, which comprises roughly 1% of the ISM, is made of refractory cores (silicates and carbon) coated with organics and ice. Molecular clouds are large, with diameters between 50-200 light years, and extremely cold temperatures (10-50K). Although dense compared to the surrounding ISM, their densities (10^4 to 10^5 particles per cubic cm) are about 100 million times lower than the best vacuums we can create in the laboratory.



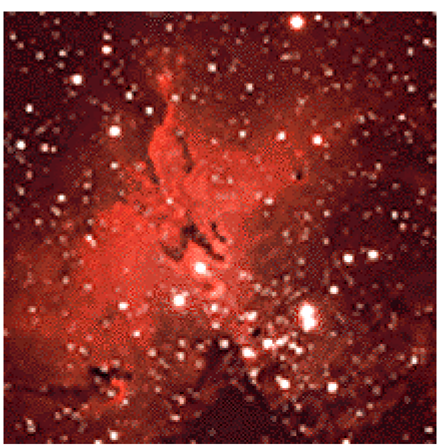
The Coalsack nebula, of Barnard 86, is what one of these dark molecular clouds might look like as the star formation process is just beginning.



(Graphic by PSRD graphic artist, Nancy Hulbirt, Univ. of Hawaii)

The process of star and planet formation (depicted in the graphic to the right) begins with the collapse of the molecular cloud **(1)**, which can be triggered by factors such as a nearby supernova explosion, or collision with another cloud. As the cloud begins to collapse, material gets drawn at an ever-increasing rate toward the center of the cloud, where it begins to heat up. At the same time, the decreasing size of the cloud causes it to spin faster (due to the conservation of angular momentum). Near the center of the cloud, where the density is the greatest, collisions between dust and gas remove energy until the particles no longer collide. This causes a general flattening of the system where the particles orbit the center in the same direction, **(2)**. This flattening occurs first near the center where the densities are the highest. During the collapse, the gravitational energy is converted to heat. At first the heat can easily escape, but as the density increases in the center, the heat cannot easily radiate away, and the temperature starts to rise. Temperatures will eventually rise high enough to break apart the molecules and vaporize of the dust in the central regions. As more and more material settles to the core and midplane of the young nebula, enough material will eventually accumulate to shield the outer regions from the growing temperatures in the central region. At this point, as the gases cool, some of the vaporized materials will re-condense into micron-sized grains, **(3)**. Closest to the central regions, to the young protostar, only high temperature refractory materials can condense, but farther from the star volatiles can also condense. Since the volatiles are the most abundant species in the original interstellar medium, they will overwhelm the refractory material farther out in the nebula. This provides a natural explanation for the difference in composition between the terrestrial planets (rocky) close to the sun, and the Giant planets (volatile-rich) farther out.

The condensing material will slowly start to clump together. Eventually, some clumps grow larger than others, becoming planetesimals, and these begin to sweep up all the other debris along their orbits about the central protostar. As the planetesimals get larger, the velocities get higher and the collisions get more violent, **(4)**. In the vicinity of the giant planets, some of the volatile-rich planetesimals get thrown into the inner solar system, bringing volatiles to the inner planets, and some get thrown out into a vast spherical swarm of small bodies surrounding the planets. The icy planetesimals which are thrown to vast distances (near 50,000 AU - the Oort Cloud) are then stored unaltered from this early epoch in the history of the Solar System, and are what we call comets today. Once the center of the nebula becomes hot enough that thermo-nuclear reactions can begin, the collapse of the nebula stops, and any remaining material (gas and dust) is blown out of the system, and the era of planet formation has ended, **(5)**. The entire process occurs relatively quickly, taking only a few million years.



The image on the left, above, of the Eagle Nebula (M16) shows a star forming region 2 million years old. The hydrogen gas is emitting light from atoms excited by newly formed hot stars. In a Hubble Space Telescope close up of the same region (at right), we get a high resolution view of the small dense regions which are embryonic stars in the process of contraction.

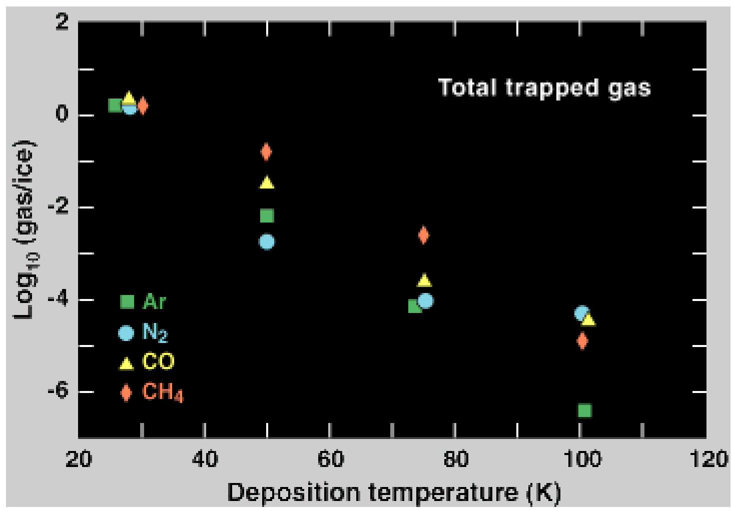
Subtleties - Comets as Cosmic Thermometers

The early models of the Solar System formation assumed that the comets (*e.g.* the icy planetesimals) formed in the vicinity of the giant planets, and that they may have contained some pristine unaltered material from the ISM. After being thrown into the Oort cloud, perturbations by nearby passing stars could alter their orbits and send them toward the inner Solar System where they would be observed as a long-period comet or captured into a low-inclination short-period cometary orbit after a close passage to Jupiter. It was believed that comets could not form too far out in the Solar System because the density of material would be insufficient for planetesimal growth. However, this scenario has changed significantly in the past few years:

- New technology, particularly in the infrared wavelengths, has permitted a detailed study of the processes of star formation. Observations of young stellar objects show that 20-50% of these objects have extended disks out to a few hundred AU associated with them. This suggests that the disks associated with the star / planet formation process are common and that they are much more massive that previously believed.

- New models of the collapse of the Solar Nebula are suggesting that because of these larger disks, comets may form much farther out in the nebula. Likewise, it may not be likely that totally pristine, unaltered interstellar grains survive the infall process. As they settle through the nebula to the mid-plane, frictional heating may vaporize the icy coating, which can later recondense on the cold grain cores at the midplane.

- Laboratory experimentation has shown that when ice condenses below temperatures of 100K, it does not develop the regular crystal structure, rather adopts an amorphous irregular structure (because there is not enough energy for the ordered crystal structure). In the amorphous phase, the water-ice can trap a large number of other molecules in the voids. The lower the temperature of condensation, the more gas can be trapped. This is shown in the graph (Owen and Bar-Nun, 1995), where it can be seen that the difference in the amount of trapped gases varies by 6 orders of magnitude between 20 and 100K. As the ice is heated, trapped gases are released as voids close up, and the release of gas may be observable as activity on the comet.



(from Owen and Bar-Nun, 1995.)

- The recent discovery of objects in the Kuiper Belt, a region between 35-50 AU (beyond the orbit of Pluto) with inclinations ranging between 0-30 degrees, has prompted a detailed investigation of the dynamics of small bodies in the outer Solar System. Dynamical models show that the short period comets, which unlike the long period comets have a flattened inclination distribution, cannot have a source in the Oort cloud, but most likely come from the vicinity of the Kuiper Belt.

Since the amount of gas trapping and release is a very sensitive function of temperature, and since we now believe that comets can form at a wide range of distances from perhaps the Uranus-Neptune zone (20-30AU) out to perhaps 50-100 AU (the Kuiper belt), observations of the activity of comets at various distances from the sun will serve as a very sensitive thermometer to probe the conditions and distances at which the planetesimals formed.

Known Extra-Solar Planets

Within the past few years, we are not only developing a new understanding of the process of planet formation from both new observational techniques and theories, but we have recently detected direct evidence of extra solar planetary systems. The first extra-solar planets detected were objects around pulsars, the ultra-dense remnants of a supernova explosion (see the first 3 listings in the table below; Wolszczan and Frail, 1992). However, during the past year, astronomers have finally discovered planets orbiting around solar-type stars (*i.e.* star systems which would be capable of supporting life). Many of the characteristics of the planets (shown in the table and figure below, from Beichman, 1996; Marcy & Butler, 1996) are challening our ideas of planet formation. The combination of new technology and high- quality observations with new theories is converging on a new more sophisticated understanding of the process of planet formation and evolution. It is believed that the detailed study of the most primitive samples we have from the era of our Solar System's formation, the comets, will contribute greatly towards our understanding of these processes.

Table of Known Extra-Solar Planetary Systems

Star System Name	Temp [K]	Mass [MJup]	a [AU]	Period [yr]	Dist [pc]	Spectrum
PSR1257+12	20,000	0.015	0.19	25.34dy	491	Pulsar
-	-	3.4	0.36	66.54dy	-	-
-	-	2.8	0.47	98.22dy	-	-
PSR1828-11	20,000	3	0.93	0.68	-	-
-	-	12	1.32	1.35	-	-
-	-	8	2.1	2.71	-	-
PSR1620-20	20,000	10?	-	100?	-	-
Beta Pic	7,000	1-10	2.5-8	2-19	16.4	-
51 Peg	5,770	0.46	0.005	4.2 dy	15.3	G2-3V
55 Cancri	5,570	0.8	0.11	14.8dy	13.0	-
-	-	5	>5	1-20	-	-
Lalande 21185	3,580	0.9	2.3	5.8	2.5	M2
-	-	>1	7	30.1	-	-
Ups And	6,200	0.6	0.054	0.126	16.6	F8V
47 UMa	5,880	2.39	2.1	2.98	14.1	G0V
Tau Boo	6,300	3.87	0.046	3.3dy	18.4	F7V
70 Vir	5,490	6.6	0.43	116.7dy	18.1	G4V
HD 114762	6,100	10	0.41	84dy	-	F9V
16 Cyg B	5,800	1.5	1.68	2.2	26.1	G2.5V
Gleiss 229	3,720	>20	>44	-	-	-

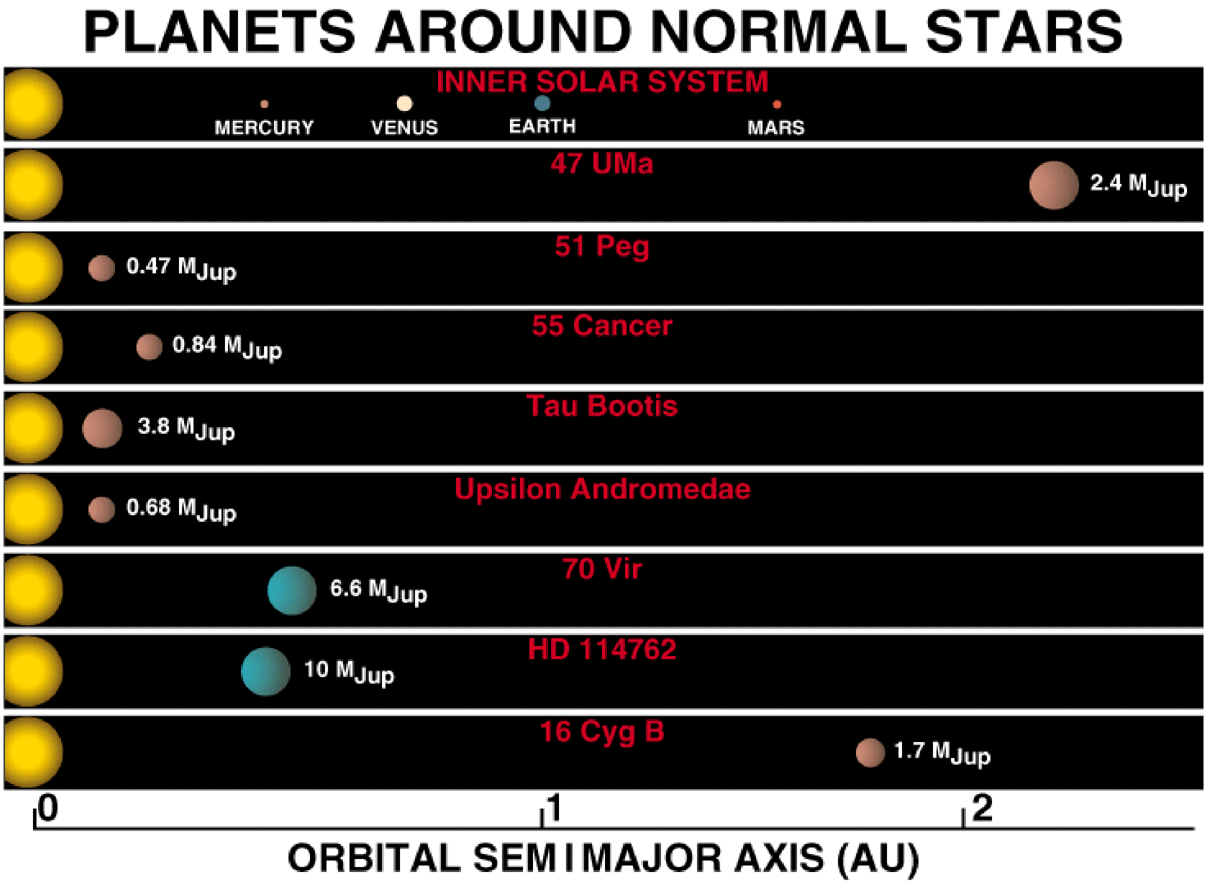


Figure Credit: NASA ExNPS report, updated by the San Francisco State University Astronomy Department.

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Hot Idea posted February 14, 1997 (updated March 24, 1997)

1997 Apparition of Comet Hale-Bopp
Discovery of Comet Hale-Bopp

by Karen Meech

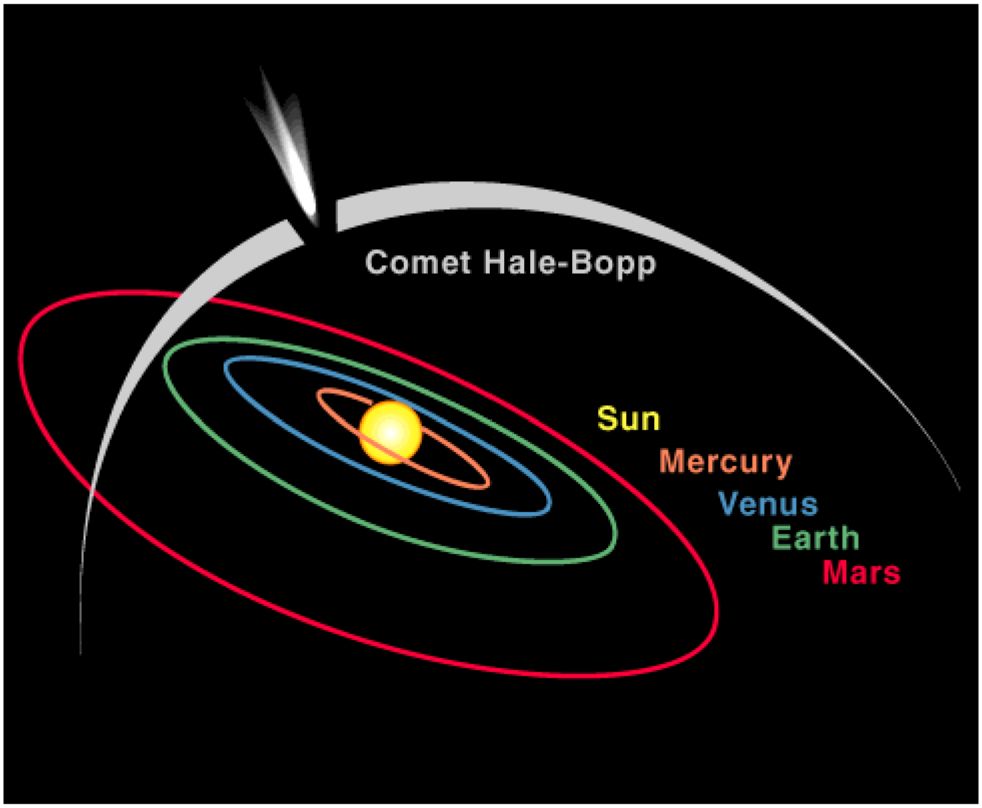
The comet was discovered independently by two amateur comet observers: Alan Hale (New Mexico, and a professional astronomer by trade), and Thomas Bopp (Arizona), on July 23, 1995. At discovery, the comet was near magnitude 10.5 - which is not unusual for comets discovered typically within 1-2 AU from Earth. However, the slow motion of the comet against the background stars suggested that this comet was very far away, making the brightness very unusual. It was the brightest modern comet discovered by amateurs, appearing nearly 50,000 times brighter than comet P/Halley did as it approached the sun at the same distance.

Both observers were waiting for other objects to rise and were passing time by looking at some deep sky objects (globular clusters of stars) in the constellation of Sagittarius. It was immediately apparent that there was a fuzzy object in the field that was not on the usual star charts, and after confirming that the object was moving against the background stars, both observers reported the discovery to the Central Bureau for Astronomical Telegrams in Cambridge, MA. Once it was confirmed that this was a new comet, it was given the designation C/1995 O1 (Hale-Bopp).

Comet C/1995 O1 (Hale-Bopp)

Event	UT Date	r [AU]
Discovery	07/23/95	7.14
Pre Discovery Image	04/27/93	13.04
Earth Closest Approach	03/22/97	1.315
Perihelion	04/01/97	0.914

The table above shows some of the important dates and distances for the comet. On August 2, 1995, shortly after its discovery pre-discovery images were found on photgraphic plates taken at the Anglo-Australian Observatory on 4/27/93, when the comet was 13.1 AU from the sun. The image showed that the comet was active (*i.e.* had a coma and tail) even at this distance. Because of the long time baseline of the observations, it was possible to quickly determine an orbit. It was found that the last perihelion passage of the comet was nearly 4200 years ago, and that in the absence of non- gravitational forces, it should next return in approximately 2380 years. This suggests that the comet is not making its first passage close to the sun from storage in the Oort cloud. It is interesting to note that the orbit of comet Hale-Bopp (see figure below) is very similar to that of the Great Comet of 1811.

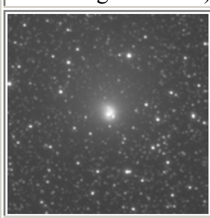


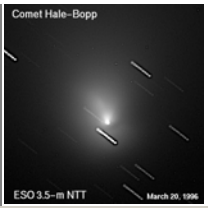
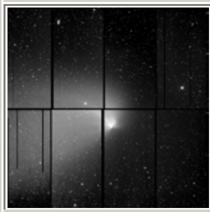
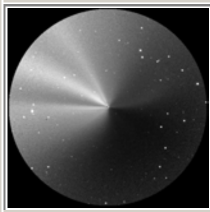
(Modified from an illustration by Larry Koehn. http://www.shadowandsubstance.com)

Comparison of the Orbits of comet Hale-Bopp and the Great comet of 1811

Comet	Perihelion Date	Period	Perihelion	Eccentricity	Inclination	Arg. of Perihelion	Ascending Node
C/1995 O1	1997 04 01.146	2380 yr	0.914 AU	0.995	89.4	130.591	282.471
1811 I	1811 09 12.756	3065 yr	1.035 AU	0.995	106.9	314.502	95.631

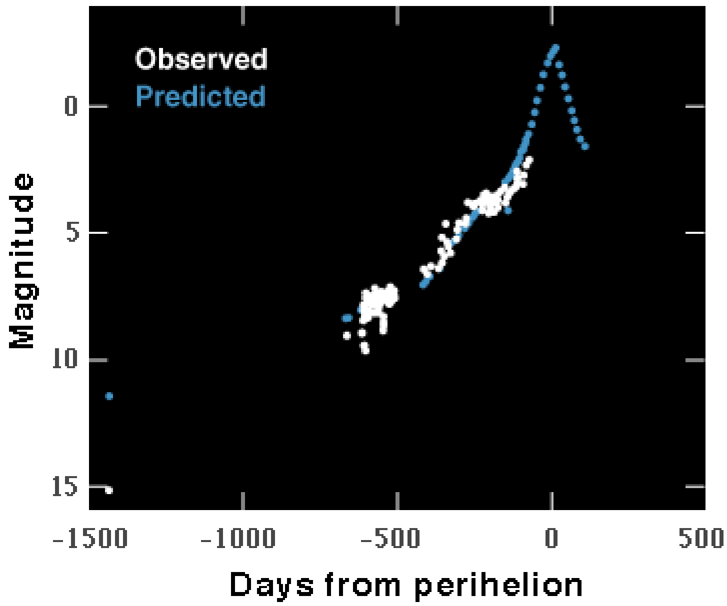
Chronology of Changes in comet Hale-Bopp

Image (click on it to see a larger version)	Date	r [AU]	Telescope	Observer	Exposure Info.
	8/25/95	6.9	La Palma, 1-m Kapteyn Telescope	A. Fitzsimmons	The jet was observed during 5 nights in August, with no significant change in the direction of the jet. The image is an R-band CCD image
	9/26/95	6.6	Hubble Space Telescope	H. Weaver	7" field of view, clump from nucleus ejected 60 hrs earlier is visible. Material is expanding from nucleus at 30 km/sec.

	3/20/96	5.3	European Southern Observatory 3.5m New Technology Telescope	O. Hainaut, R. West	Nine 1-min R-filter images from the SUSI high resolution camera are combined in this image.
	09/17/96	3.1	Canada France Hawaii 3.6m Telescope	K. Meech, O. Hainaut, J. Bauer	UH 8K CCD Mosaic camera (largest mosaic in the world) composite image, R filter, 2 min (tail) 15 s (core). Image processed by O. Hainaut.
	11/12/96	2.4	UH 2.2m Telescope on Mauna Kea	K. Meech, O. Hainaut, J. Bauer	R filter, 10 s. Jets were enhanced by subtracting off a coma varying inversely as the distance from the nucleus. Image processed by O. Hainaut.
	02/17/97	1.18	UH 2.2m Telescope on Mauna Kea	K. Meech, O. Hainaut, J. Bauer	R filter, 0.5 s. Jets near the core enhanced by subtracting off a heavily smoothed version of the image (unsharp masking). Image FOV is 2.5 arcmin.
	3/6/97	1.03	50-mm telescope, f/2.0 lens	D. Bridges	4 min. exposure with Fujicolor SG+40 film, by amateur observer, shows well-developed plasma (blue) tail, and dust tail.
	3/9/97	1.00	Meade 12-inch, LX 200 telescope, f/6.0 lens	T. Puckett	AP-7 CCD camera composite of twenty-seven 30-second exposures.
	3/12/97	0.98	180 mm lens from Koenigsleiten Austria	P. Stattmayer	12 min. exposure on Kodak Pro Gold 400 emulsion.

What Do We Know About Hale-Bopp So Far?

Brightness - The brightness of comet Hale-Bopp has been exceptional, and the predictions indicate that it could rival the Great Comet of 1811. The Great Comet of 1811 was observed for an unprecedented period of 17 months (naked eye), and at the time of its discovery, it was around 5th magnitude at a distance of 2 AU from the sun. Comet Hale-Bopp reached this brightness at a distance of 3 AU from the sun. The observations of Hale-Bopp are shown in the figure below, with the white points showing the observed brightnesses (reduced to unit geocentric and heliocentric distances) and the blue points the predicted brightness based on its behavior so far. The brightness is steadily increasing, although more current predictions place the peak brightness between -0.5 and -1.0; not quite as bright as shown in the figure.



(Graphic by Karen Meech.)

How fast a comet will brighten as it approaches perihelion will depend on the type of orbit it has. Comets which have been close to the sun before tend to brighten much more quickly than those comets which are making their first passage, however, in both cases there can be unexpected brightness outbursts which can make predicting the increase difficult. Astronomers have also never observed a comet in this type of orbit so far before its perihelion, which makes predicting the brightness more difficult. Typically a comet's visual brightness may be represented by a power-law formula:

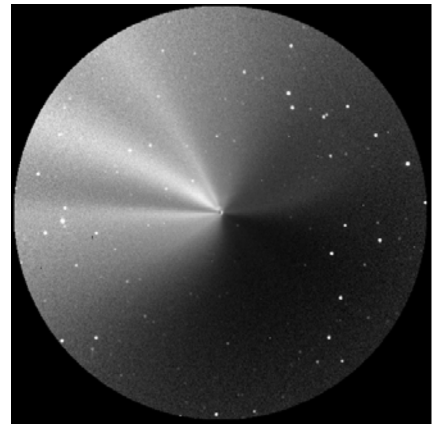
$$\text{mag} = \text{absolute mag} + 5 \log(\Delta) + 2.5\, n \log(r)$$

where the absolute mag is related to the size of the nucleus, delta is the geocentric distance, and r is the heliocentric distance. The value of n determines how fast the comet is brightening. The early observations suggested n=4, then the brightness leveled off, and now the comet is brightening with n=3, however, the comet should not be a disappointment.

Nucleus Size - Because of the great brightness, many believed that the comet may have an extremely large comet nucleus (for example the average radius of comet P/Halley was about 5 km). A team of astronomers lead by H. Weaver (Johns Hopkins University) has used the Hubble Space Telescope to get high resolution images of the inner region of dust (with resolutions of less than 500 km per pixel or detector element) surrounding the nucleus. They have used the high resolution images to model and subtract off the light contributed by the dust in the image core to infer that the nucleus is less than 40 km in diameter. This makes the nucleus large, but not exceptional in size. Ratio data taken in early March with the IRAM interferometer (Wink *et al.*, 1997) also confirm this size since the signal they detected can by accounted for by a 380K sphere with a diameter of 45 km emitting radiation.

Activity Level - The comet was active (*i.e.* producing gas and dust) when discovered at 7.1 AU, and there was coma even in the pre-discovery image from 13.0 AU. Since the amount of solar radiation is too low at these distances to heat water-ice enough to initiate sublimation, it was known early on that other volatiles were playing a role in the activity. The first detection of CO was made at 6.6AU (Jewitt, *et al.*, 1996), with the comet producing 1300 kg/sec of CO gas. In comparison, comet P/Halley attained a water production rate this high only near 2 AU! Between 4.7-4.1 AU the CO production flattened out, and the production of OH (a fragment of the water molecule) increased (Bockelee-Morvan, 1996). As the comet neared 2.4 AU, there was a rapid increase in water production. One of the first molecules usually detected in a comet is the CN molecule, which is typically released along with the sublimating water. In the case of comet P/Halley, this was first seen at the unusually large distance of 4.8 AU from the sun. In contrast, during August of 1995 the production of the CN molecule was measured at a distance of 6.8 AU. There is an indication from observations from Lowell Observatory in Arizona that in early March the gas progection began to level off. Additionally, dust production was increasing at a slower rate than the trends in mid-January and February.

Dust Level - Early measurements of the dust production, near 6.8 AU (A'Hearn *et al.*, 1995), give the largest value ever observed. Because the comet is very dusty compared to other comets, the expectation is that it should develop a nice dust tail, unlike comet C/1996 B2 - Hyakutake, which displayed a prominent gas tail.



Dust Jets and Nucleus Rotation - Beginning around May 1996 observers began reporting strong jetting activity from the comet - consisting of several straight jets, which changed very little in appearance throughout the summer and fall. Jet Propulsion Laboratory scientist, Z. Sekanina (1997) has recently interpreted the jets as being boundaries of fan-shaped formations where dust is being ejected from 3-4 discrete active sources on the rotating nucleus. In the image at the right, a technique similar to that used by H. Weaver to estimate the nucleus size was used on this image of comet Hale-Bopp obtained using the UH 2.2m telescope on Mauna Kea (O. Hainaut). By removing the smooth coma variation, the jets stand out dramatically. Observations of the dust jets made in January and February, 1997 by astronomer J. Lecacheux at the Observatory of Paris (Meudon) showed that the comet nucleus is rotating with a period near 11.5 hours. Observations by Italian astronomers the following month confirmed this rotation period by looking in the infrared at shells (which are formed by periodic ejection of gas and dust as an active source rotates into and out of the sunlight). The Italian astronomers deduced that the dust was leaving the nucleus at a velocity of about 0.35-0.45 kilometers per second. Results, published on March 11, 1997 by Jorda and others in the International Astronomical Union Circulars, from observations by French and German astronomers using the Pic du Midi telescope in France suggest that the comet may exhibit complex rotation - that the rotation period is changing between 11.2 and 11.6 hours on a timescale of 22 days. This is like a top which has not only a simple rotation about its axis, but which also has a wobble, and may be caused by uneven outgassing from the jets.

Organic Molecules - Organic molecules are being detected in both the radio wavlengths and in the infra-red and are so far providing exciting information on how similar the comet nucleus material is to the material in the interstellar medium. Below is a table of the discoveries and the implications.

Molecules Discovered in comet Hale-Bopp

Formula	Molecule	r [AU]	Reference	Significance
CO	Carbon Monoxide	6.6	Jewitt *et al.*, 1996	Producing 1300 tons/sec, compared to the production of water from P/Halley of 1000 tons/sec at 2AU
HNC/HCN	Hydrogen Cyanide	2.1	Matthews *et al.*, 1996	The isomer HNC is unstable, and the ratio is consistent with interstellar cloud origin.
HCN/DCN	Hydrogen Cyanide	1.2	Matthews *et al.*, 1997	D/H (deuterium/hydrogen) ratio is not enriched with respect to ISM as many comets have been.
HNC/HCN	Hydrogen Cyanide	1.196	Lis *et al.*, 1997	Abuncance is 0.25.
HNC/HCN	Hydrogen Cyanide	1.003	Apponi *et al.*, 1997	Abundance is 0.5.
H_2CO	Formaldehyde	1.6	Womack *et al.*, 1997	Ortho-Para spin state ratio - is similar to that observed in interstellar clouds. However, the interpretation of these observations is being contested.
H_2O:CO:C_2H_6	Water:Carbon: Monoxide: Ethane	1.5	Mumma *et al.*, 1997	Abundance ratios similar to other comets for water:CO, and a little low for water:ethane from the only other comet (Hyakutake) where it has been detected.
14N/15N	Nitrogen isotopes	1.2	Matthews *et al.*, 1997	Isotopic ratio is compatible with values seen on Earth.
HCO+	---	1.17	Veal, 1997	First detection in comets.
HCO+	---	1.165	Veal, 1997	First detection in comets.
SO	Sulfur monoxide	1.15	Lis *et al.*, 1997	First secure detection in a comet.
CH_4 C_2H_2 CH_3OH	Methane Acetelyne Methanol	1.124	Mumma *et al.*, 1997	Molecules were detected in the infrared, and are most intense at the nucleus.
---	Organics	1.03	Mumma *et al.*, 1997	Continuum is very strong - may be a signature of organic material.
SO_2	Sulfur dioxide	0.949	Wink *et al.*, 1997	First detection of molecule in comets. The molecule does not originate primarily from the nucleus.
HCOOH	Formic Acid	0.94	Wink *et al.*, 1997	Abundance is 50 times lower than for the related molecule, methanol.

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PLANETARY SCIENCE RESEARCH PSRD Discoveries

Hot Idea posted February 14, 1997 (updated March 24, 1997)

1997 Apparition of Comet Hale-Bopp
What We Can Learn from Bright Comets

by Karen Meech

Although there is uncertainty as to how bright comet Hale-Bopp will be at perihelion and there is no consensus as to whether or not it will be the "Comet of the Century", it is clear that this it will be a bright comet. Comet P/Halley may have been the most important comet scientifically this century because of the armada of spacecraft and intense ground-based observing effort, and certainly other comets have been better placed in the sky for viewing by the general public (including comet Hyakutake last spring), however, comets which are bright naked eye objects *and* are visible for several months from the northern hemisphere are very rare! This will make this an important comet both scientifically and for the public no matter what the final brightness. There are many scientific experiments which can only be done with very bright comets, either because we are spreading out the light into very small increments and therefore need a bright object (*e.g.* spectroscopy), or because the instrument technology is not as advanced as in other areas (*e.g.* in the infra-red, for detecting molecules).

Some examples of unique science which can only be done with a bright comet are discussed below for the case of comet C/1996 B2 (Hyakutake), and plans for coordinated observations of comet C/1995 O1 (Hale-Bopp) are described.

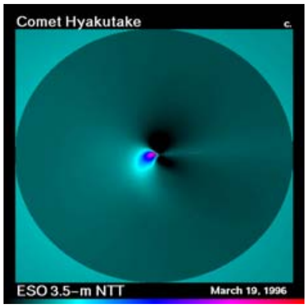
Comet Hyakutake

Comet Hyakutake was discovered on January 31, 1996 at about 11th magnitude. Like comet Hale-Bopp, the comet is not fresh from the Oort Cloud, having last passed close to the sun about 8,000 years ago. In addition, the comet was not unusually large, nor was it instrinsically an especially active comet. What was notable about this comet was the fact that its orbit (see the table below for a comparison of the orbital parameters of comet Hale-Bopp) carried it very close to Earth, passing within 0.102 AU (15.3 million km) on March 25, 1996. This provided an opportunity for astronomers to observe a bright comet (because the reflected light intensity depends on the square of the distance from the object), and to get much better resolution since the comet was so close. The first tail observations were reported during mid-February, and near the time of the closest Earth approach, the tail was reported to be as long 100 degrees! Few historical comets have had tails this long. Unlike most comets which boast prominent dust tails, this comet was not very dusty, so it had a low surface-brightness gas tail.

Comparisons for C/1995 O1 Hale-Bopp and C/1996 B2 Hyakutake

Comet	Perihelion Date	Period	Perihelion	Eccentricity	Inclination	Arg. of Perihelion	Ascending Node
C/1995 O1	1997 04 01.146	2380 yr	0.914 AU	0.995	89.4	130.591	282.471
C/1996 B2	1996 05 01.396	29,270 yr	0.230 AU	0.999	124.9	130.2	187.3

Nucleus Size - Because comet Hyakutake was passing so close to the Earth, astronomers had the unique opportunity to observe the nucleus directly by bouncing radar off the surface. S. Ostro (JPL) used the Goldstone Antenna to observe the comet on March 24 and 25, 1996. From the returned echo he was able to estimate a size for the nucleus of only 1-3 km, making the comet relatively small. Comparing the amount of dust and gas being produced to that of P/Halley, which had only 10% of the surface active, it was determined that a large fraction of this comet was outgassing (approximately 60%).



Jets and Rotation Rate - Observations during early March, 1996 from the European Southern Observatory (ESO; Chile), Pic-du-Midi in France, and other sites showed spectacular curved dust jets which were time-variable. Both the jets and observations made through narrow bandpass filters to isolate the light from either the dust or specific molecules showed that comet Hyakutake's brightness was changing on a timescale of 6.3 hours, probably due to nucleus rotation, and a single strong jet. The image at the right shows a false color image of the comet's inner coma which shows a prominent jet. The image was obtained with the ESO New Technology Telescope on March 19, 1996 (ESO Press Photo 25c/96). See larger version.

Fragmentation - During March, 1996, strong dust jets were reported in the inner coma of comet Hyakutake, and telescopes from sites with high resolution capabilities were reporting "knots" or "flakes" of material o moving away from the nucleus at velocities of 10-20 meters/sec. This type of behavior had not been seen before, but was interpreted as small pieces of the comet's surface flaking off. The image at the left from the Hubble Space Telescope taken on March 25, 1996 shows an image 3340 km across. Pieces which have broken off the comet and are forming their own tails are seen at upper left. Individual fragments could be traced from night to night in the images from the different observatories. See larger version.

Molecule Detection - Perhaps some of the most exciting discoveries with comet Hyakutake were the detections of many new molecules in the coma using radio telescopes and infra-red telescopes. Among the molecules discovered include a large suite of organic compounds such as methanol (CH_3OH), methyl cyanide (CH_3CN), hydrogen cyanide (HCN), formaldehyde (H_2CO), methane (CH_4), ethanol and ethane (C_2H_6). The ethane discovery was particularly exciting as this molecule had never before been seen on a comet. The relative abundance of ethane and methane were consistent with thermodynamic equilibrium, and suggested that they formed in a warm high-pressure region, which is inconsistent with our ideas of how comets formed. It is possible that maybe these comet constituents formed near the giant planets, say in a sub-nebula near Jupiter. However, if this interpretation is not possible, then a revision of the current astrochemical models may be needed since production of these molecules is believed to be inhibited in the ISM.

The Table below highlights some of the observed gases on comet Hyakutake and compares them to what we know about other comets and the ISM. The study of the abundance of many of these molecules, possible only with bright comets in many cases, is contributing greatly to our understanding of the origins of comets.

Comet and ISM Composition Comparison

Species	T_s*	ISM-Gas	ISM-Dust	Most Comets	P/Halley	Hyakutake	Hale-Bopp	Implications
H_2O	152	100	100	100	100	100	100	-
CH_3OH	99	4-5	1	1-5	1.5	0.023	0.049	Consistent with grains in ISM cloud cores
HCN	95	2	-	0.02	0.1	-	-	-
NH_3	78	1	10	0.1-2	0.1-2	0.25	-	Consistent with molecular clouds
CO_2	72	10	0-3	-	2-4	5	-	-
H_2CO	64	0.2-1	-	0.5	0-5	0.002	-	Variable in P/Halley
CH_4	31	0.2-7	0-5	0.02	-	0.7	-	First good detection in Hyakutake
CO	25	1000	13	1-7	7	5-5.8	6.4	Distributed source and nuclear source in Halley
N_2	22	10-1000	-	0.1	5	-	-	-
S_2	20	-	-	0.03	-	0.01	-	Seen in only 1 comet before
C_2H_6	-	-	-	-	-	0.4	0.13	Could be a lower limit
CH_4:CO	-	0.001-0.003	0.13-2.4	-	-	0.12	-	-

* T_s = Sublimation Temperature

Observing Plans for Comet Hale-Bopp

Because the comet is expected to be very bright, a large number of astronomers are planning observations of the comet. When a comet is bright, a large number of different observing techniques in different wavelength regimes may be used to investigate different aspects of cometary physics. Below are selected programs from some of the major teams which routinely observe bright comets.

At the Lowell Observatory astronomers D. Schleicher, B. Millis and T. Farnham are undertaking an extensive long-term observing campaign of comet Hale-Bopp. Schleicher and Millis are experts in the photometric observation of bright comets, and were key observers in the campaign to determine the rotation period of comet P/Halley when it was near perihelion in 1986.

- Narrowband Photometry every 2 weeks to measure how much dust and how much of each of several gas species is being produced as a function of time. This will help astronomers determine if there are differences in composition and amount of gas produced when compared to other well-observed comets.
- Narrowband CCD imaging every 10 days will be used to study the structure in the coma. In particular they will be looking for the number and location of active areas called jets, and will use these observations to try to determine a rotation period for the comet.

A team of comet scientists, lead by M. Mumma (Goddard) has been very active at looking at comets in the infra-red wavelengths to try to discover the composition of the parent molecules in the comet. The team (consisting of: N. Dello Russo, M. DiSanti, M. Fomenkova, K. Magee-Sauer, B. Novak, D. Reuter, and Y. Pendleton) plans to use the NASA Infrared Telescope on Mauna Kea in late January, late February and mid-April to do the following:

- Detection and monitoring of the abundance of organic species and water molecules, as well as CO. The first detections of CO were made in June of 1996, and organics in September of 1996.
- Mumma and Vladimir Krasnopolsky have also been studying X-rays from the comet in an ongoing program to try to understand the mechanism which produces the X-rays.

Astronomer Harold Weaver, at the Johns Hopkins University has specialized in the observation of bright comets using the Hubble Space Telescope (HST) Facility. Since 1995 Weaver and his collaborators have been monitoring the comet with the HST which can achieve superior resolution compared to ground-based instruments, which allows astronomers to study jets in the inner coma. His specific observing plans include:

- In collaboration with M. A'Hearn, C. Arpigny, J. Brandt, P. Feldman and A. Stern, Weaver plans to resume his monitoring of the comet beginning in late-August 1997. It will not be possible to observe the comet near perihelion because the HST has solar elongation exclusion limits of 50 degrees. Originally the team had hoped to get an exception to this limit and point the telescope closer to the sun during the first two weeks of March, 1997, but it is unlikely that these will be allowed.
- In addition, Weaver will be collaborating with others (T. Brooke, G. Chin, S. Kim and J. Davies) to use the NASA Infrared Telescope Facility in early march to search for organic molecules (acetylene - C_2H_2, ethylene - C_2H_4, and methane - CH_4). The presence of these organic materials are strong indicators as to how much of the original interstellar matarial is preserved in the comet.

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PLANETARY SCIENCE RESEARCH PSRD Discoveries

Hot Idea posted February 14, 1997 (updated March 11, 1997)

1997 Apparition of Comet Hale-Bopp
Observing Comet Hale-Bopp

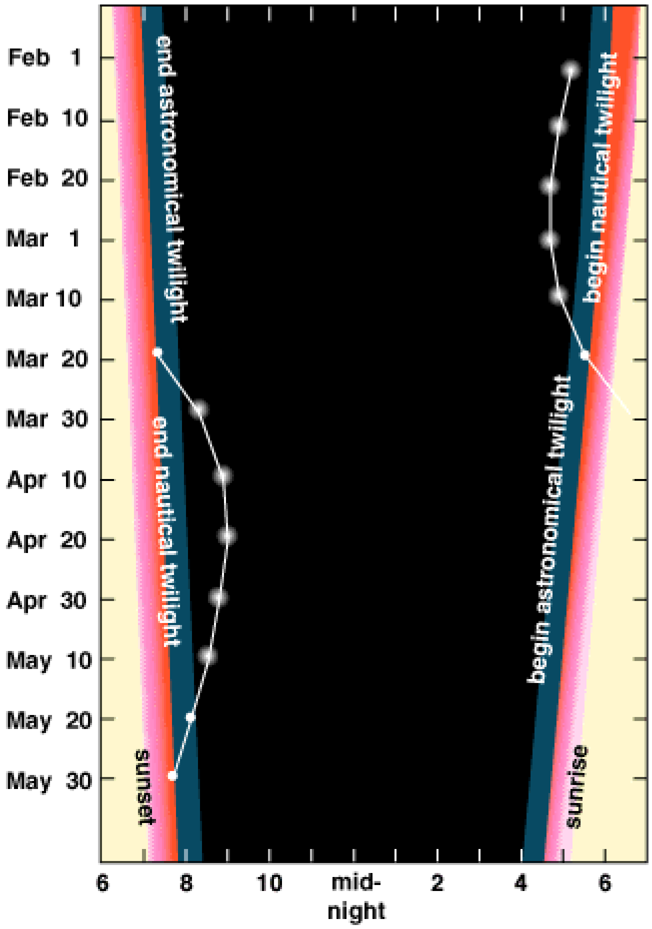
by Karen Meech

Binocular and naked-eye views of the sky from the darkest location possible should result in some satisfying comet-watching. Consult local astronomy groups and newspapers for details on viewing comet Hale-Bopp where you live. Or link now to **PSR Discoveries** visibility tables for Denver or New Orleans.

A Comet Hale-Bopp Positions generator [was] also available on-line from the United States Naval Observatory, Astronomical Applications Department. The position of the comet during twilight can be obtained for any location in local time.

Observing Opportunities from Hawaii

The comet moves fairly far north when it is at its brightest, and will not therefore be optimally placed for viewing from Hawai`i, however, it should be visible in the morning skies in February and March, and in the evening skies during April and May. The figure and table, below, show the visibility from Hawai`i.



(Karen Meech, Univ. of Hawaii.)

In the figure, solid circles indicate when the comet rises (in the morning) and sets in the evening. The sunrise and sunset on each date are shown as heavy lines, and the other 2 lines represent the beginning (in the morning) or end (evening) of nautical twilight (NTwi) and the beginning (morning) or end (evening) of astronomical twilight (ATwi). The comet should be easily visible during the astronomical twilight, and may be visible well into the nautical twilight (note, civil twilight is not plotted).

The table indicates that the comet will not be very high above the horizon while the sky is quite dark, *i.e.* during astronomical twilight. The best time to see the comet from Hawai`i from this point of view will be near Feb 20 in the morning (between 5-5:30) and again in mid April in the evening at the end of twilight. The times in the table should be accurate to about 5 minutes, but will depend on the geometry of the observer's horizon. The magnitudes were based on an early extrapolation of the lightcurve. However, after the brightness seemed to stagnate from July through October 1996, again brightening in November, some astronomers are being more conservative in the maximum brightness prediction, suggesting it may reach between -0.5 and -1.0.

Visibility of Comet Hale-Bopp from Hawaii

(revised on 11 March 97)

* see below for other localities

Date	**Comet Rise**	**Beg ATwi**	**Altitude**	**Beg NTwi**	**Altitude**	**Sunrise**	**Mag**
Feb 01	5:15 am	5:41 am	11.4 deg	6:07 am	17.4 deg	6:47 am	
Feb 10	4:58 am	5:39 am	14.8 deg	6:05 am	20.8 deg	6:45 am	
Feb 20	4:44 am	5:33 am	16.0 deg	5:59 am	21.7 deg	6:39 am	
Mar 01	4:42 am	5:29 am	15.1 deg	5:54 am	20.2 deg	6:33 am	
Mar 10	4:54 am	5:22 am	10.7 deg	5:48 am	15.5 deg	6:25 am	-0.1
Mar 20	5:32 am	5:14 am	-	5:40 am	06.7 deg	6:17 am	-0.5
Mar 30	-	5:03 am	-	5:30 am	-	6:09 am	-0.6
Date	**Comet Set**	**End NTwi**	**Altitude**	**End ATwi**	**Altitude**	**Sunset**	**Mag**
Mar 20	7:14 pm	7:21 pm	-	7:46 pm	-	6:41 pm	-0.5
Mar 30	8:14 pm	7:23 pm	12.8 deg	7:50 pm	08.3 deg	6:46 pm	-0.6
Apr 10	8:48 pm	7:28 pm	19.5 deg	7:53 pm	14.6 deg	6:47 pm	-0.4
Apr 20	8:55 pm	7:31 pm	21.1 deg	7:58 pm	15.5 deg	6:51 pm	0.0
Apr 30	8:43 pm	7:35 pm	18.8 deg	8:03 pm	12.9 deg	6:53 pm	0.5
May 10	8:25 pm	7:39 pm	14.5 deg	8:07 pm	08.2 deg	6:57 pm	1.1
May 20	8:02 pm	7:45 pm	08.1 deg	8:14 pm	-	7:02 pm	1.7
May 30	7:36 pm	7:49 pm	-	8:20 pm	-	7:07 pm	2.2

Visibility of Comet Hale-Bopp from Denver or New Orleans

Where to Find Comet Hale-Bopp

Click on the buttons below to bring up the finder chart for the desired month.

February. The comet should reappear after solar conjunction in the morning skies in late January. It will be difficult to observe during early February, accessible only during the early morning twilight hours. At the beginning of the month, the comet will have a declination of only +15 degrees, and be found just north of the constellation Aquila. During the month the comet will brighten rapidly and move north.

March. During the month of March, the comet will brigthen to something easily accessible to the general public, as it moves closer to the sun. It will move toward being visible in the evening sky late in March. The comet will be passing south of the prominent constellation of Cygnus towards Andromeda. On the date of its closest approach to Earth, March 22, the comet will be just NW (by several degrees) of the Andromeda nebula (M31) which will just be rising in the twilight.

April. During late March and early April the comet will be visible in the northwest sky just after sunset, and it should be approaching its maximum brightness. During the month, the comet will move from Andromeda to Perseus and Taurus, and during the last week it will be located just east of the star cluster the Pleiades. During late April the moon will interfere with observations as the comet fades.

May. The dust tail development should peak during May and June, but the comet will probably be lost to observation by the general public during the month. The comet begins to move south, by late June passing south of the celestial equator. During the fall, the comet will be accessible by binocular or small telescope to southern hemisphere observers only, as it reaches a maximum southern declination of -65 degrees during January 1998.

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