Chapter Eleven

Mercury, Venus and Mars
Introduction To Modern Astronomy I: Solar System

Introducing Astronomy (chap. 1-6)

Planets and Moons (chap. 7-15)

Ch7: Comparative Planetology I
Ch8: Comparative Planetology II
Ch9: The Living Earth
Ch10: Our Barren Moon

Ch11: Mercury, Venus and Mars

Ch12: Jupiter and Saturn
Ch13: Satellites of Jupiter & Saturn
Ch14: Uranus, Neptune and Beyond
Ch15: Vagabonds of Solar System

Sun and Life Highlights Chap. 16 & 28
**Mercury Data**

<table>
<thead>
<tr>
<th>Table 11-1</th>
<th>Mercury Data</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Average distance from Sun:</strong></td>
<td><strong>0.387 AU = 5.79 \times 10^7 km</strong></td>
</tr>
<tr>
<td><strong>Maximum distance from Sun:</strong></td>
<td><strong>0.467 AU = 6.98 \times 10^7 km</strong></td>
</tr>
<tr>
<td><strong>Minimum distance from Sun:</strong></td>
<td><strong>0.307 AU = 4.60 \times 10^7 km</strong></td>
</tr>
<tr>
<td><strong>Eccentricity of orbit:</strong></td>
<td><strong>0.206</strong></td>
</tr>
<tr>
<td><strong>Average orbital speed:</strong></td>
<td><strong>47.9 km/s</strong></td>
</tr>
<tr>
<td><strong>Orbital period:</strong></td>
<td><strong>87.969 days</strong></td>
</tr>
<tr>
<td><strong>Rotation period:</strong></td>
<td><strong>58.646 days</strong></td>
</tr>
<tr>
<td><strong>Inclination of equator to orbit:</strong></td>
<td><strong>0.5°</strong></td>
</tr>
<tr>
<td><strong>Inclination of orbit to ecliptic:</strong></td>
<td><strong>7° 00’ 16”</strong></td>
</tr>
<tr>
<td><strong>Diameter (equatorial):</strong></td>
<td><strong>4880 km = 0.383 Earth diameter</strong></td>
</tr>
<tr>
<td><strong>Mass:</strong></td>
<td><strong>3.302 \times 10^{23} \text{ kg} = 0.0553 \text{ Earth mass}</strong></td>
</tr>
<tr>
<td><strong>Average density:</strong></td>
<td><strong>5430 \text{ kg/m}^3</strong></td>
</tr>
<tr>
<td><strong>Escape speed:</strong></td>
<td><strong>4.3 \text{ km/s}</strong></td>
</tr>
<tr>
<td><strong>Surface gravity (Earth = 1):</strong></td>
<td><strong>0.38</strong></td>
</tr>
<tr>
<td><strong>Albedo:</strong></td>
<td><strong>0.12</strong></td>
</tr>
</tbody>
</table>
| **Average surface temperatures:** | **Day: 350°C = 662°F = 623 K**  
**Night: −170°C = −274°F = 103 K** |
| **Atmosphere:** | **Essentially none** |

- Moon-like
**Venus Data**

### Table 12-1: Venus Data

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average distance from Sun</td>
<td>0.723 AU = 1.082 \times 10^8 km</td>
</tr>
<tr>
<td>Maximum distance from Sun</td>
<td>0.728 AU = 1.089 \times 10^8 km</td>
</tr>
<tr>
<td>Minimum distance from Sun</td>
<td>0.718 AU = 1.075 \times 10^8 km</td>
</tr>
<tr>
<td>Eccentricity of orbit</td>
<td>0.0068</td>
</tr>
<tr>
<td>Average orbital speed</td>
<td>35.0 km/s</td>
</tr>
<tr>
<td>Orbital period</td>
<td>224.70 days</td>
</tr>
<tr>
<td>Rotation period</td>
<td>243.01 days (retrograde)</td>
</tr>
<tr>
<td>Inclination of equator to orbit</td>
<td>177.4°</td>
</tr>
<tr>
<td>Inclination of orbit to ecliptic</td>
<td>3.39°</td>
</tr>
<tr>
<td>Diameter (equatorial)</td>
<td>12,104 km = 0.949 Earth diameter</td>
</tr>
<tr>
<td>Mass</td>
<td>4.868 \times 10^{24} kg = 0.815 Earth mass</td>
</tr>
<tr>
<td>Average density</td>
<td>5243 kg/m³</td>
</tr>
<tr>
<td>Escape speed</td>
<td>10.4 km/s</td>
</tr>
<tr>
<td>Surface gravity (Earth = 1)</td>
<td>0.91</td>
</tr>
<tr>
<td>Albedo</td>
<td>0.59</td>
</tr>
<tr>
<td>Average surface temperature</td>
<td>460°C = 860°F = 733 K</td>
</tr>
<tr>
<td>Atmospheric composition (by number of molecules)</td>
<td>96.5% carbon dioxide (CO₂)</td>
</tr>
<tr>
<td></td>
<td>3.5% nitrogen (N₂), 0.003% water vapor (H₂O)</td>
</tr>
</tbody>
</table>
### Mars Data

<table>
<thead>
<tr>
<th>Category</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average distance from Sun</td>
<td>1.524 AU = 2.279 × 10^8 km</td>
</tr>
<tr>
<td>Maximum distance from Sun</td>
<td>1.666 AU = 2.492 × 10^8 km</td>
</tr>
<tr>
<td>Minimum distance from Sun</td>
<td>1.381 AU = 2.067 × 10^8 km</td>
</tr>
<tr>
<td>Eccentricity of orbit</td>
<td>0.093</td>
</tr>
<tr>
<td>Average orbital speed</td>
<td>24.1 km/s</td>
</tr>
<tr>
<td>Orbital period</td>
<td>686.98 days = 1.88 years</td>
</tr>
<tr>
<td>Rotation period</td>
<td>24[°] 37&quot; 22&quot;</td>
</tr>
<tr>
<td>Inclination of equator to orbit</td>
<td>25.19°</td>
</tr>
<tr>
<td>Inclination of orbit to ecliptic</td>
<td>1.85°</td>
</tr>
<tr>
<td>Diameter (equatorial)</td>
<td>6794 km = 0.533 Earth diameter</td>
</tr>
<tr>
<td>Mass</td>
<td>6.418 × 10^23 kg = 0.107 Earth mass</td>
</tr>
<tr>
<td>Average density</td>
<td>3934 kg/m³</td>
</tr>
<tr>
<td>Escape speed</td>
<td>5.0 km/s</td>
</tr>
<tr>
<td>Surface gravity (Earth = 1)</td>
<td>0.38</td>
</tr>
<tr>
<td>Albedo</td>
<td>0.15</td>
</tr>
<tr>
<td>Surface temperatures</td>
<td>Maximum: 20°C = 70°F = 293 K</td>
</tr>
<tr>
<td></td>
<td>Mean: −53°C = −63°F = 220 K</td>
</tr>
<tr>
<td></td>
<td>Minimum: −140°C = −220°F = 133 K</td>
</tr>
<tr>
<td>Atmospheric composition</td>
<td>95.3% carbon dioxide (CO₂)</td>
</tr>
<tr>
<td>(by number of molecules)</td>
<td>2.7% nitrogen (N₂)</td>
</tr>
<tr>
<td></td>
<td>0.03% water vapor (H₂O)</td>
</tr>
<tr>
<td></td>
<td>2% other gases</td>
</tr>
</tbody>
</table>

- Earth-like, similar in day and season
Viewing Mercury and Venus

- They are always close to the Sun in the sky
- Venus is brightest in the sky except Sun and Moon
- Mercury is also one of the brightest

Mercury: $a=0.38$ AU, $e=0.20$  
Venus: $a=0.72$ AU, $e=0.007$
Viewing Mercury and Venus

• Greatest eastern elongation & **Evening Star**
  – Planet appears after sunset, called “evening star”
• Greatest Western elongation & **Morning Star**
  – Planet appears before sunrise, called “Morning star”
• Venus: 47°, ~ 3 hr
• Mercury: 28°, ~ 2 hr
Viewing Mars

- Opposition: the best Earth-based view of Mars
- The Earth-Mars distance can be as small as 0.37 AU
- Opposition occurs every 25 months, the synodic period

Mars: \( a=1.52 \text{ AU}, \ e=0.093 \)
Rotation of Planets

• Why is difficult to observe rotation of Mercury and Venus?

- **Mars**
  - \( P \approx 1 \text{ day} \) (23 h 23 m)
  - \( P \) known in 1666
  - Tilt: 25°

- **Venus**
  - \( P = 243 \text{ days} \)
  - \( P \) not known till 1960!
  - Tilt: 177° (retrograde)

- **Mercury**
  - \( P = 59 \text{ days} \)
  - \( P \) not known till 1960!
  - Tilt: 0.5°

(c) Mars at opposition  
(b) Venus at inferior conjunction  
(a) Mercury at greatest elongation
Rotation of Mercury

- Rotation speed is measured using Doppler effect with Radar.
- Mercury has **3-to-2 spin-orbit coupling**, with rotation period of 58.6 days and orbital period 87.9 day.
- It is in contrast to the expected **synchronous rotation, or 1-to-1 spin-orbit coupling**, e.g., Moon, which is caused by tidal force.

Rotation of Mercury

• Explanation of Mercury’s 3-to-2 spin-orbit coupling
  – Because of its high **eccentric orbit** (e=0.20).
  – Tidal force tends to keep Mercury’s long axis point toward the Sun.
  – Because of the varying orbital speed, the pointing varies.
  – The favorable pointing occurs only at the perihelion.
  – In one orbital period, Mercury spins 1.5 times.

(b) If Mercury were in a circular orbit, its long axis would always point toward the Sun: Mercury would be in synchronous rotation (1-to-1 spin-orbit coupling).

(c) In fact Mercury is in an elliptical orbit, and its long axis only points toward the Sun at perihelion: Mercury spins on its axis 1 1/2 times during each complete orbit (3-to-2 spin-orbit coupling).
Rotation of Venus

- Rotation of Venus is peculiar
- Extremely slow: 243 days (longer than orbital period 224 days)
- **Retrograde rotation**: opposite of direction of orbital motion
  - All planets and satellites have **prograde** rotation except Venus, Uranus
  - No good explanation on the retrograde motion???
Can we construct a consistent picture on the properties of the surface, interior and atmosphere of a planet (or moon), simply based on the size of the object?

- Small object: no atmosphere, no internal heat, no geological activity, old surface, no global magnetic field, e.g., Moon
- Large object: thick atmosphere, internal heat, geological activity, young surface, global magnetic field, e.g., Earth

Mercury
- No atmosphere
- Surface is old, heavily cratered like the Moon
- No evidence of ongoing tectonics.
- These are consistent with its small size.
**Scarp**: long cliff on the surface

- As much as 3 km high and 20 to 500 km long
- Not produced by plate tectonics
- **Caused by the shrinkage of Mercury’s crust** as it cooled in the ancient time

1. The floors of these craters were flooded by lava from Mercury’s interior.
2. Some time after the lava cooled, Mercury’s crust contracted to form this scarp.
3. This crater was distorted when the scarp formed.

1103004.mov Movie: scarp formation
Mercury

- Interior of Mercury: crust, mantle and core, like Earth
- Mercury’s core is relatively large
  - The core is 75% of its diameter
  - The earth’s core is 55% of its diameter
  - the moon’s core is 20% of its diameter
To account for Mercury’s large core and high iron content, one theory proposes that a collision with a planet-sized object stripped Mercury of most of rocky mantle.

**Surprising:** Mercury has global magnetic field
- The old surface feature indicates no internal heat, thus not likely a liquid core
- It is an exception to the general rule
- No good explanation
Venus & Mars: Speculation

• Venus was thought to be a tropical paradise
  – Surface temperature 45° without greenhouse effect
  – Actual surface temperature 460° due to strong greenhouse effect of its thick atmosphere
  – Earth temperature is raised 33° due to greenhouse effect (from -19° to 14°)

• Mars was thought to have canals, plant life, even Martians

Schiparelli’s drawing of Martian canals (1877)

Lowell reported 160 canals by 1900

Scientists can be collectively wrong at one point of time
**Venus & Mars: Surface**

- Tectonics: a study of the crust
- **Earth**
  - *plate tectonics*: the crust is divided into several large pieces (~10); **young surface**
  - Due to moderate internal heat
- **Venus**
  - *Flake tectonics*: the crust breaks up into numerous flakes, producing small scale deformation and reshaping of the surface; **young surface**
  - Due to relatively strong internal heat
- **Mars**
  - Neither plate nor flake tectonics; thick & rigid crust; **old surface**
  - Due to relatively weak internal heat
Venus: Surface

- The size implies that Venus retains sufficient heat inside.
- Small number of craters indicates that Venusian surface is about 500 million year old, indicating geological activity.
- The surface of Venus is flat, only a few major highlands.
- No long chain of mountain, inconsistent with plate tectonics.
Venus: Surface

- Explanation: **flake tectonics**
- Convection currents in Venus’s interior are more rigorous than inside the Earth
- Strong convection prevents the formation of thick crust
- A thin crust undergoes wrinkling and flaking.
**Venus: Surface**

**Plate Tectonics** versus **Flare Tectonics**

1. Hot matter from the mantle rises,...
2. ...causing plates to form and diverge.
3. Where plates converge, a cooled plate is dragged under the neighboring plate,...
4. ...sinks, warms, and rises again.
5. On Venus, in contrast, convection currents are more vigorous. They prevent thick crust from forming, and push and stretch the thin crust that does form.
6. The surface crust breaks up into flakes or crumples like a rug.
7. As the mantle moves around, blobs of hot lava bubble up to form large landmasses, mountains, and volcanic deposits.
Mars: Surface

- Surface in the south is heavily cratered, indicating an old surface and no recent geological activities.
- Crustal dichotomy: Southern highlands (5 km higher) versus northern lowlands.
- Surface in the north is smooth and free of craters, indicating relatively young.
Mars: Surface

- Mars has no ongoing geological activity.
- However, Mars had ancient geological activity, e.g., huge volcano mountains and deep rift valleys.
Venus and Mars: Surface

- Volcanoes
  - Earth: mostly extinct, some remain active
  - Venus: probably like the Earth, only some active
  - Mars: no active volcanoes, all extinct
Venus and Mars: Atmosphere

The Question:

Why do Earth, Venus and Mars have dramatically different atmosphere? Even though the original atmospheres of the three planets were essentially the same, predominantly water vapor and carbon dioxide.
Venus and Mars: Atmosphere

**Earth**
- Pressure: 1 ATM (atmosphere)
- Temperature: 14°C
- Cloud: H₂O

**Venus**
- Pressure: 90 ATM, High
- Temperature: 460°C
- Cloud: H₂SO₄

**Mars**
- Pressure: 0.006 ATM, Low
- Temperature: -23°C
- Cloud: CO₂ & H₂O
Venus: Atmosphere

- **Venus is the hottest planet**, with a surface temperature of 460°C
- The high temperature is caused by extremely **strong greenhouse effect**, thanks to the presence of a large amount of CO₂, which raises the surface temperature by more than 400°C
- Composition:
  - Mostly carbon dioxide: 96.5%
  - Remaining is Nitrogen: 3.5%
  - Similar to Mars
- **Venus has perpetual thick clouds**
  - The clouds have three layers from 48 km to 68 km
  - **Clouds mainly consist of droplets of concentrated sulfuric acid** (H₂SO₄: highly corrosive).
Mars: Atmosphere

• Mars is cold, average temperature -23°C
• Its atmosphere extremely thin, 0.006 ATM
• Greenhouse effect is very weak, due to the thin atmosphere, raising temperature by only 5°C (Earth 33°C, Venus 400°C).
• Composition:
  – Mostly carbon dioxide: 95.3%
  – Remaining is Nitrogen: 2.7%
  – Similar to Venus
Mars: Atmosphere

- Seasonal changes
- In the winter, the ice cap at polar regions grow, due to freezing-out of atmospheric carbon dioxide (forming dry ice).
- In the summer, it evaporates and the cap shrinks.
Mars: Atmosphere

- Global dust storm: triggered by the flow of carbon dioxide evaporating from the polar ice cap with the coming of spring.
- Dust devil: each afternoon parcels of warm air rise from the heated surface and form whirlwinds.
Evolution of Atmosphere

• The origin of atmosphere
  – **Outgassing** of volcanoes: gases trapped in the rocks and but emitted through active volcanoes.
  – The early atmospheres should be similar in content: water vapor ($H_2O$), carbon dioxide ($CO_2$) and Sulfur dioxide ($SO_2$)
Evolution of Atmosphere

• Earth
  – Active plate tectonics “recycles” gases and maintain a moderate atmosphere

• Venus
  – No plate tectonics to “recycle” gas
  – Once released, remain in the atmosphere, giving a thick atmosphere
  – **Runaway greenhouse effect**

• Mars
  – No plate tectonics to “recycle” gas
  – Once removed and locked into rocks, remain in the rocks, giving a thin atmosphere
  – **Runaway icehouse effect**
Evolution of Atmosphere: Earth

- On Earth, H\textsubscript{2}O and CO\textsubscript{2} are recycled
- Ocean evaporates forming water vapor, which rains down returning to Ocean
- CO\textsubscript{2} dissolves in the water, falling into the ocean
- CO\textsubscript{2} and H\textsubscript{2}O are incorporated into sedimentary rocks
- most CO\textsubscript{2} is removed from the atmosphere, and locked into the Earth’s rocks.
- Released through outgassing
Evolution of Atmosphere: Venus

- **On Venus**, the atmosphere experienced a **runaway greenhouse effect**
- In the early history, it may also have liquid ocean as Earth
- Temperature was higher due to stronger radiation from the Sun, because closer to the Sun than the Earth
- The atmosphere had relatively more water vapor
- The greenhouse effect of the water vapor raised the temperature, and more liquid water evaporated
- This further intensified the greenhouse effect, and raised the temperature even higher
- This runaway process continued until oceans disappeared
- Almost all of the water vapor was eventually lost by the break-up of molecules due to ultraviolet radiation. Hydrogen escapes into space once it is isolated.
• Without ocean to dissolve in, the outgassed CO₂ would accumulate in the Venus’s atmosphere

• The Earth has roughly as much carbon dioxide as Venus, but it has been dissolved in the Earth’s oceans and chemically bound into its rocks

(b) Venus: H₂O, CO₂, and SO₂ are NOT recycled
Evolution of Atmosphere: Mars

- **On Mars**, the atmosphere experienced a *runaway icehouse effect*
- Mars originally had a similar thick atmosphere and a liquid water ocean as the early Earth
- Because Mars is small, it cooled early in its history and volcanic activity came to an end
- Any depletion of carbon dioxide due to rainwater was permanent, since no repletion from outgassing
- This weakened the greenhouse effect, and caused the temperature to drop
- A lower temperature caused more water vapor to condense to the surface, carrying carbon dioxide
- This further reduced the temperature, caused a *runaway icehouse effect*, opposite to the runaway greenhouse effect occurred on Venus
Evolution of Atmosphere: Mars

- The remaining water is frozen underneath the surface.
- Most CO$_2$ is locked in rocks; it is not recycled into the atmosphere.
- The resulted in a thin Martian atmosphere.
Mars Exploration

The questions?

Is there life on Mars?
Was there life on Mars?
Was primitive life ever formed on Mars in the ancient Martian oceans?

A good answer to these questions will help answer whether there are other lives in the universe.
Water on Mars

- No liquid water or rainfall on the planet’s surface today
- However, liquid water once flowed on Mars, as evident in many surface features
Water on Mars

- Frozen water is contained in polar caps
- Frozen water is stored in permafrost under the Martian surface
- There might be enough water to cover the planet to a depth of 500 meters

Water Measurement from Mars Odyssey Spacecraft
Exploration

- Many spacecraft have been sent to study the Mars, including both orbiting and landing spacecraft
- In 1970s, Viking 1 and Viking 2 Landers
- In 1997, Mars Pathfinder Lander called Sojourner
- In 2004, Mars Exploration Rovers: Spirit and Opportunity
- Human exploration on Mars is possible in near future
Final Notes on Chap. 11

- There are 9 sections in total.
- Section 1 to 8 are studied.
- Section 9 (satellites of Mars) is excluded.