Faces of Evil?
Announcements

- HW 3 now graded
- Midterm will be graded this week
  - Drop it altogether
  - Redo it or have a 2\textsuperscript{nd} midterm
  - Grade best 6 or 7 out of 10
  - Do something creative with HW assignments
- HW 4 will be handed out on Thurs
- Comet Holmes
Comets: Cosmic Building Blocks and Laboratories
Why are comets interesting?

Comets have immense social significance; perhaps greater than any other class of astrophysical phenomena.

- Early civilization did not realize what comets were.
- They were regarded as harbingers of doom or apocalyptic events.
Our modern understanding has not slowed our superstitions, just changed their face.

- In 1910, the combined discovery of HCN (cyanide gas) in comets with the revelation that the Earth would pass through the tail of comet Halley produced hysteria.

- In 1996, Comet Hale-Bopp was declared an ‘alien return vessel’ by a religious cult, whose members committed suicide as it approached the Earth.

- During the last two decades we have become obsessed with the concept of comets hitting the Earth, driven mainly by the realization that such an event may have destroyed the dinosaurs 65 million years ago.
Comets contribute much to our understanding of the solar system and the universe. We can break this down into three general areas.

**Basic Physics:**
- Comets are ideal laboratories for the study of the chemical and radiative transfer properties of gasses.
- They provide a means to examine the nature of mixing plasmas.

**Cosmology and Astrophysics:**
- They are primordial objects.
- Comets are tracers of modern interstellar material.
- Their distribution is a map of planetary orbital evolution.

**Earth and the Modern Solar System:**
- Comets are 'windsocks' for the Solar Wind.
- They are unique case studies of planetary atmospheres.
- They provide a means to examine the nature of mixing plasmas.
- They may have contributed the water and organics that make up the terrestrial biosphere.
- Impacts with comets have profoundly affected the evolution of life on Earth.
What Are Comets?

- Comets are 1-10 km diameter Planetesimals, icy bodies that occupy a step on the ladder toward planet formation.
- Comets formed through a ‘sticky’ accretion process (like rolling a snowball).
- Larger icy bodies (like Kuiper Belt Objects) are merely more advanced versions of the accretion process.
- Planets are distinct by their size and the fact that they accreted gravitationally, which modifies their composition with respect to comets.
Where do comets come from?

Comets originally existed throughout the outer solar system

• The development of large planets disrupted the population resulting in one of three outcomes.
  
  • They were accreted onto a planet
  
  • They were scattered out of the solar system or into the Sun
  
  • They were scattered to a region of the solar system where they were no longer affected by planetary perturbations

• Comets that formed in regions where planets weren’t have remained in their orbits to the present day (Kuiper-Edgeworth Belt)

• We are beginning to see evidence of this process in nearby young star systems (e.g. Beta Pictoris)
Comets are broken down into 3 different population groups depending on where they came from and what type of orbit they have....
Long Period Comets:

- Highly elliptical orbits
- Long $T > 300$ yr periods
- Random inclination and orbital direction

LPCs are thought to originate in the Oort Cloud

- A spherical distribution of objects 100,000 AU across
- Perturbed by passing stars and molecular clouds
- Called ‘Jupiter Family’ comets, they most likely formed near the space occupied by Jupiter and the other gas giants
- The dynamical lifespan of the Oort cloud is about the age of the solar system, suggesting there is a replenishing source, possibly an ‘inner Oort cloud’
- Examples of LPCs include Hale-Bopp and Hyakutake
Short Period Comets

SPCs are characterized by:

- Orbits with periods < 300 yrs
- Orbital inclinations close to the ecliptic
- Prograde orbits with respect to the planets

SPCs are believed to originate in the Kuiper-Belt:

- Formed in the outer solar system into stable orbits in the 30-50 AU (possibly more?) range
- Perturbed by interactions with other bodies and/or slow disturbance by Neptune
- Dominance of small body size is a clue to the size distribution in the Kuiper-Belt
- Examples include Halley, Encke, & Borrelly
Centaurs:

- Centaurs are a dynamical subgroup of SPCs and KBOs:
  - They appear to have an origin in the Kuiper Belt
  - Their orbits are chaotic and unstable (eventually doomed)
  - They do not get as close to the Sun as other comets, and have more circular orbits.
  - They are generally much larger than short period comets and thus destined to much larger displays in the future
  - They appear to occupy a position between comets and KBOs.
  - Examples of this class include Chiron, Phaeton, etc.
All you need to know….

\[(1-A_b)(F_0 e^{-\tau/r_{AU}})\pi R^2 = 4\pi R^2 \varepsilon_{IR} \sigma T^4 + QL_s/N_A + 4\pi R^2 K_T(T/z)\]
No Matter Their Type All Comets Share a Common Fate:

Because comets are icy bodies from the outer reaches of the solar system—deflection toward the sun is a death sentence.

**An example:** Comet Hale-Bopp evaporated off $10^{31} \text{ mol/s}$ at perihelion. That’s $330,000 \text{ kg/s}$. Over its close approach period it lost $5 \times 10^{12} \text{ kg}$ of material, enough for a ball of ice $\sim 1 \text{ km}$ across!

That kind of loss isn’t sustainable—one of four things will happen to a comet:

- It will evaporate away until it breaks up and disintegrates.
- It will be deflected by a gravitational interaction out of the solar system (Usually Jupiter).
- It will develop a thick mantle of debris that prevents evaporation (most short period comets are on their way to this state)
- It *hits* something (like the Earth—this is why Jupiter is important)
What are the parts of a Comet?

**The Nucleus:**

The nucleus is the comet. The rest is show.

- We rarely see the nucleus; just finding out its size is difficult
- A comet nucleus is a small icy body 1-10 km across
- Comet nuclei are dark, reflecting just 3-4% of incident light
- Nuclei are too small to be held together by self gravity and thus aren’t spherically shaped
- As they approach the Sun they evaporate off gas and dust, but not uniformly across their surface
- Their internal structure is a bit of a mystery, but they are neither dense nor terribly cohesive.
So How Does All This Look?

We have visited 2 comets with spacecraft:

During the 1986 appearance of comet Halley several spacecraft (Giotto, Vega) flew close to its nucleus.

In 2001 the Deep Space 1 spacecraft flew close to comet Borrelly.
Deep Impact

- 19 Gjoules of energy in impact → 4 July 2005
- Impactor
  - 364 kg → largely copper
  - 10.3 km/s
- Good pre-impact view of nucleus
- Effects of collisions → comet brightening??
- Structure/composition of comets
Nucleus (A’Hearn et al. 2005 Science 310, 258)

- 7.6 x 4.9 km
- Impact craters \(\Rightarrow\) size distribution of 40m – 400m
- Some smooth regions \(\Rightarrow\) is nucleus layered?
- Flat spectrum in optical/no evidence of frost
- Rotation period \(~\sim\) 1.7 days
- Total mass (from ejecta) \(\Rightarrow\) 7.2 x 10^{13} \text{ kg}
- Density \(\Rightarrow\) 620 \text{ kg m}^{-3}
- Emission features: H$_2$O, HCN, CO$_2$
Compet Tempel 1
Comet Tempel 1 - Impact
Comet Tempel 1 -- spectra
The Asymmetric Activity of the Nucleus is Obvious in Both Cases: Jets!

Comets do not evaporate uniformly. Certain areas for reasons of local albedo, composition, or topography.

- Comet jets move with the nucleus
- The jet action affects the rotation and orbit of the nucleus
- Ultimately the jet alters the surface region where it forms
What most people call a comet is the reflected sunlight off the material that is liberated from the nucleus.

This material is organized according to its state and interaction with its outside environment.
The Coma of a comet is neutral cloud of gas produced from the nucleus and surrounding debris. To first order the gas coma appears as a spherical distribution, with material escaping radially in all directions.

We can break the coma down into three regions:

1. Near Nucleus (<1 km): This region is complex. Gas accelerates rapidly, dragging dust grains in its wake. Asymmetric features are blended to a spherical shape.

2. Collision Sphere (10^2 to 10^5 km): Decoupled from Dust, the collision sphere is an expanding flow in which both photochemistry and collisions occur.

3. Ballistic Coma (>R_c): Each particle is an isolated object in orbit around the Sun. Modified by solar driven photochemistry, ionization, and interactions with the solar wind.

Varies from Comet to Comet: Hale-Bopp 10^5 km; Encke 10^2 km
The Coma is Made of Many Different Compounds

Indeed, while the spectrum tells us the composition of the nucleus, it is far more complex than it seems to interpret. Thus, while the coma may be roughly spherical, it is not uniform, but changes with distance from the SUN, distance from the NUCLEUS, and with TIME.

Indeed, while the spectrum tells us the composition of the nucleus, it is far more complex than it seems to interpret.
Variation in Coma Composition with Heliocentric Distance:

Atoms and Molecules in the nucleus are released as the local temperature rises above the sublimation point. This point is different for every species.

This means that the observed composition of the nucleus will be different as the amount of solar heating changes.....

The most abundant constituent of comet nuclei (Water) is not the most volatile one. As a result it is either not present or a minor constituent at large heliocentric distances. In General.....

- For Heliocentric distances > 2.5 AU, comet sublimation is dominated by CO and CO$_2$ (Ex. Centaurs, SW3, Hale-Bopp)
- For Heliocentric distances < 2.5 AU, comet sublimation is dominated H$_2$O
- A further complication is that many of the most volatile compounds are ‘caged’ in crystal matrices of less volatile ones
As the comet nears the Sun the rate of gas production increases for all species, with some increasing faster than others.

As the amount of gas production increases, the size of the inner two regions of the coma increase as well. This increases both the outflow velocity of the coma and its temperature.

For weaker comets with $Q_{\text{tot}} < \sim 10^{29} \text{ s}^{-1}$, the outflow velocity follows:

$$V_R = 0.85 \ R_h^{-0.5}$$
In addition to varying in volatility, different coma constituents vary in their lifetime and formation.

- Compounds that evaporate directly from the nucleus are called ‘Parent’ or ‘Primary’ species.
- Parents will accelerate up to about 1 km/sec near the nucleus and expand radially outward until destroyed by photo-dissociation, ionization, or charge exchange. The product of velocity ‘V’ and lifetime ‘T’ is called the scale length \((R_x)\).

The Parent Radial Distribution is:

\[
N_x(r) = \frac{Q_x e^{-r/R_x}}{4\pi r^2 V_x}
\]
Compounds that are formed from photochemistry of a primary species are called ‘daughter’ species.

Daughters will add the velocity of the parent to the ‘excess kinetic energy’ (up to 18 km/sec for H) of the photochemistry event. The extended region over which daughters are formed, combined with their higher velocity gives them greater scale lengths and more complex distributions.

The Daughter Radial Distribution is:

\[ N_d(r) = \frac{Q_d}{(4\pi r^2 V_d)} \frac{R_d}{(R_d - R_p)} \left[ e^{-r/R_d} - e^{-r/R_p} \right] \]
Variation in Coma Composition with Cometocentric Distance:

An example is water chemistry: We typically don’t see water in comets, because it lacks resonance lines in the UV-Visible range (some in the IR).

![Graph showing Radial OH Distribution vs. Model: 04/08/97](image1)

![Graph showing Variable Model Fit: 04/08/97](image2)

- Normalized Brightness
- Radial Distance (km)

Model Specs:
- \( V_{\text{initial}} = 0.52 \)
- \( V_{\text{final}} = 2.50 \)
- \( dV_{\text{inner}} = 3.76 \)
- \( dV_{\text{outer}} = 0.15 \)
- \( Q_{\text{H}_2\text{O}} = 1.12 \times 10^{31} \text{ s}^{-1} \)
Variation in Coma Composition with Cometocentric Distance:

This means that the coma will look very different depending on the species being observed.

While Hydrogen, which is both faster and longer lived can form a coma 10’s of millions of km across!

OH is formed from the breakup of water. It lives for about 1 day and receives an excess velocity kick of 1 km/sec. It is destroyed relatively quickly and is rarely found more than $10^5$ km from the nucleus.
Variation in Coma Composition with Time:

A final consideration is that the nucleus gas production rate changes with time.

- Gas production increases as the comet approaches the Sun.
- Gas production decreases as the comet recedes from the Sun.
- Gas production can increase dramatically in short term ‘outbursts’.

- For long lived species like H, longer these changes can be found in the radial distribution of the coma as one moves outward.
- For shorter lived species like OH, the short term small scale variations can be seen.
Formation of the Ion Tail:

In addition to breaking up a molecule, sunlight can also **ionize** them. When an ion is formed in the coma, it notices something. **The Solar Wind**, which is streaming by at ~500 km/sec.

Two things will happen in response to this:

- The solar wind and comet ions will form as standoff ‘**Bowshock**’ in the sunward direction that pushes the solar wind around the coma. This is a type of ‘**Magnetosphere**’.

- The solar wind will ‘**Pick up**’ the comet ions and begin dragging them in the anti sunward direction. As they move with the solar wind, they accelerate, forming a **tail** extending anti sunward.
We can estimate the ion production rate in comets from photochemistry rates and total species production. The dominant species are CO$^+$ and H$_2$O$^+$. From this information we can infer the properties of the incoming solar wind! Since comets go to parts of the heliosphere that we can’t, they can act as a probe of conditions there. Comets also react with the highest energy component of the solar wind, producing unexpected emission signatures at very high energy.
The Dust Tail:

- Dust in comets is important because it is thought to be similar to the dust we observe between the stars *(that we can’t get to!)*

- Dust is blown off the surface of a comet by evaporating gas. As expected, maximum size of a dust grain is limited by the activity. *(A comet like Halley at 1 AU can eject 10 cm diameter grains)*

- Once ejected, dust tends to spread out along the trailing side of the comet’s orbit, forming a long tail. It would be very narrow, but for *radiation pressure*, which pushes the smallest grains in the anti sunward direction.

- At perihelion, when dust production is highest, the orbit is perpendicular to the anti sun direction. The result is a spray of tiny particles away from the tail.
The Dust and Debris in the Coma:

Most of comet dust is made up of tiny grains about 1 micron across. Much of this material is refractory meaning it has no volatile ices to evaporate.

Some debris released from comets does contain ices and these particles can contribute significantly to comet gas production. When evaporating debris is distributed around the nucleus its evaporation contributes to the entire coma (while affecting the radial distribution similar to a parent-daughter chemistry). This type of distribution is called an icy grain halo. Occasionally a larger piece breaks off that forms its own coma interacting with the primary comet.