ASTR 620: Planetary Processes
Professor Eric Nielsen

Lecture 5: Dissipative Processes

Logistics

- Masks are encouraged

- No laptops, phones, or other electronic devices during class (I’ll let you know in advance if we’ll need laptops for an activity) **You may use a tablet to take notes if prefer, but please only use it for note-taking.**

- Remember to bring you response card to class

Review of the last class

- I, and a baseball, are in deep space. The baseball is at rest (v=0). I hit the baseball and it starts traveling at 3 m/s. I hit the baseball again, and it now travels at 6 m/s. How does the energy I gave the baseball in each hit compare?
  - (A) — Both energies are the same
  - (B) — I gave the baseball more energy in the first hit
  - (C) — I gave the baseball more energy in the second hit

Review of the last class

- These Lagrange points are on a line connecting the two large bodies:
  - (A) — L1 and L2
  - (B) — L2 only
  - (C) — L1 and L3
  - (D) — L1, L2, and L3
  - (E) — L4 and L5

Review of the last class

- If I’m at the Sun/Venus L2 point:
  - (A) — I orbit the Sun, and my orbital period is equal to Venus’ orbital period
  - (B) — I orbit Venus, and my orbital period is equal to Venus’ orbital period
  - (C) — I orbit the Sun, and my orbital period is equal to Venus’ rotational period
  - (D) — I orbit Venus, and my orbital period is equal to Venus’ rotational period
  - (E) — I orbit the Sun, and my orbital period is equal to the Sun’s rotational period

Review of the last class

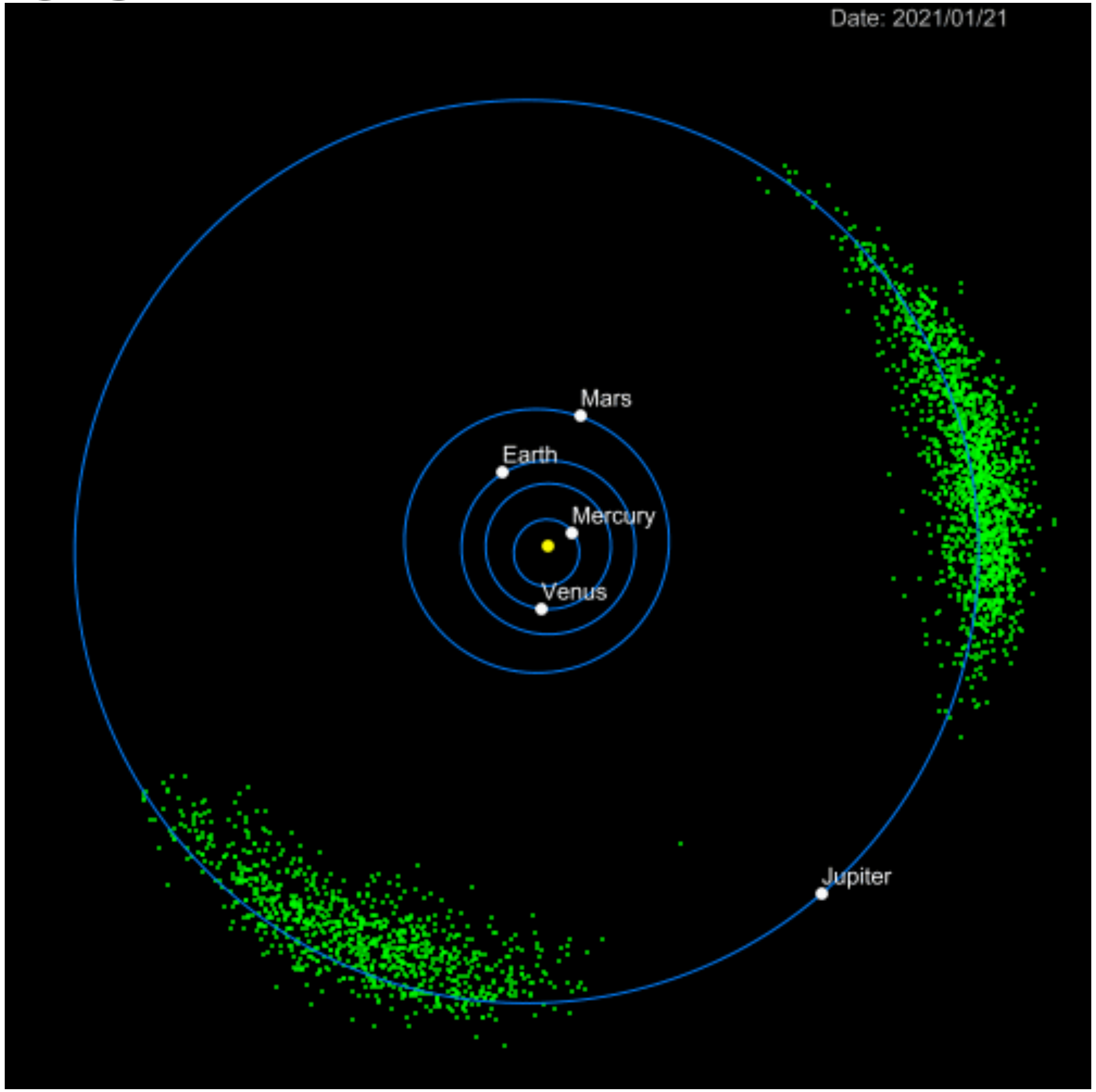
- A planet has moons and rings. Most likely:
  - (A) — The moons are outside the Hill radius, the rings are between the Hill radius and the Roche limit
  - (B) — The moons are both inside and outside the Hill radius, the rings are between the Hill radius and the Roche limit
  - (C) — The moons are inside the Roche limit, the rings are between the Hill radius and the Roche limit
  - (D) — The moons are between the Hill radius and the Roche limit, the rings are within the Roche limit
  - (E) — The moons are between the Hill radius and the Roche limit, the rings are outside the Hill radius

Review of the last class

- Why is Jupiter’s moon Io so volcanically active?
  - (A) — Jupiter’s magnetic field heats Io’s interior
  - (B) — Io has a perfectly circular orbit, so tidal forces from Jupiter are very large
  - (C) — Io has a very eccentric orbit, so tidal forces from Jupiter are very large
  - (D) — Io has a small but non-zero eccentricity, so tidal forces from Jupiter are very large
  - (E) — That’s no moon

Dissipative Processes

- We've talked mainly about how the gravity moves (or destroys) objects in the solar system
- But there are other processes (involving radiation) that can alter the orbits of small objects (gas, dust, and rocks)



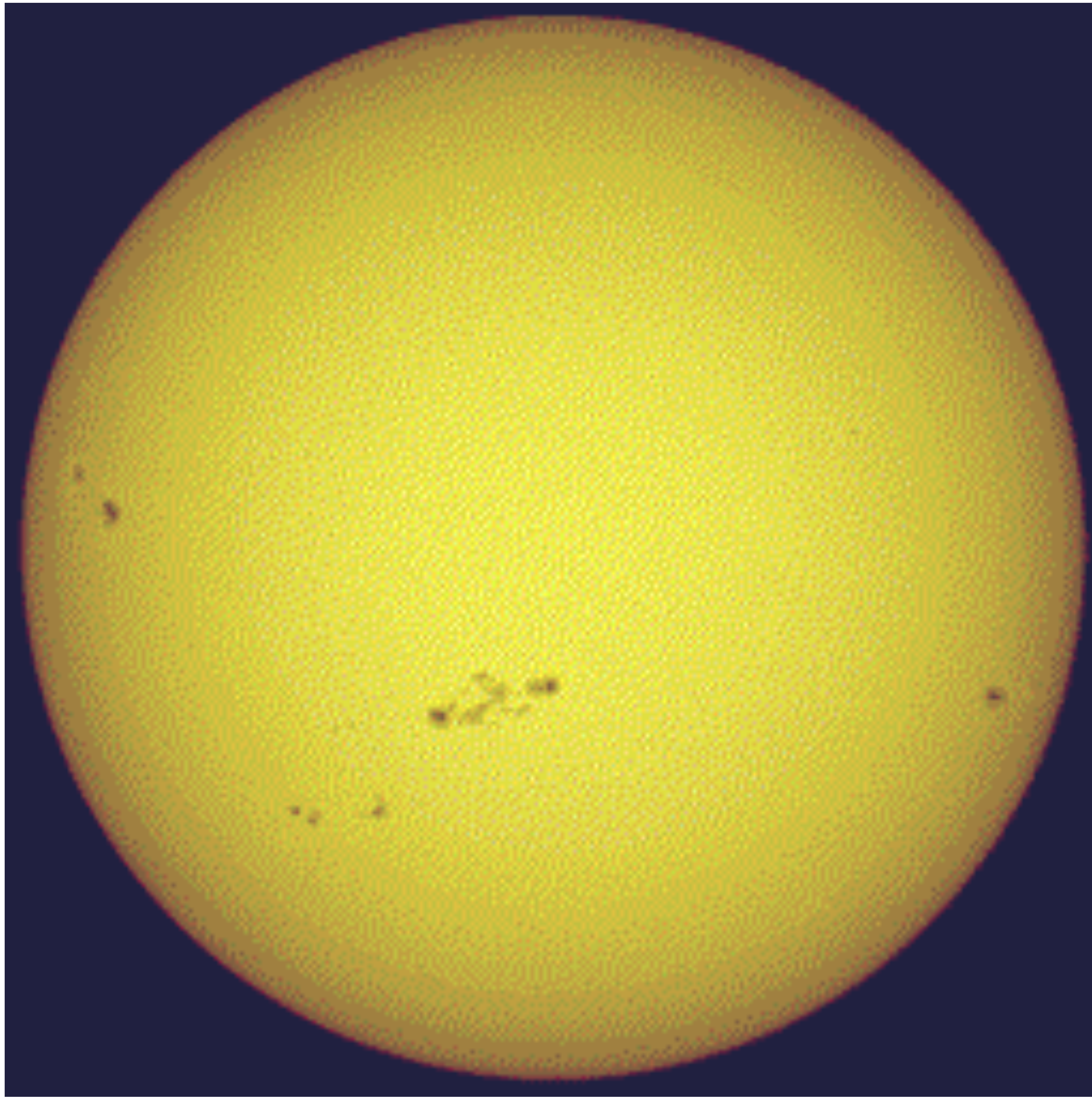
NASA/Petr Scheirich

Overview of Processes

Process	What is it?	Size of Particles
Radiation Pressure	outward spiral of small particles	micron
Poynting-Robertson Drag	inward spiral toward Sun	centimeter
Yarkovski Effect	orbit change due to uneven temperatures across surface	meter-kilometer
Corpuscular Drag	drag due to particles interacting with solar wind	sub-micron
gas drag	drag induced by planetary atmosphere	small bodies

Radiation Pressure

- Photons carry momentum
- When solar photons are absorbed or reflected by a particle, that momentum is transferred to the particle
- Radiation pressure provides an outward force (away from the Sun) on any object that reflects or absorbs photons



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Radiation Pressure

- A spherical particle of size R intercepts power (energy/time) from the Sun:

$$\frac{dE}{dt} = \frac{L_\odot \pi R^2}{4\pi d^2} = \frac{L_\odot R^2}{4d^2}$$

- A photon has momentum $p = \frac{h\nu}{c}$

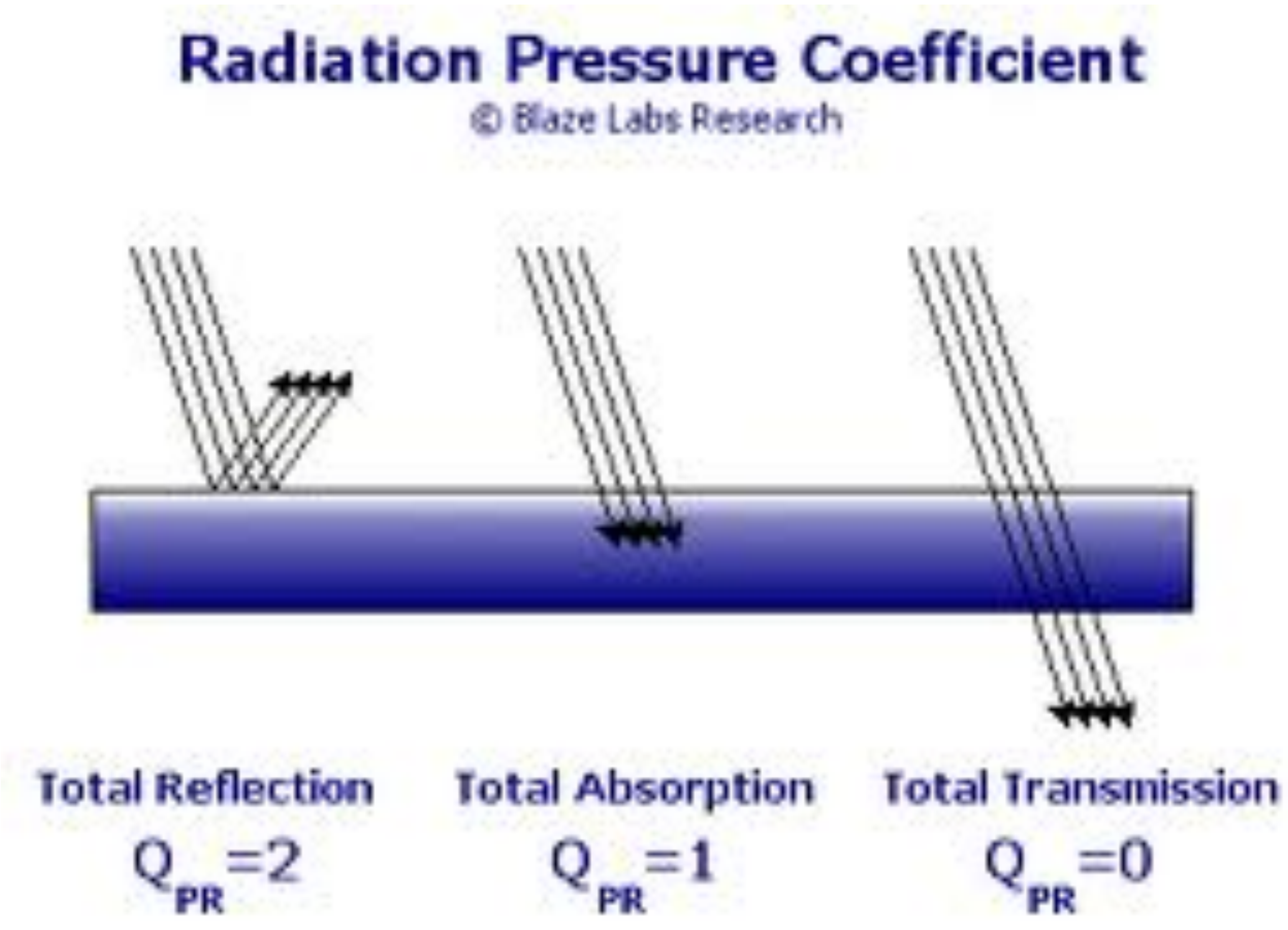
and energy: $E = h\nu$

- and so the conversion from energy to momentum of each photon is:

$$\frac{p_\gamma}{E_\gamma} = \frac{h\nu}{ch\nu} = \frac{1}{c}$$

Radiation Pressure

- We quantify how transmissive/absorptive/reflective the material is by Q_{PR}

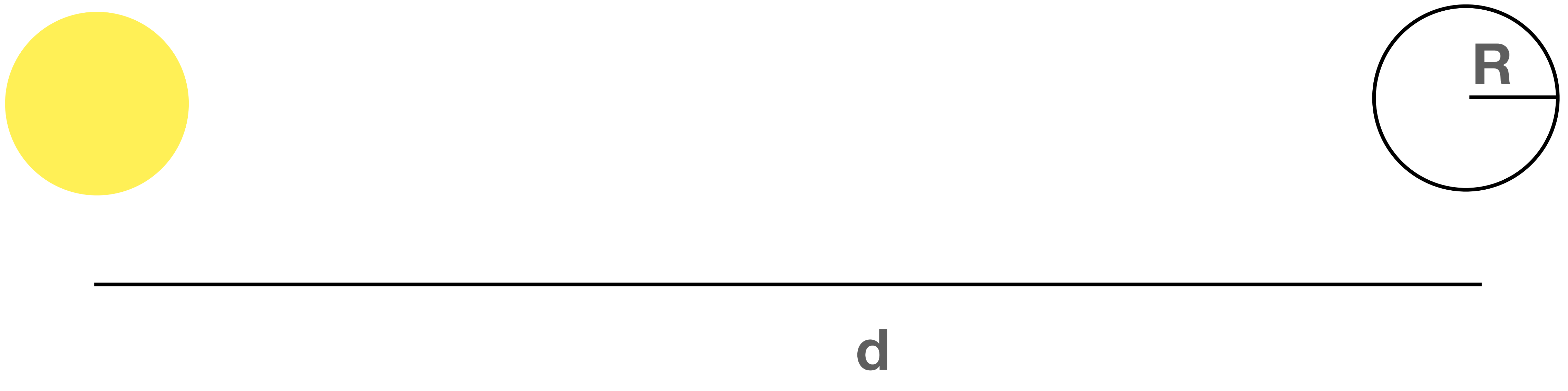


- Putting it together:

$$\frac{dp}{dt} = \frac{L_{\odot} R^2 Q_{PR}}{4cd^2}$$

- Which, from Newton's second law, is the force imparted by radiation pressure:

$$F_{rad} = \frac{L_{\odot} R^2 Q_{PR}}{4cd^2}$$



Radiation Pressure

- $F_{rad} = \frac{L_{\odot} R^2 Q_{PR}}{4cd^2}$

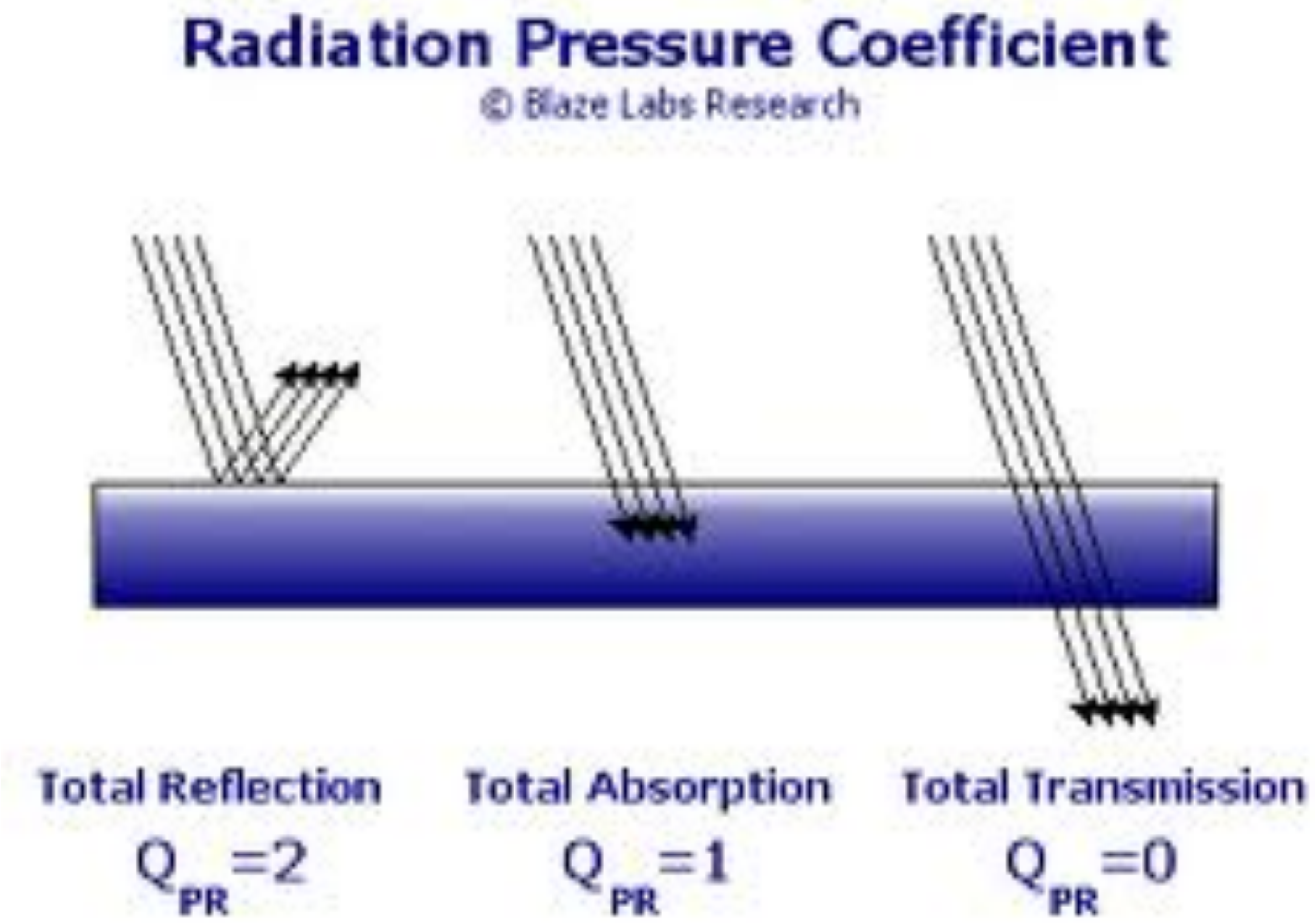
- The gravitational force felt by the same spherical particle is:

$$F_{grav} = \frac{GM_{\odot} m}{d^2}$$

- Or, if it has a density ρ: $F_{grav} = \frac{GM_{\odot} \frac{4}{3} \pi R^3 \rho}{d^2}$

- So the ratio of radiational force to gravitational force:

$$\frac{F_{rad}}{F_{grav}} = \frac{L_{\odot} R^2 Q_{PR}}{4cd^2} \times \frac{3d^2}{4\pi GM_{\odot} R^3 \rho} = \frac{3L_{\odot} Q_{PR}}{16\pi GM_{\odot} cR\rho}$$



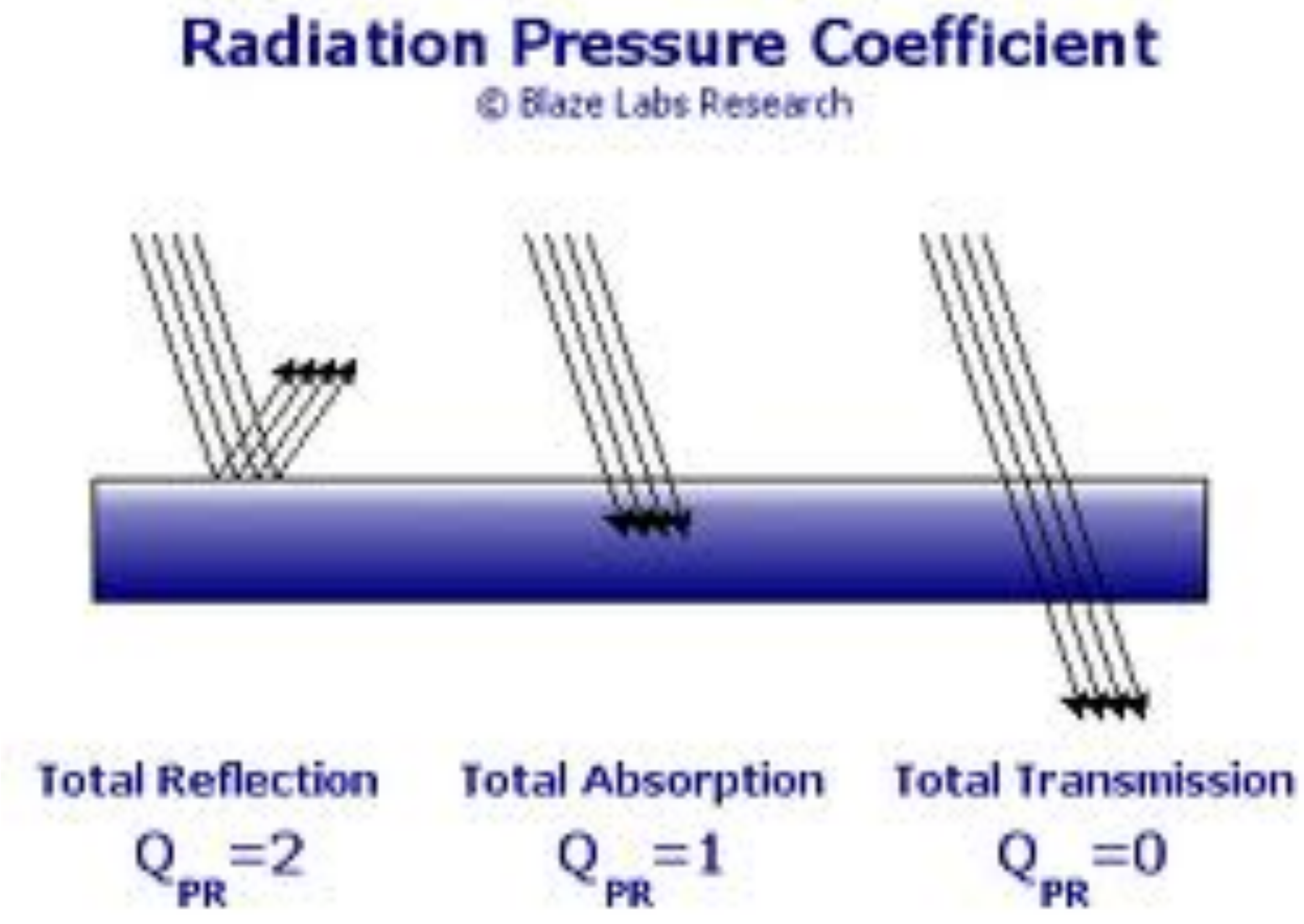
Radiation Pressure

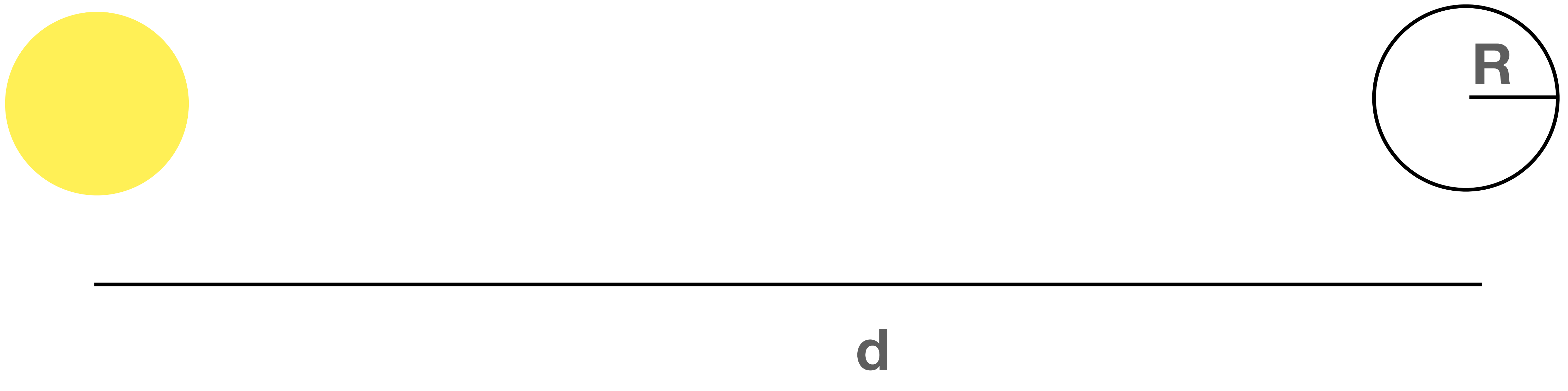
- $$\frac{F_{rad}}{F_{grav}} = \beta = \frac{3L_{\odot}Q_{PR}}{16\pi G M_{\odot} c R \rho}$$

- whether the force felt by a particle due to the Sun's gravity is larger or smaller than the force from the Sun's luminosity doesn't depend on distance!

- It depends only on the particle properties: size, reflectivity, density

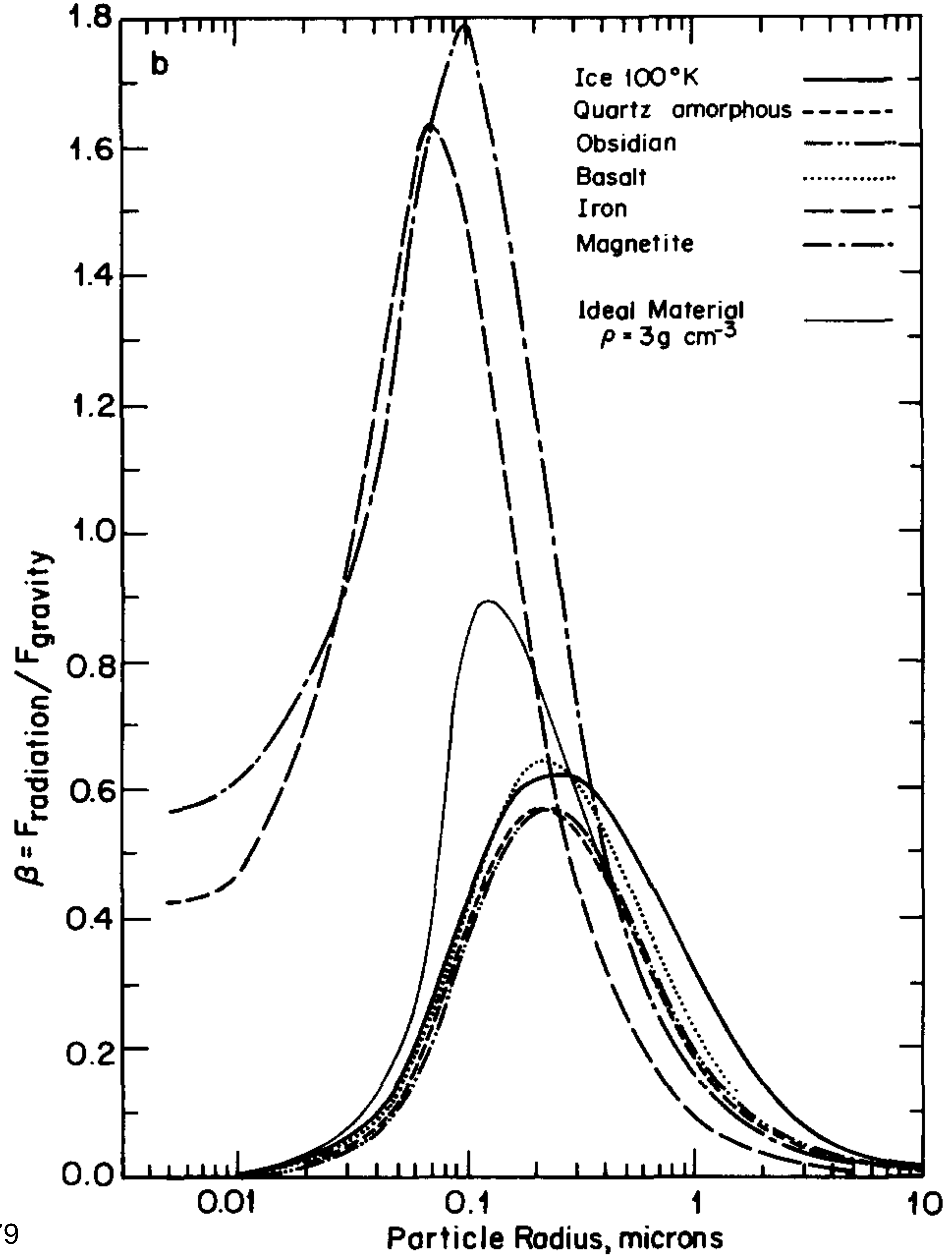
- As R becomes large, β becomes small, and radiation pressure becomes less important





Radiation Pressure

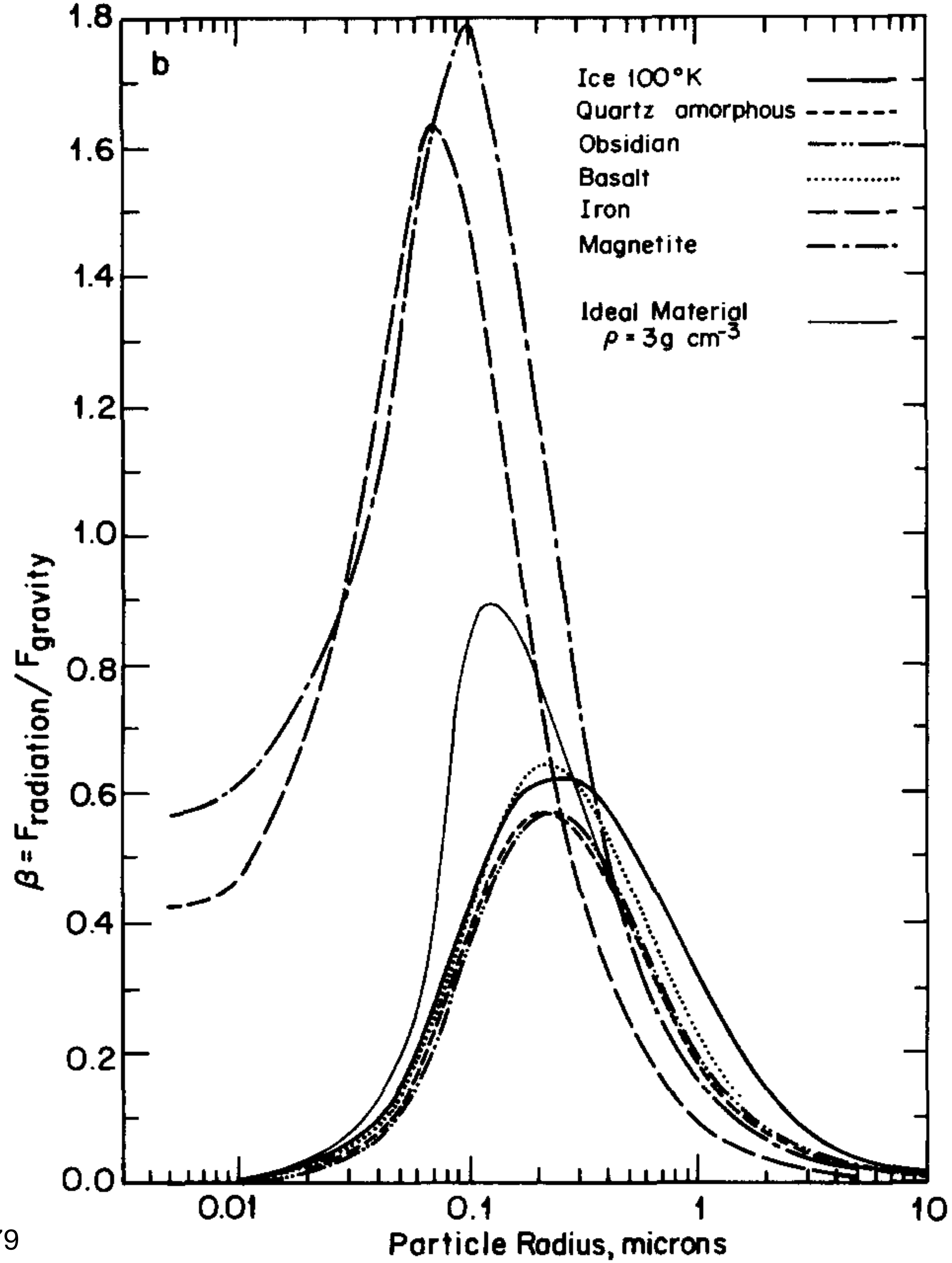
- $$\frac{F_{rad}}{F_{grav}} = \beta = \frac{3L_{\odot}Q_{PR}}{16\pi G M_{\odot} c R \rho}$$
- At small particle sizes, β goes to 0:
  - Particles are mostly transparent (Q_{PR} = 0) to light with wavelength smaller than the particle size, and most solar photons are in the visible
- At large particle sizes, β goes to 0, since it goes as 1/R
- Radiation pressure is most important for particles between about 0.1 - 1 micron



Burns et al. 1979

Response Card Question

- $$\frac{F_{rad}}{F_{grav}} = \beta = \frac{3L_{\odot}Q_{PR}}{16\pi GM_{\odot}cR\rho}$$
- The plot to the right is for particles orbiting our Sun. If we were to make a plot for particles orbiting a main sequence A star instead:
- (A) — It would look the same
- (B) — The curves would shift to the left, but have the same peak
- (C) — The curves would shift to the right, but have the same peak
- (D) — The curves would shift to the left, but have a larger peak
- (E) — The curves would shift to the right, but have a larger peak



Burns et al. 1979

Radiation Pressure and Comet Tails

astronomy.swin.edu.au

wikipedia

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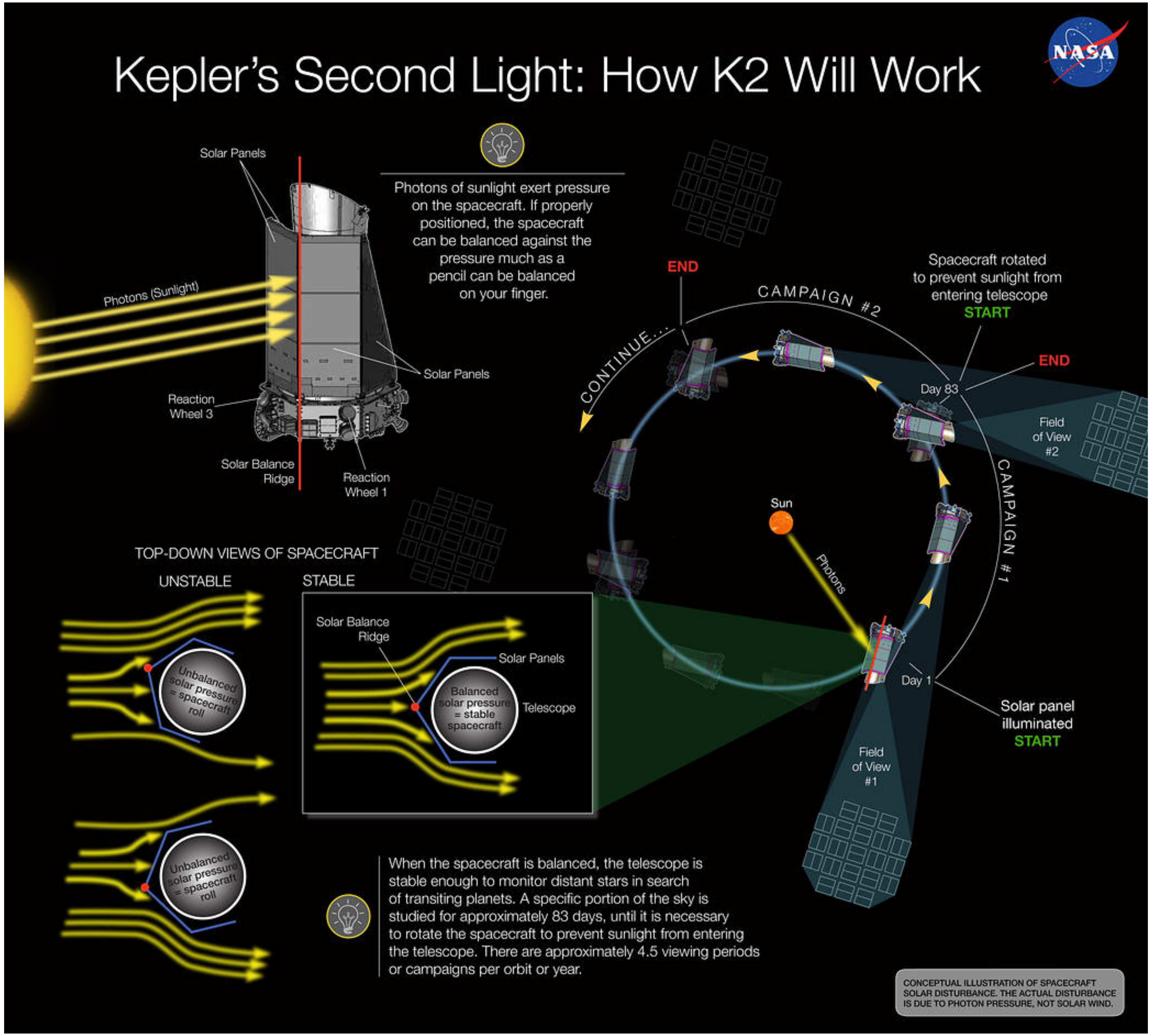
Radiation Pressure and Kepler



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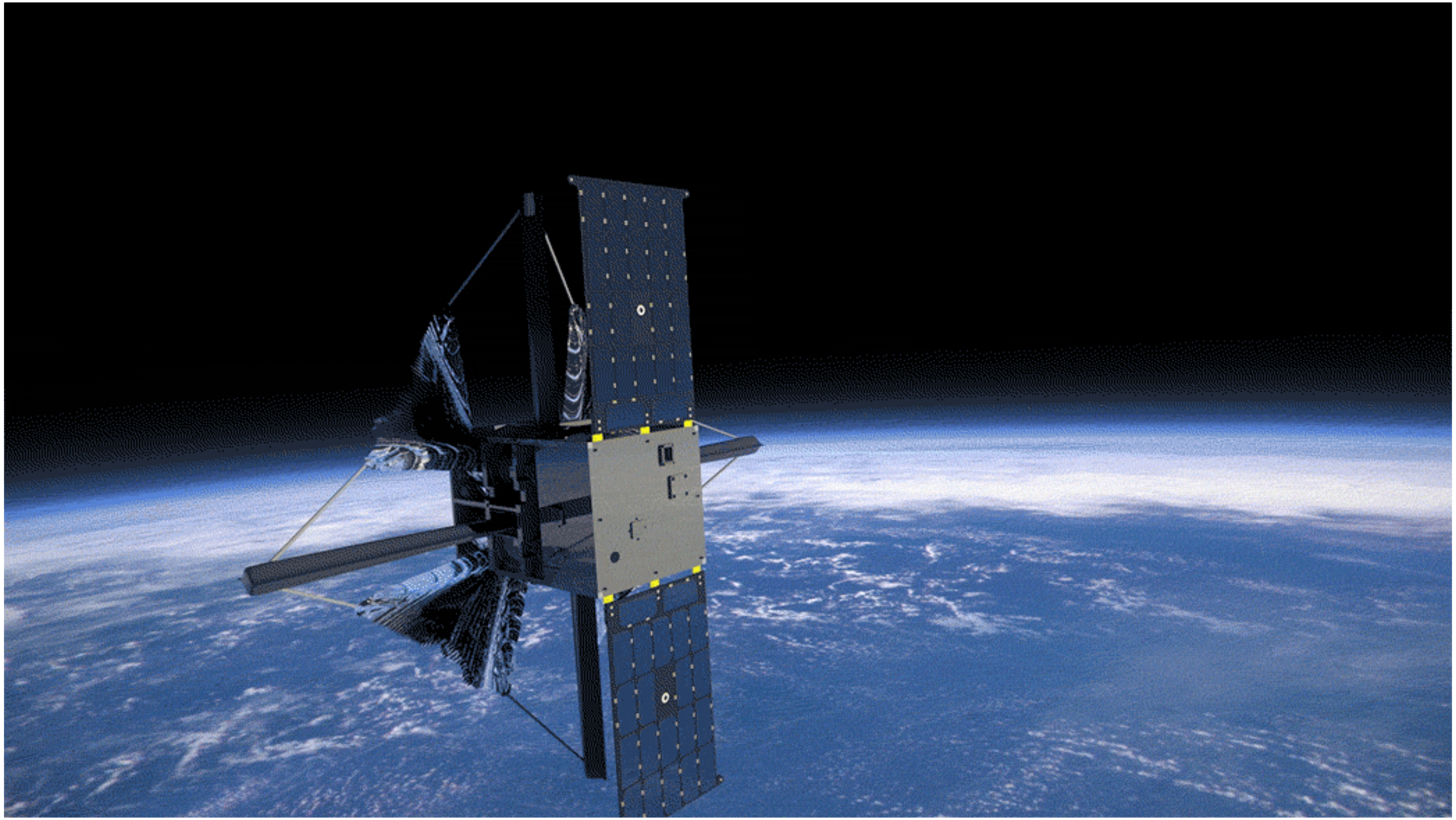
Radiation Pressure and Solar Sails



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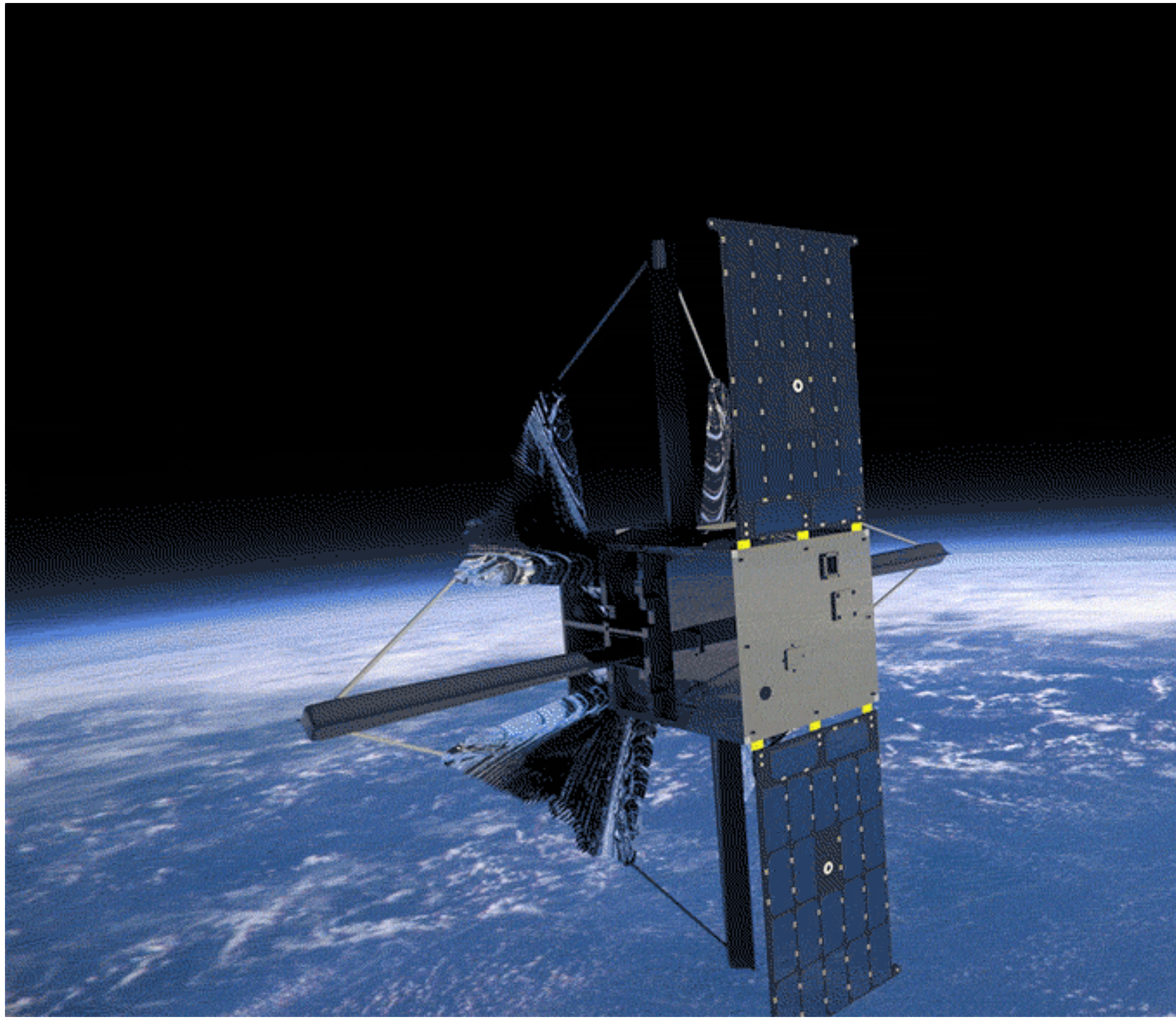
Order of Magnitude: Solar Sails

- NASA's Advanced Composite Solar Sail will have a mass of 16 kg and a square solar sail that's 10 meters on a side.
- $F_{rad} = \dfrac{L_{\odot} A Q_{PR}}{4\pi c d^2}$

  $F_{grav} = \dfrac{G M_{\odot} m}{d^2}$
- (1) What is $\dfrac{F_{rad}}{F_{grav}} = \beta$ for this spacecraft?
- (2) What is F_{grav} for this spacecraft, from the Sun, ignoring gravity from the Earth, when it starts at 1AU?
- In the reference frame where Earth is stationary (so the initial velocity of the spacecraft is 0), and ignoring the problem of escaping Earth's gravity, and ignoring the change in the Sun's gravity:
- (3) How fast is the spacecraft traveling after 1 year, in km/s?



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Order of Magnitude: Solar Sails

- m=16 kg A = (10 meters)^2
- $F_{rad} = \frac{L_{\odot} A Q_{PR}}{4\pi c d^2}$ $F_{grav} = \frac{G M_{\odot} m}{d^2}$
- (1) What is $\frac{F_{rad}}{F_{grav}} = \beta$ for this spacecraft?
- Combining the equations: $\frac{F_{rad}}{F_{grav}} = \beta = \frac{L_{\odot} A Q_{PR}}{4\pi c G M_{\odot} m}$
- Then, plugging in numbers:

$$\frac{F_{rad}}{F_{grav}} = \beta = \frac{(4x10^{33} erg/s)(10^3 cm)^2(2)}{4\pi(3x10^{10} cm/s)(7x10^{-8}\frac{cm^3}{gs^2})(2x10^{33} g)(16x10^3 g)} = \frac{4x2x10^{39}}{4\pi x3x2x16x7x10^{38}} = \frac{10^{39}}{10^3 x10^{38}} = 10^{-2} = 1\ \%$$

Order of Magnitude: Solar Sails

- (2) What is F_{grav} for this spacecraft, ignoring gravity from the Earth, when it starts at 1AU?

$$F_{grav} = \frac{GM_{\odot}m}{d^2} = \frac{(7x10^{-8}\frac{cm^3}{gs^2})(2x10^{33}g)(16x10^3g)}{(1.5x10^{13}cm)^2} = \frac{200x10^{28}}{2x10^{26}} = \frac{10^{30}}{10^{26}} = 10^4 dynes$$

- In the reference frame where Earth is stationary (so the initial velocity of the spacecraft is 0), and ignoring the problem of escaping Earth's gravity:

- (3) How fast is the spacecraft traveling after 1 year, in km/s?

$$F_{rad} = F_{grav} * \beta = 10^4 dynes * 0.01 = 10^2 dynes$$

$$F = ma = m\frac{dv}{dt}$$

$$dv = \frac{Fdt}{m} = \frac{(10^2 dynes)(3x10^7 s)}{(16x10^3 g)} = \frac{10^9}{5x10^3} = 0.2x10^6 cm/s = 2x10^5 cm/s = 2km/s$$

Break

Response Card Question

- In visible light, what is the brightest object in the Solar System?
  - (A) — Earth
  - (B) — Jupiter
  - (C) — Mercury
  - (D) — Sun
  - (E) — Something else

Response Card Question

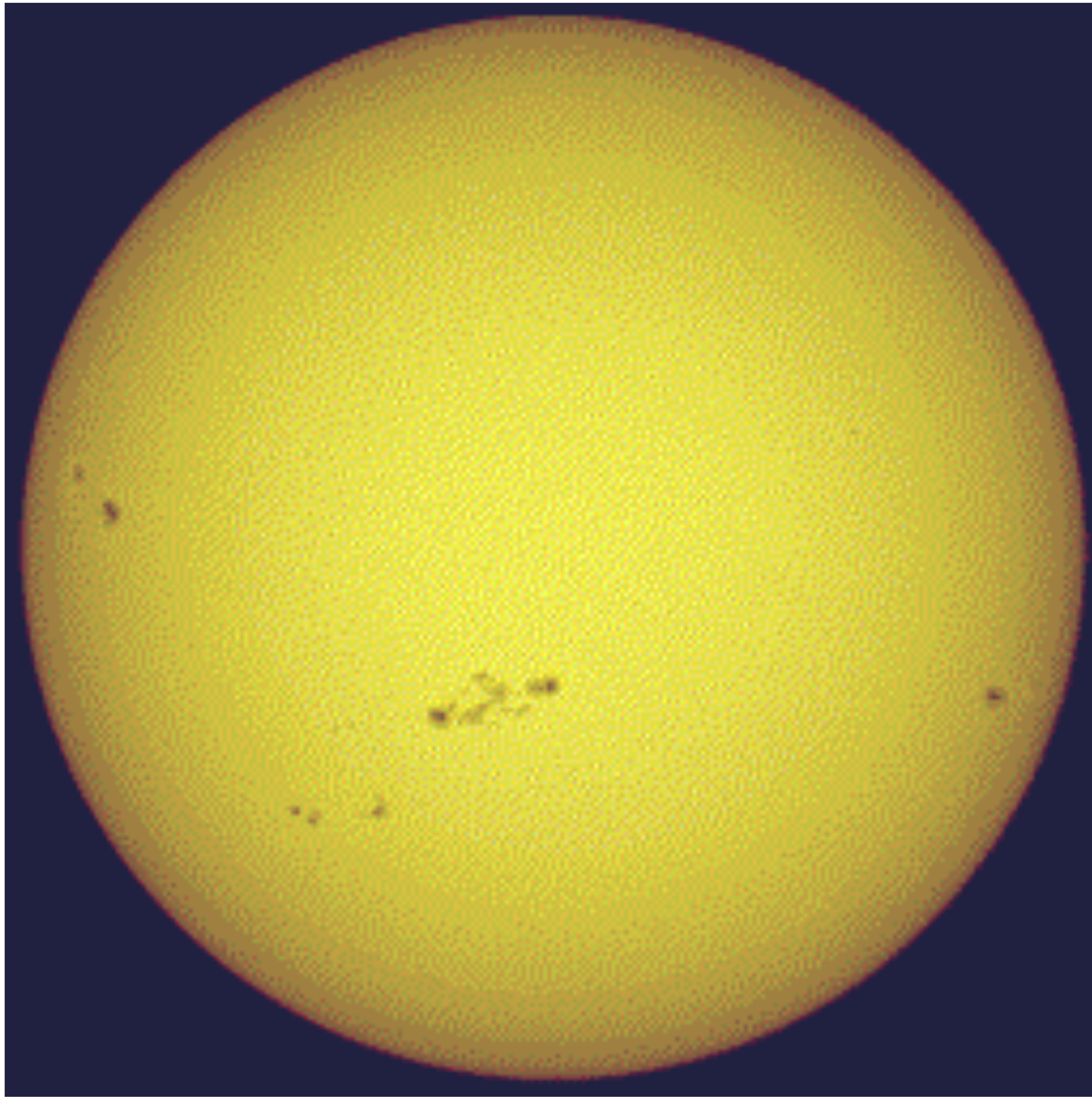
- In visible light, what is the **second** brightest object in the Solar System?
  - (A) — Earth
  - (B) — Jupiter
  - (C) — Mercury
  - (D) — Sun
  - (E) — Something else

Poynting-Robertson Drag

- Radiation pressure is important for particles about 0.1-1 micron in size (they get ejected from the solar system)

- Particles about a centimeter in size experience Poynting-Robertson Drag, and spiral inward into the Sun

- Particles experience a “headwind” of solar photons as they orbit, slowing them down



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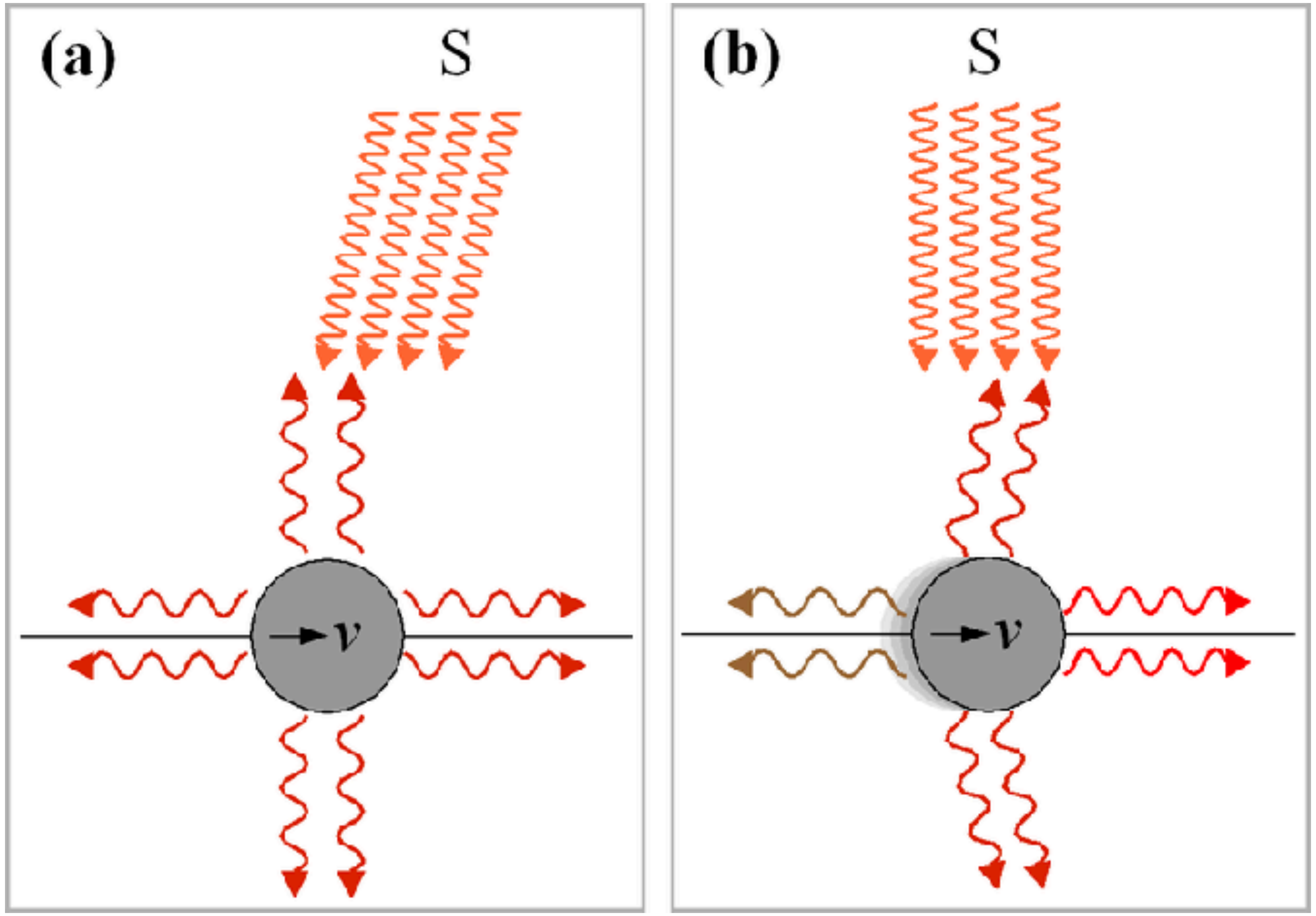
Poynting-Robertson Drag

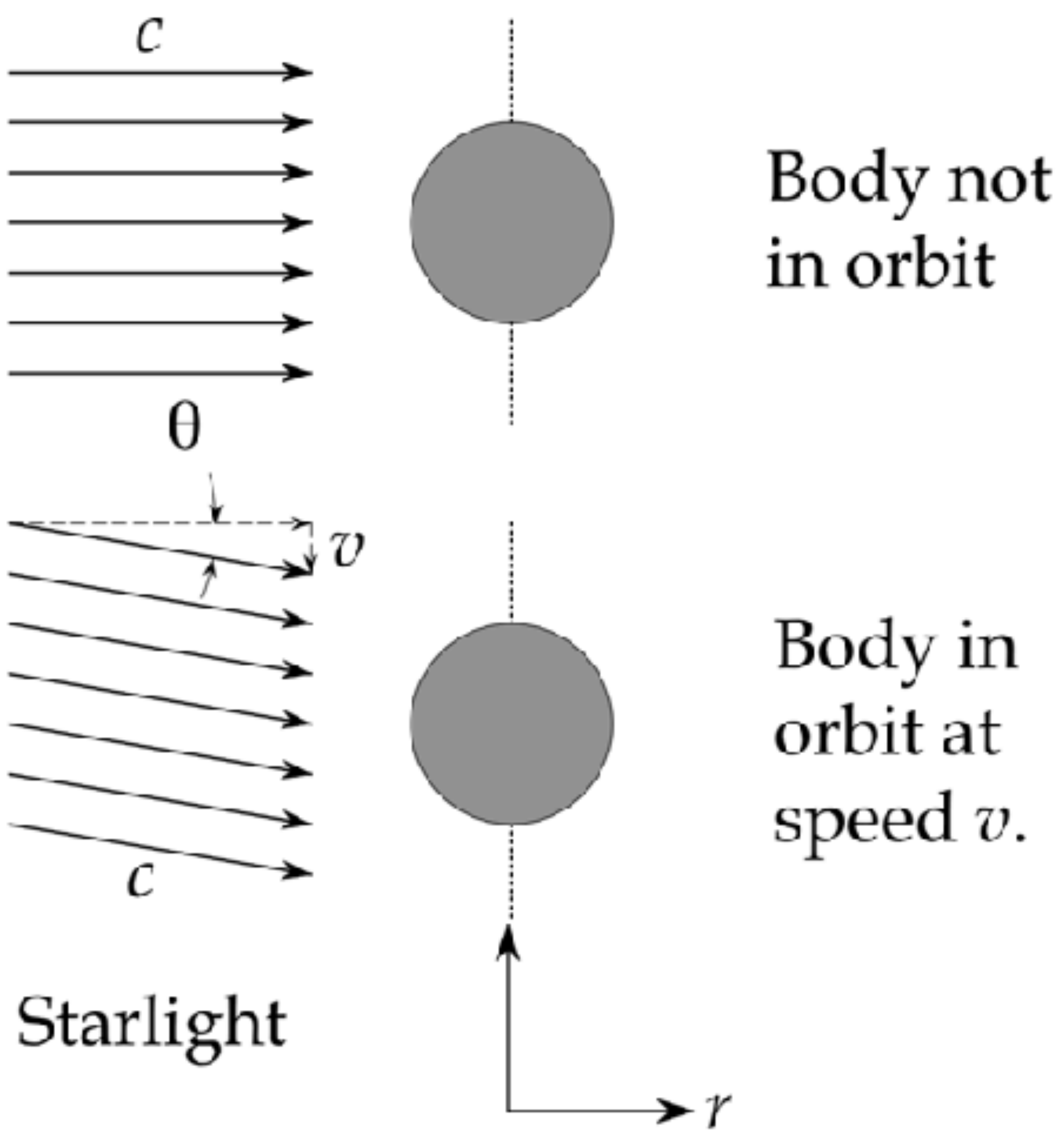
- Can describe PR drag from either reference frame of the particle, or reference frame of the Sun
- In either case, particle absorbs photons from the Sun, and reradiates them in all directions
- In particle's reference frame, aberration of angles is important:
  - because of the speed of light is finite, there's a component of the photon's velocity pointing against the particle's orbital velocity, slowing particle down
- In Sun's reference frame, the particle doesn't feel a headwind from absorbed photons, but the particle does not emit isotropically
  - Particle emits more in direction of travel, slowing particle down

Access science



Poynting-Robertson Drag

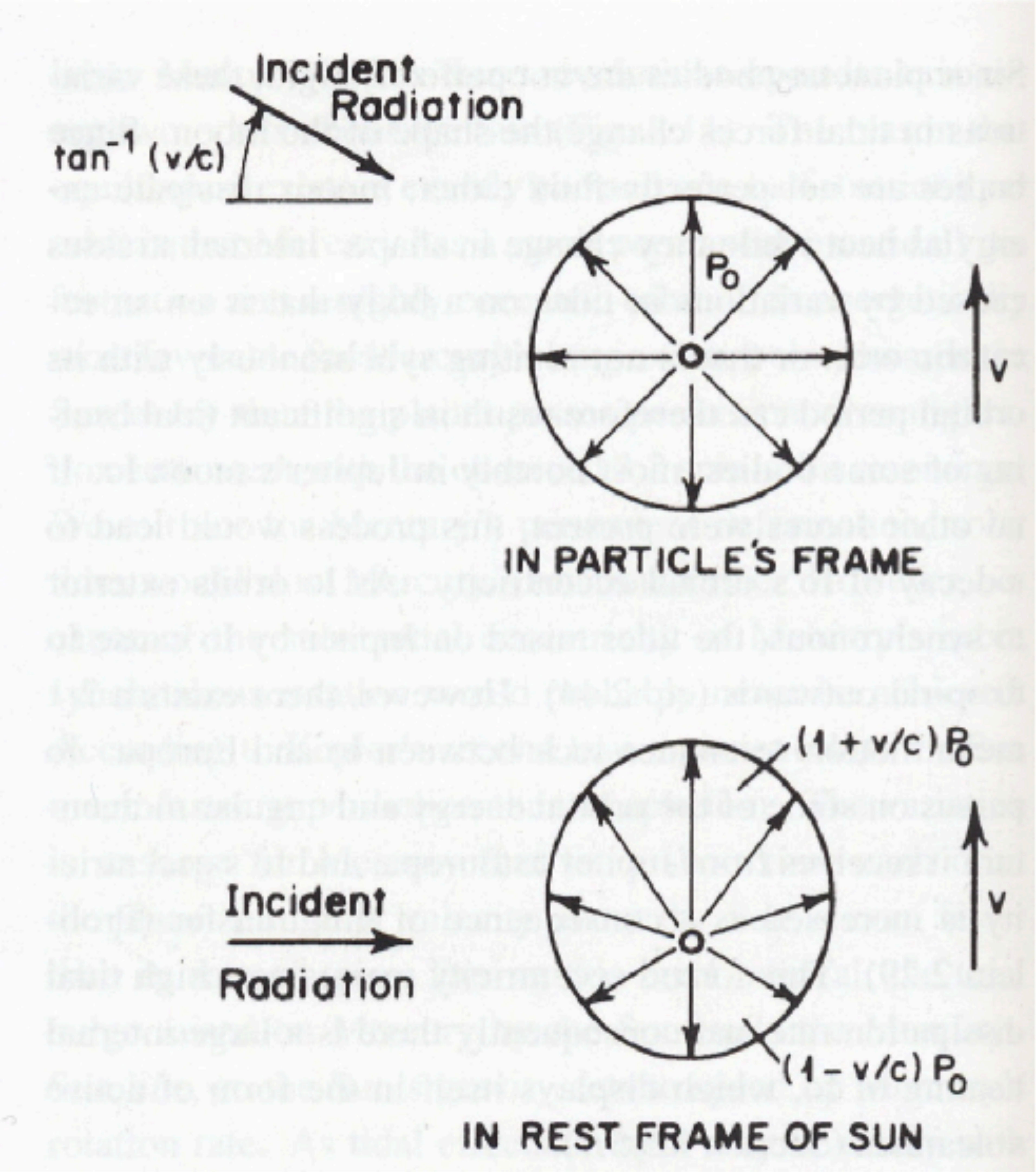
- Body's orbital velocity is v
- From body's reference frame, star moves at -v
- Light has a component of velocity opposite to the body's motion



astro.pas.rochester.edu

Poynting-Robertson Drag

- In particle's frame:
  - absorbed solar photons are not perpendicular to orbital velocity
  - emission is isotropic
- In Sun's frame:
  - absorbed solar photons are perpendicular to orbital velocity
  - emission is not isotropic
- In either reference frame the effect is the same: the particle loses orbital speed (that energy and angular momentum is carried off by photons)



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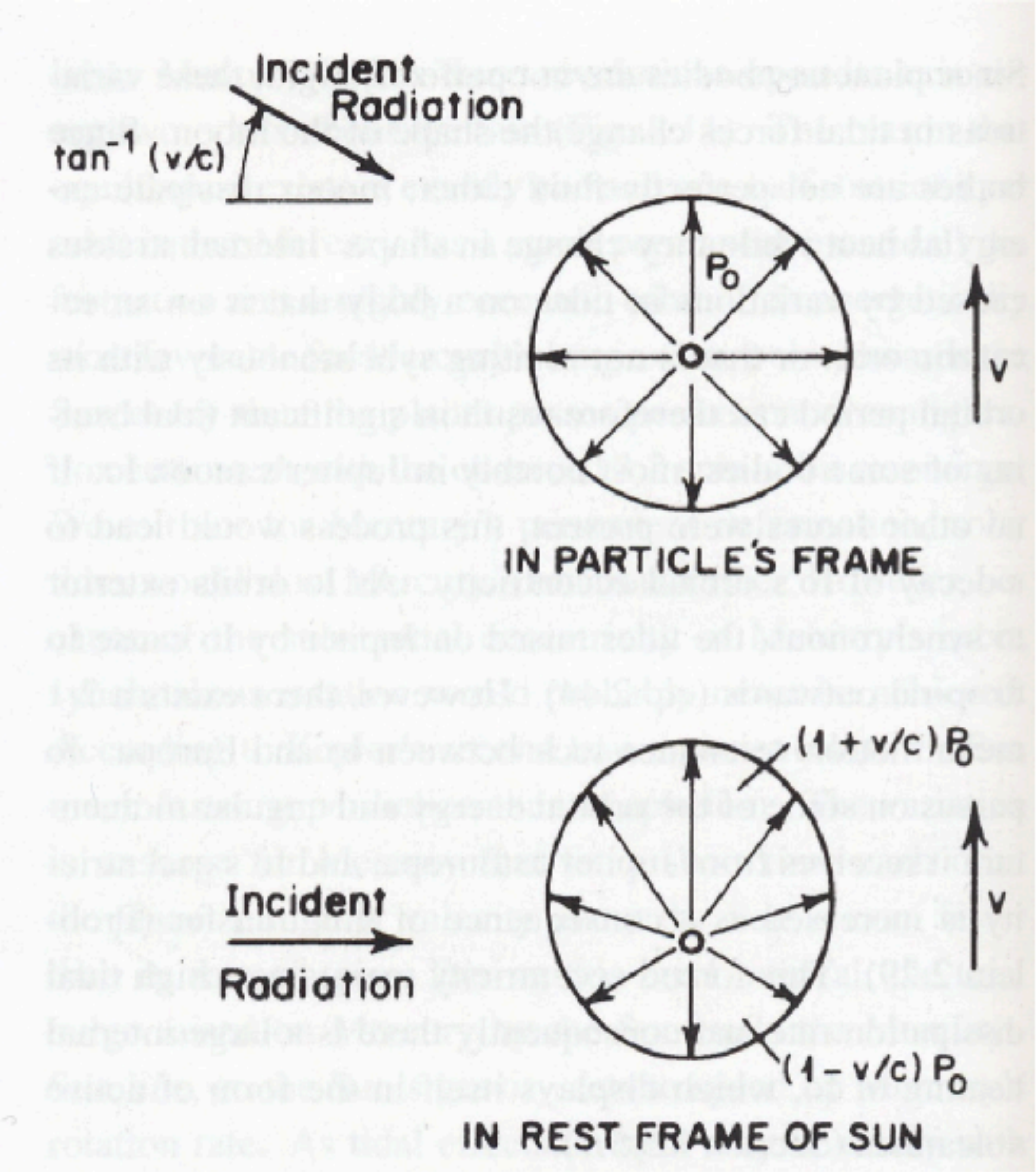
Poynting-Robertson Drag

- For a particle with orbital speed v_θ and radial speed v_r (if the orbit is circular, $v_r = 0$), the total radiation force (radiation pressure and PR drag) is:
- $$F_{rad} \approx \frac{L_\odot Q_{PR} A}{4\pi c d^2}\left[(1 - \frac{2v_r}{c})\hat{r} - \frac{v_\theta}{c}\hat{\theta}\right]$$
- PR drag is pointing in opposite direction as orbital motion: particle slows down
- PR drag is a relativistic effect, so proportional to $\frac{v}{c}$



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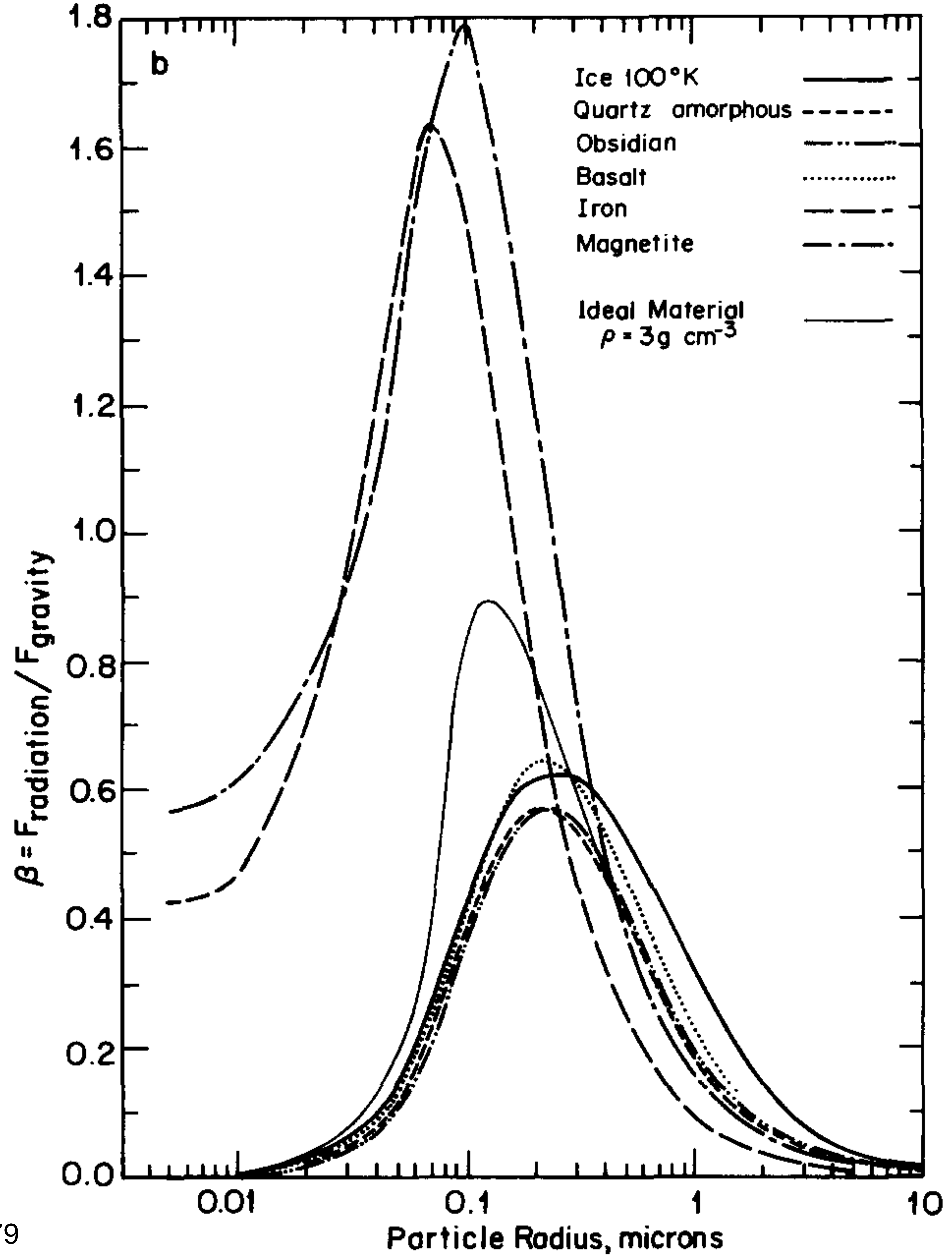
Timescales

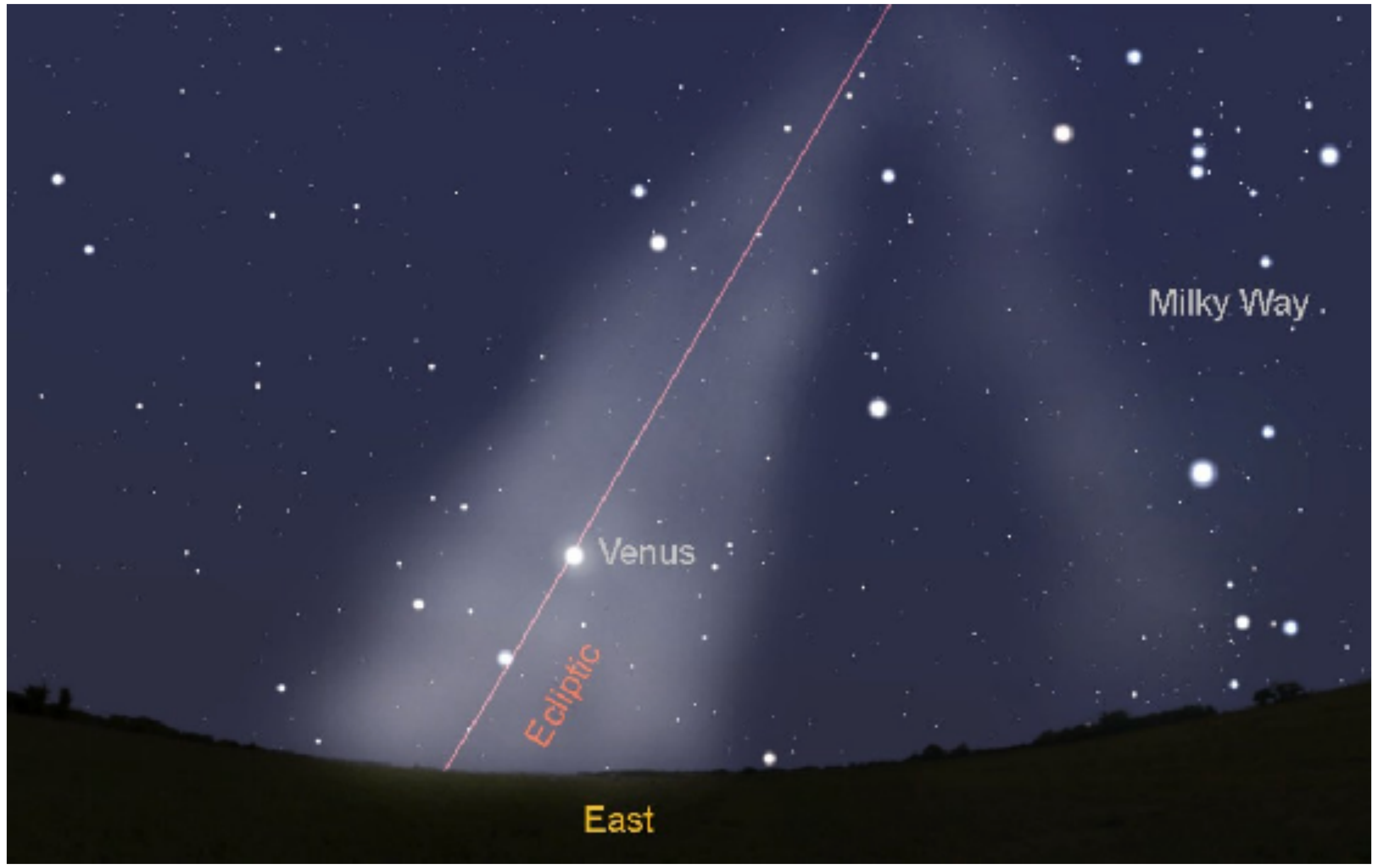
- For radiation pressure and PR drag:
- $\tau \approx 400 \frac{r_{AU}^2}{\beta}$
- For $\beta = 1$ (R=0.24 microns): 400 years at 1 AU
- For $\beta = 10^{-4}$ (R=0.24 cm): 4 million years at 1 AU
- Micron-sized dust particles are removed much more rapidly than cm-sized particles.
- If we see micron-sized or cm-sized particles in our solar system or an exoplanetary system (and we do!) they must be replenished as quickly as radiation pressure is removing them



Burns et al. 1979

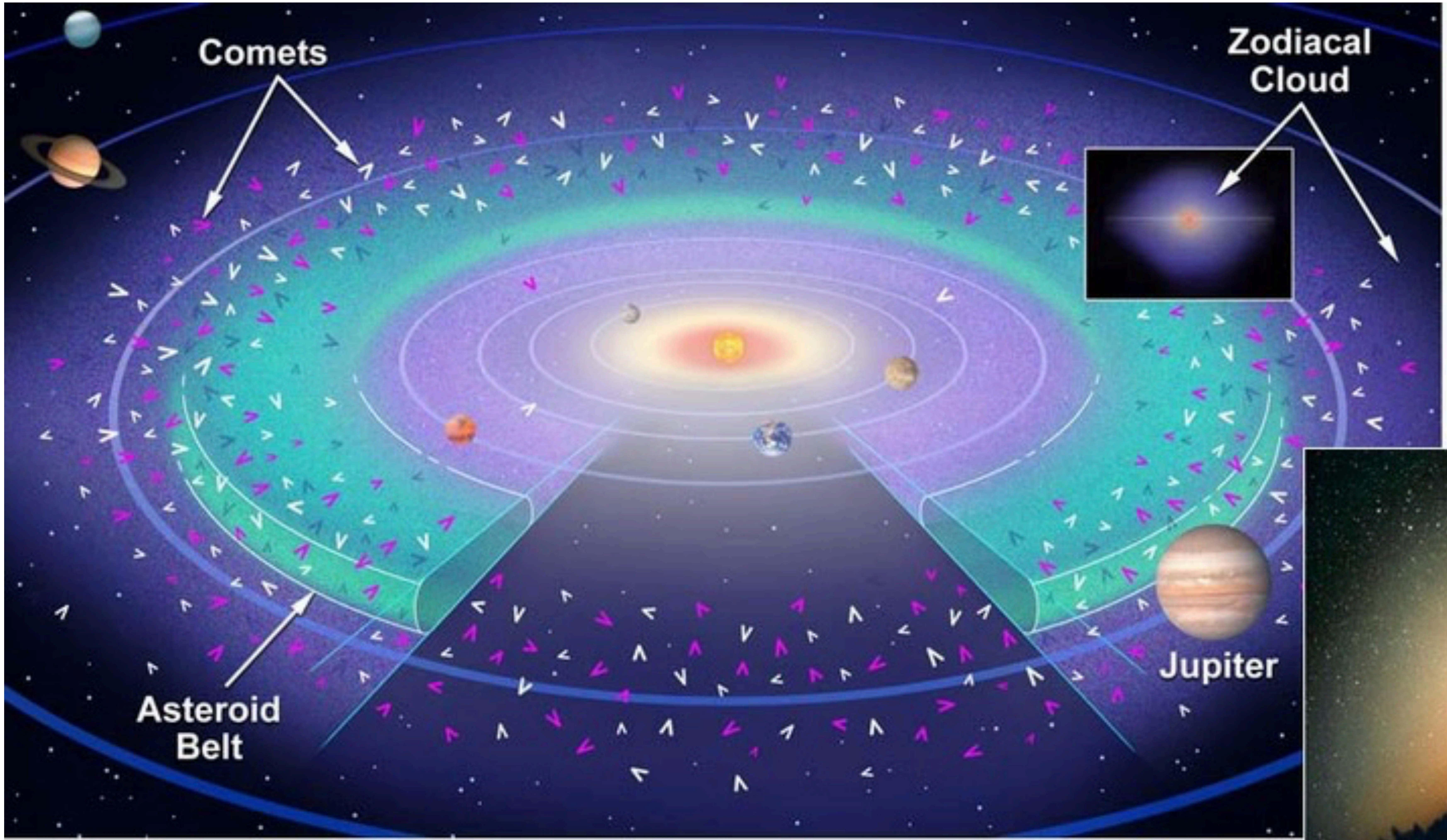
Zodiacal Light

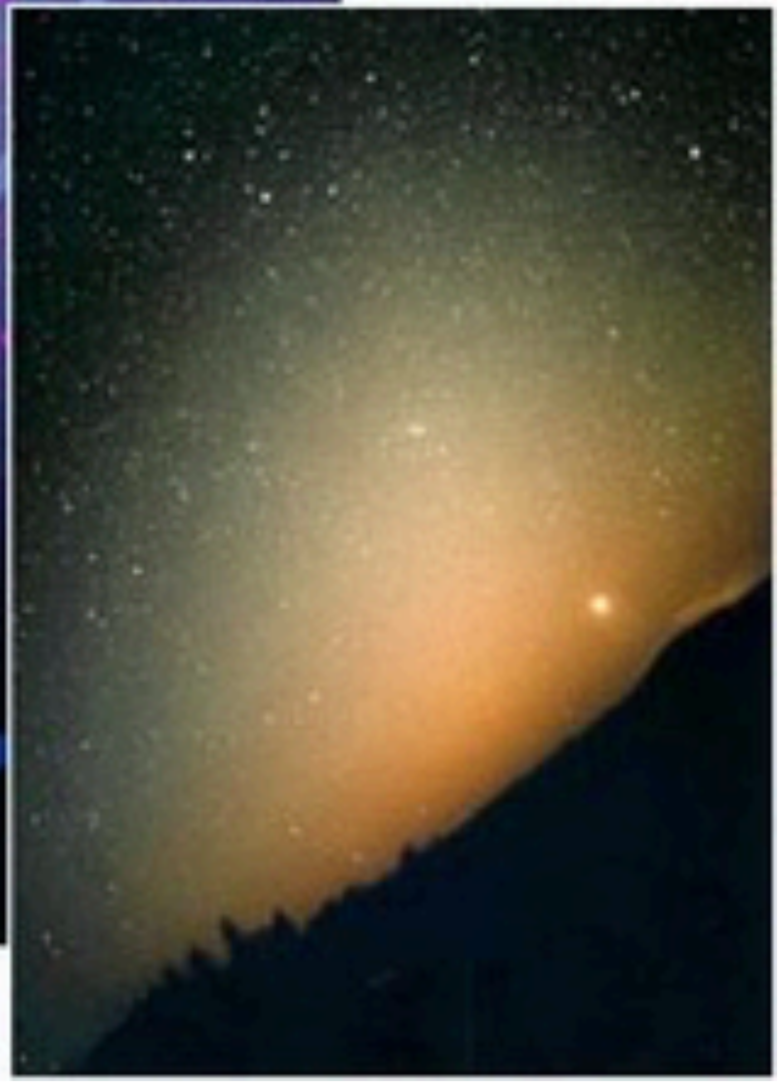
- Dust clouds in orbital plane of solar system planets scatters sunlight
- Optical depth of 10^{-7}, total mass of 10^{-9} Earth masses
- Complex structure:
    - background density
    - 8 dust trails from short-period comets
    - dust bands from asteroid families in Main Belt
    - 2 resonant dust rings



astrobob, national geographic

Zodiacal Light

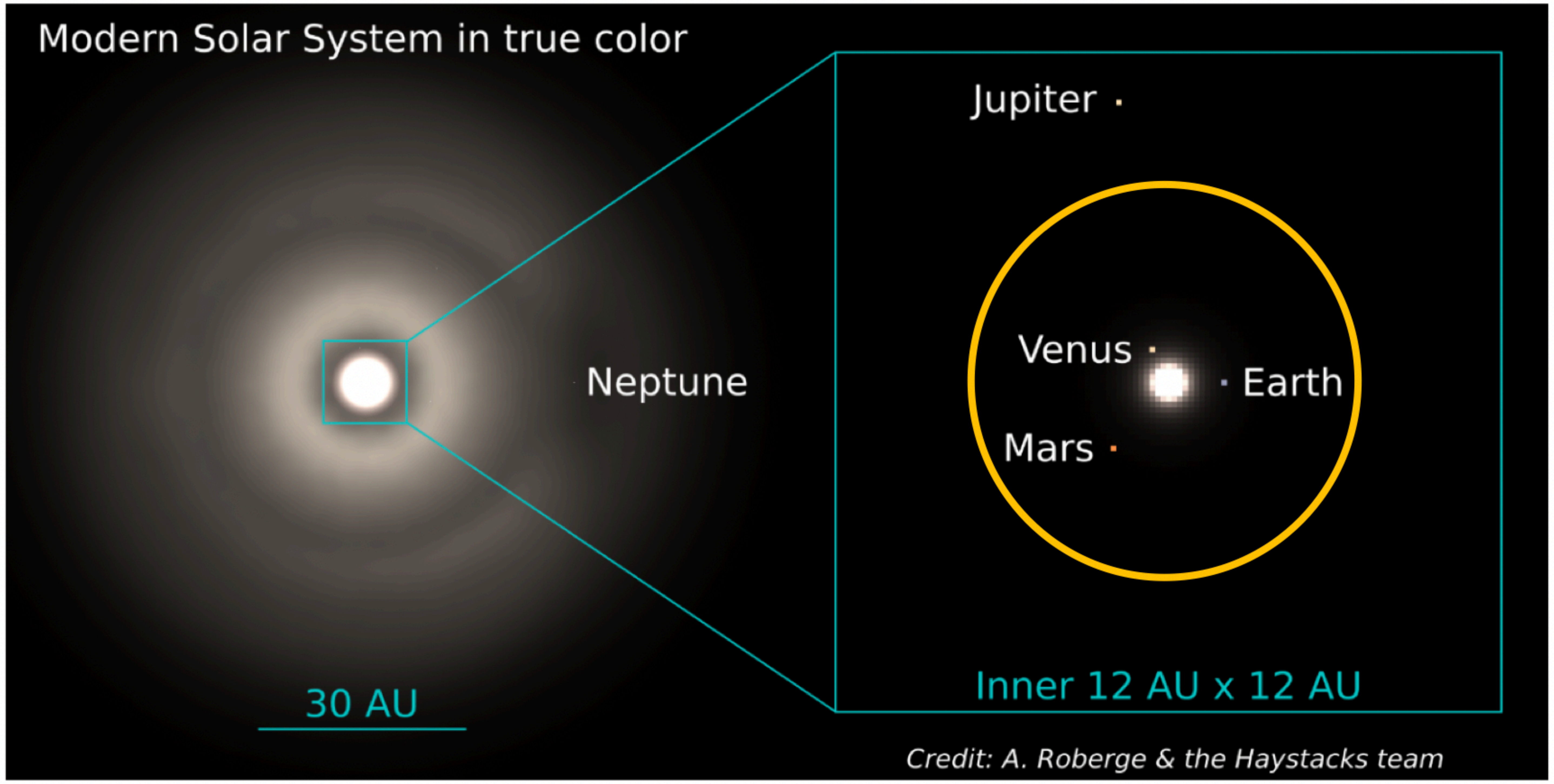




astrobites

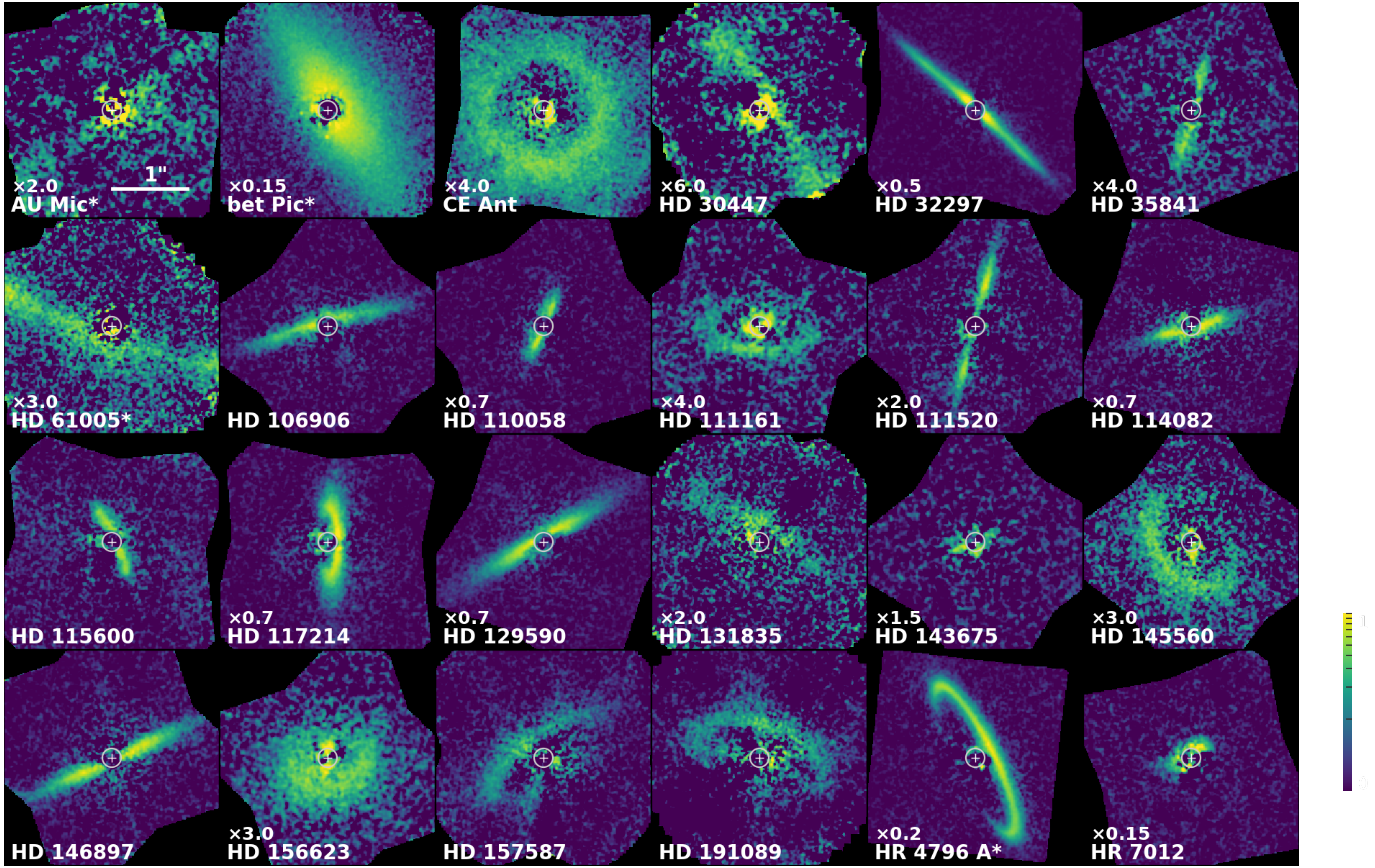
Zodiacal Light and imaging exoplanets

- “exozodi” (zodiacal light around other stars) is an important issue for imaging extrasolar planets
- Can be mitigated with larger telescopes: less exozodi per resolution element
- There is ongoing research to determine how other stars’ zodiacal emission compares to the solar system’s



Debris Disks

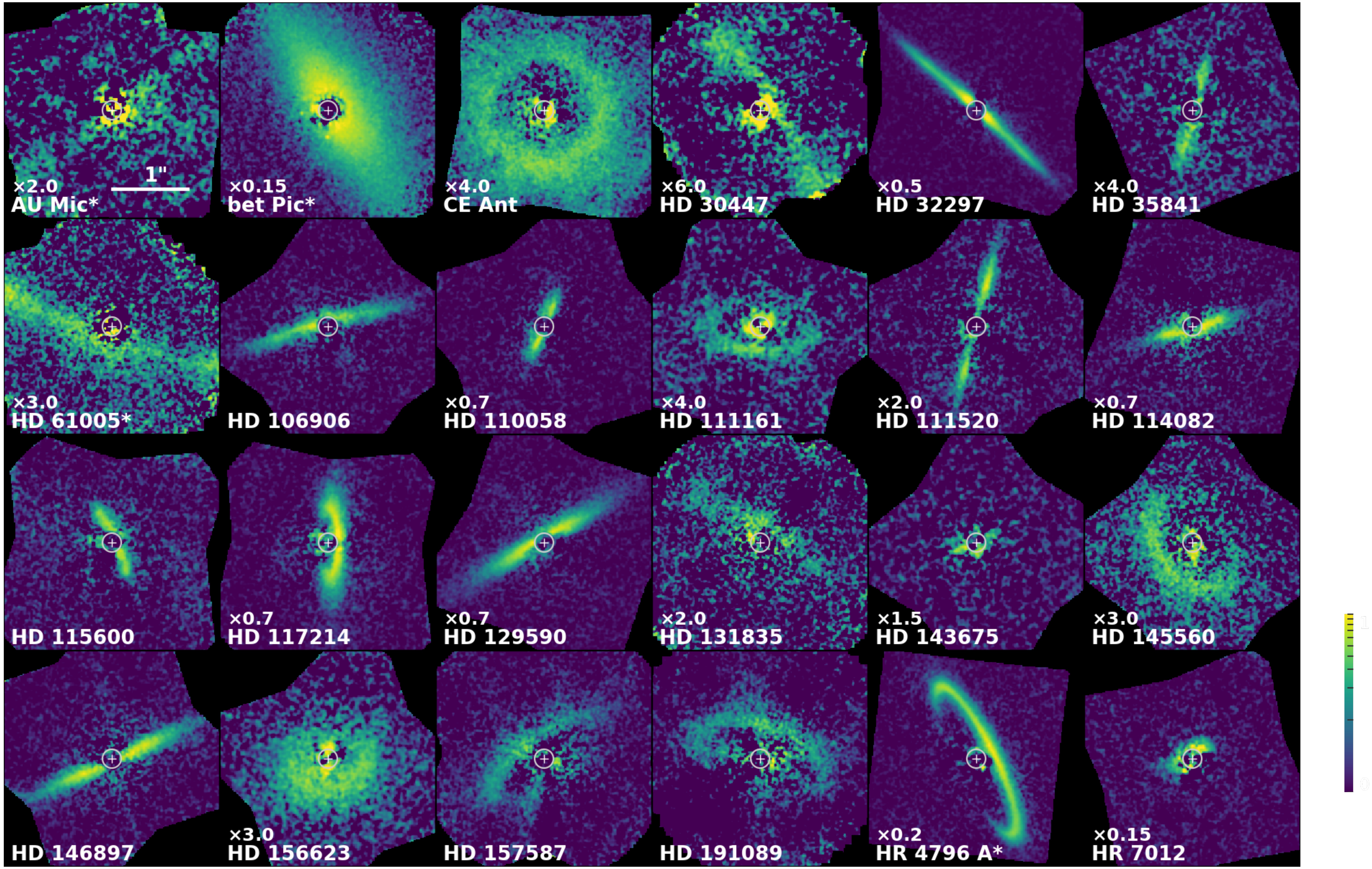
- Originally called the "Vega Phenomenon," for stars that, like Vega, had more infrared emission than expected
- Now understood to be exozodiacal dust that emits at mid-infrared wavelengths and scatters starlight at visible and near-infrared wavelengths
- ~50% of young (<100 Myr) stars have a detectable debris disk, dropping to ~1% at 1 Gyr
- Have complicated structures, and extend out to 10s to 100s of AU



Esposito et al. 2020

Debris Disks

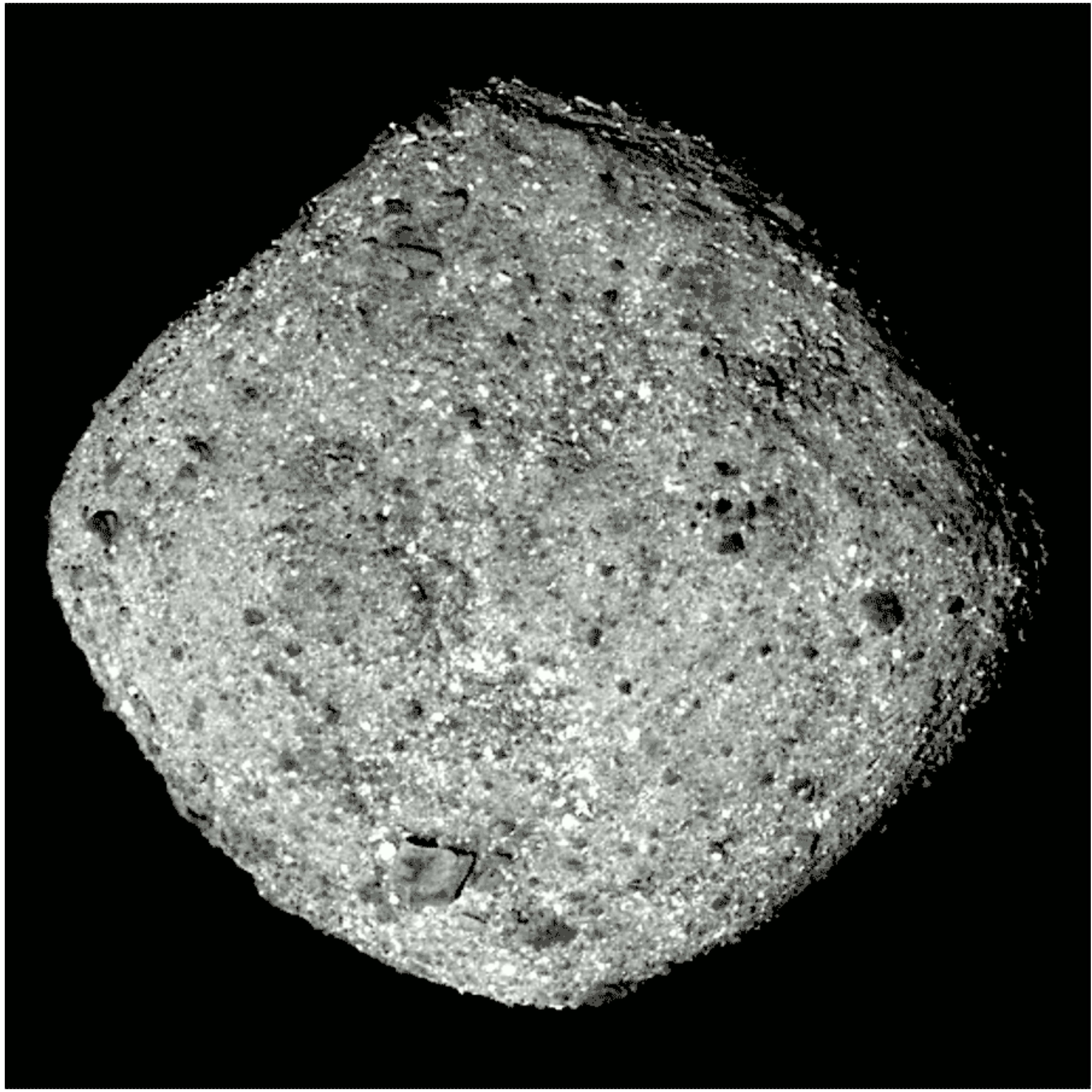
- Sometimes called “Second generation” disks: this is NOT the gas and dust that planets formed out of (those are called “protoplanetary disks”)
- PR drag and radiation pressure should be removing dust in these systems
- Dust in debris disks likely comes from recent collisions of planetesimals in these systems



Esposito et al. 2020

Yarkovsky Effect

- For larger bodies (meters to km), the rotational period is much shorter than the time it takes for heat to diffuse across the body
- The surface temperature is hotter on the dayside compared to the nightside
- Hotter areas of the asteroid emit (by blackbody) more than colder areas



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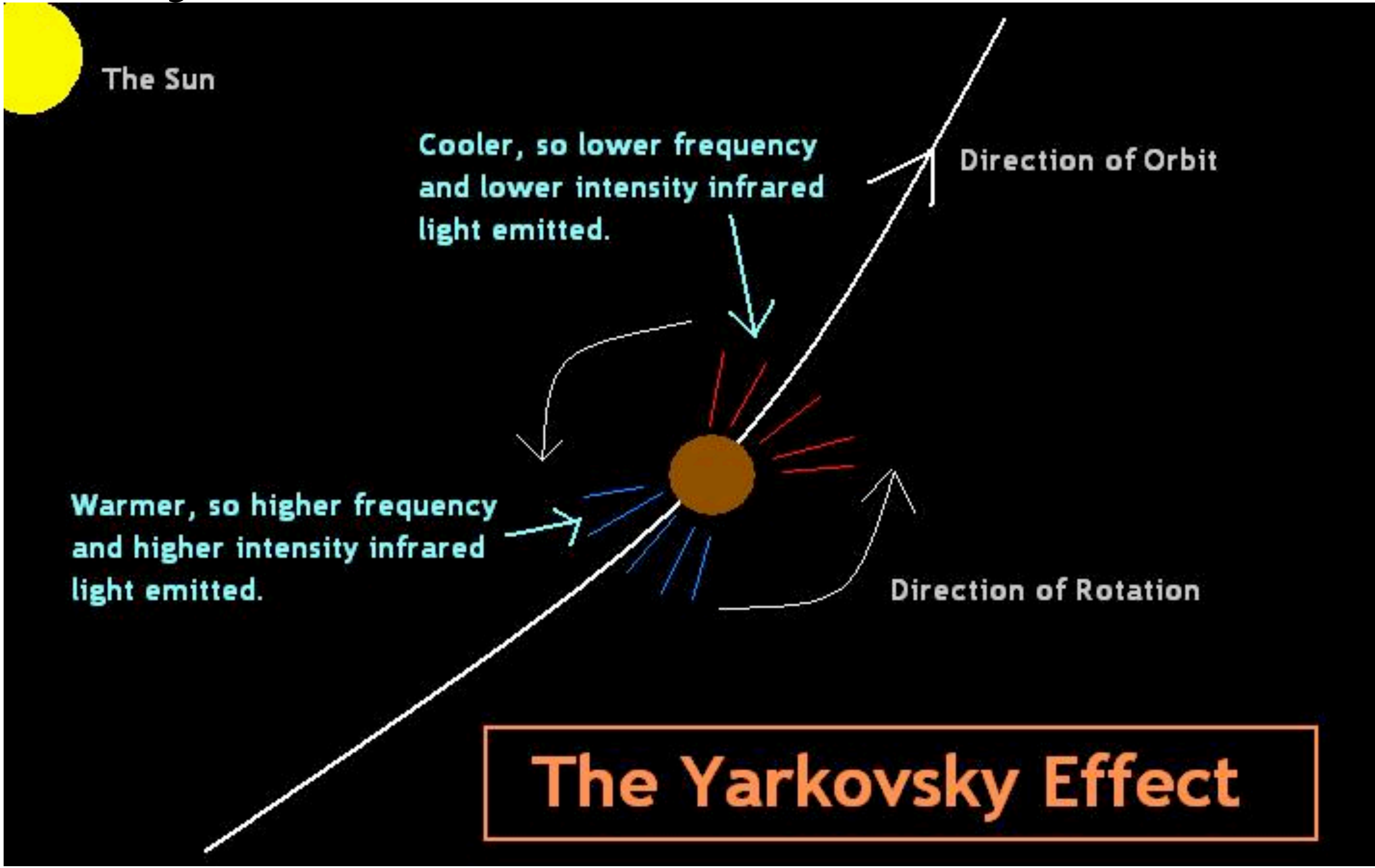
Yarkovsky Effect



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Response Card Question

- Consider two asteroids, both orbit the Sun counterclockwise when viewed from above. Asteroid 1 is rotating counterclockwise, Asteroid 2 is rotating clockwise. How will their orbital paths change due to the Yarkovsky Effect?
  - (A) — Asteroid 1 and Asteroid 2 will both move closer to the Sun
  - (B) — Asteroid 1 and Asteroid 2 will both move further away from the Sun
  - (C) — Asteroid 1 will move closer to the Sun, Asteroid 2 will move further away
  - (D) — Asteroid 1 will move further away from the Sun, Asteroid 2 will move closer

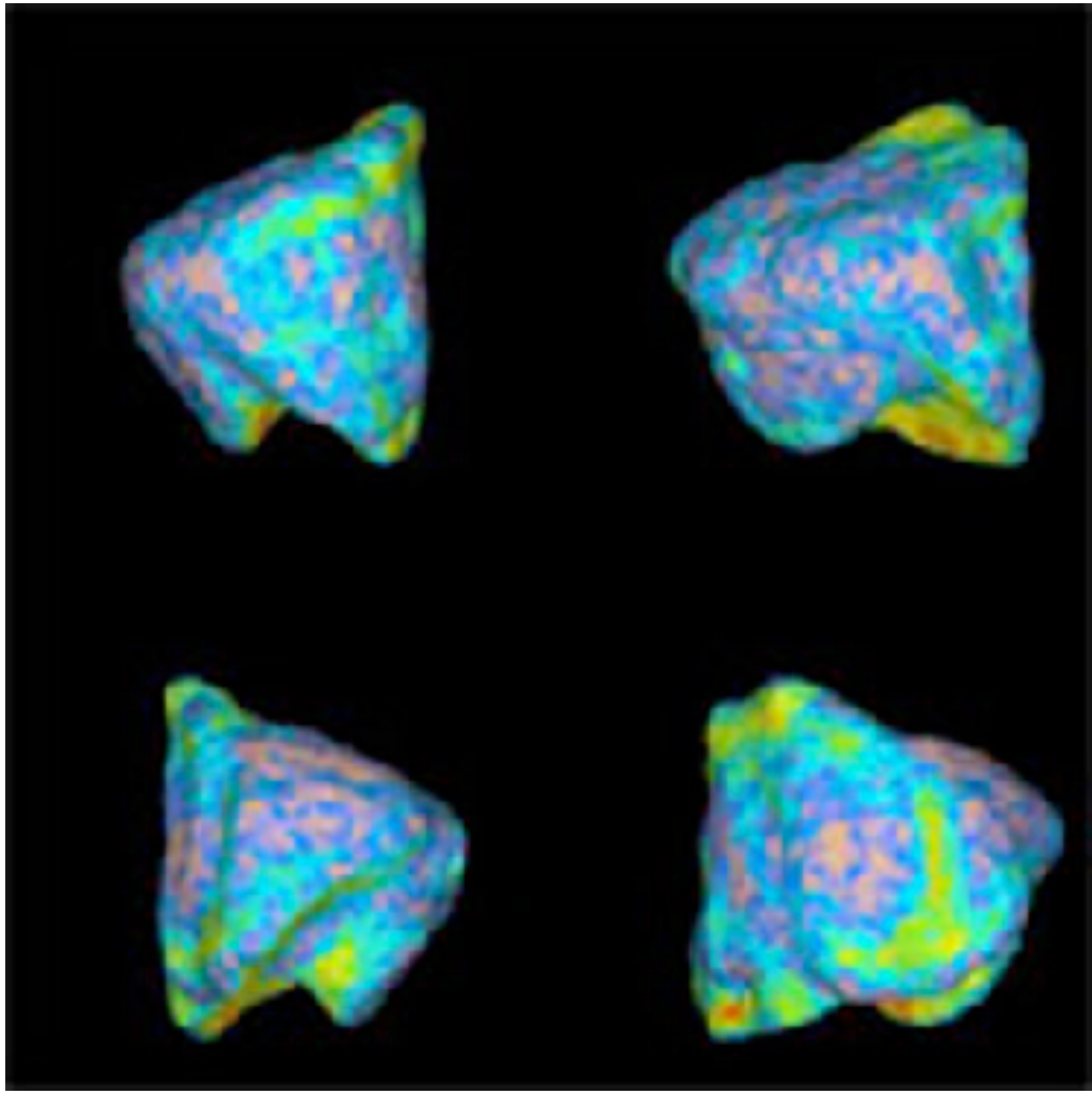
Yarkovsky Effect

- Assume evening to morning temperature difference is ΔT, then net force experience by the object is:

$$F_{yark} = \frac{8}{3}\pi R^2 \frac{\sigma T^4}{c}\frac{\Delta T}{T}\cos\psi$$

- Obliquity (ψ) is angle between angular momentum vector of object's spin and it's orbit around the Sun

- Near Earth asteroid Golevka: radar ranging showed is orbit had shifted by 15 km between 1991 and 2003.



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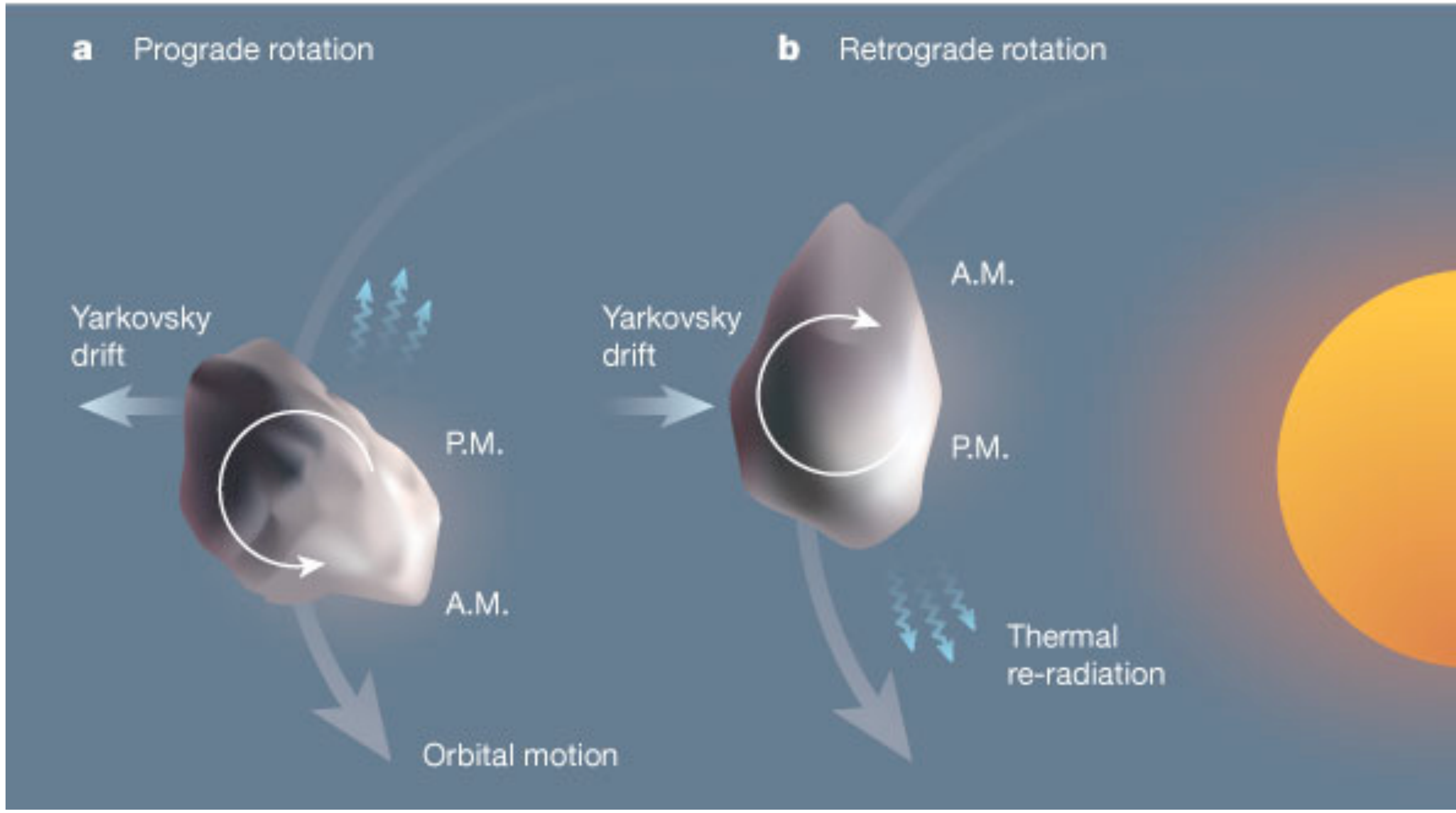
Yarkovsky Effect

- Direction of drift depends on whether the rotation of the body is prograde or retrograde:
  - Prograde (angular momentum of spin and orbit are aligned) results in an outward drift
  - Retrograde (angular momentum of spin and orbit are 180 degrees apart) results in an inward drift



Nature

For next time

- Reading: de Pater & Lissaeuer Chaper 2, section 2.7.5-2.7.6