Today in Astronomy 111: radiation forces on Solar system bodies, comet tails, and comets

- ☐ Radiation and the motion of small bodies:
  - Radiation pressure, and the Poynting-Robertson and Yarkovsky effects
  - Solar wind pressure and corpuscular drag
- ☐ Comet tails and dust survival
- ☐ Comets themselves
- ☐ The Oort cloud and the origin of long-period comets

Comet West, 1975 (John Laborde).

Radiation and the motion of Solar-system bodies

So far, we have only considered the energy brought to the planets and planetesimals by sunlight, but the sunlight brings momentum, too: photons have energy and momentum given by

$$E_{\text{photon}} = hc/\lambda \quad , \quad p_{\text{photon}} = h/\lambda = E_{\text{photon}}/c$$

and force, of course, is the rate of change of momentum, $\boldsymbol{F} = d\boldsymbol{p}/dt$. ($\lambda$ is the wavelength of light, h is Planck's constant.)

- ☐ The forces caused by the momentum of sunlight are small and can usually be neglected if the body in question is very massive and/or a long way from the Sun.
- ☐ But the forces of radiation can be significant for near-Earth and main belt asteroids and can dominate all other forces for very small particles like interplanetary dust grains.

Forces on a light-emitting, revolving body

Consider first a small black body (radius $R \ll r, \gg \lambda$) a distance r from a star with luminosity L. As we have seen many times, the power P_{in} which it absorbs from starlight is

$$P_{\mathrm{in}} = \frac{dE_{\mathrm{in}}}{dt} = \frac{LR^2}{4r^2}$$

and thus the rate at which it absorbs momentum is

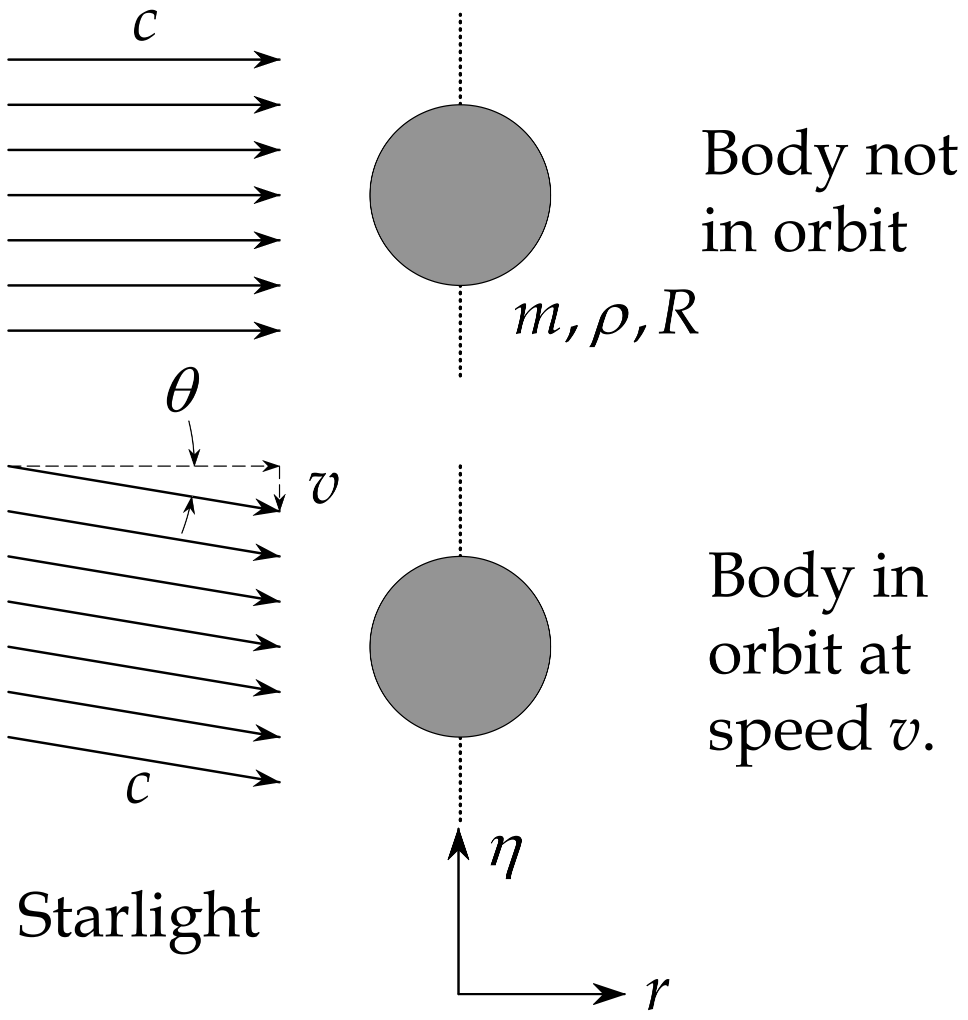
$$\frac{dp_{\mathrm{in}}}{dt} = \frac{1}{c}\frac{dE_{\mathrm{in}}}{dt} = \frac{LR^2}{4cr^2}$$

Since it emits blackbody radiation equally in all directions (net momentum zero), there is a force on the body:

$$F_{\mathrm{in}} = \frac{dp_{\mathrm{in}}}{dt} = \frac{LR^2}{4cr^2} \quad .$$

Forces on a light-emitting, revolving body (continued)

Now add the slight complication of revolution. If the body's orbital velocity is *v*, then **from the body's point of view** the star moves at *–v*, and thus the light has a component of velocity anti-parallel to the body's velocity.



Forces on a light-emitting, revolving body (continued)

Note that θ is a very small angle for planetary-system speeds $\left(\theta \ll 1 \text{ rad}\right)$:

$$\theta \cong \tan\theta \cong \sin\theta = -\frac{v}{c} \quad , \quad \cos\theta \cong 1 \quad .$$

Thus the two perpendicular components of the force on the body are

$$\begin{aligned} \boldsymbol{F} = \frac{d\boldsymbol{p}_{\text{in}}}{dt} &= \hat{\boldsymbol{r}} F_{\text{in}} \cos\theta + \hat{\boldsymbol{\eta}} F_{\text{in}} \sin\theta \\ &\cong \hat{\boldsymbol{r}} \frac{LR^2}{4cr^2} - \hat{\boldsymbol{\eta}} \frac{LR^2}{4cr^2} \frac{v}{c} \equiv \boldsymbol{F}_{\text{rad}} + \boldsymbol{F}_{\text{P-R}} \quad . \end{aligned}$$

The first term, a radially-outward force, is called the force due to **radiation pressure**; the other, the force due to **Poynting-Robertson drag**.

Forces on a light-emitting, revolving body (continued)

With m the mass of the body, ρ its density, and M the mass of the star, define the quantity

$$\beta \equiv \left|\frac{F_{\text{rad}}}{F_{\text{gravity}}}\right| = \frac{LR^2}{4cr^2}\frac{r^2}{GMm} = \frac{LR^2}{4cGM}\frac{3}{4\pi R^3\rho} = \frac{3L}{16\pi cGMR\rho}$$

and the force can be written as

$$\boldsymbol{F} = \boldsymbol{F}_{\text{rad}} + \boldsymbol{F}_{\text{P-R}} = \beta\frac{GMm}{r^2}\left(\hat{\boldsymbol{r}} - \hat{\boldsymbol{\eta}}\frac{v}{c}\right) \quad .$$

- ☐ If $\beta > 1$, the radiation force exceeds that of gravity, and the body will be blown away from the star. Rather quickly blown away, in fact. (See Homework #9.)

Forces on a light-emitting, revolving body (continued)

- ☐ The P-R drag term leads to **decrease** in the body's momentum in orbit, and therefore its orbital angular momentum: if $\beta < 1$, the orbit will gradually decrease in radius, until the body falls into the star.
- ☐ Refinements
  - For bodies similar in size to, or smaller, than the wavelengths of light typically absorbed, *scattering* reduces the absorption efficiency by a factor $Q \leq 1$ that can be calculated from the material's optical properties: $$\beta = 3QL/16\pi cGMR\rho \quad .$$
  - For larger bodies, the albedo needs to be included: $$\beta = 3\left(1 + A_b\right)L/16\pi cGMR\rho \quad .$$

Forces on a light-emitting, revolving body (continued)

- ❑ Putting in the physical constants, assuming a star just like the Sun, and taking typical values of size, density and absorption efficiency, we get

$$\beta = 0.96\left(\frac{0.1\mu\mathrm{m}}{R}\right)\left(\frac{Q}{0.5}\right)\left(\frac{3\ \mathrm{gm\ cm^{-3}}}{\rho}\right) \quad .$$

  So radiation pressure blows away small silicate particles.

- ❑ P-R drag can take what sounds like a long time to make a body fall into the Sun, but which is very short in comparison to the Solar system’s age. We can work out the time in terms of the body’s angular momentum, which in a circular orbit is

$$L = rp = m\sqrt{GMr}$$

Forces on a light-emitting, revolving body (continued)

- ☐ P-R drag provides the torque to remove this L:

$$F_\eta = \frac{dp_\eta}{dt} = \beta \frac{GMm}{r^2}\frac{v}{c} = \beta \frac{GMm}{cr^3}\sqrt{GMr}$$

$$N = rF_\eta = \beta \frac{GMm}{cr^2}\sqrt{GMr}$$

$$\frac{dL}{dt} = \frac{d}{dt} m\sqrt{GMr} = \frac{m}{2}\sqrt{\frac{GM}{r}}\frac{dr}{dt} = N$$

$$\frac{dr}{dt} = \frac{2N}{m}\sqrt{\frac{r}{GM}} = 2\beta \frac{GM}{cr^2}\sqrt{GMr}\sqrt{\frac{r}{GM}} = \frac{2\beta GM}{cr}$$

$$\tau = \frac{r}{(dr/dt)} = \frac{cr^2}{2\beta GM} = \frac{1600\text{ yr}}{\beta}\left(\frac{r}{\text{AU}}\right)^2$$

P-R drag lifetime

Forces on a light-emitting, revolving body (continued)

- ☐ Related to radiation pressure and P-R drag are the effects of the **solar wind**, a very low density (5 – 10 protons cm^{-3}) flow of **plasma** containing fast ions and electrons from the Sun.
  - Geometry of the flow same as that for radiation.
  - Thus it has an outward component, like radiation pressure…
  - …and an azimuthal component opposed to orbital motion analogous to P-R drag, called **corpuscular drag**.
  - Usually much smaller than radiation pressure and P-R except on molecules and the very smallest particles.

Forces on a light-emitting, revolving body (continued)

- ☐ Related to the Poynting-Robertson effect is the **Yarkovsky effect**, which can be significant for bodies large enough to have non-uniform surface emissivity or solar illumination, but small enough to be influenced by radiation.
  - The surfaces of slow rotators and bodies with "seasons" would generally be nonuniformly illuminated.
  - The recoil of the body from light emitted by the hotter or higher-emissivity parts is larger than that from the rest, so a net force exists in the direction opposite the sites of highest emission.
  - This is an important worry for near-earth asteroids!

Summary of forces affecting small bodies, in addition to gravity

- ☐ Solar wind and corpuscular drag: affects the smallest dust particles ($\ll 1\ \mu$m), and the even smaller atoms and molecules.
- ☐ Radiation pressure: particles 1 μm or less in size strongly affected, and blown out of the Solar system.
- ☐ P-R drag: on longer timescales, cm sized particles spiral into the Sun.
  - These particles can be trapped in resonances, though, by perturbations larger than the P-R drag.
- ☐ Yarkovsky effect: affects m – km sized bodies (e.g. asteroids).

Some consequences of radiation forces

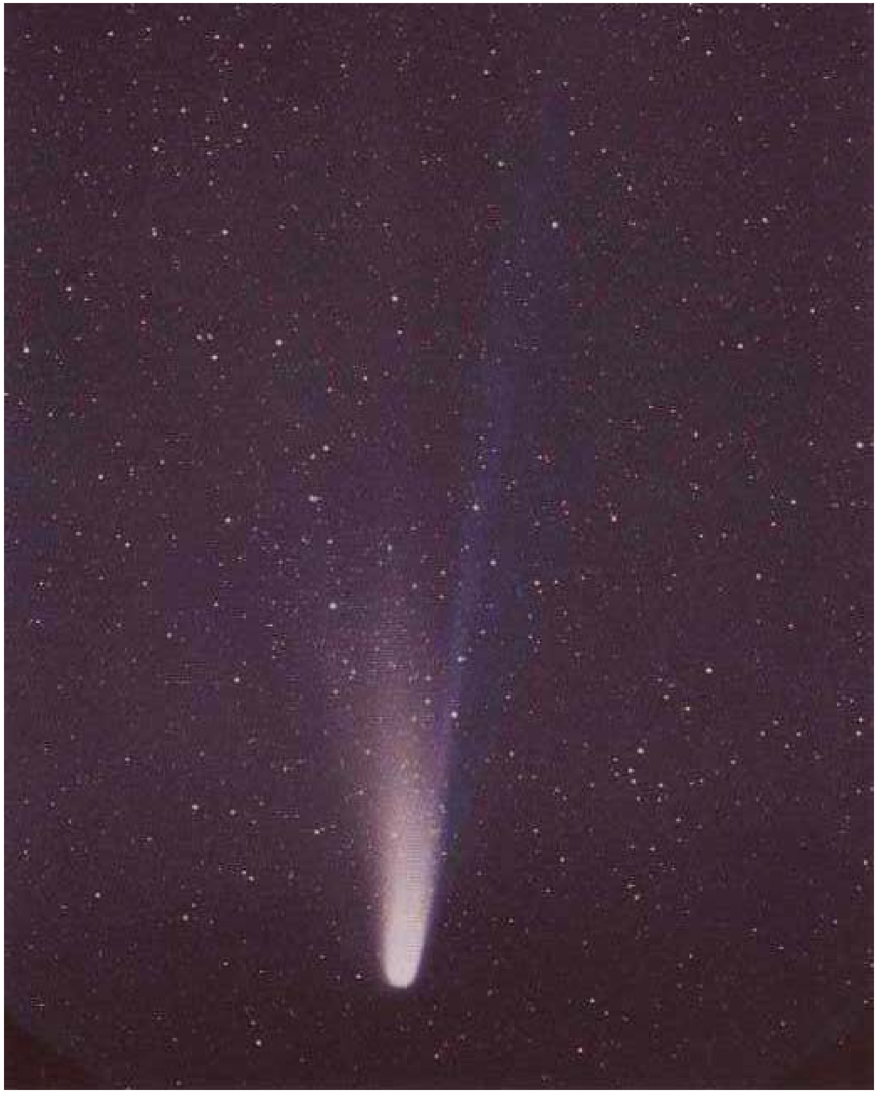
Comet tails

- ❑ Comets usually have two tails, one pointing directly away from the Sun, the other trailing slightly back along the comet's path.
- ❑ The "direct" one, called the **ion tail**, is made of ionized atoms and molecules, blown almost straight away along the coma-Sun line by the Solar wind.

Comet Hale-Bopp in 1997, by John Gleason (Celestial Images).

Some consequences of radiation forces (continued)

- ☐ The curved one, called the **dust tail**, consists of dust lifted more gently out of the comet’s coma by radiation pressure. This dust is in orbit around the Sun (with centripetal force balancing gravity *plus radiation force*), so the dust tail is curved in the orbital direction.



Comet 1P/Halley, 8 March 1986, by Bill Liller (IHW/NASA).

Some consequences of radiation forces (continued)

Dust survival

- ❑ There is μm-cm size dust in the plane of the Solar system: the zodiacal dust cloud, visible as the **zodiacal light** and the **gegenshein**. It is concentrated in the central Solar system, within Mars's orbit.
- ❑ This dust should be removed by radiation effects in a time much smaller than the age of the Solar system. That it is still there, is an indication that it gets replenished frequently.
- ❑ Comet tails and asteroid collisions are the leading producers of dust debris for the Zodiacal cloud.

Zodiacal light

Taken in Namibia, with a fisheye lens, by Stefan Seip.

Comets themselves

Typically:

Mass	$10^{17\text{-}20}$ gm
Diameter	10^{7-10} cm
Density	0.5 gm cm^{-3}
Bond albedo	0.04
Orbital semimajor axis	1 – 10000 AU
Orbital eccentricity	0 - 1
Obliquity	0 - 180°
Sidereal revolution period	$5-10^{6}$ years

Comet 1P/Halley, in 1066 (top, Queen Mathilde) and 1986 (bottom, Giotto/ESA).

Comets divide into two classes.

Short-period comets have periods shorter than about 200 years (~Neptune's period). Good examples: Halley, Encke, Tempel.

- ☐ Two sub families: the Jupiter family ($P < 20$ years) and the Halley family (20-200 years).
- ☐ Orbits tend to be prograde and lie fairly close to the ecliptic plane.

Long-period comets have periods longer than 200 years, up to ~1 Myr. Good examples: Hale-Bopp, Hyakutake, West.

- ☐ Orbits are retrograde as often as prograde, are spread evenly over all inclinations, and all have very large eccentricity.

Or three, if you count Sungrazers

Sungrazers are comets with particularly small perihelia, in the range of a few or a few tens of solar radii.

- ☐ They can be short or long period.
- ☐ Thousands seen by the current generation of solar telescopes like NASA’s SOHO. Most evaporate away completely near perihelion.
- ☐ Large ones can be extraordinarily bright. Many of the Great Comets of history were sungrazers.
  - Like 1965 (a.k.a. Ikeya-Seki; above [Roger Lynds]), 1882 and 1843, all of which were visible during the day.
- ☐ Many are clearly fragments of very large, earlier sungrazers, like the Kreutz sungrazer family.

The composition of comets

Comets have very primitive composition, and consist mainly of silicates and ices.

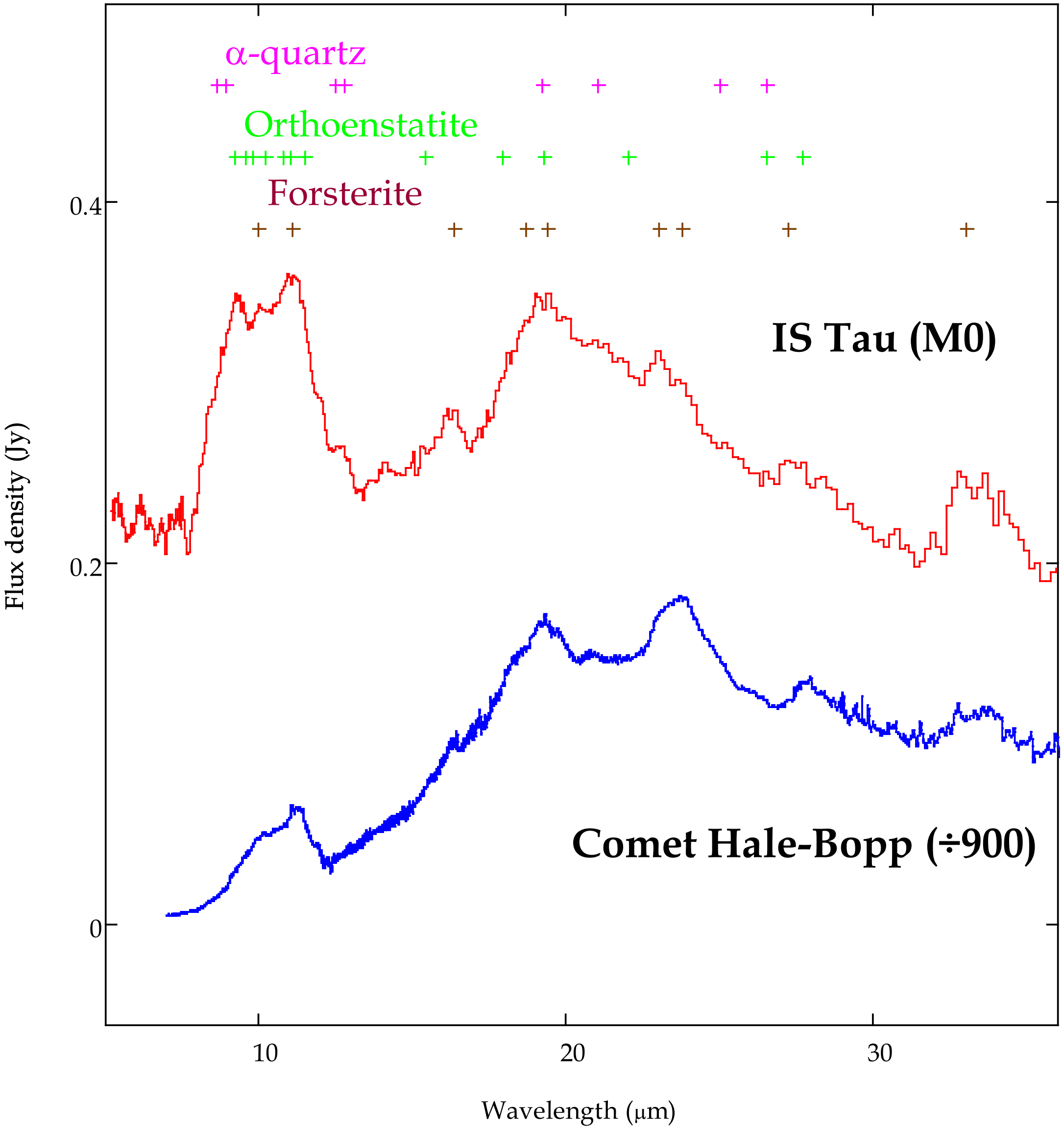
- ☐ Note the silicates, which go with the low albedo of comet nuclei. The old description of comets as “dirty snowballs” is quite inaccurate.
- ☐ In general, the composition of short-period (e.g. 9P/Tempel, the target of NASA’s *Deep Impact*) and long-period (e.g. Hale-Bopp) comets are similar to each other, and similar to that of *real* primitive planet-building material found in protoplanetary disks.
- ☐ This is unexpected: most comet experts used to think that comets contain nothing that requires high temperatures to make, like silicate minerals. Comets should be cold!

Cometary ice is perma-frozen.

And not just cold now, but *always* cold.

- ☐ Water in the tail of comet 1P/Halley is enriched in deuterium compared to the solar-system average; the same is true of Hale-Bopp and Hyakutake.
- ☐ Water in many other comets has been shown large fractions of the molecules with the spins of their hydrogen nuclei antiparallel, instead of mostly parallel.
- ☐ Both of these conditions require, not that the ice is just cold now, but that the water molecules *formed* cold ($T \sim 30$ K) and have never been any warmer before becoming part of a cometary coma.

Cometary minerals formed hot



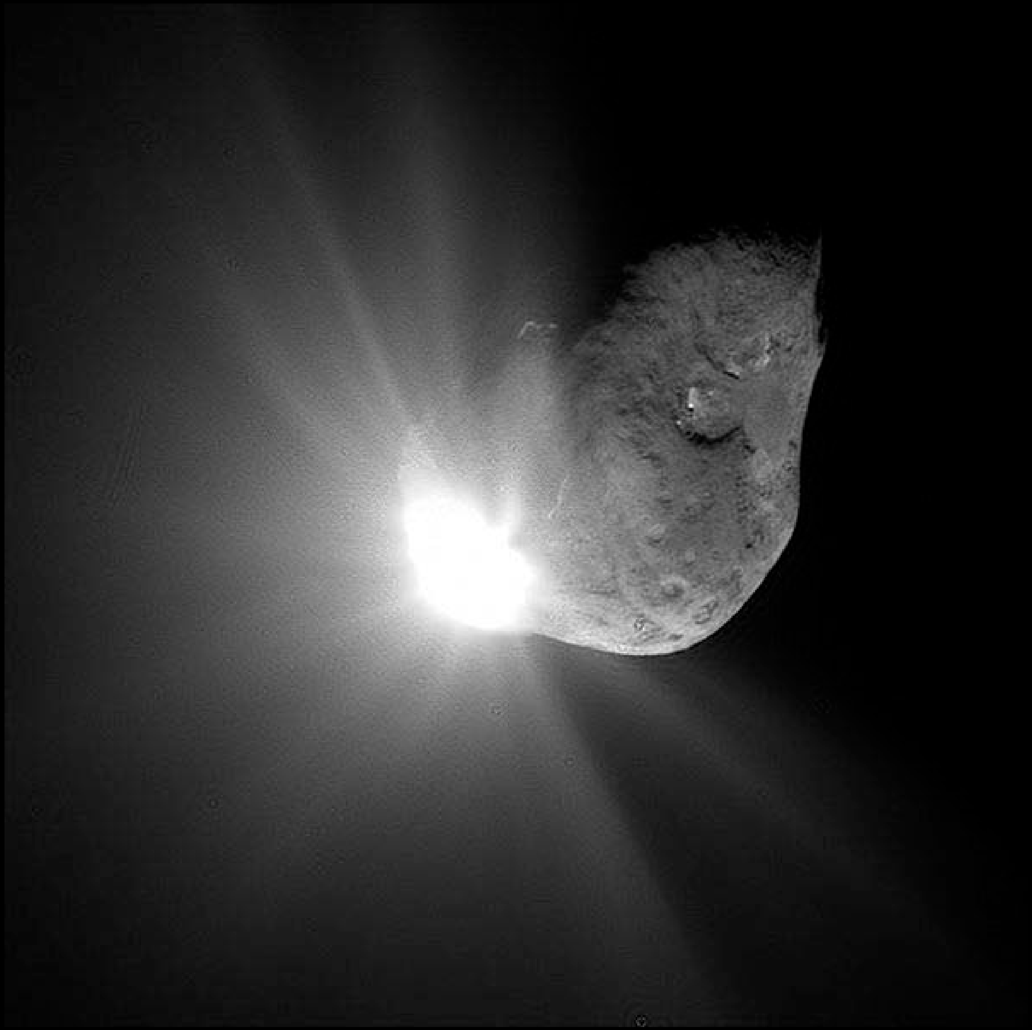
Watson et al. 2009

Infrared spectrum of a protoplanetary disk around a 1 Myr old star, IS Tau, compared to that of Comet Hale-Bopp (dust blown off the surface). Like the protoplanetary disk, the comet has lots of olivine and pyroxene minerals. Unlike the disk, the comet doesn’t have much silica.

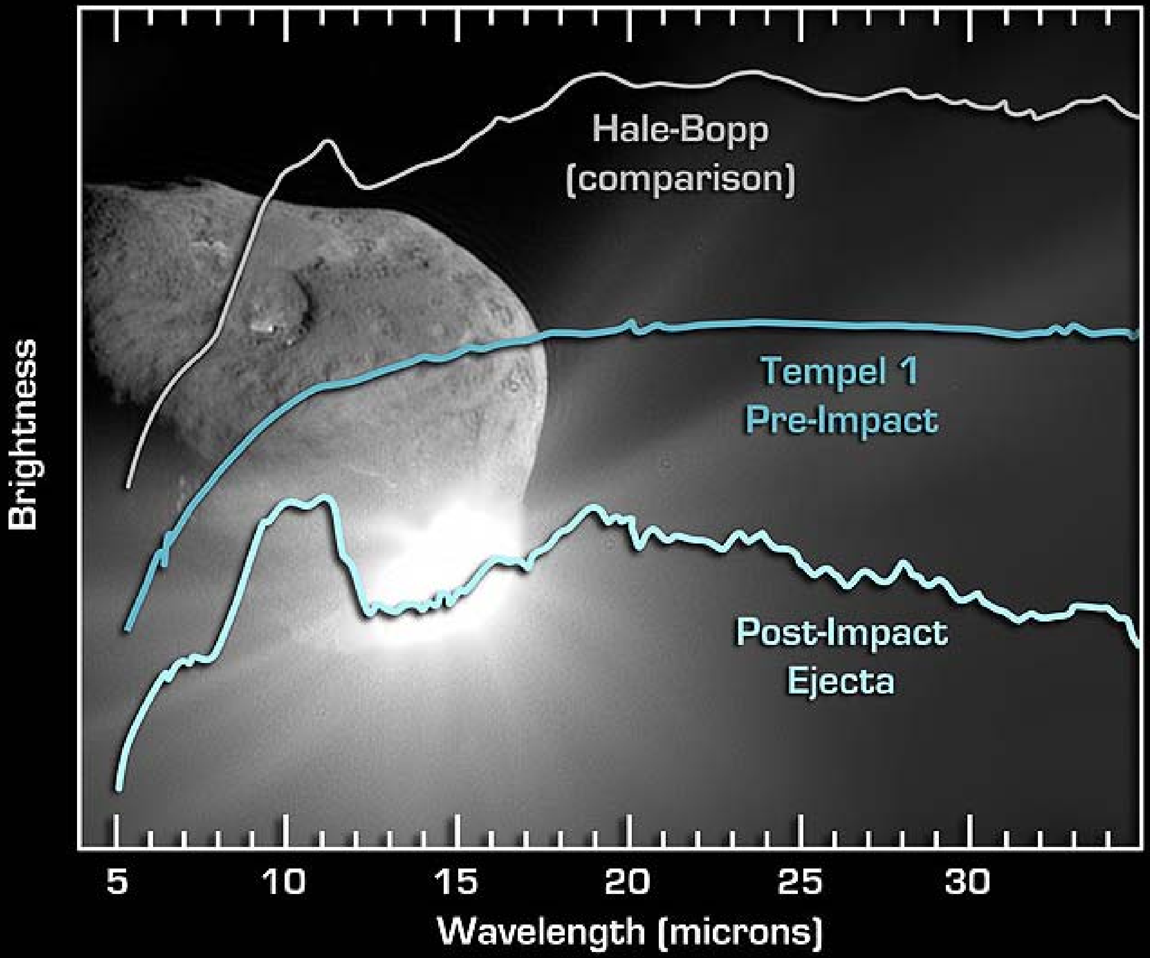
Cometary minerals formed hot (continued)

In 2005, the NASA *Deep Impact* satellite sent a "bullet" head-on into Comet 9P/Tempel in order to blast material out from the interior of the comet, and see if the interior is different from the surface.

Our telescopes watched, and analyzed the composition of the resulting cloud of dust.



Cometary minerals formed hot (continued)



The result: olivines (especially forsterite) and pyroxenes again; also some hints of more exotic minerals like carbonates and smectite.

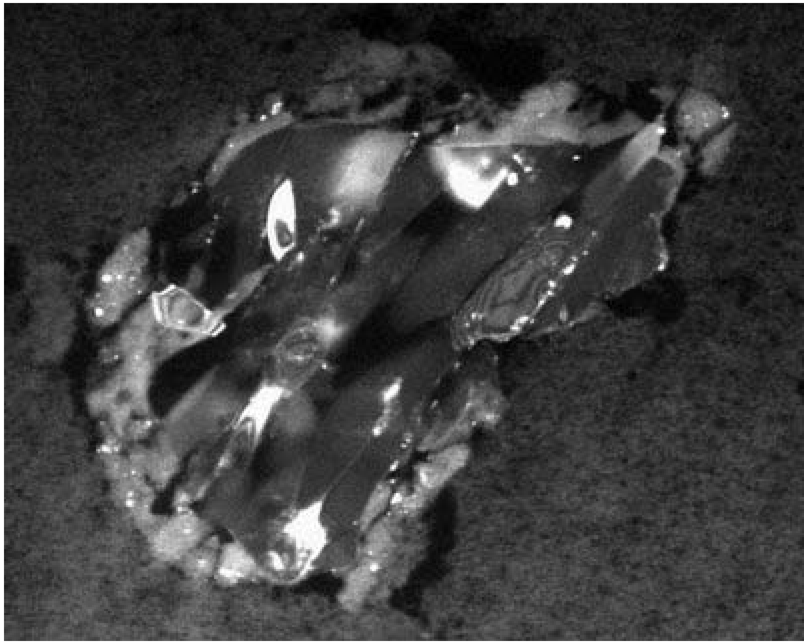
Lisse et al. 2006

Cometary minerals formed hot (continued)

In 2006, NASA's *Stardust* mission returned samples of the tail of comet 81P/Wild, which it had captured two years earlier from the near vicinity of the comet.

- ☐ Again, mineral grains were collected from the comet that require >1400 K for their formation, like various olivines, pyroxenes.

So comets are an odd mixture of ices that seem never to have been warmer than tens of K, and minerals forged in a blast furnace at 1500-2000 K.



2 μm-long forsterite grain from comet 81P/Wild (Don Brownlee, U. Washington)

The Oort cloud and the origin of long-period comets

In 1950 the great Dutch astronomer Jan Oort reasoned that the relatively-frequent sightings of long-period comets, and the large aphelion distances inferred for them, require a large reservoir of cometary bodies ~10000 AU from the Sun.

- ☐ He further reasoned from the wide range of orbit inclination among the long-period comets that this reservoir isn't nearly as flat as the inner solar system: hence the name **Oort cloud** for this material.
- ☐ Oort envisioned the origin of long-period comets to be in strong, occasional perturbations of the orbits of these distant bodies by each other, and/or by passing Galactic objects not bound to the Solar system.
- ☐ Composed of all the inner-Solar-system bodies ejected by Jupiter over the years?

The Oort cloud (continued)

- ☐ Such bodies would be small, cold, and far apart, and so *very* difficult to detect individually or collectively. Nevertheless the Oort cloud explains the long-period comets so well that it was immediately and generally accepted, and still is today.
- ☐ A massive trans-Neptunian planet, like a super-size Pluto, was long hypothesized to be one of the dominant perturbers of the original orbits of these bodies.
- ☐ And short-period comets could be explained as long-period ones perturbed into lower-eccentricity orbits by the planets. This works for the retrograde-orbiting Comet Halley (obliquity = 162.3°), for example. But…

The Oort cloud (continued)

- ☐ … in such plunging, planetary-orbit-crossing orbits, they would usually be ejected instead of settling in orbits close to the ecliptic.
- ☐ So this is at odds with the abundance of short-period comets which have low-inclination orbits with aphelia of 5-40 AU. However, there's a richer reservoir for them.