Terrestrial Planets

- Mercury
- Venus
- Mars
- (and Earth and the Moon, of course!)
Mercury
Orbit and Rotation

• Highly eccentric orbit:
  \[ e = 0.2056, \ a = 0.3871 \ \text{AU}, \ i = 7^\circ \]
  from \[ P^2 = 4 \pi^2 \ a^3/GM, \ \ P = 87.96 \ \text{days} \]

• Rotation period: 58.65 days
  – Mercury rotates 3 times for every 2 orbits
    • 3:2 resonance
  – How long is a solar day on Mercury?
    \[ 1/S = 1/P - 1/T \]
    where \[ T = \text{orbital period} \]
    \[ P = \text{sidereal rotation period} \]
    \[ S = \text{synodic period (solar day, here)} \]
    \[ S = 176 \ \text{days} = 2 \times \text{sidereal year!} \]
Physical Properties

• Physical Properties:
  \[ R \sim 2440 \text{ km} \]
  \[ M = 3.3 \times 10^{23} \text{ kg} \]
  \[ \Rightarrow <\rho> = 5420 \text{ kg/m}^3 \]
  \[ \Rightarrow \text{Mercury contains a lot of metals} \]

• Interior: Rocky mantle, large metallic core
  \[ R_{\text{core}} \sim \frac{3}{4} R_{\text{merc}} \]

• Surface albedo \( \sim 0.056 \Rightarrow \text{Rocky surface} \)

• \( T \sim 700 \text{ K at perihelion} \)
  \[ \Rightarrow \text{From } T_{\text{SS}} = 394(1 - A)^{\frac{1}{4}} D^{-0.5} \]
  \[ \Rightarrow \text{Dark side is } \sim 125 \text{ K } \Rightarrow \text{large temperature variations.} \]
Atmosphere

• High T and low $v_{\text{esc}} \rightarrow$ little atmosphere:
  For He: $v_{\text{rms}} = (3 \, \text{kT/m})^{\frac{1}{2}}$
  \[= \left[\frac{(3 \times 1.34 \times 10^{-23} \times 700)}{(4 \times 1.67 \times 10^{-27})}\right]^{\frac{1}{2}}\]
  \[= 2.1 \, \text{km/s}\]
  $v_{\text{esc}} = 4.2 \, \text{km/s}$
  $v_{\text{esc}}/v_{\text{rms}} \sim 2 \rightarrow$ few days!!

• Some He, Na, and O exist, but probably a result of outgassing (blasted from the rocky surface by solar wind).
Surface Features

• Very similar to the Moon
  – Fewer midsized craters
  – No mountain ranges
  – Shallow cliffs (scarps)
  – Fewer basins
  – More uncratered plains amid heavily cratered regions
  – More big craters \(\rightarrow\) different range of sizes of impactors

  – Long scarps indicate Mercury’s radius shrunk by 1-3 km (cooling of core or crust?) : Thrust faults.
Magnetic Field

• Weak: \( \vec{B} = 3 \times 10^{-7} \, \text{T} \)
  – Dipole, roughly aligned with rotation axis
  – Low rotation speed and solid metallic core
  \( \rightarrow \) expect little to no \( \vec{B} \)
Mercury History

- 4.6 billion years ago: formation.
- Cratering $\rightarrow$ stripping off mantle, leaving metallic core?
- Volcanism and shrinkage of crust/interior
- Lava flows $\rightarrow$ smooth broad plains
- Continued impacts
Venus
Orbit and Rotation

• Nearly circular orbit:
  \[ e = 0.0068, \ a = 0.7233 \ \text{AU}, \ i = 3.39^\circ \]
  from \[ P^2 = 4 \pi^2 \ a^3/GM, \ P = 224.7 \ \text{days} \]

• Rotation period: 243.01 days
  – Retrograde
Physical Properties

• Physical Properties:
  \[ R \sim 6052 \text{ km} \]
  \[ M = 4.86 \times 10^{24} \text{ kg} \]
  \[ \rightarrow <\rho> = 5200 \text{ kg/m}^3 \]
  \[ \rightarrow \text{very similar to Earth’s (our “sister” planet)} \]

• Interior: Rocky crust, a mantle, a metallic core
  – \( R_{\text{core}} \) is probably smaller than Earth’s since \(<\rho>\) is less
  – \( R_{\text{core}} \sim 0.4 \, R_{\text{Venus}} \)

• Surface: High albedo \((A = 0.76)\) because of clouds.
Atmosphere

• 96% CO$_2$, 3% N$_2$, trace other stuff
• $P_{\text{surface}} \sim 95$ atm
• $T_{\text{surface}} \sim 740$ K
  – Why? $T_{SS} = 394(1 - A)^{1/4} / D^2 \rightarrow$ predict $T \sim 320$ K
  – However, Green house effect:
    • Trapping of surface heat because CO$_2$ absorbs infrared radiation well.
      – Light passes through atmosphere, heating surface
      – Surface radiates as a blackbody at $\sim 300$ K $\rightarrow$ peak radiation in IR
      – CO$_2$ in atmosphere absorbs radiation, trapping the heat
      – Surface temperature rises.
    • Circulation of atmosphere spreads energy efficiently around planet
      – Similar temperature everywhere
Green House Effect

1. Sunlight arrives at the Earth
2. 39% of sunlight is reflected by clouds and the surface
3. Sunlight that is not reflected is absorbed by surface, heating it
4. Heated surface emits infrared radiation
5. Some of infrared radiation is trapped by atmosphere, heating both atmosphere and surface
6. Remaining infrared radiation “leaks” into space

Surface at 300 K

\[ \lambda_{\text{max}} \approx 10 \, \mu\text{m} \]
Green House Effect cont.

• Why is the Green house effect so strong on Venus?

On Earth, water condensed into oceans, and most of the CO$_2$ and SO$_2$ dissolved. Remaining CO$_2$ combined with surface rocks. Therefore, not much remained to create a green house (until today).

Venus is much closer to the Sun, so possibly water never condensed. Results in run away green house effect (possibly).
Cloud layers

- Visual brightness of Venus is from high albedo (0.76) of clouds and thick atmosphere

Upper cloud layer: 60 km up droplets of size 1 µm composition: H$_2$SO$_4$, H$_2$O

Lower cloud layer: 45 km up droplets of size 10 - 20 µm composition: H$_2$SO$_4$, H$_2$O, and solid grains

Winds blow from day side to night side, and from equator to polar regions.
Surface Features

- Radar mapping (peering through the clouds)
  - High plateaus, volcanos, impact craters, and plains
  - Elevation differences are small, ~ 2-3 km, except for 3 highland regions (~ 12 km)
  - Most of the surface is flat, volcanic plains punctuated by impact craters
    - Large craters only, because small meteorites burn up in atmosphere
  - Shield volcanoes: gentle slopes, often with collapsed central crater
    - Similar to Mauna Kea and Mauna Loa on Earth
  - 75% of the surface is volcanic
    → young (only 400-500 million years old)
Global view
Topographic Map
Young Lava Flows
Sif Mons
Pancake Domes
Magellan Images

• Which surface is oldest/youngest?
  – How can you tell?

• What are the “obvious” features?

• What mechanisms formed surface features?

  Mountains: Lava build up, crustal thrusts

  Craters: Impacts, volcanoes

  Domes: Thick lava flows
Magnetic Field

• None detected: $\vec{B} < 0.5 \times 10^{-8}$ T
  – Slow rotation rate suggests it would be less than Earth’s, but not expected to be zero.
  – Why? Possibly in the middle of field reversal?
Venus History

• 4.6 billion years ago: formation.
  – accretion
  – differentiation → radioactive and impact heating
  – crust formed and solidified

• 3-4 billion years ago: large masses bombarded surface and fractured crust
  – volcanoes erupted

• 3 billion years ago to present: huge volcanoes vent through cracks in surface.
  – Lava flows have reworked surface within last 400 million years.
Mars • 2001 Opposition

NASA and The Hubble Heritage Team (STScI/AURA)
Hubble Space Telescope WFPC2 • STS01-PRC01-24
Orbit and Rotation

• Moderately circular orbit:
  \[ e = 0.0934, \quad a = 1.5237 \text{ AU}, \quad i = 1.85^\circ \]
  from \[ P^2 = \frac{4 \pi^2 a^3}{GM} \], \quad P = 686.98 \text{ days} \]
  Earth-Mars distance only \( \sim 10^8 \text{ km} \) at opposition
  \( \rightarrow 14'' \) angular diameter

• Rotation period: 24h 37m 22.6s
  – Rotation axis inclined 25\(^\circ\) 12’ to orbital plane
Physical Properties

• Physical Properties:
  \[ R \sim 3394 \text{ km} \]
  \[ M = 6.4 \times 10^{23} \text{ kg} \]
  \[ \rightarrow \langle \rho \rangle = 3900 \text{ kg/m}^3 \]
  \[ \rightarrow \text{low density, so interior is different than Earth’s} \]

• Interior: Rocky crust, a mantle, a metallic core
  – \( R_{\text{core}} \) is probably smaller than Earth’s
  – Core is probably a mixture of iron and iron sulfide
Atmosphere

- 95% CO$_2$, 2-3% N$_2$, 1-2% Ar, 0.1-0.4% O$_2$
- $P_{\text{surface}} \sim 0.02$ atm
- $T_{\text{surface}} \sim 280$ K
- Composition similar to Venus, but low density limits Greenhouse effect.
Surface Features

• ~ 70% of surface is light orange and yellow-brown regions
  – composed of: 19% Ferric oxide (Fe₂O₃), 44% Silicate

• Rusty sand blown by fierce winds to create planet-wide dust storms.
  – Sand blast surface and mix → composition uniform over surface

• Liquid water does not exist on surface (too low pressure)

• Water-ice is present on surface and clouds; possibly permanent frost below surface
History

• Schiaparelli (1877) saw long, dark, almost straight features on the surface, which he named *canali* (channels, in Italian)
  – poor English translation resulted in “canals”

• Percival Lowell (1855-1915) founded an observatory in Flagstaff, AZ
  – Mapped over 500 canals
  – Argued that they were artificial waterways to carry water from polar caps to arid regions.
  – Wind blown dust may have created the temporary features that Lowell saw.
Details

- Northern polar cap does contain mostly water ice. The outer regions are CO$_2$ ice.
- Southern cap is almost exclusively CO$_2$ ice.
- Southern hemisphere is relatively flat, older, and heavily cratered
  - Craters are shallower than those on the Moon because of wind erosion and greater surface gravity.
- Northern hemisphere is younger, has extensive lava flows, collapsed depressions, and huge volcanoes
- Equator is dominated by Valles Marineris
  - Chasm 5000 km long (as big as U.S.!) and 500 km wide
- In general, surface is bleak, dry, and has large rock boulders
  - Basaltic rocks, with evidence of outgassing
  - Evidence for water on the surface is controversial
- Shield volcanoes
  - Olympus Mons, 550-600 km across at base; peak at 27 km above plain
    - Cone’s surface shows waxy structure $\rightarrow$ lava flow
    - Huge size implies a thick crust
Topography
Valles Marineris

Volcanoes on Tharsis rise

Valles Marineris
Olympus Mons
“Face” on Mars
Crater on Elysium Planitia
The “Happy Face” Crater
Twin Peaks
Dust Devils
Nanedi Vallis
Newton Crater
Magnetic Field

• Very weak: $\vec{B} = 6 \times 10^{-8} \text{T}$
  – But Mars rotates as fast as earth!?
    • Dynamo theory predicts modest B field.
  – Why so low? Possibly in the middle of field reversal?
    • Argument against: unlikely that both Mars and Venus are reversing fields now.
Mars History

• 4.6 billion years ago: formation.
  – accretion
  – differentiation $\rightarrow$ radioactive and impact heating
  – Thick crust to high elevations
• Thin regions of crust fractured
  – Tharsis ridge uplifted
  – Atmosphere: $\text{H}_2\text{O}$ vapor from outgassing decreases temperature and forces ice formation at shallow depths
  – Heating and cooling of $\text{H}_2\text{O}$ creates collapse and flow features
• Extensive volcanic activity
  – Valles Marineris forms
• Recent volcanism broke surface and spewed out great lava flows
• Wind erosion and impact craters
Mars’ Moons

- **Phobos and Deimos**
  - Close to Mars, orbit rapidly
    - Deimos: $P = 30.3$ hours
    - Phobos: $P = 7.67$ hours
      - Faster than Mars rotates $\rightarrow$ rises in West and sets East!
  - Both are tidally locked
    - Same side always faces Mars
  - Ellipsoidal shapes (and minature!)
    - Deimos: $15 \times 12 \times 11$ km
    - Phobos: $27 \times 21 \times 19$ km
  - Albedos are low
    - Deimos: 0.022
    - Phobos: 0.018
      - similar to carbonaceous chondrite meteorite and asteroids

- Possible origin: captured from Asteroid belt?
Table 7-1: Characteristics of the Planets

<table>
<thead>
<tr>
<th></th>
<th>Mercury</th>
<th>Venus</th>
<th>Earth</th>
<th>Mars</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average distance from Sun (10^6 km)</td>
<td>57.91</td>
<td>108.2</td>
<td>149.60</td>
<td>227.93</td>
</tr>
<tr>
<td>Average distance from Sun (AU)</td>
<td>0.3871</td>
<td>0.7233</td>
<td>1.0000</td>
<td>1.5236</td>
</tr>
<tr>
<td>Orbital period (years)</td>
<td>0.2408</td>
<td>0.6152</td>
<td>1.0000</td>
<td>1.8808</td>
</tr>
<tr>
<td>Orbital eccentricity</td>
<td>0.206</td>
<td>0.007</td>
<td>0.017</td>
<td>0.093</td>
</tr>
<tr>
<td>Inclination of orbit to the ecliptic</td>
<td>7.00°</td>
<td>3.39°</td>
<td>0.00°</td>
<td>1.85°</td>
</tr>
<tr>
<td>Equatorial diameter (km)</td>
<td>4880</td>
<td>12,104</td>
<td>12,756</td>
<td>6794</td>
</tr>
<tr>
<td>Equatorial diameter (Earth = 1)</td>
<td>0.383</td>
<td>0.949</td>
<td>1.000</td>
<td>0.533</td>
</tr>
<tr>
<td>Mass (kg)</td>
<td>$3.302 \times 10^{23}$</td>
<td>$4.868 \times 10^{24}$</td>
<td>$5.974 \times 10^{24}$</td>
<td>$6.418 \times 10^{23}$</td>
</tr>
<tr>
<td>Mass (Earth = 1)</td>
<td>0.0553</td>
<td>0.8150</td>
<td>1.0000</td>
<td>0.1074</td>
</tr>
<tr>
<td>Average density (kg/m^3)</td>
<td>5430</td>
<td>5243</td>
<td>5515</td>
<td>3934</td>
</tr>
</tbody>
</table>

Distances from the Sun:
- Sun: 0 AU
- Mercury: 0.3871 AU
- Venus: 0.7233 AU
- Earth: 1.0000 AU
- Mars: 1.5236 AU
Summary of Evolution (Terrestrial Planets)

1) Formation, heating of crust and interior
2) Crust solidification, intense cratering
3) Basin formation and flooding
4) Low intensity cratering; atmosphere by outgassing
5) Volcanoes, continents, crustal movement.

Mercury and Moon only to phase (3)
Mars – beginning of phase (5)
Venus – middle of phase (5)
Earth – far into phase (5)

• Internal heat drives evolutionary processes
  – Generated by radioactive decay
• Spectrum of crater sizes and surface densities can be used to estimate degree of surface evolution.