LECTURE 2: COMETS

OORT CLOUD DYNAMICS - PHYSICS AND CHEMISTRY OF THE NUCLEUS

* External perturbers on Oort cloud comets.
* Injection rate of comets into the planetary region.
* Comet showers.
* The comet nucleus: the “dirty snowball” and the “rubble pile” models.
* Collisional or primordial rubble piles?
* Outbursts and splittings of comet nuclei.
* Chemical composition.
* Formation of radicals and ions in the coma.
* Formation of the comet tails.
Perturbations by nearby stars

Geometry of a stellar encounter.

Let us consider a star of mass $M$ passing at a high relative velocity $V$ with respect to the Sun, such that $V \gg v_c$ where $v_c$ is the orbital velocity of the comet.
We can use the impulse approximation

\[ \Delta v_c = \int_{-\infty}^{+\infty} F_* \times dt = \int_{-\infty}^{+\infty} \frac{GM}{(D^2 + x^2)^{1/2}} \frac{dx}{V} = \frac{2GM}{VD} \]

where \( x \) is the distance along the star’s straight path to the point \( K_c \) of closest approach to the comet, and \( D \) is the distance of closest approach of the star to the comet. The velocity of the star can be expressed as: \( V = \frac{dx}{dt} \).

Since the sum of the impulses along the trajectory cancel out, the only nonzero component of the perturbing force exerted by the star on the comet will follow the direction \( \vec{D} \). The vector \( \Delta \vec{v}_c \) will have the same direction as \( \vec{D} \).

The star will also impart an impulse to the Sun that can be calculated in the same manner. Let \( K_\odot, \vec{D}_\odot, \) and \( D_\odot \) be the point of closest approach to the Sun, the vector of closest approach of the star to the Sun and its magnitude. The impulsive change in the comet’s velocity with respect to the Sun is

\[ \Delta \vec{v} = \Delta \vec{v}_c - \Delta \vec{v}_\odot = \frac{2GM \vec{D}}{VD \vec{D}} - \frac{2GM \vec{D}_\odot}{VD_\odot \vec{D}_\odot} \]
If the star gets much closer to the Sun than to the comet, namely if $D_\odot << D$, the previous equation can be approximated by

$$|\Delta v| \simeq |\Delta v_\odot| = \frac{2GM}{VD_\odot}$$

It is also possible that occurs the opposite situation, namely $D << D_\odot$. The change $|\Delta v|$ will be the same with the substitution of $D_\odot$ by $D$.

For distant stellar encounters in which $r << D_\odot$ and $r << D$, the vectors $\vec{D}$ y $\vec{D}_\odot$ will become quasiparallel and the impulse equation reduces to

$$|\Delta v| \simeq \frac{2GMr\cos \beta}{VD_\odot^2}$$

where $\beta$ is the angle between the vectors $\vec{r}$ and $\vec{D}_\odot$.

During an orbital revolution of period $P$ the comet will be perturbed by many stars. In order to compute the overall perturbation by passing stars, we have to know the stellar flux $\Phi_*$ in the Sun’s vicinity.
### Stellar flux in the Sun’s vicinity

#### Stellar populations in the Sun’s vicinity

<table>
<thead>
<tr>
<th>Class</th>
<th>$\rho_{*,i}$ ($M_\odot$ pc$^{-3}$)</th>
<th>$n_{*,i}$ (pc$^{-3}$)</th>
<th>$\sigma_{*,i}$ (km s$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>giants</td>
<td>0.0006</td>
<td>0.0005</td>
<td>17.0</td>
</tr>
<tr>
<td>MS$^{(2)}$ $M_V &lt; 2.5$</td>
<td>0.0031</td>
<td>0.0013</td>
<td>7.5</td>
</tr>
<tr>
<td>MS $2.5 &lt; M_V &lt; 3.0$</td>
<td>0.0015</td>
<td>0.0010</td>
<td>10.5</td>
</tr>
<tr>
<td>MS $3.0 &lt; M_V &lt; 4.0$</td>
<td>0.0020</td>
<td>0.0015</td>
<td>14.0</td>
</tr>
<tr>
<td>MS $4.0 &lt; M_V &lt; 5.0$</td>
<td>0.0024</td>
<td>0.0021</td>
<td>19.5</td>
</tr>
<tr>
<td>MS $5.0 &lt; M_V &lt; 8.0$</td>
<td>0.0074</td>
<td>0.0090</td>
<td>20.0</td>
</tr>
<tr>
<td>MS $M_V &gt; 8.0$</td>
<td>0.014</td>
<td>0.05</td>
<td>20.0</td>
</tr>
<tr>
<td>white dwarfs</td>
<td>0.005</td>
<td>0.008</td>
<td>20.0</td>
</tr>
<tr>
<td>brown dwarfs</td>
<td>0.008</td>
<td>0.12</td>
<td>20.0</td>
</tr>
</tbody>
</table>

(1) Source: Holmberg & Flynn (2000)

(2) MS: main sequence stars with absolute visual magnitudes $M_V$ in the indicated range.

By combining all the spectral types of the table (except the brown dwarfs), we obtain a stellar density in the Sun’s neighborhood $n_*=0.073$ pc$^{-3}$ and a mass density $\rho_*=0.036$ $M_\odot$ pc$^{-3}$, that gives an average mass per star $\sim 0.5$ $M_\odot$. 

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*Ciclo de Cursos Especiais - Lecture 2*
Galactic tidal force

The tidal force of the Galactic disc dominates over that of the Galactic bulge.

The Galactic disc can be approximately modelled as a homogeneous disc of density $\rho_{\text{disk}}$ in the mean plane of the Galaxy, such that its potential can be expressed as (Heisler & Tremaine 1986, Morris & Muller 1986, Torbett 1986)
\[ U = U_o + 2\pi G \rho_{\text{disk}} z^2 \]

where \( U_o \) is a constant and \( z \) is the distance to the Galactic mean plane.

Mass density in the mean plane of the Galaxy at the distance of the Sun to the Galactic center: \( \rho_{\text{disk}} = 0.10 \, \text{M}_\odot \, \text{pc}^{-3} \).

The Sun will experience oscillations in the vertical direction to the Galactic plane described by the equation of motion

\[ \frac{d^2 z}{dt^2} = -4\pi G \rho_{\text{disk}} z \]

With a half-period \( \tau_z = \sqrt{\frac{\pi}{G \rho_{\text{disk}}}} \sim 42 \, \text{Myr} \), reaching a maximum altitude of about 70 pc.

From the potential \( U \), we obtain the tidal force of the Galactic disc acting on a comet at a Galactic latitude \( \phi \)

\[ \vec{F}_{\text{disk}} = [(dU/dz)_c - (dU/dz)_\odot] \hat{z} = 4\pi G \rho_{\text{disk}} r \sin \phi \hat{z} \]
$r$: distance Sun-comet, $r \sin \phi = z_c - z_\odot$ is the difference between the distances of the comet and the Sun to the mean Galactic plane, and $\hat{z}$ is a unit vector perpendicular to the Galactic plane.

The tidal force of the Galactic disc acts changing the comet's perihelion distance by the amount (per revolution)

$$q_f^{1/2} = q_i^{1/2} + 4.5 \sqrt{2} \pi^2 M_\odot^{-1} \rho_{disk} a_7^{7/2} \cos \alpha \sin 2\phi$$

$q_i$, $q_f$: initial and final perihelion distances, $\alpha$ is the angle between the orbital plane and the plane perpendicular to the Galactic disc containing the Sun-comet radius.
Change in the perihelion distance by external perturbers

Relative change in $q$ per orbital revolution (Fernández 2005).

* The effects of the external perturbers (passing stars and the tidal force of the Galactic disc) start to be significant for semimajor axes $a \gtrsim 10^4$ au.
From the Oort cloud to the inner planetary region

Fictitious comet starts at the star and ends at the square (Kaib & Quinn 2009)

* An *inner* Oort cloud comet ($a \lesssim 2 \times 10^4$ au) must require many revolutions to change appreciably its perihelion distance. Once it approaches the Jupiter-Saturn barrier, planet perturbations are strong enough to raise its semimajor axis to values where $\Delta q/q \sim 1$ in a single revolution $\implies$ The comet can then overshoot the Jupiter-Saturn barrier to reach the terrestrial planet zone.
Dependence of the tidal force of the Galactic disc on the Galactic latitude: Observational evidence

Distribution of Galactic latitudes of 151 new and “young” comets ($a_{\text{orig}} > 500$ au). The histograms were fitted to normalized sinusoidal curves (Fernández 2005).
Very close stellar encounters: Definition of the *loss cone*

The diffusion of the perihelion distances of Oort cloud comets with small $q$ by external perturbers leads to an uniform $q$-distribution. The fraction of thermalized comets with perihelion distances $< q$ is

$$F_q \sim \frac{2q}{a}$$

valid for $q << a$. The number of comets with perihelion distances in the range $(q, q + dq)$ is

$$f_q(q) dq = \left( \frac{dF_q}{dq} \right) dq = \frac{2}{a} dq$$

*Loss cone*: Oort cloud comets with semimajor axis $a$ are thermalized, namely the velocity vectors are isotropically distributed. However, vectors very close to the solar direction will be quickly removed by planetary perturbations generating a *loss cone*. The fraction of comets with perihelion distances $q < q_L$ (where $q_L \sim 15$ au) is $F_L \sim \frac{2q_L}{a}$

$\Rightarrow$ the solid angle of the loss cone is $4\pi F_L$ and its radius $2F_L^{1/2}$.
The flux of Oort cloud comets per unit of $q$ that reach the Earth’s vicinity is

$$\dot{n}_{Earth} = \frac{1}{qL} \int_{a_{fill}}^{+\infty} F_L \frac{1}{P} \Gamma(a) da$$

where $F_L = 2qL/a$, $P = a^{3/2}$, and $\Gamma(a) da$ is the number of Oort cloud comets with semimajor axes in the range $(a, a + da)$. Numerical simulations lead to the following empirical relation

$$\Gamma(a) da \propto a^{-\gamma} da$$

where $\gamma \approx 2 - 4$ (Bailey 1983, Fernández and Ip 1987).
A very close stellar encounter can suddenly fill the loss cones of those comets close to the star’s path causing a sudden increase of the comet flux in the Earth’s vicinity.
Anomalies in the distribution of the comet aphelia

The anomalous aphelion clusterings shown in the map could uncover very close star passages in the recent past (Fernández & Ip 1991).
Comet showers

Large perturbations cause the filling of loss cones, thus provoking a substantial increase in the comet flux in the Earth’s neighborhood. This phenomenon is called a comet shower.

Could the Earth have been exposed to comet showers during its lifetime?? Could comet showers have been responsible for any of the mass extinctions that punctuated the development of life on Earth?

(Heisler 1990)
Fred Whipple’s “dirty snowball model”

Artist conception of the comet nucleus according to Whipple’s model in vogue in the 1970s.

Fred Whipple shows his model of dirty snowball consistent in a snowball of 250 kg covered with dirt.
Comet nuclei observed from spacecraft

Images of comets Halley, Borrelly, Tempel 1 and Wild 2 taken from spacecrafts at short distance (left). The “rubble-pile” model (e.g. Weissman 1986) (right).
The Giotto mission of the European Space Agency (ESA) was the first flyby to a comet (Halley) in 1986.
The *Deep Impact* mission of NASA had as a goal the study of the material of comet 9P/Tempel 1. The spacecraft arrived to the comet on July 4, 2005 releasing an impactor that collided with the comet nucleus, releasing a dust cloud that was monitored.
The Rosetta mission of ESA was launched in 2004 in a long 10-yr journey targeted to comet 67P/Churyumov-Gerasimenko.
Images of comet Churyumov-Gerasimenko

The *Rosetta* spacecraft is now orbiting the comet nucleus at about 30 km of its surface. Spectacular images of the nucleus have been taken that show 2 lobes united by a neck. The comet is about 4 km length. There is currently a discussion on whether this body is primordial, a result of a gentle collision of two planetesimals, or if it is a product of evolution.
Rosetta and Philae

The Rosetta spacecraft carried a lander called *Philae* (an old Egyptian city). Unfortunately, the landing was not as good as expected and Philae finally laid down in a shaded place, being unable to receive enough solar energy.
Physical aspects

* The equation of thermal equilibrium

\[
(1 - A_v) \frac{F_\odot e^{-\tau}}{r_{AU}^2} \pi R_N^2 = 4\pi R_N^2 (1 - A_{IR}) \sigma T^4 + \frac{Q L_S}{N_A} + 4\pi R_N^2 \kappa(T) \left| \frac{\partial T}{\partial z} \right|_{z=0}
\]
Outbursts and splittings of comet nuclei

Spectacular brightness increase (∼14 magnitudes) of the Jupiter family comet 17P/Holmes (October 2007).

Splitting process of comet C/1975 V1 (West) in 4 main pieces between 8-18/March/1976 (New Mexico State University, Las Cruces).
Estimate of the mass released in the outbursts of comets 41P/Tuttle-Giacobini-Kresák and 17P/Holmes

Approximated calculation of the dust content in the coma:

\[ I_d = \frac{N(S)\pi s^2 p(\lambda)\phi(\alpha)}{\pi r^2 \Delta^2} F_\odot \]

- \( I_d \): Intensity in the continuum (measured in the visible)
- \( N(S) \): Number of dust particles of typical radius \( s \) within the circular aperture of radius \( S \)
- \( p(\lambda) \): geometric albedo of the dust particles
- \( \phi(\alpha) \): phase function of phase angle \( \alpha \)
- \( r \): heliocentric distance (expressed in au)
- \( \Delta \): geocentric distance

Total mass of dust:

\[ M_d = N(S) \times \frac{4}{3} \pi s^3 \rho_d \]

\( \rho_d \): density of the dust grains
Brightness of the comet nucleus:

\[ I_N = \frac{F_\odot R_N^2 p_v \phi'(\alpha)}{r^2 \Delta^2} \]

Ratio of the dust coma to the nucleus brightness:

\[ \frac{I_d}{I_N} = \frac{N(S) s^2 p(\lambda) \phi(\alpha)}{R_N^2 p_v \phi'(\alpha)} \]

Converting into magnitudes:

\[ m_N - m_d = 2.5 \log \left[ \frac{N(S) s^2 p(\lambda) \phi(\alpha)}{R_N^2 p_v \phi'(\alpha)} \right] \]

For the calculations we adopt a typical dust grain size: \( s = 1 \ \mu m \ (= 10^{-4} \ cm) \)
Absolute nuclear magnitude: $H_N = 18.4$, nucleus radius: $R_N = 0.7$ km

1st *Outburst*: 25 May 1973
$m_{\text{max}}(1UA) \simeq 4.0$, previous magnitude $\sim 13$, $r \sim q = 1.152$ au

2nd *Outburst*: 5 July 1973
$m_{\text{max}}(1UA) \simeq 4.0$, previous magnitude $\sim 13$, $r = 1.25$ au

Released mass of dust: $M_d = 1.3 \times 10^{13}$ g

Mass of the comet nucleus: $M_N = 7.2 \times 10^{14}$ g

$\Rightarrow \quad \frac{M_d}{M_N} = 0.018$
17P/Holmes

Absolute nuclear magnitude: $H_N = 16.6$, nucleus radius: $R_N = 1.6$ km

*Outburst*: 23 October 2007

$m_{max}(1UA) \simeq 1.4$, previous magnitude $\sim 15.4$, $r = 2.435$ au

Released mass of dust: $M_d = 1.42 \times 10^{14}$ g

Mass of the comet nucleus: $M_N = 8.6 \times 10^{15}$ g

\[ \Rightarrow \quad \frac{M_d}{M_N} = 0.016 \]

\[ \Rightarrow \text{The mass released in splittings and outbursts can be greater than the continuous release by sublimation} \]
Frequency of splittings

JFCs $\sim 1 \ splitting / comet \ every \ \sim 77 \ revolutions$

LPCs $\sim 1 \ splitting / comet \ every \ \sim 25 \ revolutions$ \quad (Fernández 2005)

Is there a correlation with the heliocentric distance?

Number of observed splittings as a function of the perihelion distance.
Possible causes of splittings and outbursts

- Tidal force of the Sun, Jupiter or a terrestrial planet.
- Phase transition of amorphous ice to crystalline ice.
- Sublimation of pockets of a very volatile material (e.g. CO, CO$_2$).
- Thermal stresses that cause fractures.
- High rotation speed of the comet nucleus leading to rotational instability.
- Solar activity.
- Collisions with meteoroids.
- Collisions with fragments of the nucleus itself.
Generation of internal pressure and fragmentation

Fragmentation of a “rubble pile” nucleus due to the increase of the pressure of gases that cannot escape freely through the regolith mantle (right-hand side). If there were not regolith mantle, the gases would escape thus preventing the increase of the pressure (left-hand side) (Samarasinha 2001).
Cometary spectra

Spectrogram of comet C/1975 N1 (Kobayashi-Berger-Milon) showing the main molecular bands in the visible and near UV. The narrow dark strip in the middle of the spectrum along the $\lambda$-axis is the continuum produced by the scattering of sunlight by the dust particles in the inner coma (radius $\sim 10^4$ km) (Wyckoff 1982).
UV spectrum of comet Hale-Bopp taken with the *Faint Object Spectrograph* of the Hubble Space Telescope. The spectrum shows the Cameron bands of CO, a band of CS and the conspicuous band of OH (Weaver et al. 1997).
## Chemical composition

### Relative abundances of molecular species in comets

<table>
<thead>
<tr>
<th>Molecule</th>
<th>Mass fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>H$_2$O</td>
<td>$\sim 100$</td>
</tr>
<tr>
<td>CO</td>
<td>$\sim 7$-8</td>
</tr>
<tr>
<td>CO$_2$</td>
<td>$\sim 3$</td>
</tr>
<tr>
<td>H$_2$CO</td>
<td>$\sim 0$-5 (formaldehyde)</td>
</tr>
<tr>
<td>NH$_3$</td>
<td>$\sim 1$-2</td>
</tr>
<tr>
<td>HCN</td>
<td>$\sim &lt;0.02$-0.1</td>
</tr>
<tr>
<td>CH$_3$OH</td>
<td>$\sim 1$-5 (methanol)</td>
</tr>
</tbody>
</table>

Other detected molecules of biological interest:

HNCO, HC$_3$N, OCS, H$_2$CS, NH$_2$CHO, HCOOH, HCOOCH$_3$, CH$_3$CHO, HNC, C$_2$H$_2$, C$_2$H$_6$
Sublimation rate of different volatile molecules as a function of the temperature (Mukai et al. 2001).
The distribution of parent molecules and radicals in the coma

The observed radicals in the cometary spectrum cannot exist in free state. They are produced when the sublimated parent molecules are photodissociated and ionized under the Sun’s UV radiation.

Let us take the example of the most important parent molecule: $\text{H}_2\text{O}$. Its photodissociation leads to the following products:

$$\text{H}_2\text{O} + h\nu \rightarrow \begin{cases} 
\text{H} + \text{OH} \\
\text{H}_2 + \text{O} \\
2\text{H} + \text{O} \\
\text{H}_2\text{O}^+ \\
\text{H} + \text{OH}^+ 
\end{cases}$$

where $h\nu$ represents the photon energy. A percentage of 85.5% of the water molecules are dissociated in H and OH. The conclusion is that a comet must be surrounded by a huge corona of hydrogen atoms.
Hydrogen corona around comet Hale-Bopp when it approached the Sun in 1997. The image in UV light was obtained by the SWAN instrument onboard of the SOHO spacecraft. The corona occupies an extension of about $10^8$ km.
Another interesting example is:

\[ \text{CO}_2 + h\nu \rightarrow \text{CO} + \text{O}^1\text{D} \]

where the oxygen is left in the excited \(^1\text{D}\) state from which it is de-excited emitting fluorescent radiation in the red line at 6300 Å.

**Formation of the ion tail**

The decomposition of the parent molecules leads to the production of many different ions, in particular \(\text{CO}^+, \text{N}_2^+, \text{CH}^+, \text{CO}_2^+, \) and \(\text{H}_2\text{O}^+\). The ions are trapped by the magnetic fields associated to the *solar wind* and dragged in the opposite direction to the Sun forming the ion tail. Its blue color is due to the fluorescent radiation emitted by the ion \(\text{CO}^+\).
Formation of the dust tail

The motion of the dust particles will be ruled by 2 opposite forces: the gravitational attraction of the Sun $F_G$ and the force associated to the solar radiation pressure $F_R$. For a dust particle of radius $a$ and density $\rho$ at a heliocentric distance $r$, these 2 forces can be expressed as

$$F_G = \frac{G M_\odot}{r^2} \left( \frac{4}{3} \pi a^3 \rho \right)$$

$$F_R = \frac{Q_{pr}}{c} \left( \frac{L_\odot}{4 \pi r^2} \right) \pi a^2$$

where $c$ is the light speed and $Q_{pr}$ is the efficiency factor for the radiation pressure. Since both forces $F_G$ y $F_R$ are radial, opposite, and vary as $r^{-2}$, a dust particle will follow a Keplerian trajectory that corresponds to an “effective” gravitational field reduced by the factor $(1 - \beta)F_G$ where

$$\beta = \frac{F_R}{F_G} = 0.585 \times 10^{-4} \frac{Q_{pr}}{\rho a}$$

($\rho$ and $a$ are expressed in cgs units).
The dust particles released from the nucleus at different times $t_1$, $t_2$, $t_3$ ... will follow diverging trajectories from the nucleus in such a way that appear collectively as a curved tail opposite to the Sun.