LECTURE 4: COMETS
ORIGIN AND INTERRELATIONS

* Comets: residual planetesimals of the planet formation.
* Rocky and icy bodies: the snowline.
* Accretion of the giant planets and scattering of the residual material: Formation of the Oort cloud and the trans-neptunian belt.
* Galactic environment in which the solar system formed.
* The search for a planet X.
* How pristine are comets?.
* Collisions of comets and asteroids with the Earth.
* The problem of the terrestrial water.
* Comets and the origin and development of life on Earth.
Star formation in giant molecular clouds

Typical physical parameters in giant molecular clouds:

Temperature: $T \simeq 10$ K
Mass: $10^5 - 10^6$ M$_\odot$
Diameter: $\sim 50$ pc
Average density: $\sim 10^2$ H$_2$ cm$^{-3}$ (up to $\sim 10^{5-6}$ H$_2$ cm$^{-3}$ in dense cores)

* A large number of organic molecules have been detected in giant molecular clouds, in general compounds rich in C, H, O, N, that can be incorporated into the planets that formed there.
Condition to form a star

Jeans’s criterion for the collapse of a gas cloud of density $n$ and temperature $T$:

Self-gravity $> \text{Thermal pressure} \Rightarrow$

$$M_J \approx 10 \frac{T^{3/2}}{\sqrt{n}} \, M_\odot$$

In a dense region: $M_J \approx 1 \, M_\odot$
Protoplanetary discs in the Orion nebula

HST images (NASA)

Half-lifetime: $\sim 10^7$ yr. The surrounding gas is swept by the strong UV flux of nearby O and B stars, and/or strong stellar winds from the central star.
Collapsing nebula and formation of a protoplanetary disc: Integral view of the process
Physical properties of the protoplanetary disc:

- Mass: $0.01 - 0.1 \, M_\odot$
- Mass density: $\rho = \rho_o \left(\frac{r}{r_o}\right)^{-m}$
- Temperature: $T = T_o \left(\frac{r}{r_o}\right)^{-n}$

Artist concept of the protoplanetary disc during the stage of planetesimal formation.

Condensation of the different materials as a function of the heliocentric distance.
The final stage of planet formation

“Snowline”: between $r \sim 2 - 5 \text{ au}$
The most primitive material is the less differenciated in elemental abundances

Example of primitive material: Carbonaceous meteorites
At the beginning the dust particles settle in a thin equatorial disc. Then they start to accrete by gentle mutual collisions (adhesion by van der Waals forces) leading to kilometer-size *planetesimals*. The planetesimals continue their accretion by mutual collisions until the formation of planets. A fraction of the residual planetesimals is scattered toward the inner planetary region and to the outermost part. The latter form the Oort cloud.
Residues of the primordial accretion

Brownlee particle collected in the stratosphere. It is a highly porous aggregate of micrometer and sub-micrometer dust particles.
Planet migration in the scenario of planetesimal scattering

∗ Planet migration by exchange of angular momentum between the protoplanets and the scattered planetesimals.

The orbital radius $a_N$ of a planet (Neptune) will experience a change $\Delta a_N$ due to the exchange of angular momentum with the interacting planetesimal, which it is given by

$$\frac{\Delta a_N}{a_N} \sim -2 \frac{m}{M_N} \frac{\Delta h}{h_N}$$

$\Delta h$ : change of the specific angular momentum of the interacting planetesimals.

There are two possible results:

(a) Scattering inwards toward Jupiter’s influence zone.

(b) Ejection to interstellar space or the Oort cloud.
(a). Let us first assume that all the interacting planetesimals are ejected to interstellar space.

A planetesimal gains an amount of specific angular momentum:

\[ \Delta h = (\sqrt{2} - 1)a_N v_N \]

\[ v_N = (\mu/a_N)^{1/2} : \text{heliocentric circular velocity at Neptune's distance.} \]

\[ m_r : \text{total mass of planetesimals ejected to interstellar space.} \]

Change in the orbital radius:

\[ \frac{\Delta a_N}{a_N} \sim -2(\sqrt{2} - 1) \frac{m_r}{M_N} \]

For example, if Neptune ejected a total mass \( m_r = 0.5M_N \), its orbital radius would have shrunk to \( a'_N = a_N + \Delta a_N \sim 0.6a_N \).
(b). All the residual planetesimals of Neptune’s accretion zone are scattered inward towards Jupiter’s influence zone, from where they are ejected by Jupiter’s perturbations.

The specific angular momentum by each one of the interacting planetesimals (and gained by Neptune) is

\[ \Delta h \approx - \left[ 1 - \left( \frac{2a_J}{a_N + a_J} \right)^{1/2} \right] a_N v_N \]

\( a_J \) : Jupiter’s orbital radius.

In this case Neptune will increase its orbital radius by

\[ \frac{\Delta a_N}{a_N} \approx +2 \left[ 1 - \left( \frac{2a_J}{a_N + a_J} \right)^{1/2} \right] \frac{m_r}{M_N} \]

* The balance is not zero: Process (b) predominates over Process (a) in the cases of Neptune, Uranus and Saturn, so these planets will move outwards. On the other hand, in the case of Jupiter Process (a) predominates over Process (b), so it will move inwards (Fernández & Ip 1984, 1996).
Planet migration: A numerical model

(Fernández & Ip 1984)
Orbital evolution taken from an N-body simulation with 35 $M_\oplus$ (3500 particles truncated at 30 au). The evolutions of the semimajor axis $a$, minimum perihelio distance $q$ and maximum aphelion distance $Q$ are considered for each planet. The vertical dotted line indicates the time of orbit crossing of proto-Uranus and proto-Neptune induced when Jupiter and Saturn enter into the 1:2 mean motion resonance (MMR) (Tsiganis, Gomes, Morbidelli & Levison 2005).
Simulation showing the outer planets and the planetesimal disc: a) primordial configuration before the time Jupiter reached the 1:2 MMR; b) scattering of planetesimals toward the inner solar system triggered by the displacement of Neptune (dark blue) and Uranus (pale blue); c) planet configuration after the ejection of planetesimals by the planets (Tsiganis, Gomes, Morbidelli & Levison 2005).
How comets are born: collisional or primordial rubble piles?

Artistic conception of the accretion and fragmentation of comets in two scenarios: collisional (product of the later evolution of the comet), or primordial (preserved from the formation time).

The study of 67P/C-G shows that it has low density, high porosity, weak strength and contains supervolatiles that experienced little to no aqueous alteration. These features seem to favor a primordial origin, yet at a slow rate than TNOs whose rapid growth led to thermal processing and compaction by heating by the short-lived $^{26}$Al radioisotope (Davidsson et al. 2016).
Formation of the Oort cloud in different galactic environments

(Fernández & Brunini 2000)

* loose star cluster : 10 stars pc\(^{-3}\)
* dense star cluster : 25 stars pc\(^{-3}\)
* superdense star cluster : 100 stars pc\(^{-3}\)

⇒ These simulations show that different Galactic environments are coupled with the degree of compactness of the formed Oort cloud.
Are there distant massive planets? The search for a planet X

What are the reasons to support the existence of distant massive planets?
(1) Cosmogonic reasons.
(2) The discovery of dwarf planets.
(3) Anomalies in the distribution of orbital elements of some populations (comets, TNOs).
Sedna: An anomalous case

Sedna with a perihelion distance $q = 76$ au shows that there are objects decoupled from the TN region moving in very eccentric orbits.

POSSIBLE ORIGIN:
1) Objects of planetary size formed within the solar nebula scattered by the Jovian planets.
2) Objects captured within a star cluster in which the Sun was assumed to be formed.
2012VP_{113}: a new extremely distant object

There is an anomalous alignment of the argument of perihelion of extreme TNOs ($q > 30$ au, $a > 150$ au) around $\omega \approx 0$ attributed to the perturbations of a super-Earth mass body at some hundreds au from the Sun (Trujillo & Sheppard 2014).
Two other extreme objects have been recently discovered, 2013 FT28 and 2014 SR349 with perihelion distances \( q = 43.6 \) and \( q = 48 \) au and semimajor axes \( a = 310 \) au and \( a = 288 \) au respectively. Their arguments of perihelion also fall within the clustering around \( \omega \approx 0 \) (Sheppard & Trujillo 2016).

Such an alignment of the arguments of perihelion can be maintained by a distant eccentric planet of mass \( \gtrsim 10 \, M_\oplus \) whose perihelion is \( 180^\circ \) away from the perihelia of these extreme objects (Batygin & Brown 2016).
Could the resonant dynamics explain the high perihelion distances?

* $q$ raises due to the conjunction of a mean motion resonance with the Kozai mechanism:

$$\theta = (1 - e_o^2) \cos^2 i_o = (1 - e_1^2) \cos^2 i_1$$

$\Rightarrow$ when $i_1$ is maximum, $e_1$ is minimum, and since $1 - e^2 \simeq q/2a$, $q$ must also be maximum.
Other hypotheses

* Decouple of Sedna caused by a massive body bound to the Sun (Gomes, Matese & Lissauer 2006).

* Clustering of aphelia of new comets along a great circle attributed to a gravitationally bound solar companion (Murray 1999; Matese, Whitman & Whitmire 1999).

WARNING! SMALL SAMPLES CAN BE MISLEADING!

Murray’s (1999) planet X based on a sample of 13 comets with aphelion distances between 30,000 and 50,000 au taken from Marsden & Williams’s (1994) catalog.

Updated sample from Marsden & Williams (2008).
Perturbations by a distant solar companion

Simulations for $10^9$ yr of a sample of fictitious scattered disc objects with initial $q_o$ between 32 and 38 au, subject to perturbations by a companion of mass $M_c = 5 \times 10^{-5} M_\odot$, semimajor axis $a_c = 1500$ au, eccentricity $e = 0$, and the inclination indicated in each panel. The triangles indicate the locations of objects 2000 CR$_{105}$ and Sedna (Gomes, Matese & Lissauer 2006).
Birth of the Sun in a star cluster

$\rho_0$: central density of the cluster ($M_\odot$ pc$^{-3}$)
Small black circles: Sedna, 2000 CR$_{105}$, 2003 UB$_{313}$ (Brasser, Duncan & Levison 2006)
All-sky searches of massive objects

VISIBLE

<table>
<thead>
<tr>
<th>distance (au) / apparent (visual) magnitude</th>
<th>Jupiter</th>
<th>Neptune</th>
</tr>
</thead>
<tbody>
<tr>
<td>10^3 / 20</td>
<td></td>
<td>23</td>
</tr>
<tr>
<td>5000 / 27</td>
<td></td>
<td>30</td>
</tr>
</tbody>
</table>

INFRARED

* Wide-field Infrared Survey Explorer (WISE) launched in December 2009 provided an all-sky map at 3.4, 4.6, 12 and 22 µm

WISE could have detected objects size similar to:

- Jupiter at distances $\lesssim 2 \times 10^4$ au
- Saturn $\lesssim 10^4$ au
- Neptune $\lesssim 600$ au

But no such objects were discovered!
Collisions of comets and asteroids with the Earth

It is a relevant topic for the origin of life on Earth and the risk of provoking mass extinctions.
For an object in an orbit with elements \( q, a, i \), the collision probability with the Earth is (Öpik 1951):

\[
P_{JFC} = \frac{\sigma^2 U}{\pi \sin i |U_x|}
\]

where \( \sigma^2 \) is the collision cross-section enlarge by gravitational focusing, we have

\[
\sigma = \pi R_p^2 \left(1 + \frac{v_{esc}^2}{u^2}\right)
\]

where \( R_p \) is the planet radius and \( v_{esc} \) the escape velocity, \( u \) is the encounter velocity of the body with the planet, assuming that it moves on a circular orbit of radius \( a_p \) and velocity \( v_p \), we have

\[
U^2 = 3 - \frac{1}{A} - 2\sqrt{2Q(1 - Q/2A)} \cos i
\]

where the variables are in relative units: \( U = u/v_p \), \( A = a/a_p \) and \( Q = q/a_p \).
The radial component $U_x$ is given by

$$U_x^2 = 2 - \frac{1}{A} - A(1 - e^2)$$

By introducing appropriate values for the populations of JFCs and NEAs in Earth-crossing orbits with diameters $> 1$ km ($\sim 20$ and $650$ respectively), we can compute the average collision probability of a NEA and a JFC with the Earth, we obtain

$$p_{JFC} = 2.6 \times 10^{-8} \text{ yr}^{-1}$$

$$p_{NEA} = 1.5 \times 10^{-9} \text{ yr}^{-1}$$

Namely, one collision of a JFC every $\sim 1.9 \times 10^7$ yr, and one collision of a NEA every $\sim 6.7 \times 10^5$ yr (objects with diameters $> 1$ km).
## Frequency of collisions

**Impact rate (Number of objects with $D > 1$ km per 100 Myr)**

<table>
<thead>
<tr>
<th>Object</th>
<th>Impact velocity (km s$^{-1}$)</th>
<th>Impact rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>LPCs</td>
<td>56</td>
<td>0.67</td>
</tr>
<tr>
<td>JFCs</td>
<td>18</td>
<td>2.6</td>
</tr>
<tr>
<td>HTC s</td>
<td>40</td>
<td>0.23</td>
</tr>
<tr>
<td>Dormant comets</td>
<td>18</td>
<td>1.0-7.8</td>
</tr>
<tr>
<td>Comet showers</td>
<td>56</td>
<td>$\lesssim$ 70</td>
</tr>
<tr>
<td>ECAs</td>
<td>18</td>
<td>150</td>
</tr>
</tbody>
</table>

**Ratio of the Asteroid/Comet impact rate for different sizes**

<table>
<thead>
<tr>
<th>Diameter: $D &gt;$</th>
<th>A/C: 40</th>
<th>$D &gt; 1$ km</th>
<th>$D &gt; 5$ km</th>
<th>$D &gt; 10$ km</th>
<th>$D &gt; 15$ km</th>
</tr>
</thead>
<tbody>
<tr>
<td>$0.2$ km</td>
<td></td>
<td>6.7</td>
<td>2.0</td>
<td>0.19</td>
<td>$\sim 0$</td>
</tr>
</tbody>
</table>
Contribution of comet material to the terrestrial planets during the last formation stages

* The Earth formed in a region near the Sun where the high temperature only permitted the condensation of the most refractory materials (silicates, Fe, Ni). Then, how and from where did the water and other volatiles rich in H, C, N, O, necessary for life, reach the Earth?

<table>
<thead>
<tr>
<th>Cometary matter (g)</th>
<th>Time (years)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>$2.0 \times 10^{14-18}$</td>
<td>$2.0 \times 10^9$</td>
<td>Oró (1961)</td>
</tr>
<tr>
<td>$1.0 \times 10^{25-26}$</td>
<td>Late accretion</td>
<td>Whipple (1976)</td>
</tr>
<tr>
<td>$3.5 \times 10^{21}$</td>
<td>Late accretion</td>
<td>Sill &amp; Wilkening (1978)</td>
</tr>
<tr>
<td>$7.0 \times 10^{23}$</td>
<td>$4.5 \times 10^9$</td>
<td>Chang (1979)</td>
</tr>
<tr>
<td>$2.0 \times 10^{22}$</td>
<td>$4.5 \times 10^9$</td>
<td>Pollack &amp; Yung (1980)</td>
</tr>
<tr>
<td>$1.0 \times 10^{23}$</td>
<td>$2.0 \times 10^9$</td>
<td>Oró et al. (1980)</td>
</tr>
<tr>
<td>$1.0 \times 10^{24-25}$</td>
<td>$1.0 \times 10^9$</td>
<td>Delsemme (1984, 1991)</td>
</tr>
<tr>
<td>$6.0 \times 10^{24-25}$</td>
<td>$1.0 \times 10^9$</td>
<td>Ip &amp; Fernández (1988)</td>
</tr>
<tr>
<td>$1.0 \times 10^{23-26}$</td>
<td>$4.5 \times 10^9$</td>
<td>Chyba et al. (1990)</td>
</tr>
<tr>
<td>$3.0 \times 10^{24-25}$</td>
<td>some $10^8$</td>
<td>Fernández &amp; Ip (1997)</td>
</tr>
<tr>
<td>$4.5 \times 10^{24-25}$</td>
<td>some $10^7$</td>
<td>Brunini &amp; Fernández (1999)</td>
</tr>
</tbody>
</table>

(*) the values cited before 1997 were taken from Oró & Lazcano (1997)
Besides water, comets could have implanted on the Earth a large variety of complex organic molecules.
The origin of the terrestrial water: Does it come from comets?

The problem is that the D/H ratio in the water from comets is a factor of about two larger than that found on the Earth’s oceans! → Part of the terrestrial water must have come from material formed in the outer asteroid belt.

In order to be depleted in deuterium (with respect to comets), the H$_2$O ice must have sublimated. The gaseous H$_2$O molecules have the capacity to transfer their deuterium to the hydrogen molecules of the protoplanetary disc through the reaction:

$$\text{HDO} + \text{H}_2 \rightleftharpoons \text{H}_2\text{O} + \text{HD}$$
Some meteorites (carbonaceous chondrites) seem to have the right $D/H$ and $^{15}\text{N}/^{14}\text{N}$ isotopic ratio

Marty (2012)
THANK YOU FOR YOUR ATTENTION!