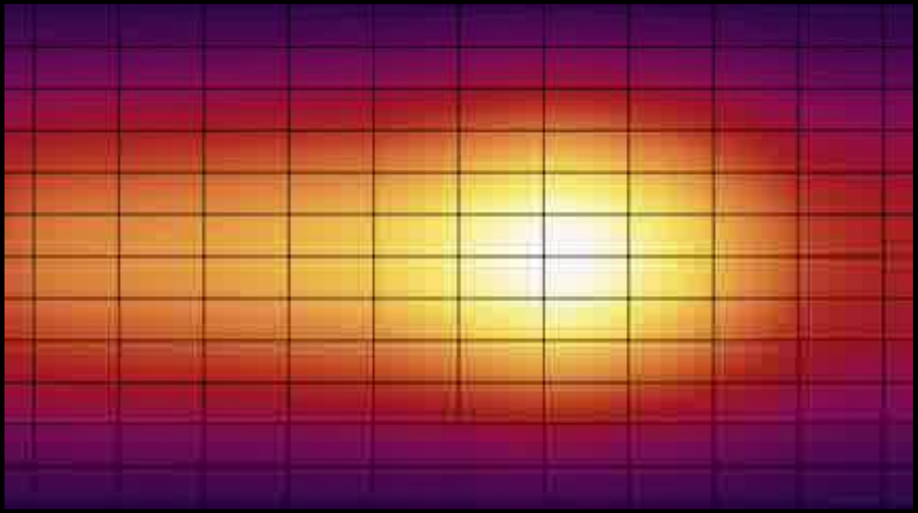
Today in Astronomy 106: habitability

- ❑ The temperature of dust grains in disks
- ❑ The snow line and the formation of icy bodies and giant planets
- ❑ Orbital and rotational evolution of planets
- ❑ The habitable zone for starlight-heated bodies
- ❑ Habitability of tidally-heated bodies



Measured surface temperatures for the exoplanet HD 189733b. Animation by T. Pyle, SSC/JPL/Caltech/NASA.

Back to the disks: temperature of dust grains

While planet-building is in progress, the temperature of dust in protoplanetary disks is set by heating from the central star and cooling by the dust's **blackbody radiation**.

- All opaque bodies emit light. Even you. You don't notice it because the light you emit comes out at infrared wavelengths, at which your eyes don't work.
- The **total flux** *F* (power per unit surface area) emitted by an opaque, perfectly light-absorbing body with temperature *T* turns out to be

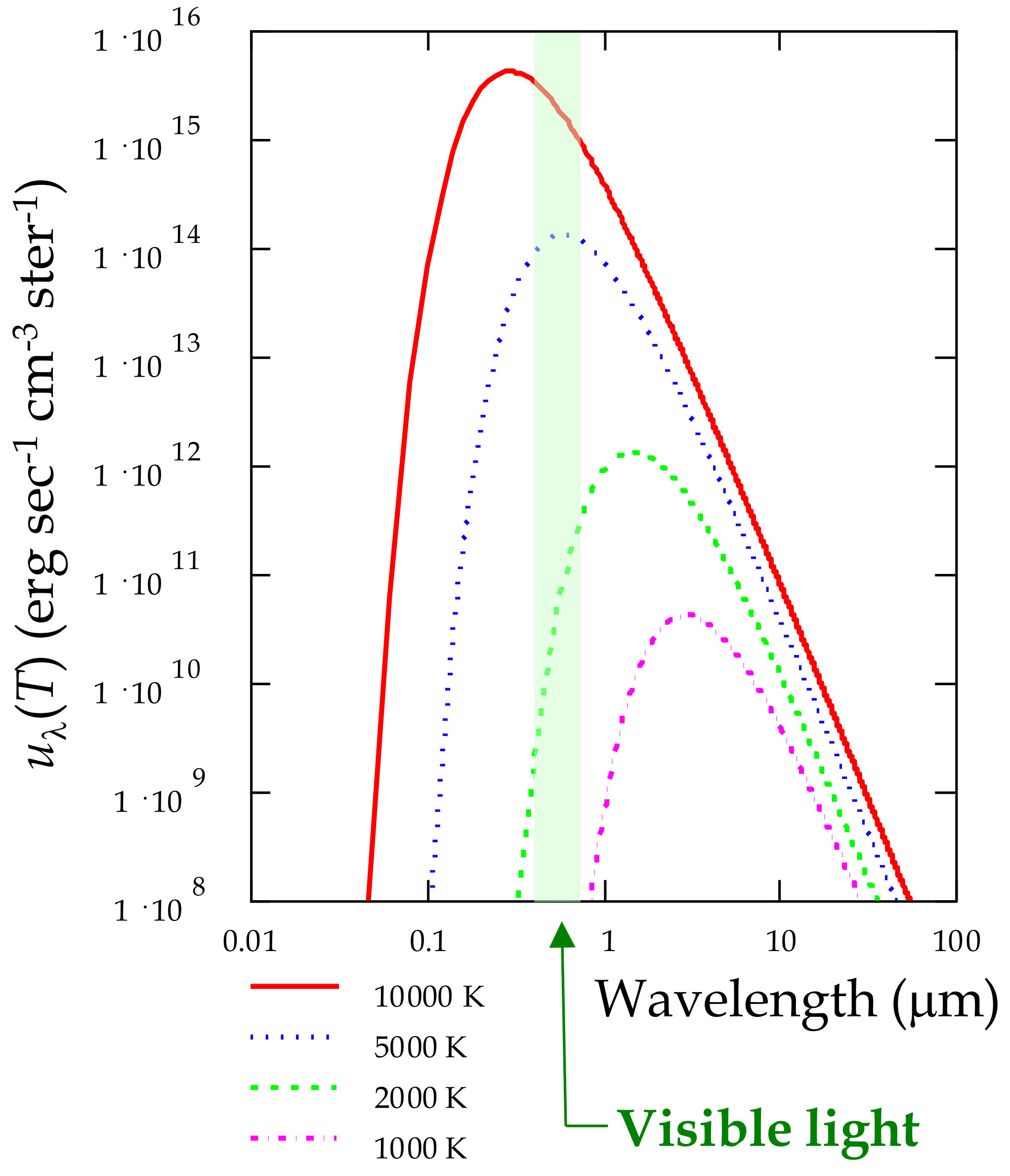
$$F = \sigma T^4$$ **Stefan's Law**

where $\sigma = 5.67 \times 10^{-5}$ erg sec^{-1} cm^{-2} K^{-4}. **Stefan-Boltzmann constant**

Blackbodies

Blackbodies with different temperatures emit different total fluxes *and* have different spectra.

- ❑ The wavelength at which a blackbody is brightest is inversely proportional to its temperature, and this turns out to be a good way of measuring temperatures of distant blackbodies.



Temperature of dust grains (continued)

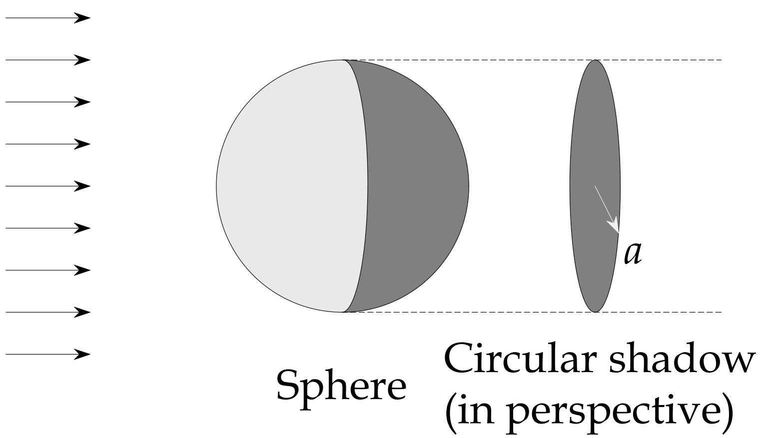
Time for another Derivation. You will be responsible for knowing the result and understanding the reasoning, but not for the algebra.

Consider a spherical, perfectly black dust grain with radius a (surface area $4\pi a^2$), which lies a distance r away from a star with luminosity (total light power per unit time) L.

- Starlight flux at location of grain: $F_* = L/4\pi r^2$.
- Spheres cast circular shadows, so the total **power** (energy per unit time) absorbed, P_{abs}, is

$$P_{abs} = F_* \times \text{shadow area}$$

$$= \frac{L}{4\pi r^2}\pi a^2$$



Temperature of dust grains (continued)

- Suppose the dust grain is **uniform** in temperature (same T at all points on its surface. Then the power it emits in blackbody radiation is

$$P_{\mathrm{emit}} = F_{\mathrm{blackbody}} \times \mathrm{surface\ area} = \sigma T^4 4\pi a^2 .$$

- If its temperature is **constant** in time, then it emits exactly as much power as it absorbs: $P_{\mathrm{abs}} = P_{\mathrm{emit}}$, or

$$\frac{L}{4\pi r^2}\pi a^2 = \sigma T^4 4\pi a^2$$

$$T = \left(\frac{L}{16\pi\sigma r^2}\right)^{\frac{1}{4}}$$

Temperature of dust grains (continued)

- Usually it will be convenient to use units of solar luminosity, $L_\odot$, and Earth-Sun distance, AU, instead of ergs/sec and cm:

$$L_\odot = 3.83 \times 10^{33} \text{ erg sec}^{-1}$$ **Solar luminosity**

$$\mathrm{AU} = 1.496 \times 10^{13} \text{ cm}$$ **Astronomical unit**

- In which case the equation for dust-grain temperature becomes

$$T = \left(\frac{L_\odot}{16\pi\sigma \mathrm{AU}^2} \right)^{\frac{1}{4}} \left(\frac{L/L_\odot}{\left(r/\mathrm{AU} \right)^2} \right)^{\frac{1}{4}} = 279 \text{ K} \times \left(\frac{L\left[L_\odot \right]}{\left(r\left[\mathrm{AU} \right] \right)^2} \right)^{\frac{1}{4}}$$

[X] means "in units of X."

Albedo

- Few grain, or planetary, surfaces are perfectly black. Most reflect a bit of the light.
- We call the fraction of incident light reflected the **albedo**, usually given the symbol *A*.
- This reduces the absorbed power by a factor of 1-*A*. That's the same as having a factor 1-*A* lower luminosity, so our formula becomes

$$T = \left(\frac{(1-A)L}{16\pi\sigma r^2}\right)^{\frac{1}{4}} = 279\ \mathrm{K} \times \left(\frac{(1-A)L\left[L_{\odot}\right]}{\left(r\left[\mathrm{AU}\right]\right)^2}\right)^{\frac{1}{4}}$$

You need to understand how to use this equation.

In reverse

If you know the temperature you want, you can also calculate the appropriate distance, by solving for *r* instead of *T*:

$$r\,[\mathrm{AU}] = \left(\frac{279\ \mathrm{K}}{T}\right)^2 \sqrt{(1-A)\,L\,[L_{\odot}]}$$

You also need to understand how to use this formula.

- **Example: the snow line**. Ice makes dust grains shiny ($A \sim 0.7$). In the vacuum of space, water ice sublimates at a temperature of 150 to 170 K, depending upon what other ices it's mixed with. In a disk, how far away from a $1L_{\odot}$ star would ice be found?

$$r\,[\mathrm{AU}] = \left(\frac{279\ \mathrm{K}}{150\ \text{to}\ 170\ \mathrm{K}}\right)^2 \sqrt{(0.3)(1)} = 1.9\ \text{to}\ 1.5\ \mathrm{AU}.$$

The snow line and planet formation

This last result is significant for large and icy Solar system bodies, as well as a helpful example.

- Freezing of ices concentrates a lot of mass that would otherwise be in the gas, onto the surfaces of dust grains.
- This would speed up the core-accretion process of planet formation substantially: more massive solid bodies form in a shorter time.
- If very massive solid bodies form in the disk when it still has lots of gas, they will accrete the gas and become giant planets. The position of the planets and the snow line in our Solar system is probably not an accident.

What	*r* (AU)
Mercury	0.4
Venus	0.7
Earth	1.0
Mars	1.5
Snow line	**1.5-1.9**
Jupiter	5.2
Saturn	9.5
Uranus	19.2
Neptune	30.1

Mid-lecture Torment.

- Homework #2 is Wednesday 1 June by midnight.
- **Exam #1 Friday, on WeBWorK, in any 75-minute window between 10 AM and 6 PM.**
- A practice exam appeared on WebWork this morning.
- Questions can be addressed tomorrow in class or in office hours Thursday from 1-3pm or by appointment.

Third panel of *The Garden of Earthly Delights,* Hieronymus Bosch (Museo del Prado).

Evolution of disks after planet formation

After planets form they begin, with the gravitational forces they exert, to perturb the orbits and rotation of smaller Solar-system bodies and each other. This results in

- orbital **migration**: the large-scale changing of planetary orbits.
- capture into, or ejection from, **resonant orbits**.
- systematic **ejection** of small planetesimals, sometimes *en masse*.
- **tidal locking**: the slowing of rotation of a body due to tidal forces by another, orbiting body.

These effects influence the habitability of given planets and the existence in a planetary system of habitable planets.

Perturbations and resonant orbits

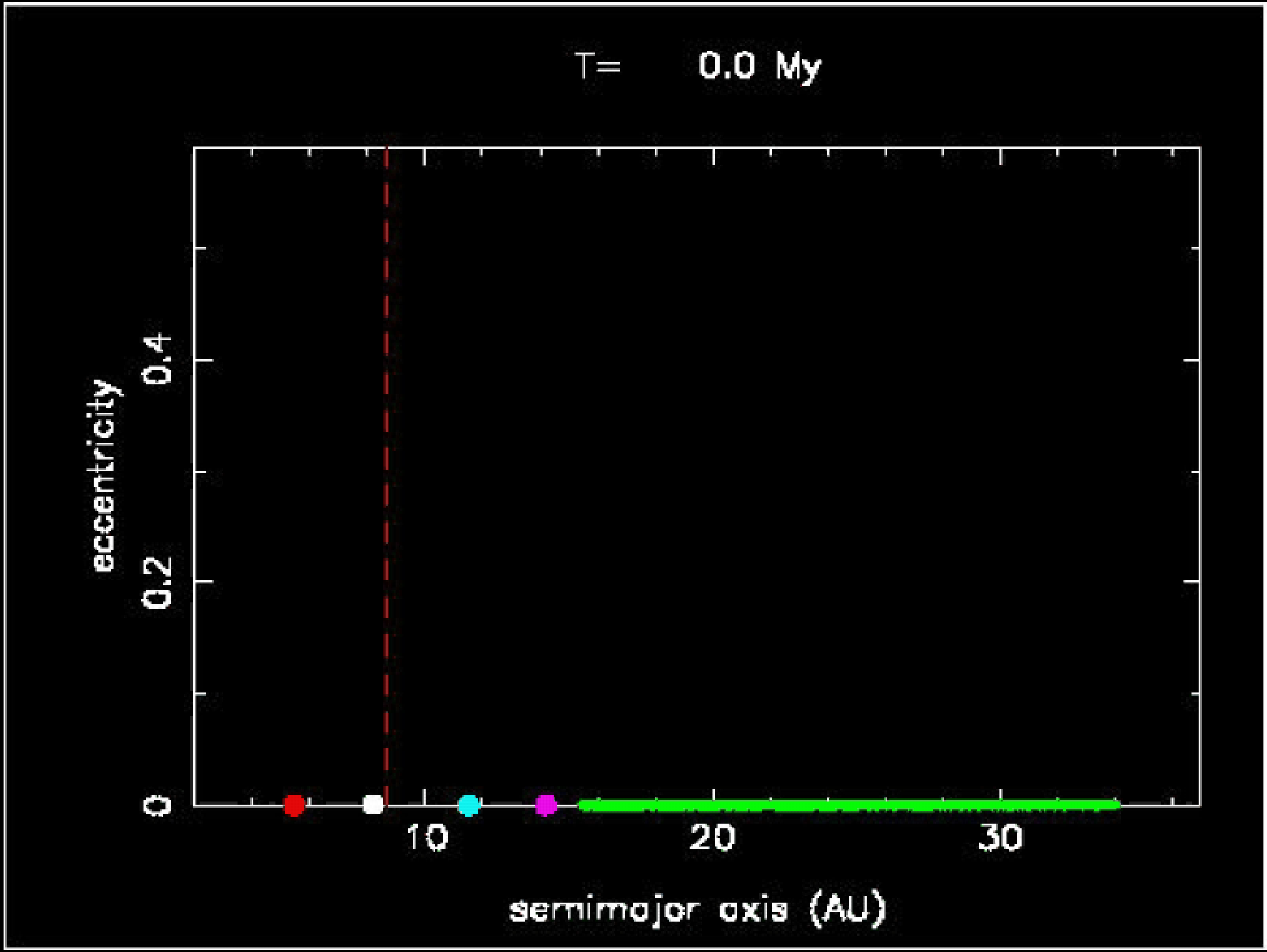
Inhabitants of disks are constantly under the influence of the gravity of each other as well as that of the central star.

- The effects are largest, of course, when they are closest together in their orbits, because gravitational forces are steeply dependent upon distance: $F_{a-b} = -GM_a M_b / r_{a-b}^2$.
- Thus you can think of each body suffering an impulsive "tug" – technical term **perturbation** – at closest approach.
- If closest approach happens in the same place in each orbit – a situation in which the orbits of the two are called **resonant** – the perturbations can build up over time to large differences, instead of tending to average out.
- If the orbital periods of two bodies have a ratio very close to a ratio of integers (whole numbers), they are resonant.

Migration of planets and ejection of planetesimals

Planets, especially giant ones, can force each other to change orbits drastically.

- This can have huge effects on smaller bodies. If a giant planet migrates by a substantial amount, planetesimals in between are subject to ejection or consumption.
- **Example**: the early history of our Solar system, according to the Nice Model, from the Planetology Group at the Observatoire de la Côte d'Azur (Allesandro Morbidelli and coworkers). See next page.
  Main events: perturbation of Jupiter and Saturn by each other migrate these planets outward, eventually resonantly perturbing Neptune and Uranus, swapping their orbits and ejecting 99% of the smaller bodies.


T= 0.0 My
eccentricity
0
0.2
0.4
10
20
30
semimajor axis (AU)

Rotational evolution and tidal locking

Planetesimals aren't infinitesimally small, and during perturbations they tug on each other's near side harder than the far side.

- ❑ They also tug each other's right and left sides closer together.
- ❑ These force differences are known, of course, as **tides**.
- ❑ The planetesimals stretch and compress in response to the tidal forces, and relax back to their previous shapes after the perturbation passes.

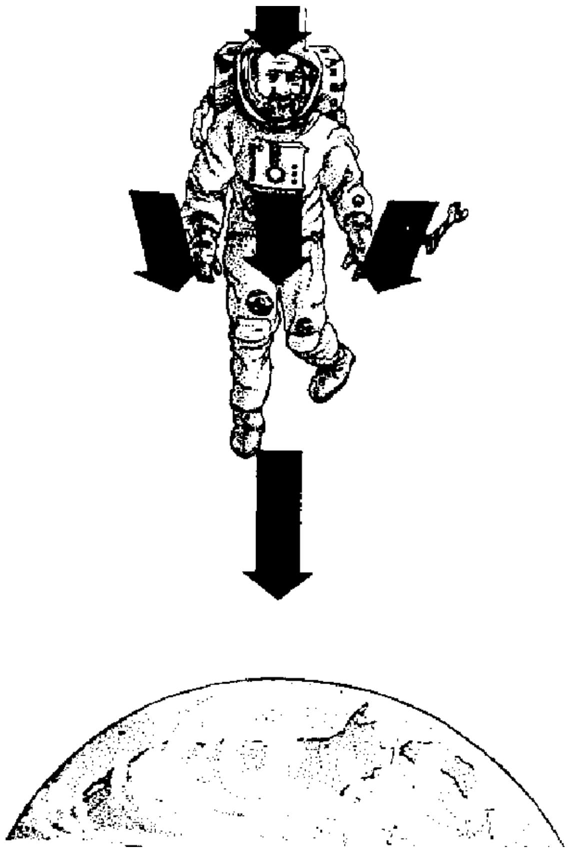


Figure from Thorne, *Black holes and time warps*

Tidal locking (continued)

- It took work to stretch/compress the planetesimal, and not all the energy springs back when it relaxes to its previous shape.
  - Friction and viscosity within the planetesimal dissipate some of the energy as heat, then radiated away.
- Because the tidal heating depends upon the state of rotation of the planetesimal as well as its orbit, it drains the rotational and orbital energy, **rotating more slowly** and drifting to larger orbital distance.

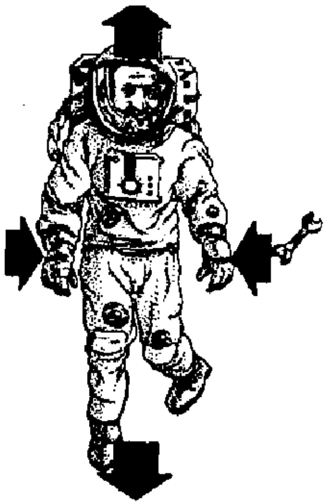


Figure from Thorne, *Black holes and time warps*

Tidal locking (continued)

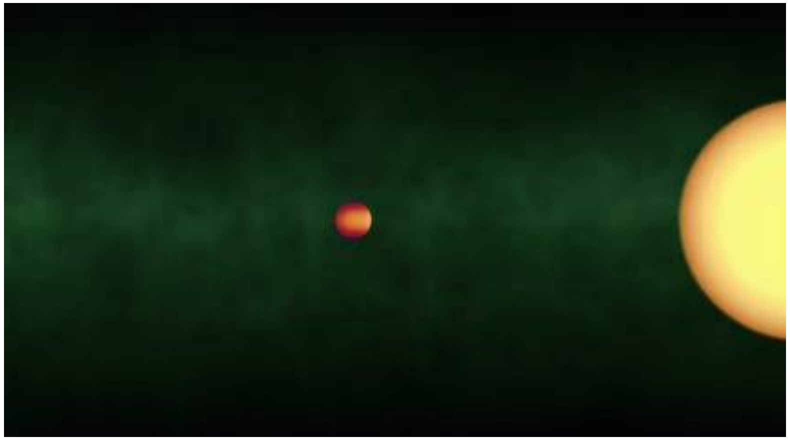
Eventually (in 1-100 Myr), this results in a special relation, such as equality, between the orbital and rotation period, corresponding to the minimum of tidal heating. This is called tidal **locking**.

- The Moon is tidally locked: it rotates once per revolution.
- Pluto and its largest moon Charon and mutually tidally locked: each rotates once every 6.4-day revolution.
- All the large moons of Jupiter and Saturn are tidally locked.
- **Planets in orbits very close to their stars will tend to be tidally locked**. (Mercury, for example.)
- This changes their heating situations. To wit:

Temperatures of fast and slow rotators

Implications for the temperature of a planetesimal that is mainly heated by starlight:

- If a body rotates faster than it can cool off, its surface will have a fairly uniform temperature, therefore approximately given by the formula for dust grains.
  - This is the case for the Earth and Mars, for example.
- If not, it will have hot and cold sides.
  - If tidally locked in circular orbit around its star, it can have **permanently** hot and cold sides.



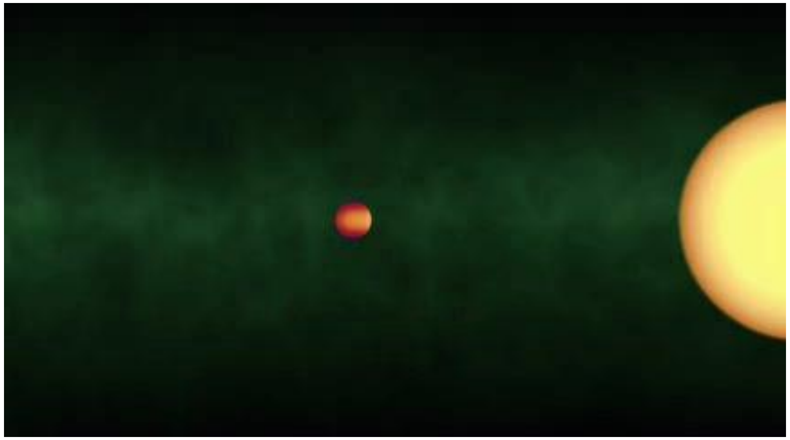
T. Pyle, SSC/JPL/Caltech/NASA

Temperatures of fast and slow rotators (continued)

- For a slow rotator, the maximum temperature, which is reached at the substellar point, is

$$T = \left(\frac{(1 - A)L}{4\pi\sigma r^2} \right)^{\frac{1}{4}} = 394\ \mathrm{K} \times \left(\frac{(1 - A)L\,[L_\odot]}{\left(r\,[\mathrm{AU}]\right)^2} \right)^{\frac{1}{4}}$$

You need to understand how to use this equation.



T. Pyle, SSC/JPL/Caltech/NASA

Temperatures of disks and planets: the habitable zone

Since the interstellar medium already provides infant solar systems with the basic, and some processed, ingredients of life, the next basic requirement for habitability is for the ingredients to have the right temperature.

- What's the right temperature? Clues from Earth:
  - Simple organisms are not killed by prolonged exposure to temperatures slightly below the freezing point of water, or slightly above the boiling point. (These beasts are called **extremophiles.**)
  - Complex organisms are most abundantly found in habitats a bit closer to freezing than boiling.
- That is, Earth suggests that **liquid water** promotes habitability by organic chemical/water based life.

The habitable zone (continued)

- So the most common definition of the habitable zone in a planetary system is that for which water exist permanently in liquid form on a suitable planet.
  - That is T = 273 – 373 K under normal pressure conditions on Earth, and this range is often taken.
  - The water need not be exposed on the surface; if it is, the planet better have an atmosphere.
- Found here:

$$r\left[\mathrm{AU}\right]=\left(\frac{T_0}{T}\right)^2\sqrt{(1-A)L\left[L_{\odot}\right]}$$

You also need to understand how to use this formula.

where T_0 = 279 K for fast rotators and 394 K for slow ones, and T runs from 273 to 373 K.

By this token, the habitable zone for Earthlike planets (A = 0.39) in the Solar system lies between 0.44 and 0.82 AU from the Sun. How many planets lie in the Solar system's habitable zone?

(numerical answer required)

Habitability outside the habitable zone

We chose starlight as the energy source above because it is generally provided at a steady rate for billions of years, and other heat sources are not. All but one, anyway:

- Tidal heating of suitably-placed moons and planets can be significant sources of energy for as long as they rotate rapidly and/or don't have circular orbits.
- On the one hand, as the moon or planet radiates away the energy, the rotation slows and the orbit circularizes over time, reducing the tidal heating to zero. But on the other…
- If something can force a suitably-placed planet or moon to rotate or follow an elliptical orbit permanently, the tidal heating would be permanent.

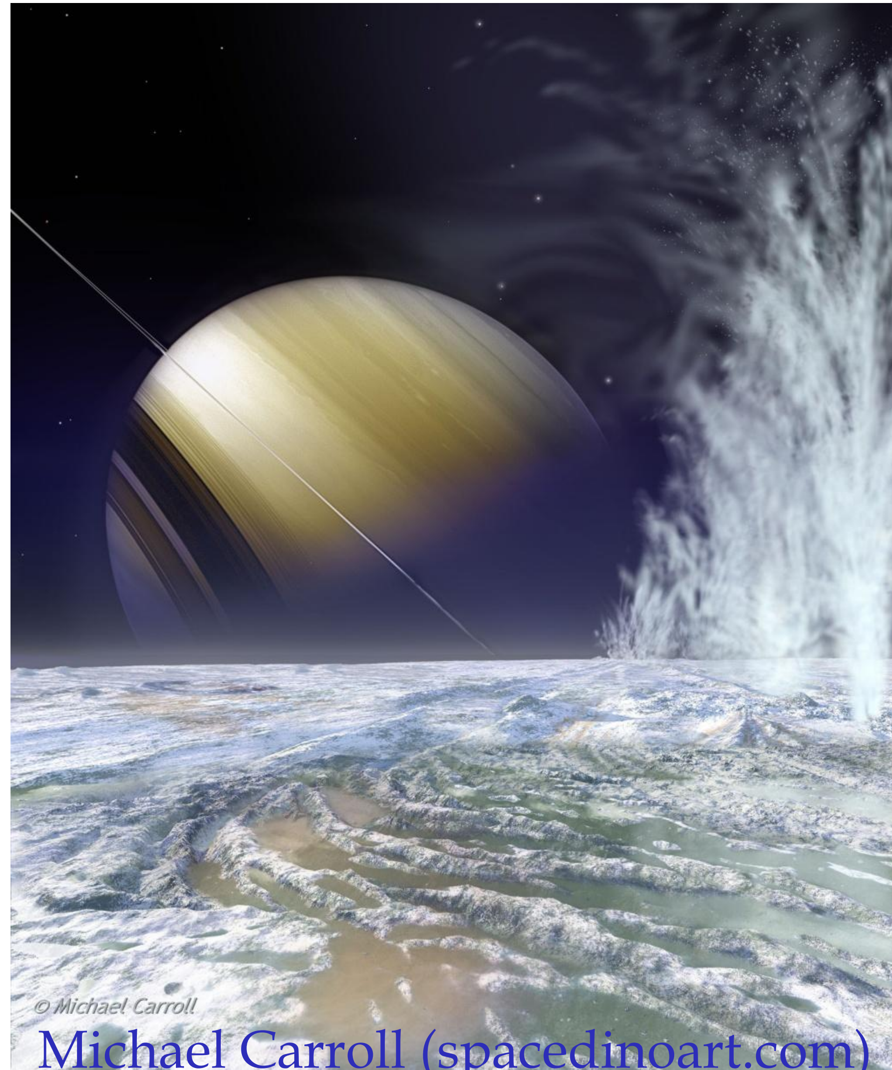
Habitability outside the habitable zone (cont'd)

- And something can: perturbations of moons and planets on each other's orbit can result in orbits being locked into orbital resonance.
- Since there's an attractive impulse at closest approach, and since for resonant orbits this happens in the same spot in the orbit every time, these **resonantly-locked** orbits can't be precisely circular.
- Thus tidal heating can be permanent, and substantial.

This is the case, as we have discussed, for the large moons of Jupiter and Saturn. It can lead to permanent liquid water further away from the star than the habitable zone.

What a life.

- In what important ways would life be different on such a habitable world outside the habitable zone?
- Do you think that microbial life could develop in such a place? Complex organisms?
- Do you think life could survive in such a place if implanted from elsewhere?



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