Review

- How do you carry out spectroscopic study of extra-solar planets? What do we learn?
- What makes a “terrestrial” planet?
  - Rocky, small
  - Importance of plate tectonics and geological activity
- Collisions
  - Kinetic energy of impactor, density of surface material → pressure of impact
  - Vaporization of rock → excavation of crater
  - Crater size ~ 10 times diameter of impactor (for Earth)
    - \( D = 1.8 \rho_m^{0.11} \rho_p^{-0.32} g_p^{-0.22}(2R)^{0.13} E_k^{0.22}(\sin \Theta)^{1/3} \)
  - What is the importance of crater density?
Probing Planetary Interiors

- Mean density/surface density
- Moment of inertia \( I = kMR^2 \)
  - Hollow sphere, \( k = 0.67 \)
  - Sphere with a core, \( k = 0.35 \)
  - Homogeneous sphere, \( k = 0.4 \)
- Magnetic field \( \rightarrow \) how?
- Geological activity (e.g. seismic data)
- Mean crater density
- Physics of matter at various densities
  - How large/small can you make a gravitationally bound object out of H and He? Si? Fe?

Ways of studying planetary interiors

- In situ probes of interior
  - “Earth”quakes
  - Variation of sound speed in different media
- Remote probes of the interior
  - Geological activity \( \rightarrow \) indicates molten interior
  - Past geological activity/crater density \( \rightarrow \) indicates previously molten interior
  - Global magnetic field \( \rightarrow \) dynamo
  - Gravity
  - Moment of inertia \( I = kMR^2 \), where \( 0 < k < 1 \)
    - \( L = I \times \omega \) (angular momentum) \( \rightarrow \) this is observable
    - \( I = \iiint \rho(r) d_r \; dr \; (d_r = \text{distance from axis in question}) \)
    - So angular mo reflects the distribution of mass within the planet \( \rightarrow \) requires accurate measurements of \( L \)
Distribution of Elements in Earth

- **Starting assumption → accretion (of what?)**
  - Net loss of volatiles
  - Chemical differentiation (but can you estimate the degree to which the Earth was molten enough to allow for differentiation?)

- **Current best guess**
  - Inner core – largely Fe
  - Outer core – lower density, maybe some K?
  - Mantle – partially molten, chemically inhomogeneous

Mantle Geochemistry

- **What’s a “basalt”**?
  - One flavor of igneous rock

- **Mid-Ocean Ridge Basalt (MORB)**
  - Depleted in “incompatibles”
  - Differentiated → primitive?

- **Ocean Island Basalt (OIB)**
  - Less depleted/not primitive
  - Originates deeper in mantle → recycled crust?
Heat Sources

- Accretion $\rightarrow$ kinetic energy of impacts $\rightarrow$ melting
  - $v_{\text{collision}} \sim v_{\text{escape}} \rightarrow E_{\text{accretion}} \sim GM/R$
  - Per mass $\rightarrow E/m = (GM/r^2)dr = -GM/R_s$
  - Heating via conductivity $= \rho c_p \Delta T$, but some gets radiated away
  - $\rho \Delta T c_p = [(GM/R) - \sigma (T^4(r) - T_o^4)]$

- Differentiation $\rightarrow$ just gravity
- Radioactivity $\rightarrow$ very important

Sources of Heating

- Accretion – kinetic energy of impacts $\rightarrow$ melting
- Differentiation – release of gravitational thermal heat
- Radioactivity (particularly K, Ur, Th)
Radioactivity

- Key elements: K, Ur, Th
  - $^{238}\text{U} \rightarrow ^{206}\text{Pb} + 8\text{He} + 6\beta$ (4.5 Gyr, $\sim 3$ J g$^{-1}$ yr$^{-1}$)
  - $^{235}\text{U} \rightarrow ^{207}\text{Pb} + 7\text{He} + 7\beta$ (0.7 Gyr, $\sim 19$ J g$^{-1}$ yr$^{-1}$)
  - $^{237}\text{Th}, ^{40}\text{K}$ both yield $\sim 0.9$ J g$^{-1}$ yr$^{-1}$

- Lifetime is limited
  - $-(dP/dt) = (dD/dt)\lambda P \rightarrow -\ln(P) = \lambda t + \text{constant}$
  - $\ln(P) - \ln(P_0) = \lambda \rightarrow t = (1/\lambda)\ln((D-D_0)/P + 1)$
  - For Earth radioactive heating was $\sim 10$ times more important right after formation than it is now

Distribution of Elements

- Starting assumption $\rightarrow$ formation by accretion
  - Net loss of volatiles
- Differentiation
  - Chemical $\rightarrow$ siderophiles vs lithophiles
  - Physical $\rightarrow$ denser material sinks
- Inner core density $\rightarrow$ solid Fe
- Outer core density $\rightarrow$ lower density, liquid, Fe plus something else (K?)
- Mantle $\rightarrow$ partially molten, chemical inhomogeneous
  - Mid-ocean ridge basalt (MORB) $\rightarrow$ differentiation, more pristine?
  - Ocean Island Basalt (OIB) $\rightarrow$ less depleted, not primitive?
Chemical Heterogeneity

- Implies differentiation
  - Accretion heats, Fe sinks
  - Differentiation (20-30 Myr post formation)
  - Density isn’t only parameter → chemically, which elements stick to which other elements?

- Guiding question → what do elemental ratios tell us about the history of the accretion/differentiation process?

- Relative (not absolute) abundances are key

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Case Study: Mercury

- Hey! There’s a magnetic field!!!!
  - Mariner 10 flybys detected field – but it’s weak (a factor of 10000 too weak for a normal dynamo)

- One solution – convective circulation in the mantle

- Another solution – its all residual
The interesting part is: how do you build a model of the interior of a terrestrial planet?

- Heat transport – convection and conduction
  - Do it in 1-dimension with shell overlaying core
- Inner core growth/cooling
  - Growth \( \rightarrow \) release of gravitational heat
- Composition
  - Radioactive heating, chemical differentiation
- Response of lithosphere
Mercury

In the end you get …..

Mercury – tectonic history: shrinkage?

![Graphs and images related to Mercury's tectonic history and shrinkage.](image-url)
What is an atmosphere?
- Gravitationally bound
- Exist as gases above planetary surface (volatile at local temperatures)
  - Treat as an ideal gas ($E = 3/2nkT$ – per particle)
  - Kinetic energy $\rightarrow E = 1/2mv^2$
  - Maxwellian velocity distribution
    \[ f(v)dv = n\left(\frac{2}{\pi m}\right)^{1/2}(m/kT)^{3/2}e^{-mv^2/2kT}dv \]
    - Mean velocity $\rightarrow v_{\text{mean}} = (2kT/m)^{1/2}$
- Physics dominated by collisions
  - Moon, Mercury $\rightarrow$ “collisionless”, transient

Terrestrial Atmospheres
- Composition
- Structure
- Energy Balance
- Atmospheric Circulation
  - Formation and evolution of clouds
  - Effect on thermal properties
- Origin and Evolution
Structure of Atmospheres

- \( P = R \rho T / \mu \)
- So balancing gravity with pressure: \( dP(z)/P(z) = \mu g dz / RT(z) \)
- Pressure falls off exponentially: \( P(z) = P(0) \exp[(z-z_0)/H] \)
- \( H = \text{scale height} = RT / \rho g \)
- \( dT/dz = -g/C_p \) (thermal heat capacity at constant pressure)

Composition of Terrestrial Atmospheres

- **Venus**
  - CO\(_2\) \(\rightarrow\) 86.4 bar, 95%
  - N\(_2\) \(\rightarrow\) 3.2 bar, 3.5%
  - Ar \(\rightarrow\) 0.0063 bar, 0.007%
  - H\(_2\)O \(\rightarrow\) 0.009 bar, 0.01%

- **Earth**
  - CO\(_2\) \(\rightarrow\) 0.000355 bar, 0.035%
  - N\(_2\) \(\rightarrow\) 0.78 bar, 77%
  - Ar \(\rightarrow\) 0.0094 bar, 0.94%
  - H\(_2\)O \(\rightarrow\) 0.01 bar, 1%
  - O\(_2\) \(\rightarrow\) 0.21 bar, 21%

- **Mars**
  - CO\(_2\) \(\rightarrow\) 0.0062 bar, 95%
  - N\(_2\) \(\rightarrow\) 0.00018 bar, 2.7%
  - Ar \(\rightarrow\) 0.0001 bar, 1.6%
  - H\(_2\)O \(\rightarrow\) <0.00001 bar, 0.006%

Note differences in total pressure…

What about the rocks? Instant Venus?
### Fate of Solar Radiation (Earth)

- 22% absorbed in atmosphere
- 24% absorbed by ground
- 47% scattered by clouds
  - 26% reflected back into space
  - 21% scattered to ground
- 7% reflected back into space by ground
- Total → 45% gets to ground → total albedo ~ 33%
- Venus → 2.5% gets to ground

### Basic Structure

- **Troposphere**
  - Closest to ground, highest density
  - T decreases with increasing altitude
- **Stratosphere**
  - Up to ~50 km
  - Constant T on Earth, Mars, decreasing with altitude on Venus
- **Mesosphere**
  - 50 km < H < 100 km
  - Constant T on Earth, Mars, decrease flattens out on Venus
- **Thermosphere**
  - Diurnal variations
  - T dramatically increases with altitude on Earth
  - exosphere
Saturates

- Gases reach maximum concentration of vapor that the atmosphere can hold and then they condense
- Result = clouds → affect energy balance via reflection of incoming radiation
  - H₂O on Earth
  - H₂O, CO₂ on Mars → condensation then sublimation when it warms up
  - H₂SO₄ on Venus

Atmospheric Circulation → driven by temperature gradients...

- Vertical circulation → convection
  - Packet of gas rises, pressure is less, packet expands and cools, or packet is compressed, sinks, and warms
  - Redistribute energy vertically through atmosphere
  - Surface heating via solar radiation → more thermal mixing
- Isothermal approximation → apply to one layer at a time?
  - “scale height” → height over which pressure/density decreases by e.
- Variation with latitude – equatorial regions warmer than the poles → warm air moves towards poles
  - Mixing over latitudes in largescale cells → Hadley cells.
  - Combine with rotation → trade winds, etc
Mercury & The Moon

- H $\rightarrow$ 200 cm$^{-3}$
- He $\rightarrow$ 6000 cm$^{-3}$
- O $\rightarrow$ <40,000 cm$^{-3}$
- Na $\rightarrow$ 20,000 cm$^{-3}$
- K $\rightarrow$ 500 cm$^{-3}$
- Ar $\rightarrow$ $10^7$ cm$^{-3}$
- H $\rightarrow$ <17 cm$^{-3}$
- He $\rightarrow$ 2000-4000 cm$^{-3}$
- O $\rightarrow$ <500 cm$^{-3}$
- Na $\rightarrow$ 70 cm$^{-3}$
- K $\rightarrow$ 16 cm$^{-3}$
- Ar $\rightarrow$ 40000 cm$^{-3}$

Transient, easily ionized via solar radiation; lifetimes of hours/days
Originate in impacts, solar wind
Re-freeze on surface or escape

Origin of Terrestrial Atmospheres

- Hydrated minerals in "planetesimals"
  - Asteroids $\rightarrow$ up to 20% by mass of H$_2$O
  - N$_2$ also found in asteroids
- comets
- Atmosphere by accretion
  - Accretion $\rightarrow$ heating/releasing gas $\rightarrow$ thick primordial atmosphere
    - Initial outgassing
    - Continued outgassing via differentiation
    - Ongoing volcanism/tectonics
  - Condensation only after end of accretion
- Geochemistry – $^{40}$Ar/$^{36}$Ar ratio
  - $^{40}$Ar product of radioactive decay of $^{40}$K
  - $^{36}$Ar "primordial"
Evolution of Terrestrial Atmospheres

- CO₂ feedback → removed from atmosphere → deposited onto ocean floor as carbonates → eventually recycled via subduction/volcanism
- Life → O₂ production
- Runaway greenhouse (Venus) → increase temp, increase H₂O evaporation, increase atmospheric density, increase temp → H₂O dissociates, H escapes, total net loss of water from Venus
- Mars → loss of atmosphere, big cooldown
  - Impact ejects atmosphere
  - Solar wind stripping (particularly of ionized particles)
  - Is it all in the rocks?

Basic Observations
- Earth's atmosphere isn't primordial
- Terrestrial planets are missing H compounds

Lack of volatiles
- Volatiles = H,He,Ar,Kr,Xe,N,F,Cl
  - H,He should be able to escape
  - What about the rest?

Sources for atmospheres
- Volcanism – produces lots of CO₂ on Earth
CO₂

- Earth – most of it resides in rocks in the form of CaCO₃ – depleted from atmosphere via rain
- Venus
  - Without H₂O there is no mechanism to remove CO₂ from atmosphere → CO₂ is mostly in the atmosphere
  - Lack of H₂O → increase viscosity of mantle → no convection → no tectonics → rigid “lid”
- Mars
  - No means of releasing CO₂ from rocks