Chapter 10 - Comets

Astronomy 9601

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Topics to be covered

- Comet orbits and reservoirs (10.2)
- Coma and tail (10.3)
- Composition (10.4)
- Nucleus (10.6)
- Comet formation: (10.7)

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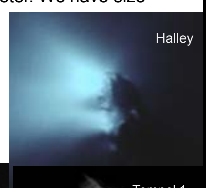
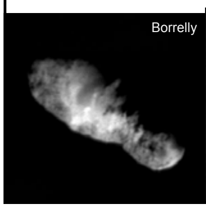
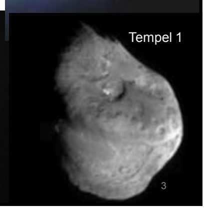
Comet nuclei

An icy/rocky body a few to 10-20 km in diameter. We have size measurements of about 10 nuclei

Resolved:
Halley (Giotto 1986) 8x15km
Borrelly (Deep Space 1) 8km long
Wild 2 (Stardust) 5km
Tempel 1 (Deep Impact, Stardust) 8x5 km







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Comet nuclei

Inferred diameters:
Schwassmann-Wachmann 1: 30 km
Hale-Bopp: 60 km
Swift-Tuttle: 26 km
Neujmin: 20 km

Schwassmann-Wachmann 1 (IR)

Albedos:2-5%,
darker than coal

Hale-Bopp

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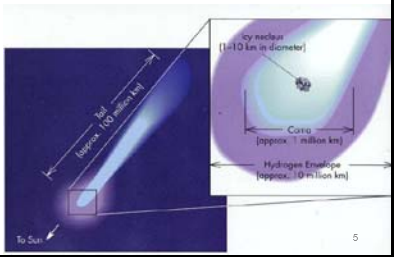
When comets approach the Sun

When (if?) a comet's orbit takes it near the Sun (r <~ 3 AU), ice begins to vaporize and produces a *tail* up to 10^8 km long. The near-spherical cloud of gas near the nucleus is the *coma* and is typically 10^4 to a few x 10^5 km across.

A *hydrogen coma*, invisible to the naked eye, stretches out to several times 10^7 km, composed primarily of H dissociated from H_20 (observed in UV)

Tail to nucleus size ratio: 10,000,000 to 1



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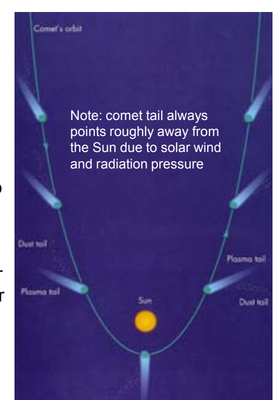
Comet orbits are typically (but not always) highly elliptical.

As a result, they only spend a small fraction of their lives as active comets. Most of the time, they are frozen inert bodies, far from the Sun.

When inactive, comets are difficult to detect even with large telescopes. So the properties of these objects (including any which may remain permanently exiled in the outer Solar System), must be deduced from their brief active phases.



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Active comets

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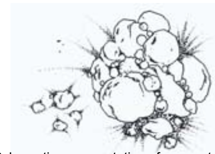
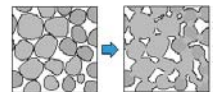
Nucleus: a dirty snowball

- Whipple (1950) proposed the "dirty snowball" theory of cometary nuclei
- This theory has stood up well, though some argue comets are more like 'snowy dirtballs"
- Densities of cometary nuclei are hard to determine, but models indicate 0.3-0.7 g/cm^3, which is less than most ices.
- Low density points to a porous "rubble-pile" model containing significant void space
- Comet nuclei may be held together by "sintering" and other relatively weak contact forces



Schematic representation of a cometary nucleus according to the rubble-pile model; individual fragments are lightly bonded by thermal processing or sintering (Weissman 1986)



sintering

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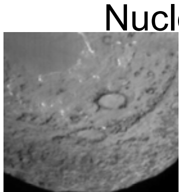
Nuclear surface layers



Tempel 1 90 seconds before the Deep Impact probe hit

One of the last images before Deep Impact

- Comet nuclei that do not pass near the Sun are expected to build up a dark, reddish, tar-like surface *irradiation layer* of *tholins*, carbon chains produced by long-time irradiation of the nucleus constituents. Recent observations, however, indicate that some distant comet nuclei have much higher albedos (later)
- Comets that have passed by the Sun on many occasions are thought to have a *dust crust*, an accumulation of large non-volatile rocky material that builds up as the ices disappear.

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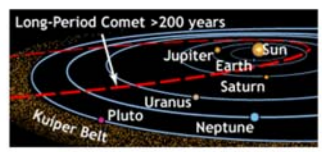
Different dynamical families of comets

A **long-period comet** is one with an orbital period (year) longer than 200 years.

These comets have orbits which extend beyond the orbits of the planets.

Perhaps more importantly, the orbits of these comets are quite different from those of **short-period comets**, those with P < 20yrs.



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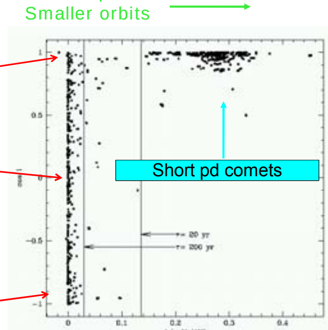
Shorter periods
Smaller orbits

Inclinations near those of the planets (prograde)

Inclinations at right angles to those of the planets

In the plane of the planets, but moving in the opposite direction (retrograde)



Long-period comets

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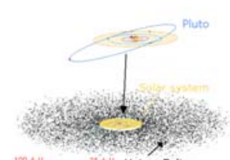
Q: What makes SP and LP comets different?

A: Their origin

Short-period comets come from the Kuiper-Edgeworth belt, a ring of "leftovers" at the edge of our Solar System.



Kenneth E. Edgeworth
1880-1972

Gerard P. Kuiper
1905-1973

These remnants of planetary formation orbit in the plane of the planets, hence their low inclinations.

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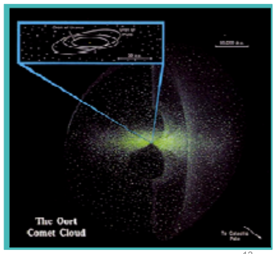
Jan Oort
1900-1992

Long-period comets come from the Oort Cloud, a spherical cloud of frozen comet nuclei reaching up to half-way to the nearest stars (around 10^5 AU or 1.6 ly; recall α Cen is 4.3 ly away).

Both the Oort cloud and the Kuiper belt are made up of planetesimals left over from the era of the formation of the planets.



So why are they different?

The formation of the solar system

Solid matter condensed out of the original spinning, flattened cloud of gas and dust (the "solar nebula") surrounding the proto-Sun.

Elements at the edge of what would become our planetary system were too sparse to form planets. The Kuiper Belt is what still remains of this material.

Solid bodies within the planetary system itself were all swept up into the growing planets.

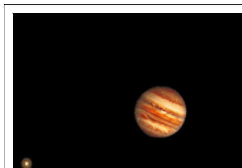
Or were they?

Gravitational Slingshot

A number of space probes, including Voyager 1 and 2, have deliberately used a planet's gravity to slingshot themselves into different orbits.

Many planetesimals in the early Solar System would have, by happenstance, undergone a similar effect.

Some of these would have crashed into planets, some would have received only minor orbital changes. Still others would have been ejected into deep space, never to return.



SEGWay (UC Berkeley)

A few would have been flung far but not quite out...

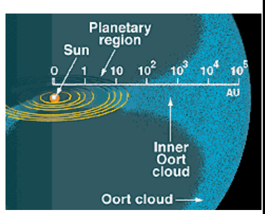
The edge of the Oort cloud

Comets ejected into the Oort cloud end up on orbits with large values of a (or $1/a \sim 0$).
These large orbits are only very weakly bound and can be removed by perturbations by passing stars, for example. Only orbits up to a of perhaps 50,000 AU are stable, defining the edge of the Oort cloud, which is thought to contain ~10^{12} objects > 1 km.

Comets in the Oort cloud go around the Sun in tens of millions of years, and might be expected to have returned to the inner part of the Solar System many times over its 4.5 billion year history (recall $P = a^{1.5}$) but they usually don't. Why?

Life in the Oort cloud

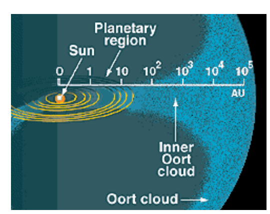
Passing stars and galactic "tides" (perturbations due to the overall mass distribution of the galaxy) modify the orbits of Oort cloud comets. The effects are varied, but often result in large, quasi-random changes in perihelion q.



- This *raising of the perihelion* removes their orbit from the inner solar system, preventing their return to the vicinity of the Sun.
- These perturbations also scramble the comets' inclinations, making the originally largely planar distribution of orbits essentially spherical.
- These effects are much stronger for larger a, and so there is a transition between different dynamical regions

Dynamical regions

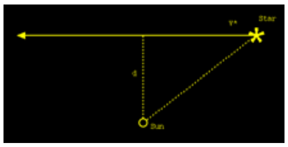
- 35-50 AU: *Kuiper Belt*
- 50-2000 AU: dynamically inert region
- 2000-15000 AU the *inner Oort cloud*, affected by galactic tides
- 15000-100,000 AU: the *outer Oort cloud* (tides and stellar perturbations)



Stellar perturbations

- Stars in the disk of the Milky Way share a common motion around the center of the galaxy, but also move relative to each other.
- The typical velocity differences among stars in the solar neighborhood are about 20 km/s.
- As a result, comets in the Oort Cloud are perturbed a few times per million yrs by the gravity of passing stars.
- When a star of mass M* passes the Sun at distance d and speed V*, the *impulse approximation* to the change in the velocity of an orbiting Oort Cloud comet is

$$\Delta V = \frac{2GM_*}{V_* d}$$



Stellar perturbations

- For a solar mass star passing at 0.5 parsec (330 000 AU) with V* = 20 km/s, the velocity change is about 1 m/s.
- This is to be compared with the Keplerian orbital velocity of about 100 m/s in the Oort Cloud.
- The stars approach from random directions, so the velocity changes are sometimes positive, sometimes negative.
- The combined effect is a *random walk* in the magnitude of the velocity perturbation such that, after 10,000 stars have passed by, the original orbit of the comet has been drastically altered.

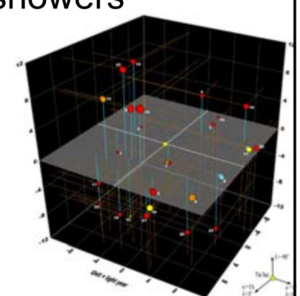
Stellar perturbations

How long does this take?

- The answer depends on where in the Oort Cloud the comet resides.
- At the outer edge, the attraction to the Sun is weak and passing stars have a big effect.
- Most of the LPCs are thought to fall from the outer parts of the Oort Cloud.
- Closer to the Sun, the Oort Cloud comets are tightly held and may never be dislodged by the gravity of passing stars.

Comet showers

- A particularly close encounter between the Sun and a star could produce a strong perturbation that would send a *comet shower* into the inner Solar System (note *DV ~ 1/d*). The duration is ~ one orbital time (millions of years), the frequency ~ 1 per 10^8 yr
- Most Oort cloud comets currently arrive from the outer Oort cloud where perturbations are usually stronger.



Stars in the solar neighbourhood

A stellar passage within the inner Oort cloud (with a population 5-10x larger than the current outer cloud) could produce an increased flux in the inner solar system, as well as transferring comets from the inner Oort cloud to the outer one.

Return from the Oort cloud

The perturbations that raised the comets' perihelia eventually return them to low values, allowing them to re-enter the planetary system. When Oort cloud comets return to the inner Solar System, they must run the gauntlet of the planets.

Being on nearly unbound orbits, these comets have *E~0*. Even a small energy gain due to the gravity of the planets can send them onto unbound orbits, or much more tightly bound ones. Recall *E = -GM/2a,* so a change in *E* means a change in *a,* which means a change in orbit size.

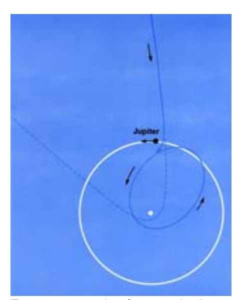
The distribution of energy kicks for comets with *q* inside the giant planets has $D(|1/a|) \sim 4x10^{-4}\,AU^{-1}$. For a comet starting with *E~0* this means a transfer to an orbit with a~2500 AU

Dynamically new Oort cloud comets: one time only

Roughly half of *dynamically new Oort cloud comets* (distinguishable by their very large *a* upon arrival) have their orbits so disturbed they are subsequently ejected from the Solar System.

The other half end up on various smaller, more tightly bound orbits.

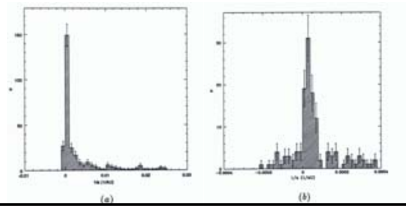
Few return to the Oort cloud.



Extreme example of a perturbed dynamically new Oort cloud comet

Oort cloud: the evidence

- Since Oort cloud comets cannot be imaged yet *in situ*, the measured large *a* values for some comets is the primary evidence for the Oort cloud's existence.
- Note the absence of large negative 1/a implies no interstellar comets
  - vel. dispersion in solar neighbourhood is 20-30km/s, so we would expect interstellar comets to come in with this much energy above the parabolic limit (which is 72km/s at Earth (q=1AU), so a 20-30 km/s excess would be easily seen)



Histogram of 1/a for the long-period comets. "Error bars" are just sqrt(N) to indicate statistical noise.

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Kuiper belt comets: path to visibility

- The 10^9-10^{10} comet nuclei in the Kuiper Belt are on orbits outside Neptune, typically with
  - 30 AU> *a* > 50 AU
  - low *e* (<0.2)
  - low *i* (< 30°)
- These orbits do not bring them near the Sun. How do these objects eventually become visible comets?

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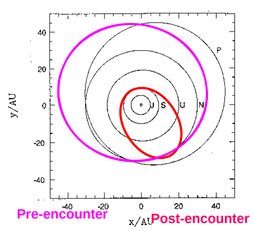
Kuiper belt comets: path to visibility

- Neptune is the dominant player out here. Secular and mean-motion resonances can modify KBO orbits to ones that cross Neptune.
- A close approach with that planet will change the orbit: if *a* is decreased the comet is "handed down" to the inner giant planets, where it "pinballs" between them, possibly eventually reaching the inner solar system, and visibility as an active comet (a SP comet).



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Comet classification reprise

- Oort cloud comets (long-period comets)
- Jupiter-family comets
  - aphelion Q ~ 5.2 AU (near Jupiter) (short-period comets)
  - low inclinations
  - orbit dominated by encounters with Jupiter
  - most originated in the Kuiper Belt (only 0.1% of OCC reach this stage)
- Halley-type comets
  - spherical distribution of inclinations
  - various a's, but usually 20yr < P < 200yrs
  - originated in the Oort cloud, orbits changed by planet encounters
- Centaurs
  - orbits between the giant planets
  - low inclinations, moderate eccentricities
  - normally do not get close enough to Sun to display coma/tail
    - notable exception: first centaur 2060 Chiron shows intermittent coma
  - origin: KBOs being handed down
  - as a result, these orbits are unstable with lifetimes of 10^6-10^8 years

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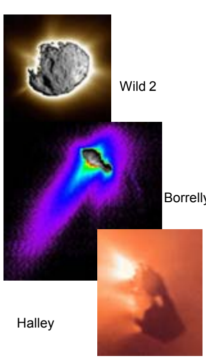
Non-gravitational forces



Wild 2

Borrelly

Halley

- The sublimation of ice from the nucleus is non-isotropic. As a result, there is a net reaction force (called *non-gravitational force*)
- The effect is normally small, but measurable for some comets.
- The *standard Type II* (or *symmetric* model) empirically best-fits 3 coefficients A_1, A_2, A_3 to the NG force based the observed motion of the comet
  - A_1 is the radial (Sun-comet) component
    - largest, but averages to ~zero
  - A_3 is normal to the comet orbit plane
    - smallest, usually neglected
  - A_2 is in comet orbit plane, but at right angles to the radius vector
    - Caused by rotation of the nucleus/thermal lag
    - Usually the one with the largest net effect

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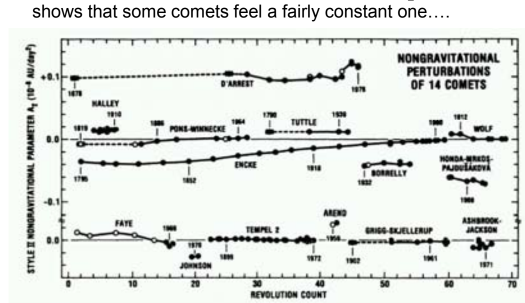
The A parameters are typically of order 10^{-8} AU day^{-2} (approx. 1 cm/s per day)

The empirical determination of the tangential (A_2) force shows that some comets feel a fairly constant one….



Yeomans 1993

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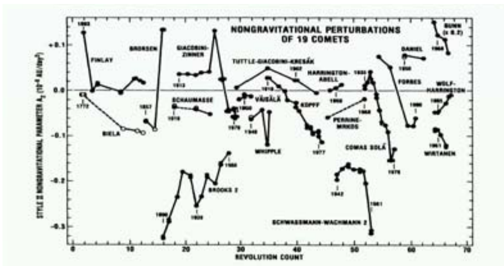
…while others feel a force whose magnitude and sign is rapidly changing. All comets appear as individual cases



Yeomans 1993

Cometary gas production

- Cometary activity (gas production) is triggered by proximity to the Sun (solar heating)
  - Most comets at r > 3 AU are inert, and begin to produce gas inside this distance
- The onset of activity near 3 AU is indicative of water ice on the nucleus, as this is the location at which solar heating should begin to sublimate it in significant quantities
- Some comets produce little gas even at smaller distances (eg P/Tempel 2)
- Some produce gas at larger distances
  - 2060 Chiron (between Sat. & Ura): intermittent coma (*outbursts*)
  - Hale-Bopp displayed a coma at r > 6 AU
  - Comae at larger r are indicators of more volatile species eg CO, CO_2

Hyakutake

C/2001 Q4 (NEAT)

Brightness

- The light received by a comet from the Sun decreases in brightness as $1/r^2$ (r = Sun-comet distance), and the light we receive from the comet decreases as $1/r_\Delta^2$ (r_Δ = Earth-comet distance, often called Δ) so we might expect a comet's apparent brightness B_ν at a particular wavelength ν to vary like

$$B_\nu \propto \frac{1}{r^2 r_\Delta^{\,2}}$$

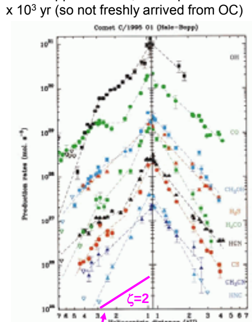
- This equation is correct for inert bodies like asteroids, but comets get brighter as they approach the Sun, as gas production increases their effective optical cross-section.
- As a result comets typically show a sharper increase in brightness as r_{Sun} decreases, typically as a power larger than 2

$$B_\nu \propto \frac{1}{r^\zeta r_\Delta^{\,2}}$$

An example: C/Hale-Bopp

Hale-Bopp is an LPC, with a period of a few x 10^3 yr (so not freshly arrived from OC)

- Water production is usually traced by OH, photo-dissociated by solar UV (water lines blocked by atmos).
- Note sharp drop in water production beyond 3 AU inbound
- However, Hale-Bopp showed coma at r up to 6 AU: what was the source?
- CO (either primary or as photoproduct of CO_2) was most abundant at r >3 AU
- CO production rate decreased from 3 to 1.6 AU: depletion of surface layer?
- Also note presence of CH_3OH (methanol), H_2S, H_2CO, HCN, CS and other species. These may be primary or photoproducts.
- Note slope z generally > 2



Biver et al 1999 (radio)

Visual magnitude

$$m_v = -2.5\log B_v = M_v + 2.5\zeta \log r + 5\log r_\Delta$$

- m_v is the comet's *apparent visual magnitude*
- M_v is the comet's *absolute visual magnitude*

basically the apparent visual magnitude as determined for an observer 1 AU from both the Sun and the comet

- Comets tend to be brightest a few days after perihelion (presumably due to thermal lag)
- Clearly from observations of Hale-Bopp, ζ is not really a constant, so neither is M_v

Visual magnitude

- New comets tend to be bright at larger distances r ~ 5AU (presumably due to relatively fresh supplies of more volatile elements like CO and CO_2) but do not brighten as sharply near perihelion (ζ~ 2.5)
- Older comets (eg. short-pd comets) typically are faint at large distances but brighten more sharply at perihelion (ζ~5)
- ζ ~4 is the "standard" value, and the derived estimate of the comet's absolute magnitude with this z is called H_{10}

Thermal balance of the nucleus

$$(1-A_b)\frac{F_{Sun}e^{-\tau}}{r^2}\pi R^4 = 4\pi R^2 \varepsilon_{ir}\sigma T^4 + \frac{QL_s}{N_A} + 4\pi R^2 K_T\left(\frac{\partial T}{\partial z}\right)$$

Assuming only solar heating, the heat received must be balanced by heat lost (radiatively as well as through the loss of gas) as well as heat transmitted deeper into the nucleus.

A_b = Bond albedo: the total radiation reflected from an object compared to the total incident radiation from the Sun, may be complicated to compute
F_{Sun} = solar constant at Earth (1.37 kW/m^2)
r = heliocentric distance (AU)
τ = optical depth of the coma
R = comet radius

ε_{ir} = infrared emissivity (~1 for most ices)
σ = Stefan-Boltzmann constant
Q = gas production rate (molecules s^{-1})
L_s = latent heat of sublimation per mole of nuclear ice
N_A = Avogradro's number
K_T = thermal conductivity of the nucleus (usually small)
$\delta T/\delta Z$ = thermal gradient in the nucleus

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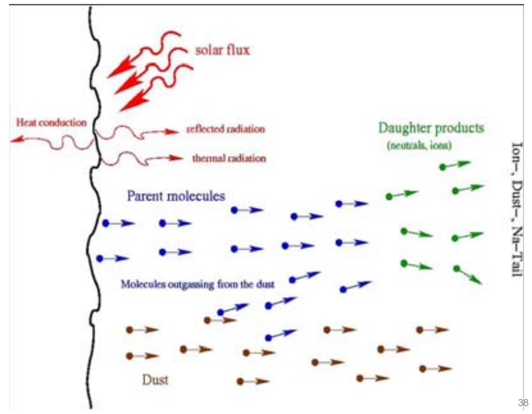

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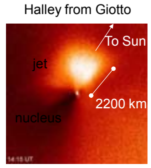
Conditions in the coma

- The terms in the thermal balance equation are complicated by compositional questions, asymmetries in the nucleus, constants that are difficulty to determine, etc.
- However, if one molecule dominates, we can get some handle on things
  - If sublimation is primarily CO, the surface temperature of the nucleus T is between 30-45 K for 0.2 < r < 10 AU
  - for CO_2, 85 < T < 115 K, for H_2O, 90-210K
- Note: sublimation carries away a lot of heat and so the nuclear temperature is generally far below the equilibrium blackbody temperature of an asteroid, for example, at the same r.
- Sublimation is also generally not symmetric but concentrated on the sunward side (non-gravitational forces)

Halley from Giotto



HST image of Tempel 1 pre-Deep Impact

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Gas outflow

- The gas leaves the nucleus at the *thermal expansion velocity* v_0 $\qquad \frac{1}{2}\mu v_0^2 = \frac{3}{2}kT$
  - where m is the molecular mass
- at r~1AU, v_0 is ~ 0.5km/s, much larger than the escape velocity of the comet
- The gas accelerates away from the nucleus, reaching terminal velocity, its final velocity, within ~1000km
- The gas density drops as roughly 1/r^2 so the flow eventually changes from *hydrodynamic* (collisional) to *free molecular* (collisionless) flow.
- The transition distance R_c is defined to be where the chance of an outward-particle having another collision drops to 50%, usually 1000-5000km from nucleus

$$\int_{R_c}^{\infty}\frac{Q\sigma_x}{4\pi r^2 v_0}dr = 0.5$$

where r = cometocentric distance
σ_x = collisional cross-section

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Gas flow is complicated

- The expanding gases, at least until the flow becomes collisionless, may interact chemically or exchange momentum through collisions.
- The photolysis of molecules by solar UV may also affect the velocity profile of the gas.
  - Photolysis products (particularly H and OH) colliding with other molecules can accelerate them
- Complicating matters is dust (non-volatile silicates and/or organics)
  - dust slows the gas over the first few tens of meters by impeding its flow
  - dust may be both a source and a sink of gas
    - **source** as "dust" grains may really be ice grains that continue to sublimate
    - **sink** as molecules may recondense on/react with dust grains further from the nucleus

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Chemical evolution

- The optical depth of the coma is generally < 1 except for the inner 100km
  - result: the gas is largely transparent and all the coma receives significant exposure to solar radiation
  - the mean lifetime t_l of molecules against photo-dissociation by sunlight is

$$\frac{1}{t_l} = \frac{1}{r^2}\int_0^{\lambda_t}\sigma_x(\lambda)F_{sun}(\lambda)d\lambda$$

r = heliocentric distance in AU
$F_{sun}(\lambda)$ is the solar flux at wavelength λ at 1 AU
$\sigma_x(\lambda)$ = photo-destruction cross-section
λ_t = threshold wavelength for photo-destruction (longest wavelength that dissociates the molecule, usually in UV)

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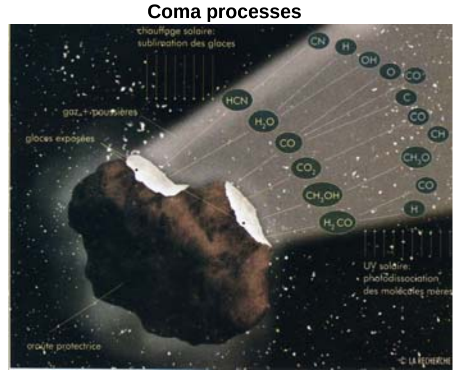
Photo-destruction and the coma

- At r=1 AU, a free water molecule has a lifetime of 5-8 x 10^4 s (25000-40000 km at 0.5 km/s)
- Typically H_2O photo-dissociates to H and OH, which gain an average of 18 and 1 km/s excess speed resp., though excited O, H_2O^+, OH^+, O^+ and H^+ are other options
- OH subsequently dissociates to O and H, where H now gets a 7 km/s kick
- The large kicks H receives are fundamental in creating the large hydrogen coma discussed earlier
- Neutral H is then ionized either by UV or charge exchange with the solar wind.

Coma processes



Crovisier & Encrenaz 1995

Modelling the coma

- A knowledge of the collisional and photo-destruction cross-sections of various species (often not well known) allows the distribution of molecules in the coma to be modeled
- The simplest approach is the *Haser model*, which assumes smooth isotropic outflow and a finite lifetime for molecules.
- The distribution of parent molecules (subscript p) is given by

$$N_p(r) = \frac{Q_p}{4\pi r^2 v_p} e^{-r/R_p}$$

N = number density
r = cometocentric distance
$R_p = v_p t_{lp}$ is the *scale length* for a given molecule p
v_p = velocity of molecule p

- If the daughter products (subscript d) continue to move out with $v_d = v_p$, we get their distribution from

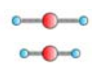
$$N_d(r) = \frac{Q_p}{4\pi r^2 v_d} \frac{R_d}{R_d - R_p} \left(e^{-r/R_d} - e^{-r/R_p}\right)$$

Excitation of radiation

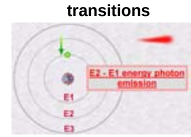
Radiation by: rotational, vibrational and electronic transition between different energy levels of gaseous molecules and atoms.

Example: triatomic molecules

Electronic transitions



Vibrational excitation



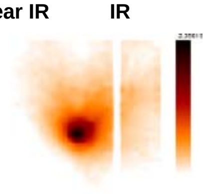
Rotational excitation

Allowed transitions between energy levels with wavelength λ:

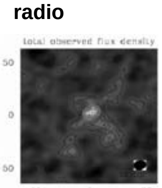
$$\frac{1}{\lambda} \propto (E'_{el} - E''_{el}) + (E'_{vib} - E''_{vib}) + (E'_{rot} - E''_{rot})$$

λ~1 μm -100 nm	~10 μm	~1 cm
UV, optical, near IR	**IR**	**radio**

Hale-Bopp (optical)



Hale-Bopp (7.75 microns)



Hale-Bopp (3mm)

Mean lifetime of an excited energy state u(pper) to drop to state l(ower): $\tau_u = \frac{1}{A_{ul}}$

electronic transitions: $\tau_{el} \sim 10^{-8}$ s

vibrational transitions: $\tau_{vib} \sim 10^{-3}$ s

rotational transitions: $\tau_{rot} \sim 1$ s

If an electronic state is excited, the transitions are much faster than others → this is the case for radicals emitting in optical range

In parent molecules usually only rotational and vibrational transitions are excited. Higher excitation energies lead to dissociation of the molecules.

Fluorescence

The primary optical emission mechanism is *fluorescence*, where electrons are excited by solar radiation and they re-emit upon their return to the ground state

The strongest lines are usually *resonance transitions* (between the first excited state and the ground state)

The brightness of a spectral line depends on the number of molecules multiplied by the *g-factor* or emission rate per molecule, which could be complicated to compute as it depends on the populations of the various levels above the one in question.

For simple fluorescence, if most species are in the ground state (ie. the time to emit a photon << time between absorbed photons), we first compute the absorption rate of photons that excite the molecule g_a

$$g_a = \frac{B_{lu} F_{sun}(\lambda_{lu})}{r_{sun}^2}$$

B_{lu} = Einstein coefficient from l(ower) to u(pper)

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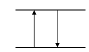
Fluorescence

Once we have g_a, we just need the branching ratio of the downward transition to get the g-factor

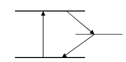
$$g = g_a \frac{A_{ul}}{\sum_{j \le u} A_{jl}}$$

simple resonance:



$g=g_a$

general resonance fluorescence:



$g < g_a$

Important: g and g_a are proportional to the incoming solar flux!

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Converting to column density

Once g is known, we can determine the column density N_c (molecules per unit area) of molecules along our line of sight through the coma if we know the brightness of a particular line B_λ in photons s^{-1} cm^{-2} and Ω_s, the solid angle observed

$$N_c = \frac{B_\lambda}{g} \frac{4\pi}{\Omega_s}$$

For simple resonance, we can show gas production Q is

$$Q = \frac{4\pi r_\Delta^{\ 2} B_\lambda}{g t_l}$$

Note: the heliocentric distance cancels out of gt_l, which does not change with r (recall t_l = scale length of molecule)

If more excitation/de-excitation levels, dissociation, etc have to be included the idea is the same, but the equations are more complex

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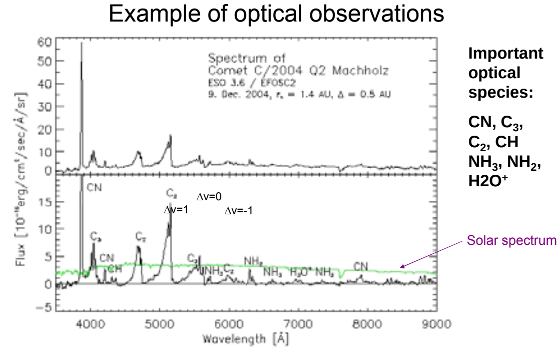
Example of optical observations



Important optical species:

CN, C_3, C_2, CH
NH_3, NH_2, $H2O^+$

Some molecular transitions are very close together and can be resolved only by very high-resolution spectroscopy → *band sequences*

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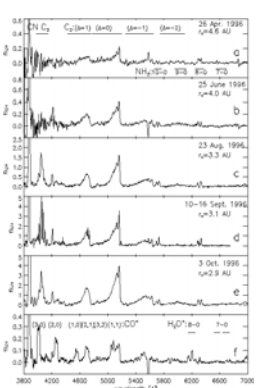
Changing spectral features



Comet C/Hale-Bopp:

discovered: 23 July 1995 at r=7.1 AU

perihel: 1. April 1997, r=0.914 AU

period: 2380 years

inclination: 89.4°

diameter: 27-42 km

Hale-Bopp long-term observations:

- April 1996 – January 2001
- r = 4.6 – 2.9 AU, 2.8 – 12.8 AU
- Optical Spectroscopy + imaging
- European Southern Observatory

Rauer et al., 1997, Science 275, 1909

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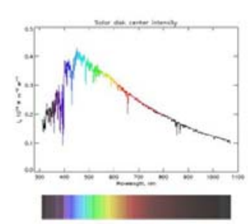
Doppler effect and radiation excitation

In the optical and UV the solar flux has many absorption lines → shifts in wavelengths by the Doppler effect can lead to variations of the solar flux at the wavelengths that excite cometary lines by up to a factor 2 and more



Swings effect (Swings 1941)

Doppler shift of the solar spectrum at the comet due to the heliocentric velocity component of the comet on its orbit around the Sun.

typical heliocentric velocity components: -50 km/s < v_{hel} < +50 km/s, this corresponds to Δλ ~ 0.7 A at 400 nm

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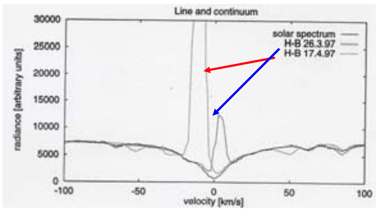
Swings effect

Doppler-shift of a cometary Na emission line relative to a strong solar Na solar absorption line before and after the perihelion of comet Hale-Bopp in 1997. The higher the Doppler shift, the more solar excitation = stronger line



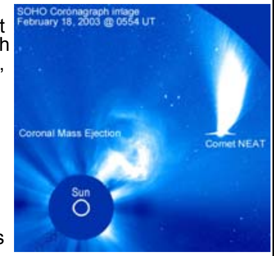
Arpigny et al. 1997, A&A

Greenstein effect (Greenstein 1958)

Doppler shift of the solar spectrum due to the motion of the ions/atoms relative to the comet nucleus (important e.g. for ions, H, Na)

Coma composition

- Water and its derived species (H,OH, H_20^+, H_3O^+,O) are dominant
- Carbon compounds are important (C, C_2, C_3, CH, CH_2, CN, CO) with a probable origin from CO_2, HCN, CH_4, H_2CO (formaldehyde), CH_3OH (methanol)
  - CO production ~15-20% of water, CO_2 ~ 3% and others lower still
- N and S compounds are present in small amounts
- Na is regularly seen in comets, though only Sun-grazing comets (r <0.2AU) show other metal lines such as Ca, K, Fe, Ni, Co, etc, presumably from vaporizing dust particles

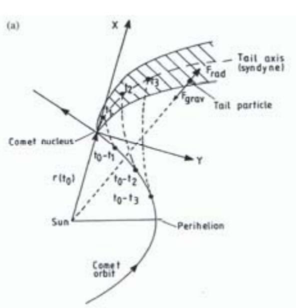


Dust

- Dust is entrained away from the nucleus as the ices sublimate
- Dust-to-gas ratio varies: 0.1 to 10
- Small (submm) particles can reach the gas velocity (~1km/s) but larger ones barely reach escape velocity (~1m/s)
- At a few nuclear radii, the dust and gas decouple
- After decoupling, the dust is "blown" back into the *dust tail* which owing to the slightly different dynamics of the gas and dust, is usually separate from the *gas tail* (or *ion tail*)
- The dust tail is usually yellow-ish (reflected sunlight) with the gas tail is usually bluish (CN, C_3, C_2 lines)
- The colour of the dust tail implies few particles < 0.1mm; calculations of the maximum size that could be entrained by gas implies the largest dust particles are < 10 cm or so; thermal emission puts most dust grains at 0.1 – a few mm.

Active comets

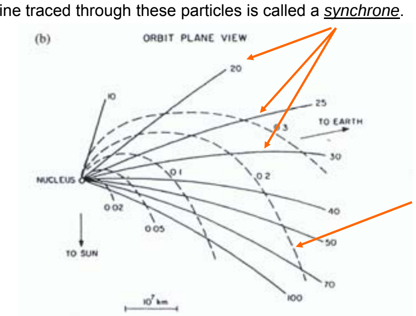
Syndynes



- Because dust particles released have different sizes and hence b (recall b = ratio of radiation force to solar gravity in discussion of P-R drag) they will follow different paths.
- Consider a comet that has been releasing particles over a number of days. A snapshot of the positions of all particles with the same b at a particular instant is called a *syndyne.*
- The syndynes of all b combined trace out the dust tail of the comet

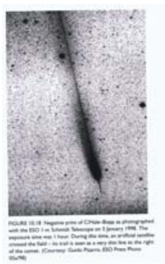
Synchrones

- Alternatively we can ask: where are all the particles, regardless of size, that were released at a particular time t?
- A line traced through these particles is called a *synchrone*.



Dashed lines are syndynes

Anti-tails




Comet Bradfield

- If the Earth is near the plane of the comet's orbit, the curvature of the dust tail may allow material behind the comet to appear to stick forward of it in a phenomenon called an *anti-tail*

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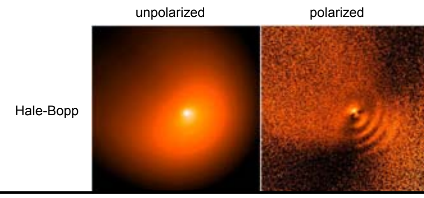
Dust features

- Dust emission from comets is often uneven, resulting in inhomogeneities in the dust tail (*dust jets, streamers, striae*)
- The rotation of the nucleus may result in a spiral pattern of dust being ejected from a strong jet, a feature often detectable using polarimetry.
- Rotation is very difficult to measure due to the coma, and only a few (~7) have had their spin state estimated (often by radar or from dust jets): a few hours to several days



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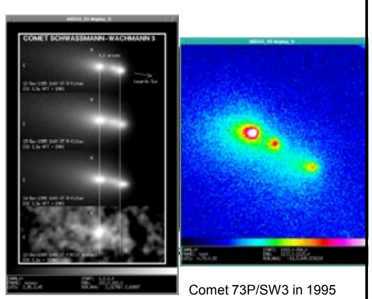
Splitting and disruption

- Comets are sometimes seen to break apart (about 2 dozen cases reported so far), shedding a few small pieces, other times undergoing more dramatic breakups
- Splits are often first seen as outbursts of gas and dust from the nucleus, as it usually takes some time for the fragments to drift apart enough to become visible individually



Comet 73P/SW3 in 1995

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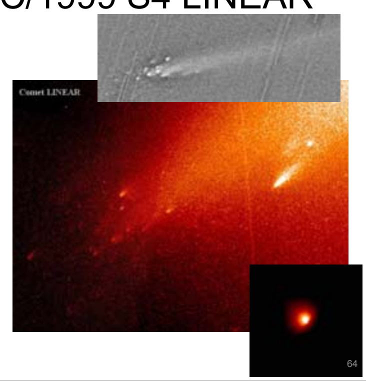
Comet C/1999 S4 LINEAR

- broke into at least 16 "cometesimals" as it passed the Sun in 2000



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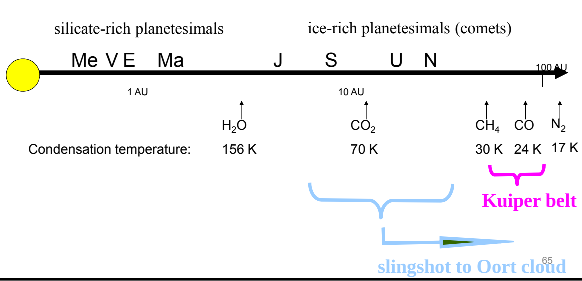
Formation: the outer reaches of the Solar System

The volatile components of comets indicate they formed far from the Sun. The most volatile components N_2, S_2 and CO indicates condensation temperatures of 20-25 K



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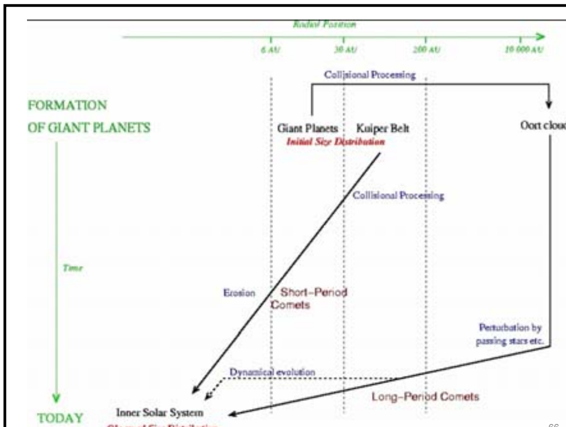

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The End

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