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COMETS

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Abstract

This seminar discusses the basic principles of comets. We first discuss their origin, classification and types of orbits. Short-period comets usually originate from trans-Neptunian region called Kuiper belt, and long-period comets originate from spherical region $\sim 10^5$ AU away from the Sun called Oort cloud. Further on, the basic physical properties of cometary nucleus, coma and tails are discussed. Finally, The Great Comets of the last two centuries are presented.

Contents

1 Introduction

> “`When beggars die, there are no comets seen:`
> `The heavens themselves blaze forth the death of princes.`”
>
> Calphornia in *Julius Caesar*

The apparition of a bright comet on the night sky is one of the most spectacular phenomena a human race can witness. Systematic astronomy, which first appeared during the third millennium BC on the ancient land of Shinar (now mostly modern Iraq), and astronomy, first recognized as a science in the ancient city of Babylon during the second millennium BC, has left us numerous records that contain a wealth of detailed information on a variety of astronomical topics, including the observation of comets. Even though that modern word ’comet’ is derived from a Greek word $\kappa o\mu\eta\tau\eta\zeta$ meaning ’long-haired one’ [1], Man was interested in comets long before the time of the Greeks. First observations of comets were made purely to predict future events.

Nevertheless in parallel of comet observations the theories of its origin were also developed. The one that persisted for almost two millennia was the atmospheric theory of comets first proposed by Aristotle around 350 BC. Aristotle proposed that comets, shooting stars, and even regions of the Milky Way were fiery atmospheric phenomena produced by violent winds at the top of the atmosphere. With the arrival of Copernicus and with the development of theory of orbits, Aristotle proposal was forgotten. Suprisingly, Kepler (and as Newton later believed) first proposed that comets move in straight line. This theory was later proven wrong by Halley, who realized that a bright comet which appeared in 1682, could be on the same elliptical orbit as that followed by comets in 1378, 1465, 1531 and 1607 [1]. Although that orbital periods were not the same, it was discovered that comet changed its orbit slightly when (and only when) it passed close to one of the giant planets. Newton’s laws were then used to estimate the gravitational effect of these encounters. Halley calculated that past observations refer to the same comet - Halley’s comet with an orbital period of 76 years.

In the 1950’s, at the same time as Oort was proposing his comet-cloud concept, Fred Whipple developed a new model for the structure of the cometary nucleus [2]. To that time, comets were believed to be structured the same as meteors, which were basically a swarm of dust grains or a discrete ball of ices and meteoric material. Whipple proposed that comets resembled a ’dirty snowball’ with radius of a few kilometers. Under the influence of solar heating the more volatile species would undergo sublimation and stream away from the comet in gaseous form, carrying with them the less volatile ices and meteoric dust. Whipple’s drity snowball model was first argued by some who thought that the nucleus might not even exist and that the meteor model fitted the observations equally well. Whipple’s model was widely accepted when Giotto probe photographed Halley’s nucleus from close range in 1986.

2 The classification, orbits and origin of comets

> “`There are three kinds of lies: lies, damned lies, and statistics.`”
>
> *Disraeli*

2.1 The classification of comets

Before we discuss the structure of comets, let us first clarify where comets come from and how are they classified.

Comets are classified by their orbits as long-period and short-period comets (Table 1 lists some selected short-period comets). Short-period comets have orbital period less than 200 years instead of long-period comets that have an orbital period larger than 200 years and can extend even to more than 10^7 years. 60% of short-period comets have an orbital period of about 5 to 6.5 years and have aphelia near the orbit of Jupiter and, to a lesser degree, Saturn [3]. It is worth noting that measurments show that key isotopic ratios (^{12}C:^{13}C, ^{14}N:^{15}N, and ^{32}S:^{34}S) of comets are consistent with Solar System values. From these we can conclude that comets were created with the planets and not in the interstellar medium. This is why both short- and long-period comets were created at the same time as planets, but their orbits are different. Orbits of short-period comets usually lie within the Solar System (their aphelion lies somewhere in the orbit of Jupiter and to some extend Saturn), but the aphelion of long-period comets can reach values of multiples of 1000 or even 10000 AU.

Comet name	**a [AU]**	**Eccentricity**	**Inclination**	**Period [y]**
Encke	2.219	0.8463	11.93	3.31
Grigg-Skjellerup	2.959	0.6657	21.14	5.09
Tempel 2	3.036	0.5444	12.43	5.29
Tempel 1	3.116	0.5197	10.54	5.50
Wirtanen	3.117	0.6521	11.67	5.50
Pons-Winnecke	3.433	0.6347	22.31	6.36
d'Arrest	3.441	0.6248	19.43	6.38
Schwassmann-Wachmann 2	3.443	0.3984	3.76	6.39
Kopff	3.461	0.5445	4.72	6.44
Giacobini-Zinner	3.516	0.7076	31.88	6.59
Gunn	3.597	0.3164	10.38	6.82
Arend-Rigaux	3.604	0.5987	17.84	6.84
Brooks 2	3.622	0.4907	5.55	6.89
Holmes	3.687	0.4118	19.19	7.08
Faye	3.779	0.5783	9.09	7.34
Harrington-Abell	3.845	0.5421	10.25	7.54
Arend	4.005	0.5364	19.93	8.02
Wolf	4.072	0.4068	27.51	8.21
Whipple	4.163	0.2606	9.94	8.49
Vaisala 1	4.910	0.6334	11.61	10.9
Neujmin 3	4.919	0.5813	3.94	10.9
Klemola	4.931	0.6405	10.96	10.9
Van Biesbroeck	5.368	0.5527	6.62	12.4
Wiid 1	5.602	0.6471	19.90	13.3
Tuttle	5.674	0.8241	54.69	13.5
du Toit	6.004	0.7879	18.69	14.7
Schwassmann-Wachmann 1	6.042	0.0447	9.37	14.9
Neujmin 1	6.921	0.7756	14.17	18.2
Oterma	7.228	0.2430	1.94	19.4
Crommelin	9.102	0.9192	29.10	27.4
Tempel-Tuttle	10.337	0.9056	162.48	33.2
Brorsen-Metcalf	17.075	0.9720	19.33	70.6
Halley	17.854	0.9673	162.23	76.0
Typical long-period comet	10000	0.9999	any	1000000

Table 1: Orbital elements of selected comets [3].

The orbits of short-period comets are ellipses of moderate eccentricity and inclination. Almost all have inclinations of less than 20° relative to the ecliptic plane (Fig. 1). Their orbital eccentricities lie mostly between 0.2 and 0.7. Some short-period comets are ruled out and do not belong to this group (Fig. 2). Orbits of long-period comets are randomly oriented - inclinations are random, eccentricity is about 0.9999 [3].

Both families of comets are depleted by two important dynamical factors. First, comets that cross the orbits of several planets must from time to time collide with one, resulting in the destruction of a comet. Second, less obvious but still important, is the possibility that an encounter with a massive planet may eject the comet from the Solar System at a speed above the local escape velocity of the Sun, thus causing the comet to be lost forever from the Sun vicinity. The encounter with a massive planet may also reduce the total angualr momentum of a comet to such degree that a comet is decelerated and eventually falls into the Sun or a massive planet (usually Jupiter).

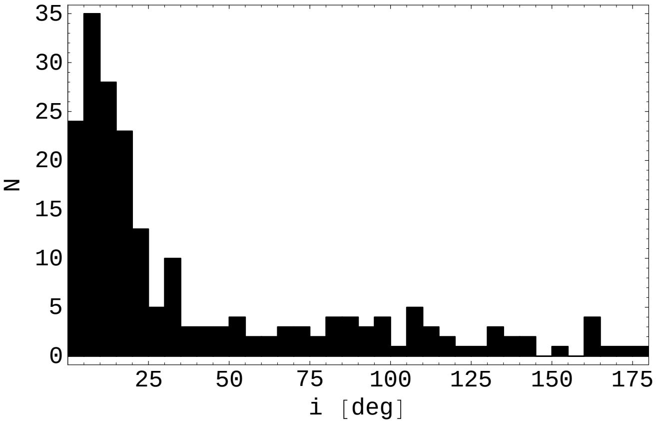

Figure 1: Frequency-inclination plot. Most known comets are short-period comets with a small orbital inclination of about 13°.

2.2 Gravitational effects on comet's orbit

What is the possibility of a comet striking a planet? Suppose that the critical perihelion distance is about 2 AU. The cross-section area of a sphere, centered on the Sun equals:

$$S_{cross} = \pi \left(2 \cdot 150 \times 10^{6}\right)^{2} \mathrm{km}^{2} \approx 10^{16}\ \mathrm{km}^{2}, \tag{1}$$

where 1 AU $= 150 \times 10^{6}$ km. All planets within volume derived in Eq. (1) (Mercury, Venus, Earth [including the Moon] and Mars) have a total cross-section area of only $\approx 10^{8}$ km^{2}. Thus a comet randomly crossing the inner Solar System *once* has probability of about 10^{-8} of striking a planet. A long-period comet with a period of 10^{6} years that has been in its present orbit (we assume that the orbit has not changed dramatically in its lifetime) for 10^{9} years has passed through the inner Solar System 10^{3} times. The probability at the last crossing was about 10^{-5} and decreases every time the same comet passes through the inner Solar System. This probability is true if we neglect the gravitational attraction of the target planet (gravitational focusing by the planet is negligible for fast-moving comets).

The change of orbital velocity can cause a short-period comet to become a long-period comet and *vise versa*. The orbital velocity of a comet can be calculated from [3]:

$$v^{2}_{aphelion} = GM_{\odot}\left(\frac{2}{r} - \frac{1}{a}\right), \tag{2}$$

where r is comet's distance from the Sun, a comet's orbit semi-major axis, $G = 6.673 \times 10^{-11}$ m^{2}N/kg^{2} gravitational constant and $M_{\odot} = 2 \times 10^{30}$ kg Sun mass. Comet's perihelion can be calcucated from $q = a(1 - e)$ where e is orbital eccentricity[1] and a is a semi-major axis of comet's orbit. For example, we take a long-period comet which has pressumably originated from Oort cloud at $a = 10000$ AU. Comet's orbital velocity at $r = a$ from the Sun is ~ 300 m/s. Perihelion for such comet is $q = 1$ AU (and aphelion $Q = a(1+e) = 19999$ AU). Orbital velocity at perihelion ($r = q$) is $v_{orb.perih.} = 42.4253$ km/s. Local escape velocity at 1 AU is $v_{orb.local} = 42.4264$ km/s.

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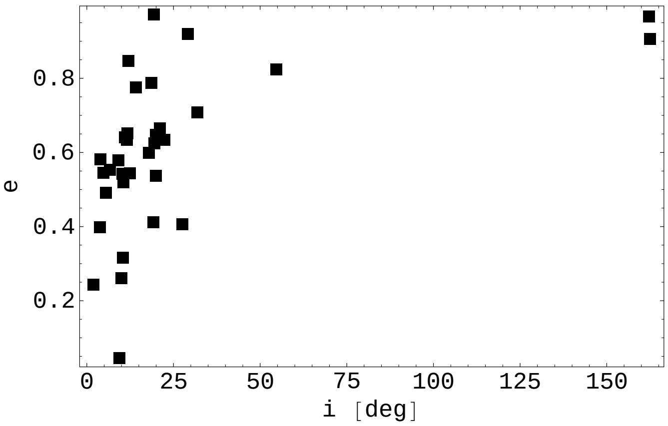
[1] ~ 0.9999 for long-period comets.



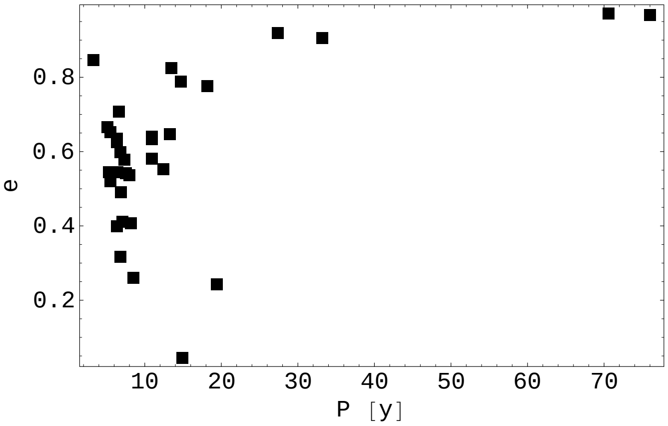


Figure 2: Eccentricity-inclination plot and eccentricity-period plot for short-period comets. The orbits of short-period comets are ellipses of moderate eccentricity and inclination. Almost all have inclinations of less than 20° relative to the ecliptic plane. Their orbital eccentricities lie mostly between 0.2 and 0.7. Some short-period comets are ruled out and do not belong to this group [2]. (see Table 1).

By comparing these two velocities we conclude that a orbital velocity increment of a comet of only 1.1 m/s would push the comet above the escape velocity of the Solar System.

Velocity perturbation is also possible at aphelion. Because semi-major axis of long-period comets is tipically very large ($\sim 10^4$ AU) the aphelion orbital velocity is thus very small (from eq. 2 where $r = 19999$ AU and $a = 10000$ AU the orbital velocity equals 2.1 m/s). The velocity perturbation at aphelion can be produced by a passing star. The acceleration (g) felt by the comet can be expressed as [3]:

$$g = \frac{GM_*}{D^2}, \tag{3}$$

where D is the distance of the star and M_* is its mass. The velocity change of comet's orbital velocity is the product of the acceleration and the duration of the encounter with the passing star [3]:

$$\delta v = \frac{GM_*}{D^2} \times \frac{2D}{v_*} = \frac{2GM_*}{v_* D}, \tag{4}$$

where v_* is the velocity of the star relative to the Sun (~ 20 km/s). Most stellar encounters involve M-class red dwarfs with mass of $0.1 M_\odot$ [3]. A M-class red dwarf passing at a distance of 10000

AU at $v_* = 20$ km/s from a comet at aphelion can produce orbital velocity change of about 1 m/s. This is closely comparable to the orbital velocity of the comet and is easily sufficient to cause it to escape or to change its perihelion distance, orbital period or inclination dramaticaly.

Long-period comets can also change its orbital properties if they pass close to a massive planet in their journey through the Solar System. The most massive planet in the Solar System is Jupiter. If a comet passes within 10^6 km of Jupiter, the Jupiter swing-by will produce a velocity change of 2 km/s. The orbital velocity at 5 AU (Jupiter's distance from the Sun) is ~ 18 km/s. A velocity change derived before can cause a change in comet's semi-major axis and change it to short-period comet with a period of about 50 years.

2.3 Nongravitational effects on comet's orbit

Because long-period comets have very small orbital velocities near aphelion, they spend virtually all of their lives at great distances from the Sun, stored at extremely low temperatures. A dark object that would have a radiative steady-state temperature of 300 K at 1 AU would be maintained at only about 3 K by solar illumination at 10^4 AU [3]. Solar heating is so weak at that distance that the Big Bang cosmic background radiation is an important source of heat.

Most stellar encounters involve M-class red dwarfs of mass $0.1M_\odot$. Any comet that gets close enough to an M star to be significantly heated will certainly be ejected from the Solar System. Mass-luminosity relation for Main Sequence stars above a few $\frac{1}{10}M_\odot$ is of form $L_* \propto M_*^{3.5}$ and for smaller stars $L_* \propto M_*^2$.

At large distances from the Sun the absorption of sun-light governs the surface temperature of an icy body and the surface temperature in turn governs the vapor pressure of the ice and its rate of evaporation. The steady-state balance between absorbed and emitted radiation at the large distances from the Sun is given by [3]:

$$\frac{(1-A)F_\odot}{R^2} = 4\epsilon\sigma T_s^4 = 4\sigma T_e^4, \tag{5}$$

where the term on the left side is the absorbed solar energy and the term on the right is the thermal emission. T_s is the surface temperature of the body averaged over its entire surface, ϵ is the thermal emissivity (~ 1), T_e is the effective temperature, $F_\odot$ is the solar constant, A is the albedo, and σ Stefan-Boltzmann constant.

The vapor pressure of a substance at low pressures is given by:

$$\ln(P_{vap}) = \frac{\Delta H_{vap}}{RT} - \frac{\Delta S_{var}}{R}, \tag{6}$$

where molar enthalpy H_{vap} and entropy of vaporization S_{vap} change only slowly with temperature. At higher temperatures (and closer to the Sun) the vapor pressure is larger. The evaporation of ice can absorb larger amount of the incident heat flux. The rate of evaporation of a substance is related to its vapor pressure by:

$$\frac{\mathrm{d}m}{\mathrm{d}t} = P_{vap}\left(\frac{m}{2\pi kT}\right)^{\frac{1}{2}} \tag{7}$$

The escaping gas from the comet exerts a back-pressure on the comet surface. This force is *non*gravitational and is greatest where the evaporation rate is greatest. The force generally has a radial component that offsets the gravitational atraction of the Sun, and a component normal to the comet - Sun line. Because the spin axis of the comet nucleus can be oriented in any direction the normal component of nongravitational force can accelerate or decelerate the comet in its orbit. It can also influence the rotation of the nucleus.

Once the comet gets closer to the Sun, the heat carried off by evaporating surface ices becomes a significant part of Eq. (5) which has to be now modified to [3]:

$$\frac{(1-A)F_\odot}{R^2} = 4\sigma T_e^4 + q_e\frac{\mathrm{d}m}{\mathrm{d}t}, \tag{8}$$

where q_e is the latent heat of evaporation of ice. The force of evaporating ice on the comet is the greatest on the dayside of the nucleus. The jetting gases from the dayside imparts a maximum nongravitational acceleration of [3]:

$$a_{nongrav} = \frac{F}{m} = \frac{3P_{vap}}{4\rho r}, \tag{9}$$

where ρ is (mean) nucleus density and r nucleus radius. The acceleration caused by evaporating ices on the comet surface depending upon the orientation of the spin axis of the nucleus, may increase or decrease the orbital period.

At perihelion the rate of nucleus heating varies greatly over each cometary spin orbit, because comet nuclei are rotating. Axial tilt of the comet nucleus is random and is likely to be large, so the latitude has a strong effect on the range of daily temperatures. Nongravitational forces can modify both the spin and the orbit. Evaporation near the equator of a comet nucleus can reduce its principal rotational moment of inertia thus making it unstable against tumbling. Temperature gradients at the surface of the nucleus may be very large because near perihelion temperatures in the dust layer may be well above 200 K, whereas those at modest depth are still comparable to interstellar space temperature of 3 K.

We have seen that nongravitational forces among gravitational forces play a significant role in how comet behaves on its orbit around the Sun. Heating of comet nucleus can cause the same effect on comet orbit as the gravitational pull of a passing star or a planet.

2.4 The origin of comets

At first it was thought that long-period comets originate from outside the Solar System. Oort (1950) and Marsden *et al.* (1978) both discussed the numbers of comet orbits per interval of orbit energy [2]. Because long-period orbits are very eccentric, even small observational errors introduce significant errors into the determination of aphelion a. The-numbers-of-comet-orbits-per-interval-of-orbit-energy plot does not exaggerate these errors (Fig. 3).

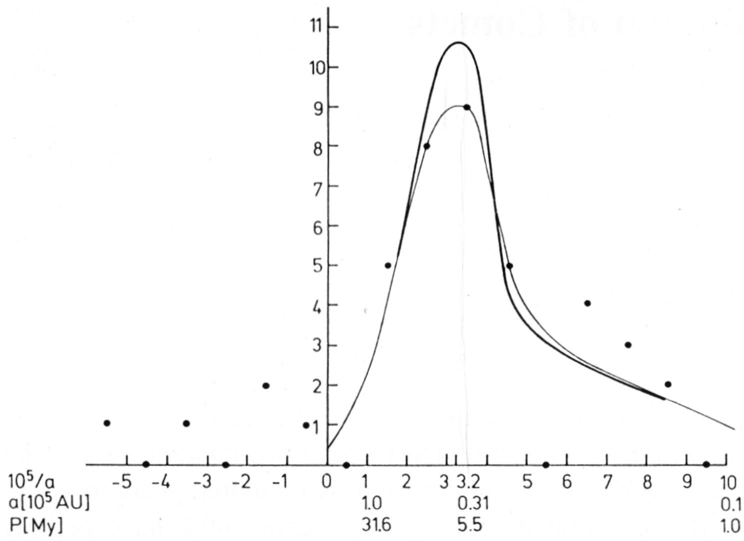


Figure 3: The numbers of comet orbits per interval of 10^{-5} AU^{-1} vs. $1/a$ in units of 10^{-5} AU^{-1}. The abscissa also shows the semi-major exis in units of 10^5 AU and the period in 10^6 y. The data constains 66 long-period orbits. Comets that belong to the narrow peak at $1/a = 3.2 \times 10^{-5}$ AU^{-1} are 'new' comets - these comets have never before passed through the inner Solar System [2].

The abscissa in Fig. 3 is the reciprocal of the semi-major axis, $1/a$ in units of 10^{-5} AU^{-1}. This is a measure of the orbital energy per unit mass, $M_{\odot}G/a$. The figure shows that long-period comets can have very large aphelion values - even up to 10^5 AU. Suprisingly, it also shows a very narrow peak at $1/a = 3.2 \times 10^{-5}$ AU^1, with a width of only 2×10^{-5} AU^{-1}. The average mean error is $\pm 0.8 \times 10^{-5}$. A single passage through the inner Solar System produces an average dispersion in $1/a$ of $\pm 35 \times 10^{-5}$ AU^{-1} [2]. Width of the narrow peak shows that the comets with aphelion that belongs to this peak could not have previously passed through the Solar System. These comets are on their first journey towards the Sun. Their aphelia are in interval between about 0.2×10^5 and 0.7×10^5 AU from the Sun.

Comets were created with the Solar System in much the same way and in the same regions where the planets were formed. These *proto-comets* were transported to their present large distances through perturbations by Jupiter, other large planets and passing massive stars. The short-period comets formed in the trans-Neptunian protosolar disk (now called Kuiper belt) and are almost free from perturbations. If perturbations acure they become short-period comets with aphelion somewhere in the orbit of Jupiter. The long-period comets where formed in the region of the giant planets. Those that did not collide with planets where subjected to strong perturbations by the planets and have been diffused away. 90 % were thrown out of the Solar System, remaining were bounded to Solar System at distance of about 3×10^5 AU. At these distances Sun cannot produce any orbit perturbations, but perturbations caused by passing stars and tidal forces of the Galaxy take effect. These perturbations can cause changes in perihelion distances and inclinations. Numerical calculations [2] have shown that comets, first formed in the giant planets region, only require some 10^6 years to be transfered from their strongly bounded initial orbits of $a \sim 6$ AU into present orbits with $a \in [2 \times 10^4, 10^5]$. This region is now called Oort cloud (Fig. 4) and is purely theoretical. The stellar perturbations formed the spherical shape of the Oort cloud and randomized orbital inclinations [2].

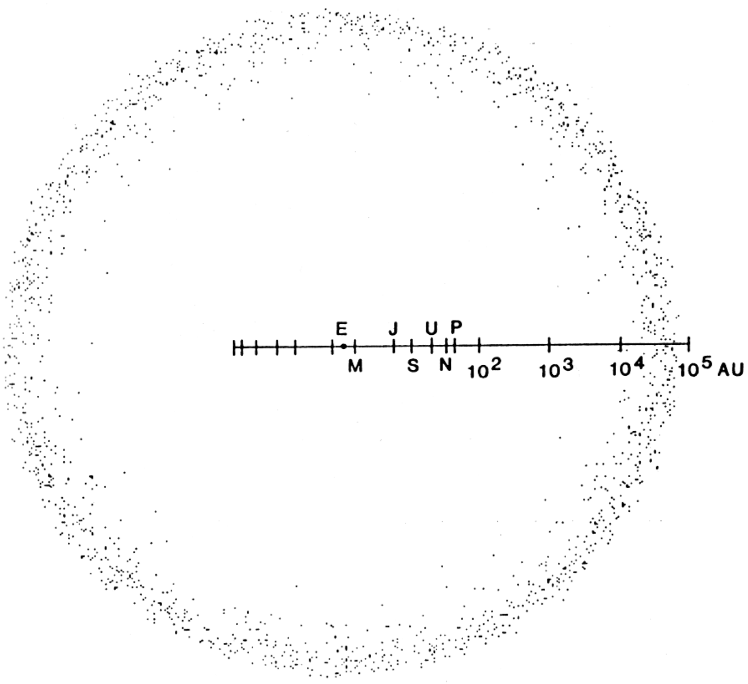


Figure 4: A schematic presentation of the spherical Oort cloud relative to the planetary system, projected on a plane perpendicular to the ecliptic. The radial dimensions of the projection are logarithmic in astronomical units (1 AU = 150×10^6 km). E marks Earth, M marks Mars, J marks Jupiter, etc. Oort cloud extends from about 2×10^4 to 10^5 AU from the Sun and it is the source of long-period comets [2].

3 The structure of comets

> `“Observation, not old age, brings wisdom.”`
>
> *Publilius Syrus*

3.1 Nucleus

The nucleus defines a comet. Before the *in situ* imaging of P/Halley nucleus in 1986, scientists struggled with the idea of what comet nucleus is made of. The existance of comet nuclei as solid bodies and sources of the diffuse and faint dust and coma was implied by Newton in his *Principia.* He suggested that solid bodies lose material when they come close to the Sun and are heated up. Newton's idea led to the promotion of the sand bank model by Lyttleton in 1948. In this model the observed radicals CN, C_2, C_3, CH, etc., were thought to be adsorbed on dust grains. Unfortunetly sand bank model could not explain the variety of other observed phenomena.

A few years later, in 1950's, Fred Whipple proposed a new model - icy conglomerate or 'dirty snowball' model. Because comae only appear when the comet is as near as 3 AU from the Sun, Whipple concluded that the water ice mixed with dust is the principal consituent of the nucleus along with frozen parent molecules CH_4, NH_3, CN, CH, C_2, C_3, etc. Dust imbedded in a snowball could also explain comet relationship with meteor streams.

The nucleus of a long-period comet has a typical diameter of 1 to 10 km, and that of short-period comet of 0.5 to 5 km. The nucleus revolution could also cause considerable brightness variations. The diameter of a nucleus can be approximated by [2]:

$$R_N = \frac{r\sqrt{Qq_e}}{\sqrt{\pi F_\odot (1 - A_v) N_0}}, \tag{10}$$

where r is the distance from the Sun, Q total production rate of gas molecules per second, q_e latent heat of sublimation of ice, $F_\odot$ solar flux, A_v effective Bond albedo, and N_o Avogardro's number. The Band albedo A_v is the integral of the monochromatic emitted flux over wavelength divided by the integral of the incident flux over the same wavelengths.

Our first *in situ* knowledge comes from the observation of the P/Halley nucleus done by Giotto space probe. For the first time it was possible to determine the size, shape and even details on the surface of a comet nucleus. The images taken by the Giotto's Halley Multicolour Camera (HMC) revealed a rather elongated and irregular shape of the nucleus with a 14 km by 7.5 km in size. The albedo of Halley surface was estimated to about 0.04. The resolution of images was from 60 m/pixel to 300 m/pixel. The spin period was also determinated to be between 52 and 54 hours (the same period was determinated in 1910).

The temperature of the nucleus will adjust to its environment and will be between 3 and 10 K for a nucleus residing in the Oort Cloud. Short-period comets will acquire temperatures that are higher and nonuniform throughout the nucleus varying along their passage around the Sun.

The mean surface temperature T_m, can be approximated by [2]:

$$T_m = \left[\frac{1}{P\epsilon\sigma_0} \int_0^P [F_\odot(t) - \phi(t)] \mathrm{d}t \right]^{\frac{1}{4}}, \tag{11}$$

where P is the orbital period and ϕ power lost by dissipative processes (e.q. sublimation). The central temperature T_c, depends on the time scale, τ_D, of heat diffusion into the interior of the nucleus. If constant diffusivity is assumed, the time scale is $\tau_D \approx C_v \rho R^2/\kappa\pi^2$, where κ is heat conductivity, C_v the heat capacity, and ρ the density.

If time scale is similar to the comet orbital period ($P \approx \tau_D$), the temperature will vary within the period with amplitudes that increase the larger P is to τ_D. If $\tau_D \ll P$ the central temperature will vary almost in parallel with surface temperature and with the same amplitude. If $\tau_D \gg P$ then the T_c will approach T_m with the relaxation time depending on the composition of the nucleus (crystalline or amorphous ice). Fig. 5 shows relaxation times for an icy sphere as function of radius given for different temperatures and diffusivities of the ice. For a nucleus of 5 km radius and compact ice at a temperature 30 K, τ_D is as small as several 100 years and reaches values of more than 10^5 years for the same size nucleus composed of compact amorphous ice. The equilibrium temperature depends not only on the material constants but also on the orbital parameters. As a comet approaches the inner Solar System, all impact solar flux is used for heating the nucleus. When the impact rate of impact flux is sufficient, the surface layers become warm enough to trigger the sublimation of ices. As the ices vaporize, a dusty crust forms that insulate the deeper layers and regulates the sublimation process. Irregularities in the composition of nucleus (Fig. 5) cause sublimation to occur faster in some areas. These irregularities produce jets and the irregular shape and surface of the nucleus (the nucleuses were first belived to be perfect spheres).

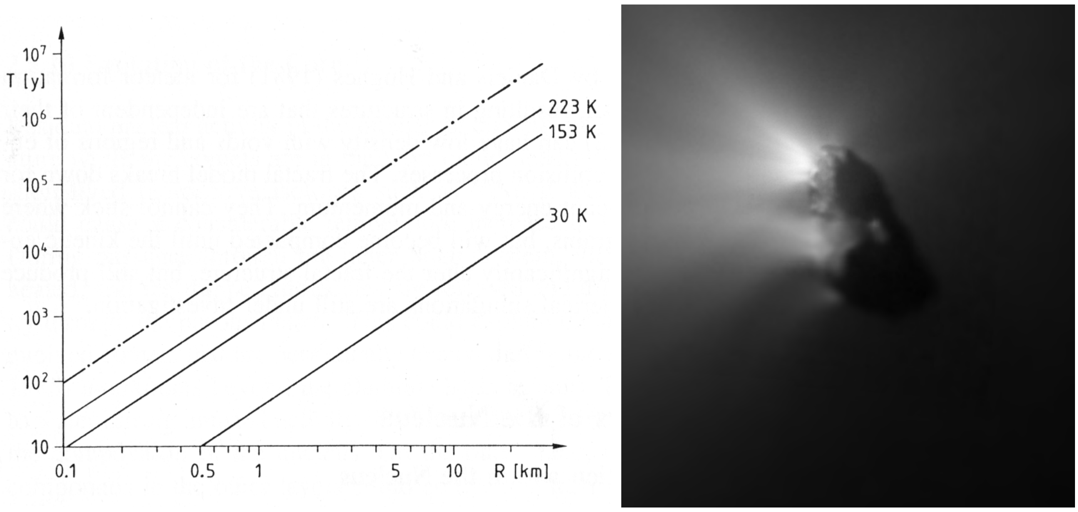


Figure 5: (*left*) Relaxation times for an icy sphere as function of radius given for different temperatures and diffusivities of the ice [2]. (*right*) A composite of six HMC images ranging in resolution from 320 m to 60 m per pixel [4]. Illumination by the Sun is from left, about 28° above the horizontal and 12° behind the image plane. The nucleus is irregular in shape because sublimation of ices occurs faster in some areas. The albedo of Halley's nucleus was determinated to be about 0.04.

Sublimation process occuring on the surface of comets is much more important that phase transitions that are observable on Earth. Under a normal pressure of 1 bar, the ices first melt then vaporize (Fig. 6). Becase the ices on the surface of comets vaporize well below the pressure of triple-point for water (6 mbar), the liquid water is not observed but only ice and vapor.

3.2 Coma

The gases and dust expanding outward around the nucleus form a roughly spherical envelope called *coma*. Both, nucleus and come are collectively called *the head* of the comet. The coma expands at an average speed of 0.5 to 1 km/s and at the distance of thousand of kilometers to about 100000 km from the nucleus becomes so tenuous that the gases and dust in it become uncoupled and begin to stream systematically away from the nucleus, albeit in different directions. The gas flows in the direction radially outward from the Sun, whereas the dust roughly follows ballistic trajectories.

Comae usually appear at about 3 AU from the Sun when water ice begins to sublimate. It is through comae and tails that comets lose mass. Expansion of coma continues until the dynamic pressure of gas expansion reaches a balance with the dynamic pressure of the solar wind [3]:

$$\rho_g v_g^2 = \rho_{sw} v_{sw}^2 \tag{12}$$

The *coma expansion time* is the time interval when any species in the coma may photodissociate or photoionize and is measured from the point when gas and dust leave the surface of nucleus to the

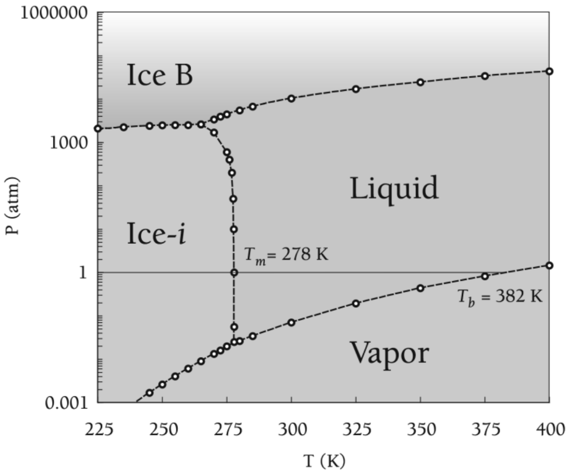


Figure 6: Phase diagram for water [5]. Because the ices on the surface of comets vaporize well below the pressure of triple-point for water (6 mbar), the liquid water is not observed but only ice and vapor.

point when the pressure balance in Eq. (12) is reached. Once the ions in the coma reach pressure balance with the solar wind, they become entrapped in the solar wind magnetic field.

When water vapor in coma is exposed to the solar UV flux, the initial reactions are [3]:

$$\begin{aligned} \mathrm{H_2O+h\nu} &\xrightarrow{\text{diss.}} \mathrm{OH+H} \\ &\xrightarrow{\text{diss.}} \mathrm{O+H+H} \\ &\xrightarrow{\text{diss.}} \mathrm{O+H_2} \\ &\xrightarrow{\text{diss.}} \mathrm{O\left(^1D\right)+H_2} \\ &\xrightarrow{\text{ion.}} \mathrm{H_2O^{+}+e^{-}} \end{aligned}$$

where 'diss.' marks photodissociation and 'ion.' marks photoionization. The first reaction is driven by photons with wavelengths as long as 200 nm (1950 Å). The second and third reactions require more energetic photons and the last reaction (photoionization) requires even more energetic photons with wavelengths less than about 100 nm (1000 Å). Solar photons with sufficient energy to ionize cometary gases are very rare relative to those capable of dissociating these same gases. Hence, the most probable process of destroying a polyatomic molecule in the coma is photodissociation.

It can be shown that the gas near a comet nucleus can be completely opaque to the chemically active ultraviolet radiation. In this near-nucleus regime the chemical reactions are unimportant and gas expands outward at a speed of:

$$c = \sqrt{\frac{8kT}{\pi m}} \tag{13}$$

Once a molecule gets far enough from the nucleus it is exposed to nearly unattenuated sunlight and it is broken apart very quickly. The mean time that it takes to break apart a molecule is called *the photodissociation time* and is of a few orders less that *the photoionization time*, because of the low count of high energetic photons in solar flux.

Spectroscopic observations of numerous comets have revealed the presence of H, NH, NH_2, O, OH and S in cometary comas. Microwave observations have directly comfirmed the presence of the H_2O molecule and even a number of carbon-based species have beed observed in the coma - C, C_2, C_3, CH, CN, ... Visible and UV spectroscopy farther from the nucleus, where the gas density is much lower and the neutral coma gases have had sufficient time to be photoionized, have revealed the presence of the ions C^+, CH^+, CO^+,$CO_2{}^+$, H_2O^+, OH^+, $N_2{}^+$ and CN^+. These ions then stream out anti-Sunward to form the plasma tail.

Comas are dominated by photodissociated fragments of molecules and thermally dissociated vapors of minerals and not by molecular species that actually compose the solid nucleus.

3.3 Tails

At some distance from the nucleus, gas and dust in the coma become uncoupled and begin to stream away from the nucleus in two different directions, forming two distinct kinds of tails: *dust* and *ion* (or plasma) tail. Tails usually stretch across 1 AU or more, in some rare cases even as far as 4 AU. The two tails form differently because of the different processes they are governed by.

3.3.1 Dust tail

When the comet is far away from the Sun it is too cold for the evaporation of ices to occur. At its passage through the Solar System, evaporation becomes rapid enough to blow away smaller grains, whereas larger grains stay on the surface of the comet nucleus. A small particle resting upon the surface experiences several forces: the gravitational force, the centrifugal force, the drag force (casued by the outward flow of gases from evaporating ices in the nucleus) and the inward force. The full force balance on a grain *at the surface* of the nucleus is given by [3]:

$$\frac{GM_{nuc}m_{grain}}{R_{nuc}^2} - \phi_{gas}v_{gas}\sigma_{grain} - m_{grain}R_{nuc}(\Omega\cos l)^2 = ma, \tag{14}$$

where M_{nuc} and R_{nuc} are the mass and radius of the comet nucleus, m_{grain} is the mass of the particle resting upon the surface, σ_{grain} is the cross-section area of the particle, ϕ_{gas} is the gas flow rate (g cm^{-2} s^{-1}), v_{gas} is the velocity of the gas stream, Ω is the rotational angular velocity of the nucleus, and l is the latitude at which the grain rests. The inward acceleration of the grain is a.

Dust tail (Fig. 7) consists of those particles that are blown away from a comet surface by the gas drag. Sufficiently large grains will be massive enough for the gravitational attraction to overcome the gas drag casued from evaporating ices and will stay at the comet surface. For any given set of environmental constraints (l, Ω, M_{nuc}, v_g and ϕ_g) there is a critical size for the grain (m_{grain}, σ) below which the grain is blown away from the surface. The critical size is that at which is $a = 0$.

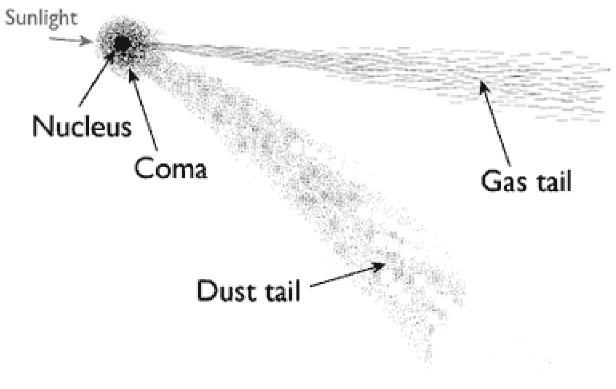


Figure 7: Formation of a dust and plasma tail. Smaller grains are blown further away from the nucleus than the larger grains, because the radiation force is stronger ($\sim R_{grain}^2$) than the gravitational force ($\sim R_{grain}^3$). Larger grains experience stronger gravitational pull.

Once *off* the comet surface, particles in addition to the gravitational attraction of the Sun also experience forces due to their interaction with the Solar radiation field. For an idealized spherical dust grain of radius R_{grain} that is located at a distance r from the Sun and that absorbs *all* of the incident light, the force caused by radiation pressure is calculated as:

$$F_{rad} = \frac{L_\odot \pi R_{grain}^2}{4\pi r^2 c} = \frac{L_\odot R_{grain}^2}{4 r^2 c}, \tag{15}$$

where πR_{grain}^2 is the particle's cross section and $L_\odot$ Sun's luminosity.

Also the Sun's gravitational force is acting on the grain:

$$F_{grav} = \frac{G M_\odot m_{grain}}{r^2} = \frac{4\pi G M_\odot \rho R_{grain}^3}{3 r^2}, \tag{16}$$

where $M_\odot$ is Sun mass and ρ density of a grain. By comparing Eq. (15) and Eq. (16) and setting $F_{grav}/F_{rad} = 1$, we obtain the critical radius of a grain [2]:

$$R_{critical} = \frac{3 L_\odot}{16\pi G M_\odot \rho c}. \tag{17}$$

If the force due to the radiation pressure F_{rad} is negligible compared to Sun's gravitational force ($F_{rad} \ll F_{grav}$) then the partice will stay in the same orbit as the comet. With increasing F_{rad} the particle's orbit eccentricity also increases. When both forces are equal ($F_{rad} = F_{grav}$ and $R_{grain} = R_{critical}$) the net force acting on the particle is zero and the particle travels in a straight line. When F_{rad} becomes larger than F_{grav} the particle begins to move away from the Sun.

3.3.2 Ion (or plasma) tail

After a suficient time, gas in the coma is ionized and interacts with the solar wind. Some of the ions become trapped in the magnetic field lines that are carried away by the solar wind. The field decelerates in the vicinity of the comet and wraps around the nucleus, forming the ion (or plasma) tail. Direct measurments by Giotto probe confirmed numerical simulations that a reversal of magnetic polarity occurs in the central denser tail. Shock fronts were also detected because comets are ionized obstacles in the solar wind. A shock lowers the wind speed and allows the wind to flow around the comet. The ions of carbon monoxide (CO^+) in the ion tail radiate in the presence of sunlight, thus making the ion tail blue in color. The emission peak is at about 420 nm. Ion tails usually point radially outward from the Sun, are straight in shape and can reach lengths up to 100×10^6 km or more.

Ion tails routinely become detached from the comet's head during disconnection events. During a disconnection event, part or all of the old ion tail drifts away and a new one forms. The disconnection events occur when the polarity of solar wind magnetic field changes. Adjacent field lines within the tail cross and reconnect, severing the connection to the near-nucleus region on the Sunward side. Such events are relatively common. During the observation of Halley's comet 19 such events were reported and one dramatic in the tail of Hyakutake comet.

4 The Great Comets

A Great Comet is a comet which becomes particularly bright and is very spectacular to a casual observer on Earth. Great comets appear, on average, once every decade.

Predicting whether a comet will become a great comet is notoriously difficult, as many factors may cause a comet's brightness to depart drastically from predictions. Broadly speaking, if a comet has a large and active nucleus, will pass close to the Sun, and is not obscured by the Sun as seen from the Earth when at its brightest, it will have a chance of becoming a great comet [6].

Some of Great Comets of the past two centuries were: the Great Comet of 1811, the Great Comet of 1843, comet Donati (1858), the Great Comet of 1882, the Great Daylight Comet of 1910, comet Hale-Bopp (1995), comet Hyakutake (1996) and comet McNaught (2006).

4.1 The Great Comet of 1811

The Great Comet of 1811 (formally C/1811 F1) was visible to the naked eye for around 260 days. In October 1811, at its brightest, it displayed an apparent magnitude of 0, with an easily visible coma. In December one length of the double tail extended for over 60°. It was categorized as a Great Comet, the 54th in recorded history and one of eight in the 19th century.

It was discovered on March 25, 1811 by Honoré Flaugergues at 2.7 AU from the sun and confirmed by Jean-Louis Pons and Franz Xaver, Baron Von Zach in April.

The sightings continued until June when it was lost to solar glare. It was recovered in August as a 5^{th} magnitude object. The comet brightened as it approached perihelion in September and its minimum distance from Earth at 1.1 AU. The comet nucleus was estimated at 30-40 km in diameter and the orbital period was calculated at 3757 years (later adjusted to 3065 years). In total, the comet was visible to the naked eye for 9 months.

4.2 The Great Comet of 1843

The Great Comet of 1843 (formally C/1843 D1) became very bright in March 1843 (it is also known as the Great March Comet of 1843). It was discovered on February 5, 1843 and rapidly brightened to become a great comet. It was a member of the Kreutz Sungrazers, a family of comets resulting from the breakup of a parent comet (X/1106 C1) into multiple fragments in about 1106. These comets pass extremely close to the surface of the Sun within a few solar radii and often become very bright as a result.

First observed in early February, 1843, it raced toward an incredibly close perihelion of less than 830000 km on February 27, 1843; at this time it was observed in broad daylight roughly a degree away from the Sun. It passed closest to Earth on March 6, 1843, and was at its greatest brilliance the following day; unfortunately for observers north of the equator, at its peak it was best visible from the Southern Hemisphere. It was last observed on April 19, 1843. At that time this comet had passed closer to the sun than any other known object.

The Great Comet of 1843 developed an extremely long tail during and after its perihelion passage. At over 2 AU (300 million km) in length, it was the longest known cometary tail until that time.

4.3 The Donati Comet (1858)

Comet Donati (Fig. 8), or Donati's Comet (formally C/1858 L1) was named after the Italian astronomer Giovanni Battista Donati who first observed it on June 2, 1858. The comet is considered a non-periodic comet. After the Great Comet of 1811, it was the most brilliant comet that appeared in the 19^{th} century. It was also the first comet to be photographed. It was nearest the Earth on October 10, 1858.

4.4 The Great Comet of 1882

The Great Comet of 1882 (formally C/1882 R1) became very bright in September 1882. It was a member of the Kreutz Sungrazers, a family of comets which pass within 1 $R_\odot$ of the Sun's photosphere at perihelion. The comet was bright enough to be visible next to the sun in the daytime sky at its perihelion.

The comet was rapidly approaching perihelion when it was discovered. At perihelion, the comet is estimated to have been only 450000 km from the sun's surface. Subsequent orbital studies have determined that it was a Sungrazing comet, one which passes extremely close to the surface of the Sun. For many hours on either side of its perihelion passage, the comet was easily visible in the daytime sky next to the Sun. It reached an estimated magnitude of 17.

4.5 Comet Hale-Bopp (1995)

Comet Hale-Bopp (formally C/1995 O1) was probably the most widely observed comet of the twentieth century, and one of the brightest seen for many decades. It was visible to the naked eye for a record 18 months, twice as long as the previous record holder, the Great Comet of 1811.

Figure 8: Comet Donati of 1858 (left) and Comet Hyakutake of 1996 (right) [6]. Comet Donati was named after the Italian astronomer Giovanni Battista Donati who first observed it on June 2, 1858. The comet is considered a non-periodic comet. Comet Hyakutake was discovered in January 1996 when it passed very close to Earth. Its passage near the Earth was one of the closest cometary approaches of the previous 200 years.

Hale-Bopp was discovered on 23 July 1995 at a very large distance from the Sun, raising expectations that the comet could become very bright when it passed close to the Sun. Although comet brightnesses are very difficult to predict with any degree of accuracy, Hale-Bopp met or exceeded most predictions for its brightness when it passed perihelion on April 1, 1997.

After its perihelion passage, the comet moved into the southern celestial hemisphere. In March 1996 the comet passed within 0.77 AU of Jupiter, close enough for its orbit to be affected by Jupiter's gravity. The comet's orbit was shortened considerably to a period of 2380 years, and it will next return to the inner solar system around the year 4377. Its greatest distance from the sun (aphelion) will be about 360 AU, reduced from about 525 AU.

4.6 Comet Hyakutake (1996)

Comet Hyakutake (formally C/1996 B2) was discovered in January 1996, which passed very close to Earth in March of that year (Fig. 8). It was dubbed The Great Comet of 1996. Its passage near the Earth was one of the closest cometary approaches of the previous 200 years. Hyakutake appeared very bright in the night sky and was widely seen around the world. The comet temporarily upstaged the much anticipated Comet Hale-Bopp, which was approaching the inner solar system at the time.

Scientific observations of the comet led to several discoveries. Most surprising to cometary scientists was the first discovery of X-ray emission from a comet, believed to have been caused by ionised solar wind particles interacting with neutral atoms in the coma of the comet. The Ulysses spacecraft unexpectedly crossed the comet's tail at a distance of more than 500 million km from the nucleus, showing that Hyakutake had the longest tail known for a comet.

Hyakutake is a long-period comet. Before its most recent passage through the solar system, its orbital period was about 15000 years, but the gravitational influence of the giant planets has increased this period to 72000 years.

5 Conclusion

Comets are one of the most amazing objects known to Man. Scientists have gained an enormous knowledge about comets after the Giotto and Vega encounter with comet Halley in 1986 and with recent encounters with comet Wild 2 (Stardust probe) in 2004 and comet 9P/Tempel (Deep Impact probe) in 2005. Also, Whipple's dirty snow-ball model adequately described the structure of comets and cometary orbit studies have determinated their origin in cosmos. Still a large quantity of questions remains unanswered: as what lies below the surface of the comet; of what are comets actually made of; has the composition of comets changed in over their life time, etc. Undoubtedly, the future of comet exploration and research will answer at least some, if not all, of these questions.

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