Solar Heating
Solar Heating

TEMPERATURE

4 phases of substances (don’t forget pressure, too)

- **plasma** Sun, Jovian interiors
- **gas** weather, atmospheric chemistry
- **liquid** ocean currents, volcanism, tectonics
- **solid** orbiting bodies

Planetary atmospheric structures and motions
Planetary internal structures
Temperature gradients important in Solar System ... location

“temperature” is used to describe the random kinetic energy of molecules, atoms, ions, etc. for a perfect gas, the energy is:

\[ E = \frac{3}{2} N k T \]

N = number of particles/volume \hspace{1em} k = Boltzmann’s constant
Solar Radiation Effects

1. **Corpuscular Drag** --- sub-micron-sized particles fall into the Sun because they are hit by solar wind particles (i.e. electrons and protons)

2. **Radiation pressure** --- micron-sized dust particles pushed away from Sun

\[ F_{\text{rad}} \sim \frac{L_{\text{sun}} A_{\text{particle}} Q}{4\pi cr^2} \quad \text{and} \quad F_{\text{grav}} \sim \frac{GmM}{r^2} \]

\( Q \) = radiation pressure coeff

independent of distance from the Sun!

3. **Poynting-Robertson drag** --- centimeter-sized particles spiral inward toward the Sun due to absorption followed by isotopic radiation of a *moving* particle

4. **Yarkovski effect** --- meter to 10 kilometer-sized objects change orbits because of different temps on different parts (push direction depends on rotation)

5. **YORP effect** --- changes rotation rates of asteroids up to 20 km in size because of torques due to asymmetric heating of rotating, non-triaxial bodies, i.e. those that have shadowing … reflected and reradiated photons not uniformly distributed
Blackbody Equation

Planck radiation law (Planck Function)

\[
B_\nu(T) = \frac{2\pi^2 \nu^3}{c^2 \epsilon(\nu/kT)^2} \quad \text{for } kT \ll \nu
\]

\[
B_\nu(T) \sim \frac{2\pi \nu^2}{c^2} kT
\]

\text{brightness } B_\nu(T) \text{ has units of } \text{erg s}^{-1} \text{ cm}^{-2} \text{ Hz}^{-1} \text{ ster}^{-1}

Rayleigh-Jeans tail

\[
\nu \ll kT \quad B_\nu(T) \sim (2\nu^2/c^2) kT
\]

decreasing freq … shallow second power drop

Wien cliff

\[
\nu \gg kT \quad B_\nu(T) \sim (2\pi \nu^3/c^2) e^{-(\nu/kT)}
\]

increasing freq … steep exponential drop
Blackbodies
Using Blackbody Equation

Two important applications of the blackbody equation:

1. **Stefan-Boltzmann Law** --- flux (and luminosity)
   
   brightness multiplied by solid angle (gives erg s\(^{-1}\) cm\(^{-2}\) Hz\(^{-1}\))
   
   \[ B_v \Omega = F_v \quad \ldots \text{ flux density} \]
   
   integrate the flux density over all angles and all frequencies

   \begin{align*}
   \text{flux} & \quad F = \sigma T^4 \quad \text{(erg s}^{-1}\text{ cm}^{-2}) \\
   \text{luminosity} & \quad L = 4\pi R^2 \sigma T^4 \quad \text{(erg s}^{-1})
   \end{align*}

2. **Wein’s Law** --- peak wavelength of emission
   
   differentiate the blackbody equation with respect to \( \lambda \) …

   \[ \lambda_{\text{max (microns)}} = \frac{2900}{T_{(\text{Kelvin})}} \]
### Blackbodies --- SS Applications

<table>
<thead>
<tr>
<th>Object</th>
<th>Temp (K)</th>
<th>Flux (W/m²)</th>
<th>Radius (m)</th>
<th>L (W)</th>
<th>λ_{max} (microns)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sun</td>
<td>5800</td>
<td>6.4e7</td>
<td>7.0e8</td>
<td>3.9e26</td>
<td>0.5</td>
</tr>
<tr>
<td>Venus</td>
<td>733</td>
<td>1.6e4</td>
<td>6.1e6</td>
<td>7.7e18</td>
<td>4.0</td>
</tr>
<tr>
<td>Earth</td>
<td>288</td>
<td>3.9e2</td>
<td>6.4e6</td>
<td>2.0e17</td>
<td>10.1</td>
</tr>
<tr>
<td>Jupiter</td>
<td>124</td>
<td>1.3e1</td>
<td>7.1e7</td>
<td>8.5e17</td>
<td>23.4</td>
</tr>
<tr>
<td>Neptune</td>
<td>59</td>
<td>0.7</td>
<td>2.5e7</td>
<td>5.4e15</td>
<td>49.2</td>
</tr>
<tr>
<td>Pluto</td>
<td>45</td>
<td>0.2</td>
<td>1.1e6</td>
<td>3.5e12</td>
<td>64.4</td>
</tr>
</tbody>
</table>

We have ignored reflected light.
Blackbodies are a Big Fat Lie!
Non-Blackbody Features
Earth Radiation

trace gas < 3% variable
trace gas 400 ppm
21% and 10 ppm
trace gas 2 ppm
trace gas 0.4 ppm
Non-Blackbody Features: Reflection

remember, blackbodies are big fat lies

**monochromatic albedo** --- \([A_\lambda]\) ratio of emitted/incident energy at a specific wavelength (emitted = reflected + scattered)

**geometric albedo** --- \([A]\) ratio of emitted/incident energy if you are looking at the object head-on (zero phase angle for the Sun)

**Bond albedo** --- \([A_b]\) ratio of total emitted/total incident energy, integrated over all wavelengths

\[
\begin{align*}
\text{Bond} & \sim 0.1 & \text{Me/Ma/Moon} \\
\text{Bond} & \sim 0.3 & \text{E/J/S/U/N} \\
\text{Bond} & \sim 0.8 & \text{V}
\end{align*}
\]

reflectivity leads to implications for planet observability…
Star vs. Planet

The graph compares the spectral energy distribution of the Sun, Earth, Jupiter, and Uranus. There are two vertical arrows indicating the difference in the reflected and emitted radiation.

- The reflected radiation shows a difference of $10^8:1$.
- The emitted radiation shows a difference of $10^4:1$.
Astrometry Instead?

Sun as seen from 10 parsecs over 65 years

- Jupiter: 11.9 yrs, 0.52 milliarcsec
- Saturn: 29.4 yrs, 0.95 milliarcsec
- Uranus: 83.8 yrs, 1.91 milliarcsec
brightness temperature \( (T_b) \) --- temperature measured if you fit a small bit of spectrum with a flux for a blackbody curve that bit of spectrum

effective temperature \( (T_{\text{eff}}) \) --- temperature measured if you get the total flux from an object and you match that flux under the non-blackbody spectrum to a blackbody that has the same total flux under its curve

equilibrium temperature \( (T_{\text{eq}}) \) --- for planets, temperature measured if the emitted radiation depends only on the energy received from the Sun, assuming energy in = energy out

any discrepancies between the effective temperature and the equilibrium temperature contain valuable information about the object
Tweaks to Planet Temps

The Planet
solar irradiation is not uniform across planetary surface
albedo is not constant due to surface features
albedo is not constant due to clouds
reradiation will certainly be at different wavelengths than incident

The Dynamics
planet’s rotation is assumed to be fast
planet’s obliquity will change energy deposition/emission
planet’s orbital eccentricity will affect radiation input

The Sun
solar constant is not constant
### Planet Temperatures

<table>
<thead>
<tr>
<th>Planet</th>
<th>$T_{\text{equil}}$</th>
<th>$T_{\text{surf}}$ or $T_{\text{eff}}$</th>
<th>causes of differences</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mercury</td>
<td>446</td>
<td>100-700</td>
<td>slow spin: complete reradiation of heat</td>
</tr>
<tr>
<td>Venus</td>
<td>232</td>
<td>737</td>
<td>runaway greenhouse</td>
</tr>
<tr>
<td>Earth</td>
<td>255</td>
<td>288</td>
<td>moderate greenhouse</td>
</tr>
<tr>
<td>Mars</td>
<td>210</td>
<td>215</td>
<td>micro greenhouse</td>
</tr>
<tr>
<td>Jupiter</td>
<td>110</td>
<td>124</td>
<td>heat source: continuing settling</td>
</tr>
<tr>
<td>Saturn</td>
<td>81</td>
<td>95</td>
<td>heat source: helium rain</td>
</tr>
<tr>
<td>Uranus</td>
<td>58</td>
<td>59</td>
<td>no heat source: complete reradiation</td>
</tr>
<tr>
<td>Neptune</td>
<td>46</td>
<td>59</td>
<td>heat source: continuing settling (CH$_4$ blanketing?)</td>
</tr>
</tbody>
</table>

$T_{\text{equil}}$ and $T_{\text{surf}}$ or $T_{\text{eff}}$ refer to the equilibrium temperature and surface or effective temperature of the respective planets, respectively. Differences in these temperatures are caused by various factors, including slow spin, runaway greenhouse effect, moderate greenhouse effect, micro greenhouse effect, heat source due to continuing settling, heat source due to helium rain, and no heat source resulting in complete reradiation.
Research Paper Level 1
due Tuesday, February 12

outline of your research project (worth 10 points)
the more original, the better

print out and hand in (Latex format)
10 pieces required:

1. Abstract (bullets)
2. Introduction (why do we care?)
3. Motivation (why do YOU care?)
4. Sections listed (observations done/planned)
5. Discussion (bullets)
6. at least two Tables listed
7. at least two Figures listed
8/9/10. three REFEREED references
How does the Sun affect objects in the Solar System?

1. Sun heats the planets via radiation, e.g. ice line
2. radiation pressure pushes objects
3. sublimes cometary surfaces
4. tidal forces affecting liquids (in particular) on surfaces
5. powers human-made satellites, e.g. JWST
6. magnetically causes space weather and aurorae
7. orbiting particles lose angular momentum and drop toward Sun
8. particles in solar wind cause erosion on surfaces
9. photons cause chemistry yielding ozone on Earth
10. solar wind shapes magnetospheres on Earth, Jupiter, …

11.

12.

13.

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19.

20.
Solar System Explorers 2012-1

How does the Sun affect objects in the Solar System?

1. post-main sequence phase will cause objects to be lost from SS because of mass loss
2. temperature affects because of location, location, location … i.e. ices further out
3. solar wind causes aurorae on Earth and other planets
4. Sun’s heliosphere protects SS from cosmic ray particles
5. visible photon peak of Sun has affected human evolution and how we observe the Universe
6. keeps planets in orbits around it
7. solar wind from Sun shapes magnetic fields of planets
8. generates/squelches atmosphere of Pluto
9. sublimation of cometary surfaces and creates tails (also plasma tail)
10. drives weather systems on Earth, Hadley cells
11. permits photosynthesis on Earth (at least)
12. causes relativistic frame-dragging, of Mercury in particular
13. solar UV leads to photolysis in Jupiter’s upper cloud decks, creating color
14. changes climate because of Maunder Minimum
15. in red giant phase, Mercury and Venus are devoured
16. Venus’ greenhouse effect to 733K
17. solar wind particles degrade astronomical spacecraft
18. UV photons cause mutations that drive evolution
19. causes very hot and very cold temps on Mercury
20. slowly blinded Galileo, The Wrangler (but not Wilhelm Carl Werner Otto Fritz Franz Wein)
Solar System Explorers 07

Give any feature seen in the spectrum of a Solar System object (not the Sun) that makes that object’s emitted spectrum NOT a blackbody. Give the atomic/molecular species and wavelength affected, e.g. CO$_2$ as an absorber on Earth at 15 microns.

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