Today Nov 13

PS 6 SOLUTIONS
meteorites
asteroids
40 meters up
homework #6

\[ V_{\text{orb}} = \frac{H}{r} \]

\[ V_{\text{orb}} = \sqrt{\frac{GM}{r}} \approx \frac{3 \times 10^5}{V^2} = \frac{3 \times 10^5}{V^3} = 17.3 \text{ km s}^{-1} \]

\[ \frac{H}{r} = \frac{3}{17.3} = 0.17 \]

\[ H = (3)(0.17) = 0.5 \text{ AU} \]

Total thickness = \( 2H = \frac{1}{2} \text{AU} \)

For \( 30 \text{ m s}^{-1} \), \( \frac{V}{V_{\text{orb}}} \) is 100 times smaller

\[ \rightarrow H = 0.005 \text{AU} \]

Total thickness = \( \frac{10^{-2}}{2} \text{AU} \)
\[ \frac{dS}{dt} = \frac{3 \omega}{8 \rho} \left( 1 + \frac{\sqrt{3} c}{V_2} \right) \]

\[ \Sigma_{1 \text{AU}} \approx \frac{3000}{100} = 30 \text{ g cm}^{-2} = 300 \text{ kg m}^{-2} \]

\[ \Sigma_{10 \text{AU}} \approx \frac{100}{100} = 1 \text{ g cm}^{-2} = 10 \text{ kg m}^{-2} = \frac{1}{30} \Sigma_{1 \text{AU}} \]

\[ \frac{dS}{dt} = (300) \left( \frac{\frac{2\pi}{3.2 \times 10^7 \text{ s cm} \text{ yr}^{-1}}} {8 \text{ Gyr}^{-1}} \right) \left( 1 + \left( \frac{1}{\sqrt{3}} \right)^2 \right) \]

\[ = 1.47 \times 10^{-8} \text{ m s}^{-1} \]

\[ R_{E} = 6400 \text{ km} \quad \text{so} \quad T = \frac{6.9 \times 10^6}{1 \text{ AU}} = 4.4 \times 10^7 \text{ s} \]

\[ \text{At } 10 \text{ AU} \]

\[ \Sigma_{10 \text{AU}} = \frac{1}{30} \Sigma_{1 \text{AU}} \]

\[ \omega_{10 \text{AU}} = \omega_{1 \text{AU}} \cdot 10^{-3} \]

\[ \omega_{10 \text{AU}} = 0.03 \omega_{1 \text{AU}} \]

\[ \left[ V^2 = \frac{6m}{r} = (\omega r)^2 \quad \text{so} \quad \omega \propto r^{-3/2} \right] \]

\[ \text{At } 10 \text{ AU} \]

\[ T_{10 \text{AU}} = \frac{1.4 \times 10^7 \text{ s}}{5} \]
\[ M_{\text{iso}} = \frac{2}{3} \pi R_{H:11} \]

\[ R_{H:11} = \frac{2}{3} \pi r \cdot \left( \frac{M_{\text{iso}}}{M_{\odot}} \right)^{\frac{1}{3}} \]

\[ M_{\text{iso}}^{2/3} = \frac{2}{3} \pi r^2 M_{\odot}^{-3/3} \]

\[ M_{\text{iso}} = \left( 4 \pi \right)^{\frac{3}{2}} r^3 M_{\odot}^{\frac{1}{2}} \]

\[ M_{\text{iso}} = 10^{\frac{3}{2}} \left( 12.56 \right)^{\frac{3}{2}} (1.5 \times 10^{12})^3 \left( 2 \times 10^{30} \right)^{-1/2} \]

\[ = 3.4 \times 10^{24} \text{ kg} \approx \frac{1}{2} \text{ M}_{\text{Earth}} \]
4. \[ \frac{V}{\text{orbit speed}} = \frac{H}{r} \]

\[ V = \frac{1}{3} V_{\text{esc}} = \frac{1}{3} (11.2) = 3.7 \text{ km/s} \] for full size Earth

\[ \frac{H}{r} = \frac{3.7}{30} \text{ ; } H = 0.12 r \text{ for final Earth} \]
5) $p \rightarrow T$
projectile $\rightarrow$ Target

\[ \frac{3}{5} \frac{G M r^2}{r_T} = \frac{1}{2} M p V^2 \]

\[ \frac{3}{5} \frac{G (4/3 \pi)^2 r_T^6 \rho_T^2}{r_T} = \frac{1}{2} \pi (4/3 \pi)^2 \rho_T^2 \rho V^2 \]

assume $\rho_T = \rho = 3000 \text{ kg m}^{-3}$

\[ \rho_T^3 = \frac{2 \pi G \rho_T r_T^5}{5 V^2} = \frac{2 \pi (6.7 \times 10^{11}) 3000 (5000)^5}{(3000)^2} \]

\[ = 3.5 \times 10^{10} \]

$\rho_T = 3 \times 10^3 m^{-3}$ - 3 km radius of blow up

\[ \rho_T = 3 \times 10^3 m^{-3} \] is a 100 km diameter asteroid

\[ E_{\text{Earth}} \]

\[ \sqrt{\frac{\text{impact}}{11.2 + 3}} = 11.6 \text{ km s}^{-1} \]

\[ \rho_T \left( \frac{r_T^5}{V^2} \right)^{1/3} = \frac{r_T^{5/3}}{V^{2/3}} \]

\[ \rho_T \text{ for Earth} \]

\[ \rho_T \text{ for 100 km asteroid} = \left( \frac{12200}{100} \right)^{5/3} \]

\[ \left( \frac{11.6}{2/3} \right) = 860 \]

\[ \frac{860}{1325} = 1325 \]

\[ \rho_T \text{ to disrupt Earth} \]

\[ 1325 \times 3 = 3975 \text{ km} \]

\[ \text{to 10,000 km} \]
How to measure the ages of really old rocks

$P(\text{parent})$ decays to $D(\text{daughter})$

$P \rightarrow D$

$D = P_0 - P$, where $P_0$ is the initial amount of parent

$P = P_0 e^{-t/\lambda}$

so $D = P e^{t/\lambda} - P = P(e^{t/\lambda} - 1)$

$\frac{D}{P} = (e^{\lambda/\lambda} - 1)$
When the rock formed - all 3 minerals had the same \(^{87}Sr/^{86}Sr\)

\(^{87}\text{Rb}\) (parent) decays to (daughter) \(^{87}\text{Sr}\) with a half life of 49 billion years

\(^{86}\text{Sr}\) is stable and is not produced by decay of another isotope (it is used for normalization)

\[\begin{align*}
\frac{^{87}\text{Rb}}{^{86}\text{Sr}} &\quad \text{decreases with time} \\
\frac{^{87}\text{Sr}}{^{86}\text{Sr}} &\quad \text{increases with time}
\end{align*}\]

Three minerals with different Rb/Sr and exactly the same Sr isotopic composition
Later all minerals lose $^{87}\text{Rb}$ & gain $^{87}\text{Sr}$
At time $t$ all points are on the line (isochrone)
Slope = $D/P$

\[
\frac{^{87}\text{Sr}}{^{86}\text{Sr}} = e^{t/\lambda} - 1
\]

$^{87}\text{Rb} / ^{86}\text{Sr}$
Meteorites vs impact craters

If the mass of air intercepted by the meteoroid is a few times that of the rock, then the meteoroid loses its high speed (>11 km/s) and falls at free-fall speed.

If the atmosphere compressed to density solid rock it would be ~3m thick.

If a rock is larger that a few meters it doesn’t slow down. Makes a hypervelocity impact crater.

To survive entry, Rocks must be strong

\[ \text{ram pressure} = \rho V^2 \]
Asteroid & Comet Impact Hazard

Approximate frequency of impacts

- Monthly
- Every year
- Every decade
- Once a century
- Once a millennium
- Every ten thousand yr
- Every 100 thousands yr
- Every million yr
- Every 10 million yr

“Annual event” ~ 20 kilotons

- Tunguska ~ 50 megatons
- “1000 year event”
- Extinction of the dinosaurs
- Global catastrophe threshold

Megatons TNT equivalent energy

1/100 1 100 10,000 100,000 million million
Interplanetary dust
>30,000 tons falls on earth each year!

$1/m^2/day > 10 \mu m$
$1/m^2/yr > 0.1 mm$

Zodiacal light
Sunlight reflected from Interplanetary dust

Earth horizon

Venus
Hypervelocity Dust craters on Lunar Rocks
Cosmic Dust

1 μm
Rocks from space
Where do they come from?
(>50,000 found)

Most meteorites are from asteroids

~100 from the Moon

~100 from Mars

any from comets?
(probably not as rocks)
Cometary meteors ⇒ comet rocks are weak!
Comet dust does survive atmospheric entry
Asteroids

early solar system material that did not form a planet
largest asteroid -1000km
Very rare Martian & Lunar meteorites

Mars

Moon

Very large Lunar Meteorite!
Martian meteorites

- Young solidification ages (< 4by)
- Rock structure → formed in a magma chamber in strong gravity
- Gas isotopic abundances identical to the Martian atmosphere measured by spacecraft
- non-Earthlike oxygen isotope composition

**the first Martians**

<table>
<thead>
<tr>
<th>Meteorite Name</th>
<th>Location Found</th>
<th>Year Found</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chassigny*</td>
<td>Chassigny, France (October 3)</td>
<td>1815</td>
</tr>
<tr>
<td>Shergotty*</td>
<td>Shergotty, India (August 25)</td>
<td>1865</td>
</tr>
<tr>
<td>Nakhla*</td>
<td>Nakhla, Egypt (June 28)</td>
<td>1911</td>
</tr>
</tbody>
</table>
Evidence that Martian meteorites are from Mars

gas trapped in glass from Martian meteorite
Chemical links - moon & lunar meteorites
distinct ratios of iron and manganese

(from Korotev, 2002a)
A) Undifferentiated (primitive)

Show range of heating but did not melt
usually contain chondrules

B) Differentiated

From parents that melted
in the early solar system

why? Ans: Something heated them
It was not the Sun!
An example of differentiation

Separation of iron metal and iron loving elements

Elements that can dissolve into metal - concentrate in the dense immiscible metal phase & sink

rock

Fe, Ni metal

melting T > 1200°C

Silicates + lithophile elements

Fe + siderophile (iron loving) elements

molten Fe & silicate are immiscible!
Primitive meteorites
undifferentiated
(approximately solar composition for rock-forming elements)
called chondrites because they contain mm-sized chondrules
(spheroids composed of silicate minerals (crystals) and glass)
crystals have order
glass does not
**Primitive meteorites**

called **chondrites** because they contain **chondrules**
~solar composition for many rock forming elements
Composed of silicate minerals, glass, metal & Fe sulfides
~4.567 by old

Main components of primitive meteorites:
A. Fine-grained matrix
B. Coarse-grained components (>0.1 mm) in matrix
   - **Chondrules** (Fe, Mg silicate crystals + glass)
   - **Calcium aluminum inclusions**
     Minerals that condense before Fe (>1400K)
Chondrules

- 1mm spheroidal particles melted in the nebula (not in a parent body!)
- ~75% of mass of some meteorites
- Formed at 1400 to 1800 °C - melted in space!
- Rapid cooling – quench mix of glass & crystals
- Origin a mystery - hi temperature - rapid cooling
- Most popular origin - heating by shock waves in nebular gas
Crystaline olivine (Mg, Fe silicate)

glass
Primitive Carbonaceous Chondrite In thin-section

Fine grained matrix

Chondrule

CAI Calcium Aluminum Inclusion

COSMIC SEDIMENTS!
Chondrules in fine-grained matrix

All this stuff orbited the Sun as individual particles before the meteorite formed
Chondrules & Calcium Aluminum Inclusions (CAIs)

CAIs

Oldest SS materials
Minerals condense >1400K
$^{16}$O rich = to Sun
0.01-10% in primitive chondrites

Chondrules

Melted in nebula
Formed at 1400-2100 K
Dominant inner nebular solid
formed >1my after CAI
Chondrules are usually younger than CAIs by 1-3 my precision Pb isotope measurements
Meteorite Types

primitive

Undifferentiated Meteorites

Chondrites

Carbonaceous Chondrites

Ordinary Chondrites

Rumuruti-Chondrites

Enstatite-Chondrites

CI CM CO CV CK CR CH

H L LL EH EL

Differentiated Meteorites

Achondrites

Primitive Achondrites:

Acapulcoites

Winonaites

Lodranites

Iron Meteorites

IA IIA IIB IIIA IIIB IVA others (main groups)

Stony-Iron Meteorites

Pallasites

Mesosiderites

Martian Meteorites

Aubrites

Ureilites

Angrites

HED Lunar Meteorites

SNC

Shergotts Nakhliites Chassigny

ALH 84001

Howardites Eucrites Diogenites
Differences between primitive meteorite classes

(similar to solar composition but with exceptions!)

A) **Volatile** element depletions (S, Zn, C, Cd etc) incomplete condensation of volatiles carbonaceous chondrites – highest volatile abundances

B) Depletion + enhancement of **refractory** elements (Ca, Al, Ti etc) effects related to accretion of 1st condensates

C) Variation of total **Fe/Si** different accretion efficiencies of metal & silicates

D) **Oxygen isotope** composition
Volatile depletion among chondrite classes

most classes are depleted in volatile elements
(Earth is also depleted in volatile elements)

CI chondrites

less abundant

More volatile ➔

ordinary chondrites
some meteorite classes are enriched or depleted in the first condensed elements

Many meteorite classes have systematic excesses or depletions of all refractory elements such as Ca, Al and Ti

This property is related to accretion of high temperature condensates.
Primitive meteorite classes
Large variation of Fe/Si ratio & Fe oxidation state
oxygen isotopes

\[ \frac{^{17}O}{^{16}O} \]

\[ \delta^{17}O \ (\%_o \ SMOW) \]

\[ \delta^{18}O \ (\%_o \ SMOW) \]

slope = 1/2

mixing line slope = 1

\[ \frac{^{18}O}{^{16}O} \]
Mix of low $^{17}$O and $^{18}$O materials (Sun & CAIs) and high $^{17}$O and $^{18}$O materials (enriched due to UV self shielding effects splitting CO to C + O)

**Diagram:**
- Wild2 refractory oxide and silicate grains
- Terrestrial Fractionation line
- CAI mixing line
- O$^{17,18}$ rich
- O$^{17,18}$ poor by ~ 4%
- Sun & CAIs

**Sources:**
- T25 "Inti"
- T22 olivine
- T69 pyroxene

McKeegan et al
Oxygen in the early solar system gas was in H$_2$O & CO

H$_2$O was very active - forming rocks and ice but CO was relatively inert (half of O was in CO). Ultraviolet (UV) light from the Sun could split CO freeing up oxygen to enter rocks and ices.

**shelf shielding effect**

UV to split CO with the abundant isotope ($^{16}$O) is adsorbed before reaching the red line.

UV to split CO with the rare isotopes ($^{17}$O & $^{18}$O) reaches greater distances.

Solar oxygen comp  $\rightarrow$  Excess $^{17}$O and $^{18}$O  $\rightarrow$
Asteroids

Small solar system bodies that are not classified as either:

- planets
- comets
- or moons

*The largest asteroid is Ceres ~1000 km diameter*
Hilda’s in stable 3:2 resonance with Jupiter (orbital period 2/3 Jupiter)
Surface temperatures of airless bodies in sunlight

\[ A = \text{albedo} \text{ the fraction of light reflected} \]
\[ [\text{zero (dark) to 1 (bright)}] \]

\[
\text{Power in} \quad \frac{L \odot}{4\pi r^2} \pi s^2 (1 - A) = (4\pi s^2) (\sigma T^4) \]

This is only the case for a constant temperature body. Most have day/night variations & pole/equator variations.

A very crude estimate of
The “black body” temperature \[ T \sim \frac{300}{\sqrt{r}} \text{ K, } r \text{ in } \text{AU} \]
Albedo

(fraction of light reflected)

Insight into material properties

Needed to estimate size from observed brightness

Observed Brightness $\propto$ area $\times$ albedo

Measure- optical & thermal IR brightness

$$\frac{\text{visual flux}}{\text{IR flux}} = \frac{A}{1 - A}$$
Inner asteroids ≠ outer asteroids
Monolithic Fast Rotating Asteroids (MFRAs)

What populates the transition region?

$(G\rho_{\text{rock}})^{-1/2}$

Rubble pile spin limit

No slow little guys?

Diameter $= 150$ m

$\nu_0^c (\text{cm/s})$

Diameter (km)

Spin Rate $(1/d)$

$P(h)$

Pravec et al. (2006)
Rotation Period vs. Diameter, 2010, 3643 Asteroids

Record 15 seconds!
Spin-up due to the YORP effect related to the Yarkovsky effect

Sunlight

Asteroid