Midterm exam – in class, July 17\textsuperscript{th}.
So far: Cosmology, galaxies, stars, planets, our Moon
Now: Impacts and water
Midterms?

A. Briefly define or explain in one sentence.

B. Answer in a couple of sentences.

C. Longer answers, choice of 4 out of 6, possibly with diagram or list.

DON’T PANIC!
Comets and Asteroids

- Comets and asteroids are debris remaining from the formation of the solar system.
- Another category is *Trans-Neptunian Objects* (TNOs)
  - includes icy bodies like Pluto (no longer designated a planet).
- Compared to the era 4.6 Gyr ago when planets were formed, the solar system is relatively empty of material.
- What we see today is the debris that is still gravitationally bound to the Sun.
- Much of the material left over from planet formation was ejected into interstellar space, including planets.
- Occasional interstellar material makes its way into the solar system (e.g. interstellar meteors).
Comets, Asteroids and Impacts

• What does their study tell us about formation of the solar system?
• What has been their importance over geological history?
• What role have comets played in the development of complex life on Earth, including *homo sapiens*?
• What is the threat of impacts from asteroids and comets today? (A possible fate for *homo sapiens*.)
• Is there an *optimal* impact rate?
Oort cloud of comets: Debris ejected from the planet-forming region.

$10^5$ AU
~ 0.5 pc
~ 1.5 LY
The solar system’s bigger picture →
The Local Galactic Neighborhood
How often do stellar encounters happen?

$R_{oort} = \text{radius of Oort cloud} \sim 10^5 \text{AU}$

- Volume of cylinder = Area $\times$ Distance traveled, $\text{Vol} = \pi R_{oort}^2 V_\odot t$.
- Number of stars in cylinder = $n_* \times \text{Vol}$
- Number density of stars = $n_* \sim 1 \text{ star} / \text{pc}^3$
  \[ n_* \sim 1 \text{ pc}^{-3} \sim (3 \times 10^{18} \text{ cm})^{-3} \sim (3 \times 10^{55} \text{ cm}^3)^{-1} \] (not so useful)
- Velocity of Sun $\sim 10 \text{ km/s} \sim 10^{-5} \text{ pc/yr}$
  This is the “peculiar” velocity of the Sun, not its rotational velocity around the Galactic center ($\sim 220 \text{ km/s}$).
How often do stellar encounters happen?

\[ R_{\text{oort}} = \text{radius of Oort cloud} \sim 10^5 \text{AU}. \]

Number of stars in cylinder,\n
\[ N_* = n_* \times \text{Vol} = n_* (\pi R_{\text{oort}}^2 V_\odot t). \]

When \( N_* = 1 \) then we get an estimate for the mean time between encounters:

\[ t = 1 / (n_* \pi R_{\text{oort}}^2 V_\odot). \]

Substituting numbers, this is about \( 10^5 \) yr.
Orbits = Conic Sections

<table>
<thead>
<tr>
<th>Section</th>
<th>Eccentricity</th>
<th>Energy</th>
<th>Bound?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Circle</td>
<td>0</td>
<td>&lt; 0</td>
<td>bound</td>
</tr>
<tr>
<td>Ellipse</td>
<td>0 ≤ e &lt; 1</td>
<td>&lt; 0</td>
<td>bound</td>
</tr>
<tr>
<td>Parabola</td>
<td>1</td>
<td>0</td>
<td>unbound (just)</td>
</tr>
<tr>
<td>Hyperbola</td>
<td>&gt; 1</td>
<td>&gt; 0</td>
<td>unbound</td>
</tr>
</tbody>
</table>

- Recall: the Universe – bound, unbound, flat.
- Each orbit type has a focus.
- For a planet orbiting the Sun the focus is the center of mass of the solar system (which is not the center of the Sun).
- More than two bodies ➔ planetary orbits are only approximate ellipses. Perturbations from multiple bodies cause a given orbit to precess.
- For the Earth, orbital precession + precession of the spin axis (e.g. 23 kyr period) underlie the Milankovitch cycle for ice ages.
A brief visit from a red and extremely elongated interstellar asteroid

Karen J. Meech¹, Robert Weryk¹*, Marco Micheli²,³*, Jan T. Kleyna¹*, Olivier R. Hainaut⁴*, Robert Jedicke¹, Richard J. Wainscoat¹, Kenneth C. Chambers¹, Jacqueline V. Keane¹, Andreea Petric¹, Larry Denneau¹, Eugene Magnier¹, Travis Berger¹, Mark E. Huber¹, Heather Flewelling¹, Chris Waters¹, Eva Schunova-Lilly¹ & Serge Chastel¹
No hint of a coma → Asteroid?

Light curve shows extreme variability → Elongated structure; tumbling in orbit.
1I/2017 U1

Location of 1I/2017 U1 when discovered by Pan-STARRS1 on 2017 October 19

Path of 1I/2017 U1

Orbit of a comet within the Solar System

Orbit of Jupiter

Orbit of Mars

Orbit of Venus

Orbit of Mercury

Orbit of the Sun

Orbit of Earth

Orbit of Neptune

Orbit of Saturn

Orbit of Jupiter

Orbit of Uranus
1I/2017 U1, ‘Oumuamua

Given its discovery and follow-up observations from multiple observatories in Hawaii, 1I/2017 U1 has been named ‘Oumuamua, which in Hawaiian reflects the way that this object is like a scout or messenger sent from the distant past to reach out to us.
A brief visit from a red and extremely elongated interstellar asteroid

doi:10.1038/nature25020

None of the approximately 750,000 known asteroids and comets in the Solar System is thought to have originated outside it, despite models of the formation of planetary systems suggesting that orbital migration of giant planets ejects a large fraction of the original planetesimals into interstellar space\textsuperscript{1}. The high predicted number density\textsuperscript{2} of icy interstellar objects ($2.4 \times 10^{-4}$ per cubic astronomical unit) suggests that some should have been detected, yet hitherto none has been seen. Many decades of asteroid and comet characterization have yielded formation models that explain the mass distribution, chemical abundances and planetary configuration of the Solar System today, but there has been no way of telling whether the Solar System is typical of planetary systems. Here we report observations and analysis of the object 1I/2017 U1 (‘Oumuamua) that demonstrate its extrasolar trajectory, and that thus enable comparisons to be made between material from another planetary system and from our own. Our observations during the brief visit by the object to the inner Solar System reveal it to be asteroidal, with no hint of cometary activity despite an approach within 0.25 astronomical units of the Sun. Spectroscopic measurements show that the surface of the object is spectrally red, consistent with comets or organic-rich asteroids that reside within the Solar System. Light-curve observations indicate that the object has an extremely oblong shape, with a length about ten times its width, and a mean radius of about 102 metres assuming an albedo of 0.04. No known objects in the Solar System have such extreme dimensions. The presence of ‘Oumuamua in the Solar System suggests that previous estimates of the number density of interstellar objects, based on the assumption that all such objects were cometary, were pessimistically low. Planned upgrades to contemporary asteroid survey instruments and improved data processing techniques are likely to result in the detection of more interstellar objects in the coming years.

On 2017 October 19 the Pan-STARRS1 telescope system detected
Reflectivity of the surface of ‘Oumuamua

Non-gravitational acceleration in the trajectory of 1I/2017 U1 (‘Oumuamua)

Marco Micheli1,2, Davide Farnocchia3, Karen J. Meech4, Marc W. Buie5, Olivier R. Hainaut6, Dina Prialnik7, Norbert Schörghofer8, Harold A. Weaver9, Paul W. Chodas3, Jan T. Kleyna4, Robert Weryk4, Richard J. Wainscoat4, Harald Ebeling4, Jacqueline V. Keane4, Kenneth C. Chambers4, Detlef Koschny1,10,11 & Anastassios E. Petropoulos3

... Various physical observations collected during its visit to the Solar System showed that it has an unusually elongated shape and a tumbling rotation state and that the physical properties of its surface resemble those of cometary nuclei, even though it showed no evidence of cometary activity. The motion of all celestial bodies is governed mostly by gravity, but the trajectories of comets can also be affected by non-gravitational forces due to cometary outgassing. ... Here we report the detection, at 30σ significance, of non-gravitational acceleration in the motion of ‘Oumuamua. ... we find comet-like outgassing to be a physically viable explanation, provided that ‘Oumuamua has thermal properties similar to comets.
The dinosaurs should have had a space program.
Habitable and Hazardous

Habitable zones:

Ingredients for life:
Liquid water, organics, stability, free energy, time (Gyr).

Hazards: changes in environment, catastrophes.

• Geophysical:
  • Volcanism, methane clathrates.

• Solar system:
  • Solar flares, impacts, orbital instabilities.

• Astrophysical:
  • Supernovae, gamma-ray bursts, magnetars.
Possible Extinction Causes (Big 5)

• Instabilities in the biosphere
  • Overshoots of a new population → resource deprivation, climate change (glaciation)
  • Tectonics/volcanism
  • Impacts of comets and asteroids
  • Local supernovae

• Relative likelihoods (occurrence rates)?
• Evidence?
FIGURE 4.13
A. Record of percent extinction per million years from data set of 9773 marine animals. The best-fit 26 m.y. cycle is shown along the top. Ticks on abscissa denote stratigraphic stages. Dots indicate centers of sampling intervals. (From Raup, D. M. and Sepkoski, J. J. Jr., 1988, Testing for periodicity of extinction: Science, v. 241, p. 95, Fig. 2. B. Extinction profiles for ten samples of 1000 genera chosen at random from a data set of 19,897. (From Raup, D. M., and Boyajian, G. E., 1988, Generic extinction in the fossil record: Paleo-biology, v. 14, Fig. 2, p. 116.)
NEMESIS
THE DEATH STAR
The Story of a Scientific Revolution

DR. RICHARD MULLER
Introduction by Dr. Luis Alvarez

THE NEMESIS AFFAIR
A Story of the Death of Dinosaurs and the Ways of Science

DAVID M. RAUP
Revised and Expanded

"Destined to take its place alongside The Double Helix as one of the great scientific memoirs written for the general public."
—James Trefil
General Extinction Trends at KT Boundary

General Trends:
- Higher Survival Rate
- Aquatic (Animals)
- Smaller Bodies (Animals)
- Deep swimming oceanic life
- Deciduous Plants

- Lower Survival Rate
- Dry Land (Animals)
- Large Bodies (Animals)
- Shallow or surface oceanic life
- Coniferous Plants

- Total Extinction
- Severe Losses
- Medium Losses
- Light Losses

- Dinosaurs
- Pterosaurs
- Mammals
- Plesiosaurs (Marine Reptiles)
- Small Lizards, Turtles, Crocodiles
- Coccolithophores
- Shelled Phytoplankton
- Plankton
- Brachiopods
- Ammonoids
- Nautiloids
- Formanifera
- Tropical Plants
- High Latitude Plants
**FIGURE 8.14**
Evolutionary radiation of mammals in the Cenozoic era. (From Gingerich, P. D., 1977, Patterns of evolution in the mammalian fossil record, in Hallam, A., ed., Patterns of evolution as illustrated by the fossil record, Fig. 1, p. 471. Reprinted by permission of Elsevier Science Publishers B. V.)

**Figure 8.** Detailed comparison of relative and absolute foraminiferal abundance changes across the K/T boundary in the El Kef, Tunisia, section. Same data set as in Fig. 2. Although most Cretaceous species are still present at the base of the boundary clay, their abundance is reduced.
The Cretaceous-Tertiary boundary (between arrows) on an abandoned, post-glacial sea cliff at Kølby Gård near Hunstrup, Jutland, Denmark. Semilihthified fragments of the latest Cretaceous White Chalk were broken away and redeposited within gray-green marls (Fish Clay equivalent) of earliest Tertiary age at the base of the Bryozoaon Limestone.

clay layer ~ 1 cm thick
Photograph of the K/T boundary sequence at Raton Basin in Colorado. The light gray unit in the middle of the photograph (marked with the red knife) is composed of two layers that mark the K-T boundary. A coal deposited in the Tertiary Period, after dinosaurs disappeared, is deposited on top of the K-T boundary layers.

From http://www.lpl.arizona.edu/SIC/impact_cratering/Chicxulub/K-Tboundary_rocks.jpg
1970s Views on the K-T Extinction

Proceedings of *Cretaceous-Tertiary Extinctions and Possible Terrestrial and Extraterrestrial Causes*:

– No mention of impacts.

– Instead:
  
  • Geomagnetic Field and the K-T Extinctions.
  • Variations of the Luminosity of the Sun and Super Solar Flares: Possible Causes of Extinctions.
  • The Effect of a Nearby Supernova explosion on the K-T Environments.
Recent Timeline in Understanding the K-T Extinction

- 1970s – Conferences on possible causes (gradualism vs. catastrophism theme)
- 1978 – PEMEX magnetic survey
  - magnetic anomaly found in Yucatan peninsula
  - Later a gravity anomaly also found
  - Data and interpretation poorly known until 1990
- 1980 – Alvarez et al. impact hypothesis
  - Prime evidence = excess iridium at the K-T boundary
  - ~ 10 km size impactor
  - acid test: find a crater ~ 200 km in diameter
- 1984 – Proposal that extinction events occur periodically (Raup and Sepkoski)
- 1991– Chicxulub crater identified in the Yucatan (Hildebrand et al.)
- 1980s- present:
  - continued debate over role of volcanic activity (Deccan traps in India, particularly)
  - ongoing studies of the duration of the extinction event and underlying mechanisms
Explanations for the KT
Impact vs. volcanism vs supernova?

Why does it matter?

- Discussion of prospects of the longevity of *h. sapiens* and of the abundance of technological civilizations elsewhere.
- Volcanism and supernovae cannot be mitigated by a species.
  - Volcanism subsides with planet age. An advanced civilization could move off its birth planet to one with less tectonic activity [but then, less effective magnetic field].
  - Supernovae will ultimately affect any location in the Galaxy.
- Impacts can be mitigated if predicted well in advance.
  - US DoD studies on mitigation methods.
  - Current technology can suffice (at high cost).
  - Complete asteroid census being conducted for sizes > 140m.
  - Cost effective compared to colonization of another planet.
  - Radar determinations of precise asteroid orbits: powerful MWatt transmitters that produce signals detectable on ~kpc distances (SETI).
The pace of knowledge!

“I would sooner believe that two Yankee professors lied than that stones fell from the sky.”

- Thomas Jefferson (1807)
Iridium

• A platinum-group element (atomic # 77).
  • platinum, iridium, osmium, rhodium.

• Platinum group elements are depleted in the Earth’s crust but overabundant in the core.
  • Iridium is underabundant in the crust compared to cosmic abundances.
  • Iridium is a siderophile = “iron loving”.
  • chondritic meteorites: cosmic abundance of iridium.

• If excess iridium is seen in a sedimentary layer:
  – it has been brought to the surface by volcanic action.
  – it has been impact delivered.

• Why focus on iridium? It is easier to detect at low levels than other platinum metals (neutron activation analysis).
### Goldschmidt classification in the Periodic Table

<table>
<thead>
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<th>2</th>
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<td>O</td>
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<tr>
<td>La</td>
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</tbody>
</table>

#### Legend:
- **Lithophile**
- **Siderophile**
- **Chalcophile**
- **Atmophile**
- very rare
Iridium Abundance

Iridium concentration shows sharp increase 65 million years ago

What could cause this?
Chicxulub Crater: A possible Cretaceous/Tertiary boundary impact crater on the Yucatán Peninsula, Mexico

Alan R. Hildebrand¹, Glen T. Penfield², David A. Kring¹, Mark Pilkington³, Antonio Camargo Z.⁴, Stein B. Jacobsen⁵ and William V. Boynton¹

1991, Geology, 19, 867

Abstract

We suggest that a buried 180-km-diameter circular structure on the Yucatán Peninsula, Mexico, is an impact crater. Its size and shape are revealed by magnetic and gravity-field anomalies, as well as by oil wells drilled inside and near the structure. The stratigraphy of the crater includes a sequence of andesitic igneous rocks and glass interbedded with, and overlain by, breccias that contain evidence of shock metamorphism. The andesitic rocks have chemical and isotopic compositions similar to those of tektites found in Cretaceous/Tertiary (K/T) ejecta. A 90-m-thick K/T boundary breccia, also containing evidence of shock metamorphism, is present 50 km outside the crater's edge. This breccia probably represents the crater's ejecta blanket. The age of the crater is not precisely known, but a K/T boundary age is indicated. Because the crater is in a thick carbonate sequence, shock-produced CO₂ from the impact may have caused a severe greenhouse warming.
There is a drastic change in marine microfossils across the ~cm thick clay layer rich in impact debris which marks the KT boundary.

(Photograph: A. Montanari)

Bouguer gravity data from the northwest corner of the Yucatán Peninsula, Mexico. Adapted from Figure 2, Hildebrand et al. in Geology 1991. The semi-circular blue and yellow feature is produced by the impact crater. The linear blue structure south of the crater is a deeper structural feature in the Earth's crust that existed before the impact event.
Each blue dot below represents a cenote such as the one to the left.

The blue dots show the locations of cenotes (groundwater springs) on the Yucatan peninsula. The outline of the cenotes ring is nearly coincident with the rim of the impact structure.

Adapted from Figure 1, P.K.H. Maguire et al. in Meteorites: Flux with Time and Impact Effects (1998).
A 0.32 mm shocked quartz grain from an intracrater breccia sample of the Chicxulub crater.

→ Clear evidence of production by impact, including mineral grains showing evidence of shock metamorphism orientations.

(Taken in cross-polarized light by Alan Hildebrand)
Altered impact melt spherules from the K/T boundary sediments in Haiti. These objects form a bed nearly half a meter thick, which is covered by a second, iridium-rich bed. The scale along the bottom of the photograph has 1mm divisions.
Altered tektites produced by the Chicxulub impact as preserved at the Dogie Creek, Wyoming, Cretaceous-Tertiary boundary locality. The scale bar shows divisions of millimetres.

At this locality the ejecta layer from the Chicxulub crater is ~2 cm thick and at some places preserves the shapes of the individual tektites that compose the layer. Originally composed of glass, the tektites have been pseudomorphed (altered and replaced by a secondary mineral while their shape is preserved) by phosphate-bearing minerals (most commonly goyazite) at this site. The tektites are predominantly spheres at this locality; this photograph includes only one egg-shaped individual.

(Image courtesy Geological Survey of Canada)
Extinctions: Cores Document Ancient Catastrophe

Richard A. Kerr

Last week, cores of ancient sea-floor sediment made a splash in the media, when a first look at deep-sea samples unloaded from the drill ship *JOIDES Resolution* revealed a layer of debris ejected from the great meteorite impact 65 million years ago. The cores, from off the U.S. southeast coast, were heralded by some as proof of the impact's potency. But researchers hardly needed proof beyond the 180-kilometer crater itself, identified nearly 5 years ago (*Science*, 14 August 1992, p. 878); for them, the real controversy is not whether the impact happened but whether it caused all or only a few of the extinctions that took place at the end of the Cretaceous period, 65 million years ago. And while public attention spotlighted the *Resolution* cores, another group of paleoceanographers has already retrieved—and analyzed—a similar core that they say convicts the impact of slaughtering most of the extinction's marine victims.

In a core drilled from a former seabed that now lies high and dry in southern New Jersey, Richard Olsson of Rutgers University and his colleagues in the New Jersey Coastal Plain Drilling Project found that many species of microfossils—remains of one-celled organisms such as foraminifera, nannoplankton, and dinoflagellates—flourished right up to the debris layer, then vanished. "It would be very hard to argue now that the impact did not occur precisely at" the time of the extinctions, says Olsson.

The chronology, Olsson says, should buttress earlier records, some of which had been disturbed, chemically altered, or partially eroded. Still, there's sure to be debate as other scientists get a look at both the New Jersey and the deep-sea cores. The New Jersey results were only just submitted to *Geology*, and the *Resolution* crew "just got off the boat," notes paleoceanographer Gerta Keller of Princeton University. "Any scientist will have to be skeptical" until the data become public.

Already, the cores establish the U.S. East Coast as a rewarding place to study the effects of the impact, which struck several thousand kilometers to the southwest on the Yucatán Coast. Closer to the crater, around the Gulf of Mexico and the Caribbean, the sea-floor...
<table>
<thead>
<tr>
<th>Agent</th>
<th>Mechanism</th>
<th>Time Scale</th>
<th>Geographic Scale (K-T)</th>
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<tbody>
<tr>
<td>Dust loading</td>
<td>Cooling</td>
<td>Y = years</td>
<td>G = global</td>
</tr>
<tr>
<td></td>
<td>Cessation of photosynthesis</td>
<td>M = months</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Loss of vision</td>
<td>M</td>
<td></td>
</tr>
<tr>
<td>Fires</td>
<td>Burning</td>
<td>M</td>
<td>G</td>
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<tr>
<td></td>
<td>Soot cooling</td>
<td>M</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Pyrotoxins</td>
<td>M</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Acid rain</td>
<td>M</td>
<td></td>
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<tr>
<td>NO₃ generation</td>
<td>Ozone loss</td>
<td>Y</td>
<td>G</td>
</tr>
<tr>
<td></td>
<td>Acid rain</td>
<td>M</td>
<td>R = regional</td>
</tr>
<tr>
<td></td>
<td>Cooling</td>
<td>Y</td>
<td>G</td>
</tr>
<tr>
<td>Shock wave</td>
<td>Mechanical pressure</td>
<td>I = instantly</td>
<td>R</td>
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<tr>
<td>Tidal wave</td>
<td>Drowning</td>
<td>I</td>
<td>R</td>
</tr>
<tr>
<td>Heavy metals, etc.</td>
<td>Poisoning</td>
<td>Y</td>
<td>G</td>
</tr>
<tr>
<td>Water/CO₂ injections</td>
<td>Warming</td>
<td>D = decades</td>
<td>G</td>
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<tr>
<td></td>
<td>Acid rain</td>
<td>Y</td>
<td>G</td>
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</tbody>
</table>

\(^a\) I = instantly; M = months; Y = years; D = decades.

\(^b\) R = Regional (10⁶km²); G = global.
Multiple Impacts and the KT Extinction?

Possible multiple impacts involved.

→ Claims of second crater near Chicxulub.
→ Claimed large crater in Indian ocean.

• Multiple impacts do occur:

Comet Shoemaker-Levy 1994

Jupiter in Ultraviolet (about 2.5 hours after R’s impact; 1995). The black dot near the top is a Galilean moon transiting Jupiter.
“It has been suggested that the Manicouagan crater may have been part of a multiple impact event which also formed the Rochechouart crater in France, Saint Martin crater in Manitoba, Obolon’ crater in Ukraine, and Red Wing crater in North Dakota. Geophysicist David Rowley of the University of Chicago, working with John Spray of the University of New Brunswick and Simon Kelley of the Open University, discovered that the five craters formed a chain, indicating the breakup and subsequent impact of an asteroid or comet, similar to the well observed string of impacts of Comet Shoemaker-Levy 9 on Jupiter”

http://en.wikipedia.org/wiki/Manicouagan_crater
The Leonid meteor shower of 1799 Nov 12

Parent comet: 55 P Tempel-Tuttle
33.3 yr orbit

The orbit of comet 55P Tempel-Tuttle in a diagram by Yeomans et al. (1996). The planet positions are shown for February 28, 1998, when the comet passed the Sun most recently. The comet travels every 33.3 years between the orbits of Earth and Uranus. Right shows an all-sky view of the Leonid outburst from Modra Observatory in a 4 hour exposure on November 17, 1998.
This NASA graphic shows the orbits of all the known Potentially Hazardous Asteroids (PHAs), numbering over 1,400 as of early 2013. Shown here is a close-up of the orbits overlaid on the orbits of Earth and other inner planets.

Credit: NASA/JPL-Caltech
SOHO Observations of Sun-grazing Comets