Splitting of Comets

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Splitting of comets is a very interesting celestial phenomenon. If we look back we find that a number of famous comets have disintegrated and the broken-up fragments are either lost forever or have survived as separate pieces. In this article, the mechanism of cometary splitting and a brief history of their fragmentation have been discussed.

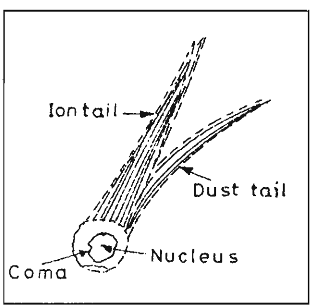
Keywords
Cometary splitting, sphere of influence.

Introduction

Comets are very spectacular as well as astonishing celestial objects. From early days, comets have generated a lot of awe and interest among people, yet our knowledge about comets was very limited. Thanks to the development of astronomical techniques, now we know that comets are members of the solar system and have gained some knowledge about their structure as well.

A moving celestial object will be called a comet if it produces a diffuse image and/or displays a tail. Periodic comets can be subdivided as short period (SP) comets and long period (LP) comets. The orbital period of SP comets is less than 200 years while that of LP comets is greater than 200 years. From the history of cometary observations, we find that some well-known comets have disintegrated. After disintegration, those comets have either been lost forever or have remained as separate parts. For understanding cometary splitting and its probable mechanism, we have to know the structure of a comet.

Figure 1.



Structure of a Comet

A fully developed comet has four components (1) nucleus, (2) coma (3) ion tail and (4) dust tail (see *Figure* 1). Cometary nucleus is an irregular-shaped body and its size varies from one to ten kilometres. The nucleus is primarily made of ice. Apart

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from ice, various elements, their compounds, ions etc. and dust particles are also present in the nucleus. The nuclei of comets move freely in a spherical region situated between 20000 to 100000 AU (1 AU = mean distance between the Earth and the Sun = 149,600,000 km) from the Sun. This region is called the Oort Cloud. If any nucleus within the Oort Cloud is perturbed sufficiently, it leaves the Oort Cloud and starts its journey independently in the solar system. When it approaches the Sun, ice and other volatile materials are released from the nucleus and the coma of the comet develops. Again, as the comet recedes from the Sun, its coma gradually disappears.

The most spectacular part of a comet is its tail. A comet can have two types of tails – an ion tail and a dust tail. Various ions in the coma move in anti-solar direction by the action of solar wind (charged particles emanating from the Sun) and form the ion tail. The ion tail becomes visible due to fluorescence of the ions present in it. Generally the ion tail develops when the comet is at a distance of about 1.5 AU from the Sun. But it has been found in some cases that the ion tail develops at a much larger distance. Statistics show that LP comets show fully developed ion tails more often than SP comets. Dust particles released from the coma by the action of solar wind form the dust tail which are visible primarily by the reflected sunlight. It is bent along the orbit of the comet.

Splitting of Some Well-known Comets

Now let us discuss briefly the splitting of some famous comets such as Biela's Comet (3D/Biela), Comet Ikeya-Seki (C/1965S1) and Comet Hyakutake (C/1996 B2).

(a) ***Biela's Comet:*** Montaigne of Limoges discovered this comet as early as in 1772 and Pons rediscovered it in 1805: yet it was W Von Biela who recovered this comet in 1826 and for the first time calculated its period correctly as 6.6 years. During its reappearance in 1846, the comet was found to be divided into two parts. Again, during its apparition in 1852, those two parts were found to be separated by a distance of 2,400,000 km, but were seen moving in the same orbit. In the subsequent trip they appeared separately and finally neither part appeared in 1866. Meteor showers were seen in November 1872 and 1885 when the Earth was scheduled to cross the cometary orbit. P/Biela and Machholz 2 (P/1994 P1) are the only two comets whose fragments were observed at more than one apparition.

Breaking up of comets before and after perihelion passage occurs almost equally and about 50% of them split up at a heliocentric distance smaller than twice the perihelion distance.

(b) ***Comet Ikeya-Seki:*** Comet Ikeya-Seki, a spectacular sungrazing comet, was discovered by the Japanese astronomers Ikeya and Seki. This comet remained visible during September 21, 1965 to January 14, 1966. Before reaching the perihelion on October 21, 1965, its nucleus fragmented into two parts A and B. The orbital period of the part A was 880 years and that of B was a little more than that. The comet was a thousand times brighter than Venus; it gradually lost its glare and faded away.

(c) ***Comet Hyakutake:*** Comet Hyakutake was discovered on January 20, 1996 by Japanese astronomer Yuji Hyakutake. The comet was only at a distance of 0.1AU from the Sun on March 25, 1996. Just after its closest approach (~15,000,000 km) to the Earth on March 26, its nucleus had split into two components. Those two parts drifted away from each other with relative velocity of about 0.8 km/sec.

After analysing the data for a large number of split comets, Sekanina and others have observed the following general features of split comets.

(1) Breaking up of comets before and after perihelion passage occurs almost equally and about 50% of them split up at a heliocentric distance smaller than twice the perihelion distance.

(2) For most of the split comets it has been found that for a brief period after their separation from the parent comets, the fragments flare up and this sudden increase in brightness is greater in smaller fragments than in their larger counterparts. According to Whipple, since smaller fragments are liberated from the inner core of the comets, their upper surfaces are free from the

layer of dust and hence due to solar heating, outgassing occurs at a rapid pace from their upper surface. The velocity of gas ejection from the fragments is inversely proportional to their sizes. For this reason, temporarily the brightness of the smaller fragments is greater than that of the larger ones.

(3) The velocity of broken up fragments remains very small (usually less than a metre per second) at the time of their separation from parent comets. For example, the components of the split comet Hyakutake had a relative velocity of about 0.8km/sec.

(4) It has been found in a number of split comets that when the components are far enough so that they no longer share the same coma, nearly parallel tails develop in them in anti-solar direction. A spectacular example of parallel tails was shown by the fragments of Shoemaker-Levy 9 (D/1993 F 2).

(5) Most secondary nuclei, particularly short-lived ones, repeatedly exhibit a noticeable elongation along the line with the principal nucleus for a brief period before fading out. This indicates a gradual expansion of the dimensions of the fragments instead of central condensation.

(6) Chen and Jewitt have estimated from their observations that the cometary splitting rate is ~ 0.01 per year per comet or even larger. They have also suggested that splitting may be an important process for destruction of the cometary nuclei. On the other hand, A Carusi and others reported in 1985 that two SP comets of Jupiter family (42P/Neujmin 3 and 53P/Biesbroeck) originated from a cometary splitting around 1850. From this investigation Rickman concluded that the splitting of cometary nuclei may also be a process of creation of new comets.

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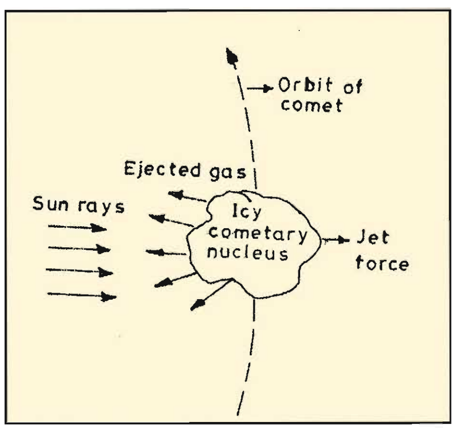
Causes for Cometary Splitting

We know that at each perihelion passage, a comet suffers mass loss because some of the particles at the farthest regions of the tail cannot return to the comet and are lost forever. But cometary splitting is something different from this type of slow but steady loss of material. Comets are subjected to two principal forces other than the gravitational force of the Sun – (1) non-gravitational force and (2) tidal force.

Effects of Non-gravitational Force

When any comet approaches the Sun, material in its nucleus is vaporised. As a result of this outgassing of the cometary material, an internal stress starts developing within the nucleus of the comet. The radial component (i.e. component acting along the line joining the Sun and the comet) of this force is typically $10^{-5} F_{\odot}$ (where $F_{\odot}$= solar attraction) although at times it may be as high as $10^{-4} F_{\odot}$. It has been found that in the vicinity of the Sun, the gas production rate of a comet varies approximately as the inverse square of its heliocentric distance. Since the nucleus is made of fragile components, it disintegrates into two or more fragments. Due to outgassing, the comet is pushed outward from its orbit (*Figure* 2). However, for a rotating comet, different portions of the nucleus are not heated at the same time. This delay causes the comet to accelerate or decelerate in its orbit. For direct rotation of the nucleus, (i.e. the rotation of the comet takes place in the same direction as that of its orbital motion) the ejection of cometary particles due to solar heating is delayed and the jet force acts in a direction as shown in *Figure* 3a. Due to this force, the comet is pushed forward and its period increases. This happened for the Comet d' Arrest (6P/1978) in the period between November 1857 and May 1897 and again since August 1976. On the other hand if a comet rotates in retrograde direction (i.e. the comet rotates in the opposite direction as that of its orbital motion), then the jet action will act in a direction as shown in *Figure* 3b and the motion of the comet will be slowed down to cause a decrease in its period. This is happening in case of Comet Encke (2P/Encke). Jet action may be responsible for disintegration of comets. For example, the parent comet of

Figure 2.



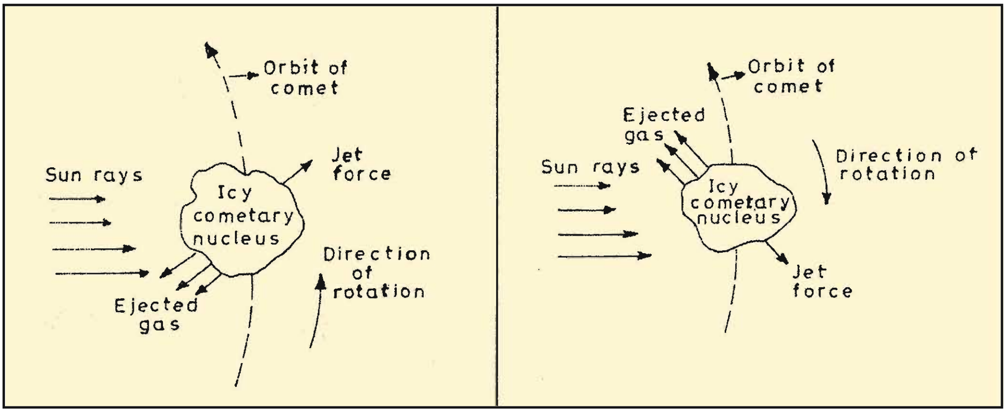


Figure 3.

42P/Neujmin 3 and 53 P/Biesbroeck might have suffered split after an outburst activity.

The net differential effect in solar attraction between the companion and the primary is denoted by γ. By convention, a positive sign of γ indicates deceleration. The relation between endurance E (to be explained later) of a companion, its differential non-gravitational deceleration and the bulk properties of the parent comet is given by

$$E = \frac{\rho \Delta R}{Z} \quad \text{and} \quad \gamma = j_{\text{companion}} - j_{\text{principal}}$$

where Z is an average mass vaporization rate per unit surface area, ρ the bulk density (assumed to be constant throughout the parent comet), ΔR an average thickness of the layer of ice evaporated during the time E and j the net force per unit mass of the fragment exerted by the momentum due to non-uniform outgassing of the fragment. Quantities Z and j refer to 1 AU from the Sun.

Effects of Tidal Force

Since cometary nuclei are made of ice and other volatile substances, they are prone to disruption due to tidal force exerted by the Sun or major planets like Jupiter, Neptune, etc. If any comet comes within the Roche limit (see *Box* 1) of the Sun, then it suffers tidal disruption due to differential gravitational force.

Box 1. Roche's Limit.

Roche's limit of the Sun is a certain limiting distance within which the gravitational influence of the Sun is strong enough to perturb any celestial object. The Roche's limit γ of the Sun for a comet may be obtained by the relation.

$$\gamma = 1.44\,(d_\odot / d_c)^{1/3}\, R_\odot .$$

where $d_\odot$ = density of the Sun
d_c = density of a comet
$R_\odot$ = radius of the Sun.

Since, $R_\odot$ = 6,96,000 km = 0.00465247 AU and $d_\odot$ = 1.41 gm cm^{-3} then the maximum value of the Roche's limit of the Sun can be obtained as

$$\gamma_{max} = 0.01618 \text{ AU}.$$

sungrazing comets including the Kreutz group (see *Box* 2) belong to this class.

The nucleus of a comet may split up if (1) during the crossing of nodes (i.e the two points of intersections of a planetary orbit and the path of a comet) or (2) at the aphelion, the comet enters within the sphere of influence (see *Box* 3) of a major planet, in particular Jupiter. Comet Shoemaker-Levy 9 discovered by Eugene Shoemaker, Carolyn Shoemaker and David Levy of Mount Palomar Observatory is a typical example.

Box 2. Kreutz Group of Comets

German scientist Heinrich Kreutz first identified peculiarities of these comets in 1888. They pass very close to the Sun (within 3 million km or less). A typical member of this group is the Great September Comet (1882 R1) which passed through the solar atmosphere and its distance from the Sun was two-third of the solar radius. After its perihelion passage on September 17,1882, the nucleus of the comet became elongated and it got clumped at four or five places. After that the comet broke up into four components A, B, C and D. The components A and D remained visible till February 28, 1883 while the fragments C and B were last seen on March 3 and May 26, respectively of the same year. Solar and Heliospheric Observatory (SOHO) (see Vol.2, No.10, *Resonance*, p.75, 1997) has detected more than 100 comets of this group, the 100th in February, 2000. Marsden of the International Bureau of Telegrams suggests, based on orbit computations, that all these may have resulted from the fragmentation of a comet which appeared in 1100 AD, which in turn may have been part of a great comet of 372 BC. Marsden's view supports the opinion of Rickman that the splitting of cometary nuclei may be a process of creation of new comets.

Box 3. The Sphere of Influence (SOI) Radius

The sphere of influence (SOI) radius is defined by the radius of a planet within which a body can describe a planeto-centric orbit more conveniently than the orbit on a heliofocal path. SOI radius γ_{SOI} of a planet is given by

$$\gamma_{SOI} = (M_p/M_\odot)^{2/5}\, \gamma_p,$$

where M_p = Mass of the planet

$M_\odot$ = Mass of the sun

γ_p = Radius vector of the planetary orbit.

Taking M = 1.99 × 1024 kg. and the corresponding values of M_p and γ_p of the nine planets of the solar system, their respective SOI radius can be calculated using the above formula. *Table* 1 gives SOI radius of all the nine planets of the solar system.

Table 1.

	SOI radius		
Planet	in AU	in 10^4 km.	as a ratio to the planetary radius
Mercury	7.518×10^{-4}	11.24	45.18
Venus	4.097×10^{-3}	61.29	99.06
Earth	6.180×10^{-3}	92.95	144.96
Mars	3.859×10^{-3}	57.73	170.80
Jupiter	0.322	4821.00	675.50
Saturn	0.365	5465.00	905.87
Uranus	0.347	5187.00	2042.26
Neptune	0.581	8694.00	3895.25
Pluto	0.081	3149.00	2736.24

At the time of discovery, on March 24, 1993, the comet was found to be broken up into 23 fragments. While passing within the sphere of influence (SOI) of Jupiter, the nucleus of the comet was split up on July 8, 1992. Then between July 16 and July 22, 1994, twenty pieces plunged into Jupiter and were destroyed. On July 16, the component A first plunged into Jupiter. Subsequently other pieces also followed the component A. The pieces J and M were lost from vision in July and December, 1993 respectively while the component P1 was last seen in March, 1994. Though splitting is very common among comets, yet no other comet has been broken up into so many fragments as Shoemaker-Levy 9.

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Whipple had shown in 1963 that a comet of density ρ, radius R cannot survive against a source of tidal perturbation at a distance Δ if

$$\sigma < \frac{GM\rho R^2}{\Delta^3},$$

where σ is the tensile strength (i.e the strength to withstand tensile force) of the comet, M the mass of the tidal attractor and G is the universal constant of gravitation. After putting the numerical values of G, M and Δ for the Great September Comet (C 1882 R1) and Comet Ikeya-Seki (C/1965S1), the above condition reduces to

$$\sigma < 840\ \rho R^2,$$

since Δ_{min} for both C/1882 R1 and C/1965 S1 equalled ~0.008 AU. Where R is expressed in km. ρ in gm cm^{-3} and σ in dynecm^{-2}. For tidal splitting of comet 16P/Brooks 2 (1886-88) due to Jupiter, the condition becomes.

$$\sigma < 400\ \rho R^2,$$

Similarly, if we consider the disruptive force due to rotational motion of the comet, then the relation between tensile strength and rotational period is given by

$$\sigma < \frac{2\pi^2 \rho R^2}{P^2}$$

where P is the period of rotation.

It has been found that the maximum tensile strength of cometary material lies between 10^3 and 10^5 dynes cm^{-2}. This value of σ is too low (the tensile strength of aluminium is of the order of 10^9 dynes cm^{-2}) to withstand the tidal force exerted on them by

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the Sun or major planets. It requires a velocity of 11 km/sec. for an object to leave the Earth, whereas a similar escape velocity for a typical comet is about 1 metre/sec.

Parent, Principal and Secondary Fragments

The individual components of a broken comet are often referred to as fragments while the presumed original nucleus is a parent. In cases where one of the fragments is dominant in terms of brightness, activity and/or persistence, the dominant fragment is called a principal (or primary) nucleus while the less conspicuous fragments are termed as secondary or companion nuclei. For nontidally split comets, the principal takes the leading position among all the pieces originated due to fragmentation. But for tidally split comets the principal nucleus may not be in the first position. For example, in case of comet Shoemaker-Levy 9 the leading component A was one of the fainter components while the four bright fragments G, K, L and Q were all near the middle of the line.

How the fragmentation sequence occurs for a split comet can be understood from the fragmentation hierarchy for Machholz 2(P/1994) as proposed by Sekanina (*Figure* 4). When D E Machholz recovered this SP comet (orbital period 5.2 years) in August 1994, it showed five condensations, viz., from A to E of which the fragment D further disintegrated into two components. All the fragments were lined up with A as the leading and

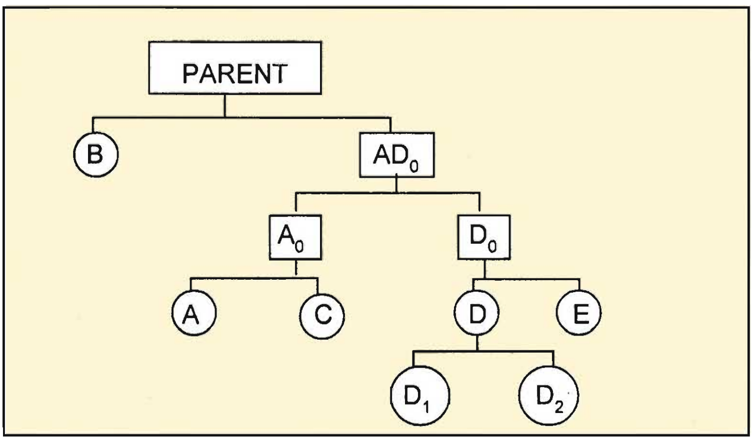

Figure 4. Fragmentation hierarchy for P/Machholz 2. (Adapted from Sekanina 1999.)

brightest component. In late 1987, approximately 600 days before its perihelion passage, the comet had disintegrated for the first time into two components B and AD_0. After surviving for about 600 days, fragment AD_0 further disintegrated into two components A_0 and D_0.

After only 5 days, A_0 gave birth to A and C while D_0 survived for about 600 days before splitting up into the components D and E. Prior to the 1994 perihelion passage, D broke into two components D_1 and D_2.

Depending on the endurance time, fragments have been divided into three categories – persistent companions, short-lived companions and minor companions.

The period of survival for a fragment is measured by its endurance. Endurance E of a fragment has been defined as an interval of time from break up time t_s to its final observation time t_f, normalized by the inverse square law to 1 AU from the Sun. Expressed in equivalent days (i.e. equivalent to Earth days), endurance measures a minimum sublimation lifetime of a companion and is given by

$$E = \int_{t_s}^{t_f} \frac{dt}{r^2} = 1.015 p^{-1/2} A_{sf} ,$$

where p is the length of the semi latus-rectum of the fragment's orbit expressed in AU and A_{sf} is the length of the heliocentric arc of orbit (expressed in degrees) swept out by the fragment between t_s and t_f.

Depending on the endurance time, fragments have been divided into three categories – persistent companions, short-lived companions and minor companions. For persistent companions endurance exceeds 80 equivalent days, while endurance for short-lived companions lie between 10 and 100 equivalent days. Endurance for minor companions are less than or equal to 30 equivalent days.

A New Approach

Thus we see that two principal mechanisms are responsible for splitting of comets. Apart from those two processes, there is another alternative mechanism for cometary splitting proposed by Whipple and Stefanik in 1966. Due to radioactive heating (i.e. generation of heat due to radioactive transmutations of elements), a brittle shell of volatile material may be formed around the nucleus by mass transport (i.e transfer of mass from the core of the cometary nucleus towards the outer surface). As the comet approaches the Sun for the first time, this outer shell may fail to resist the heat shock and related differential expansion (i.e. uneven expansion). Further investigations may tell us the plausibility of this new alternative process.

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Suggested Reading

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