ASTR 620: Planetary Processes

Professor Eric Nielsen

Lecture 6: 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
- Homework 2 will be due in 1 week, Wednesday September 14, 11:59pm

Review of the last class

- Objects that feel significant radiation pressure:
  - (A) — Are about 1 micron in size, and spiral into the Sun
  - (B) — Are about 1 cm in size, and spiral into the Sun
  - (C) — Are about 1 meter in size, and spiral into the Sun
  - (D) — Are about 1 micron in size, and feel an outward force from the Sun
  - (E) — Are about 1 cm in size, and feel an outward force from the Sun

Review of the last class

- Objects that feel significant Poynting-Robertson Drag:
  - (A) — Are about 1 micron in size, and spiral into the Sun
  - (B) — Are about 1 cm in size, and spiral into the Sun
  - (C) — Are about 1 meter in size, and spiral into the Sun
  - (D) — Are about 1 micron in size, and feel an outward force from the Sun
  - (E) — Are about 1 cm in size, and feel an outward force from the Sun

Review of the last class

- Which of these sets the minimum size for an object to feel significant radiation pressure?
  - (A) — When the object is about the size of a solar wind electron
  - (B) — When the object is about the size of a typical solar photon
  - (C) — When the object is about the size of the mean free path for a photon in the solar system
  - (D) — When the object is about the size of a typical gas molecule in Earth’s atmosphere.
  - (E) — There is no minimum size

Review of the last class

- Which best describes why objects feel a “headwind” from photons that are emitted radially from the Sun?
  - (A) — Only objects on elliptical orbits feel that headwind
  - (B) — Photons follow the Sun’s magnetic field lines and take a curved path through the solar system
  - (C) — The speed of light is finite
  - (D) — Heisenberg uncertainty principle tells us momentum is uncertain, so some component is in the non-radial direction
  - (E) — There is no such thing as Poynting-Robertson drag, it’s an elaborate social experiment we use to see if grad students will question the things taught in astronomy classes

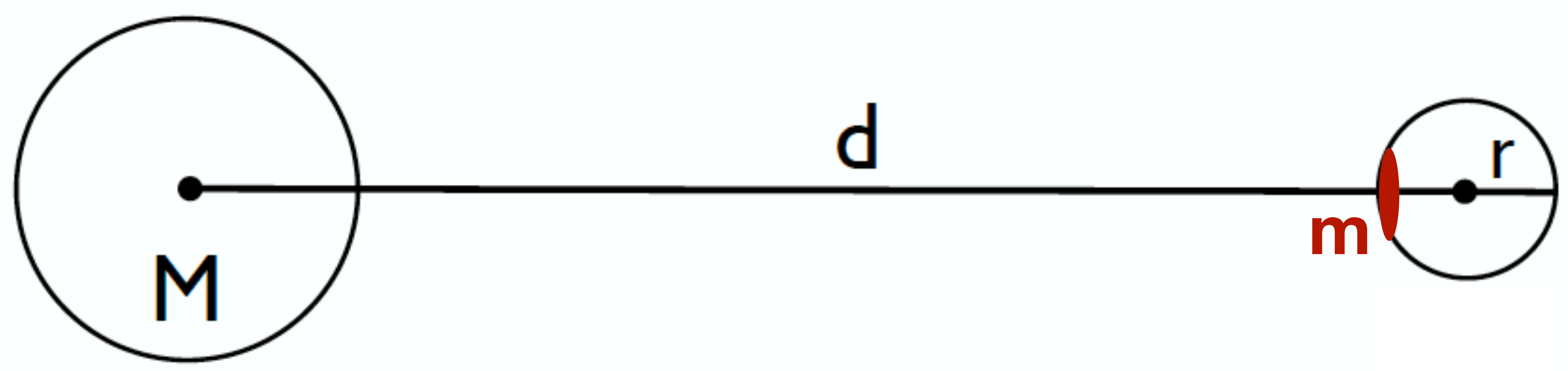
Review of the last class

- An asteroid that is rotating prograde:
  - (A) — Has its spin and orbital angular momentum vectors aligned, and will move toward the Sun
  - (B) — Has its spin and orbital angular momentum vectors aligned, and will move away from the Sun
  - (C) — Has its spin and orbital angular momentum vectors anti-aligned, and will move toward the Sun
  - (D) — Has its spin and orbital angular momentum vectors anti-aligned, and will move away from the Sun
  - (E) — Has its spin and orbital angular momentum vectors anti-aligned, and will stay the same distance from the Sun

Tidal Force

- $$F_{tidal} = \frac{2GMmr}{d^3}$$
- M: mass of the object causing the tide (say, the Moon)
- m: mass of the thing (say, a part of the ocean) feeling the tidal force
- (mass of the body feeling the tide does not appear)

- Magnitude falls off as $1/d^3$
- Magnitude decreases for smaller planets (smaller r)
- Magnitude is larger for the tides from a more massive body
- Magnitude does not depend on mass of the body feeling the tide

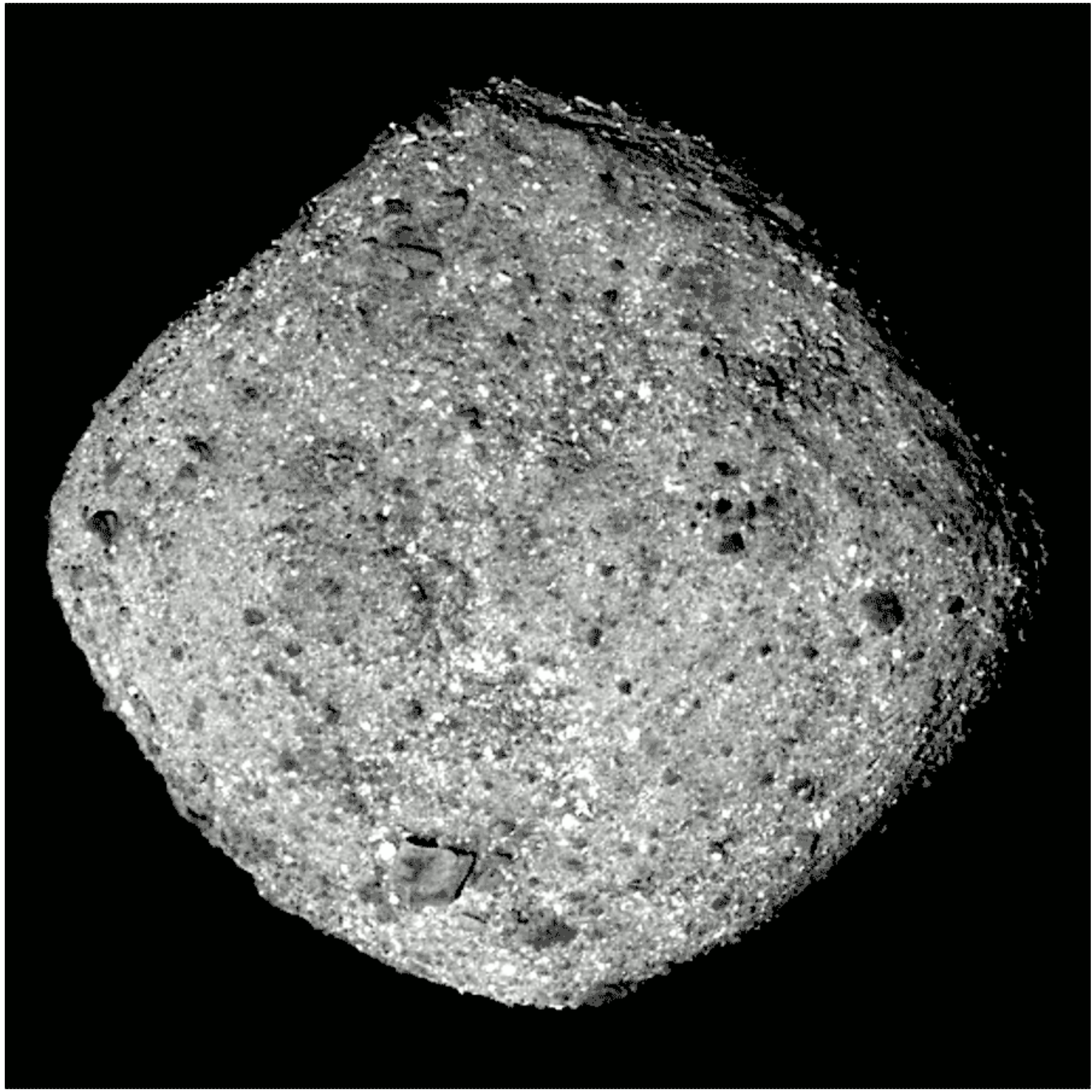


Overview of Processes

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

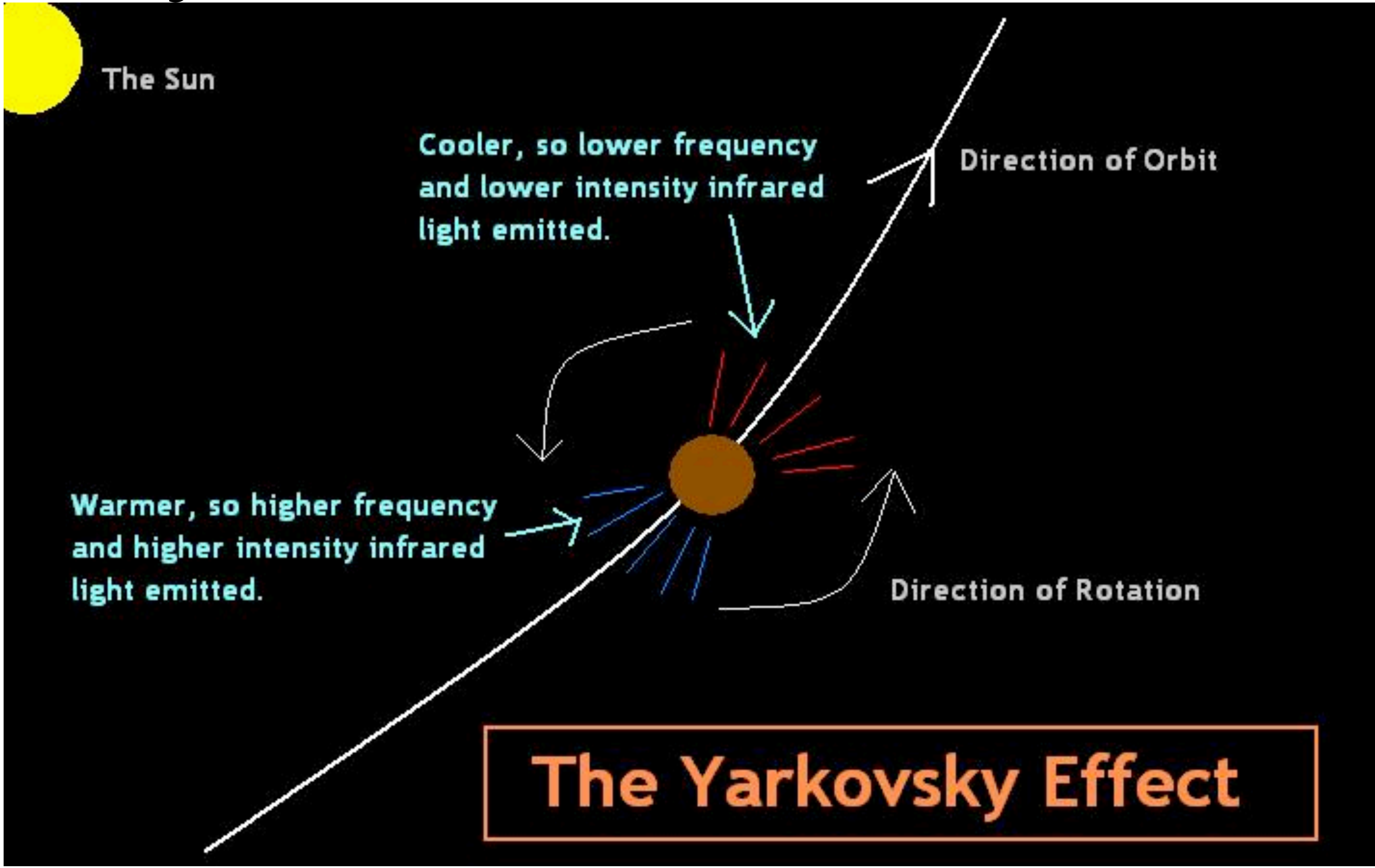
Yarkovsky Effect

- 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



NASA

Yarkovsky Effect



astroprofspage.com

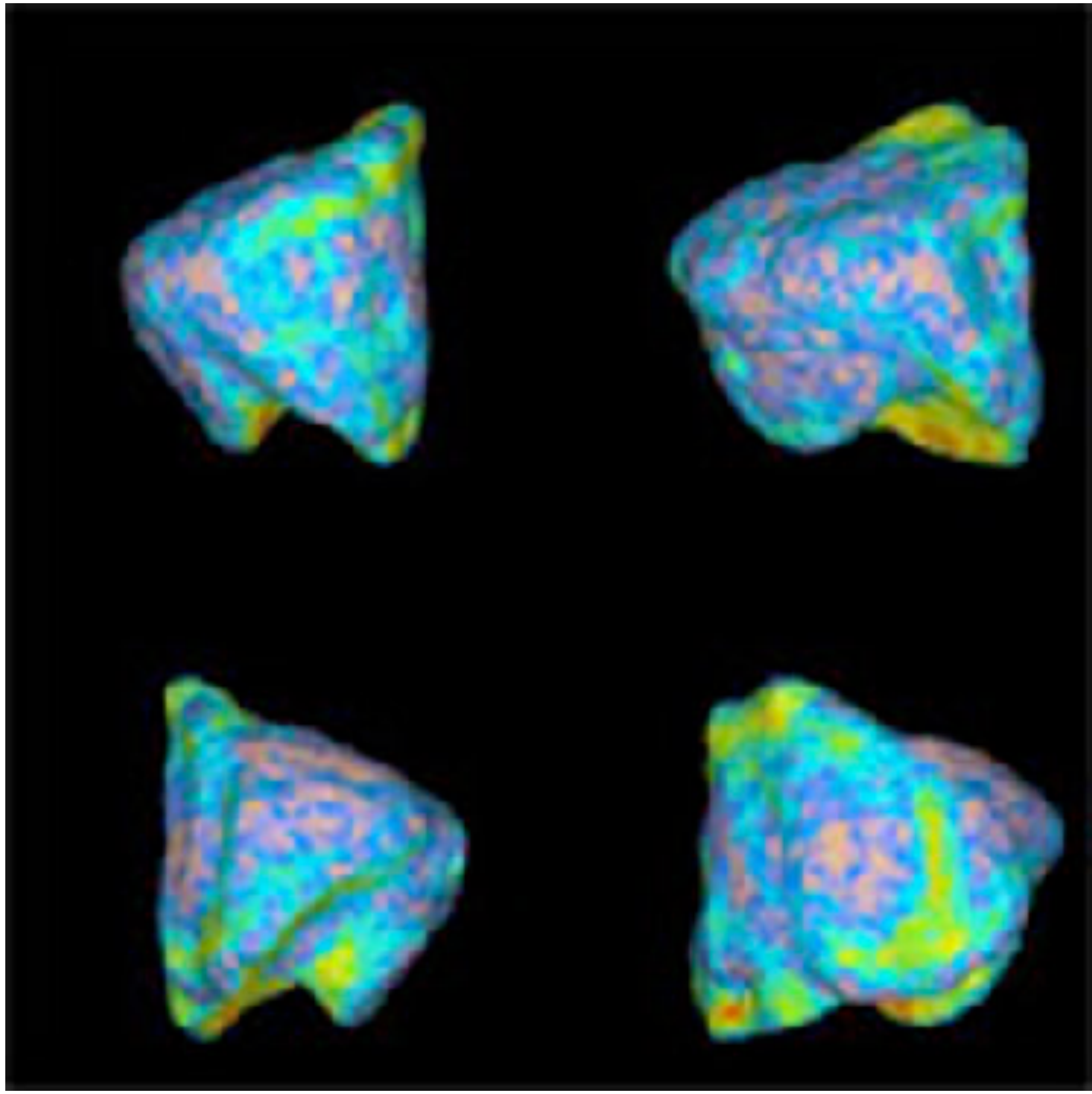
Yarkovsky Effect

- 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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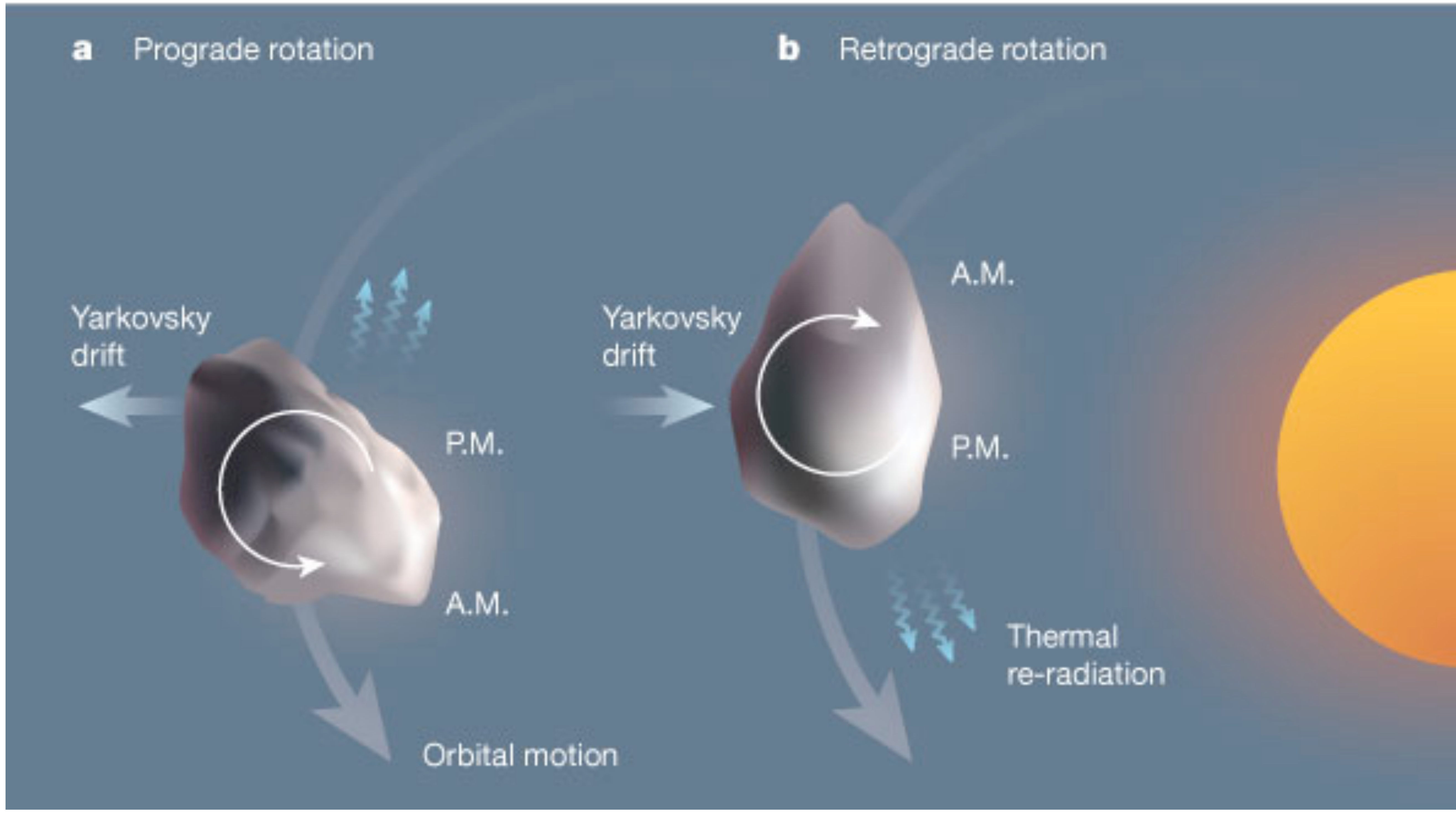
Yarkovsky Effect

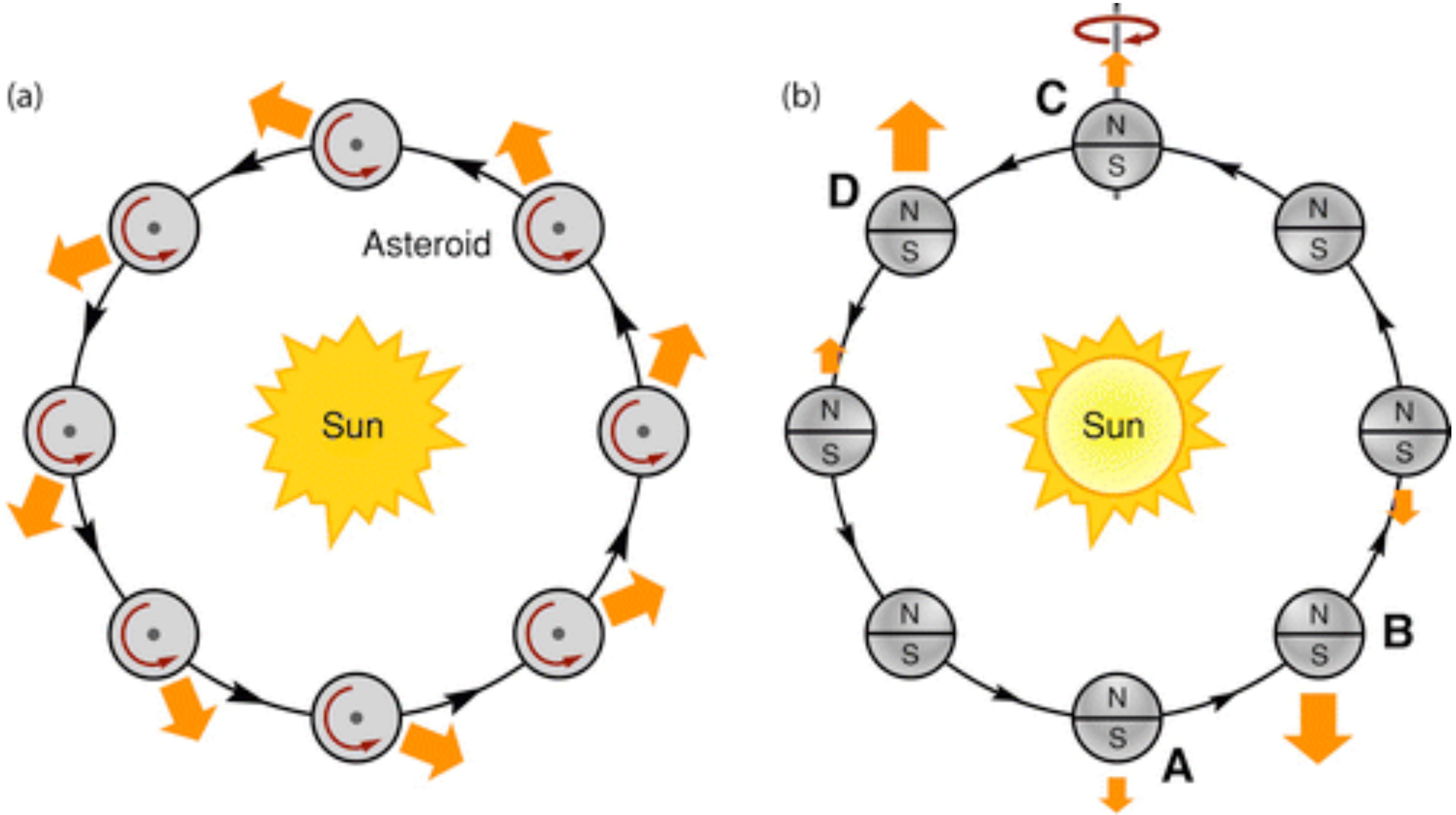
- Direction of drift depends on whether the rotation of the body is prograde or retrograde:
  - Prograde (angular momentum of spin and orbit are aligned) results in an outward drift
  - Retrograde (angular momentum of spin and orbit are 180 degrees apart) results in an inward drift



Nature

Obliquity and the Yarkovsky Effect

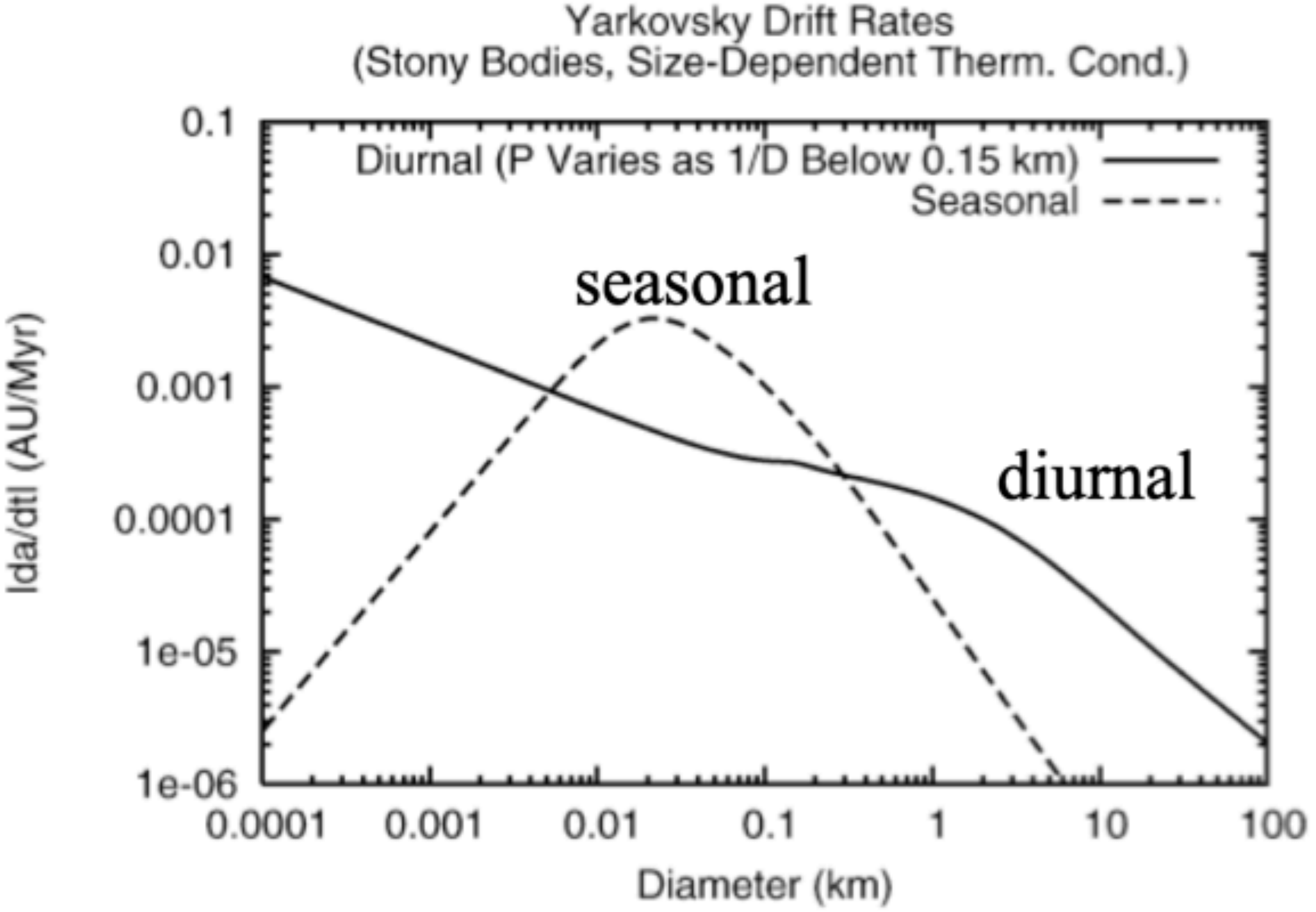
- Asteroids with low obliquity (a) have a diurnal (day/night) Yarkovsky Effect
- Asteroids with a high obliquity (b) have a seasonal (first half of orbit/ second half of orbit) Yarkovsky Effect



Bottke WF, Jr., et al. 2006.
Annu. Rev. Earth Planet. Sci. 34:157–91

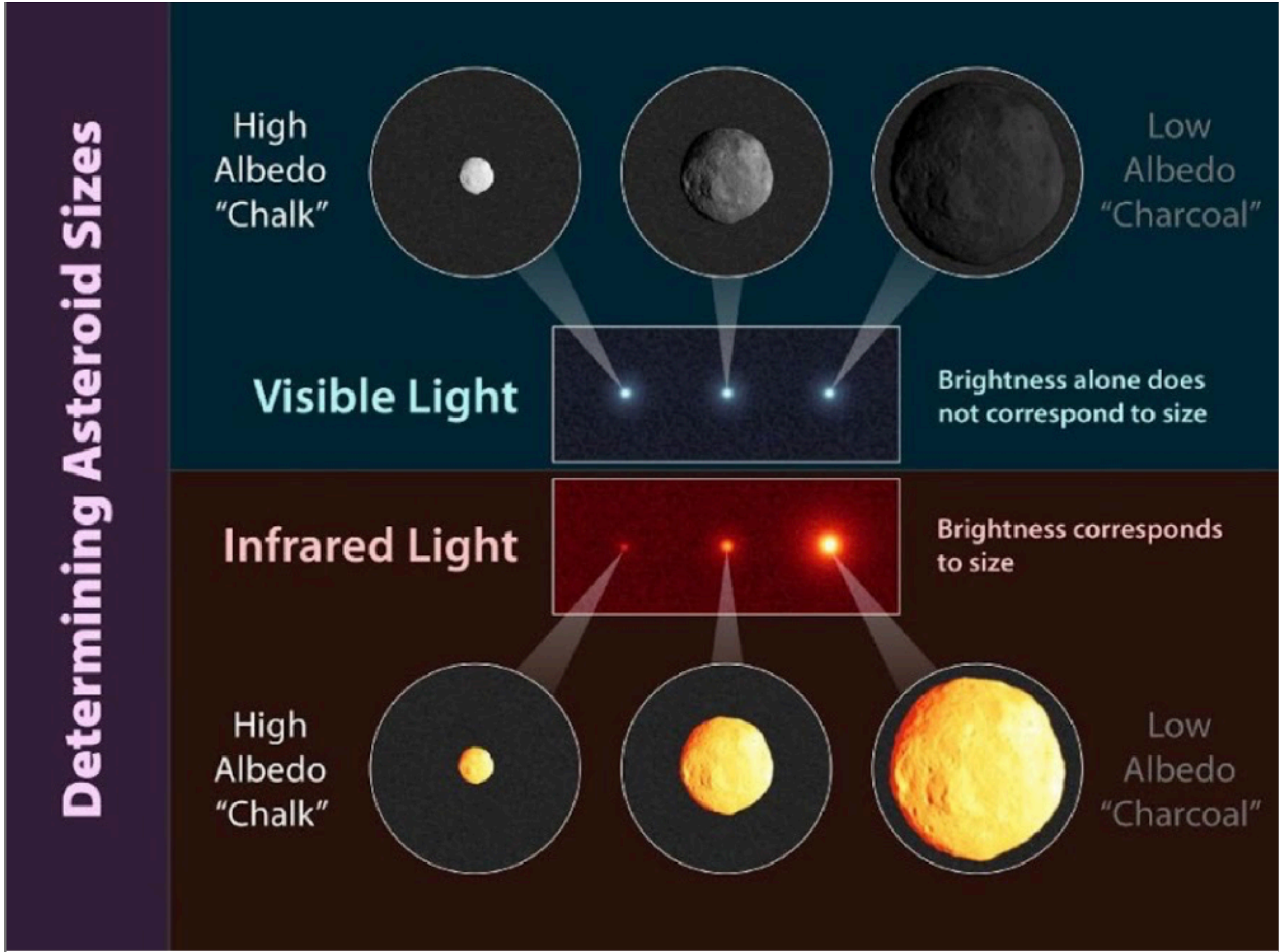
Asteroid Size Distributions and the Yarkovsky Effect

- Amplitude of the Yarkovsky effect for two asteroids of the same size depends on their obliquity (seasonal vs. diurnal)
- Near Earth Asteroids vs. Main Belt Asteroid have a different size distribution, partially due to Yarkovsky Effect



O’Brien & Greenberg (2006)

Measuring Asteroid Sizes



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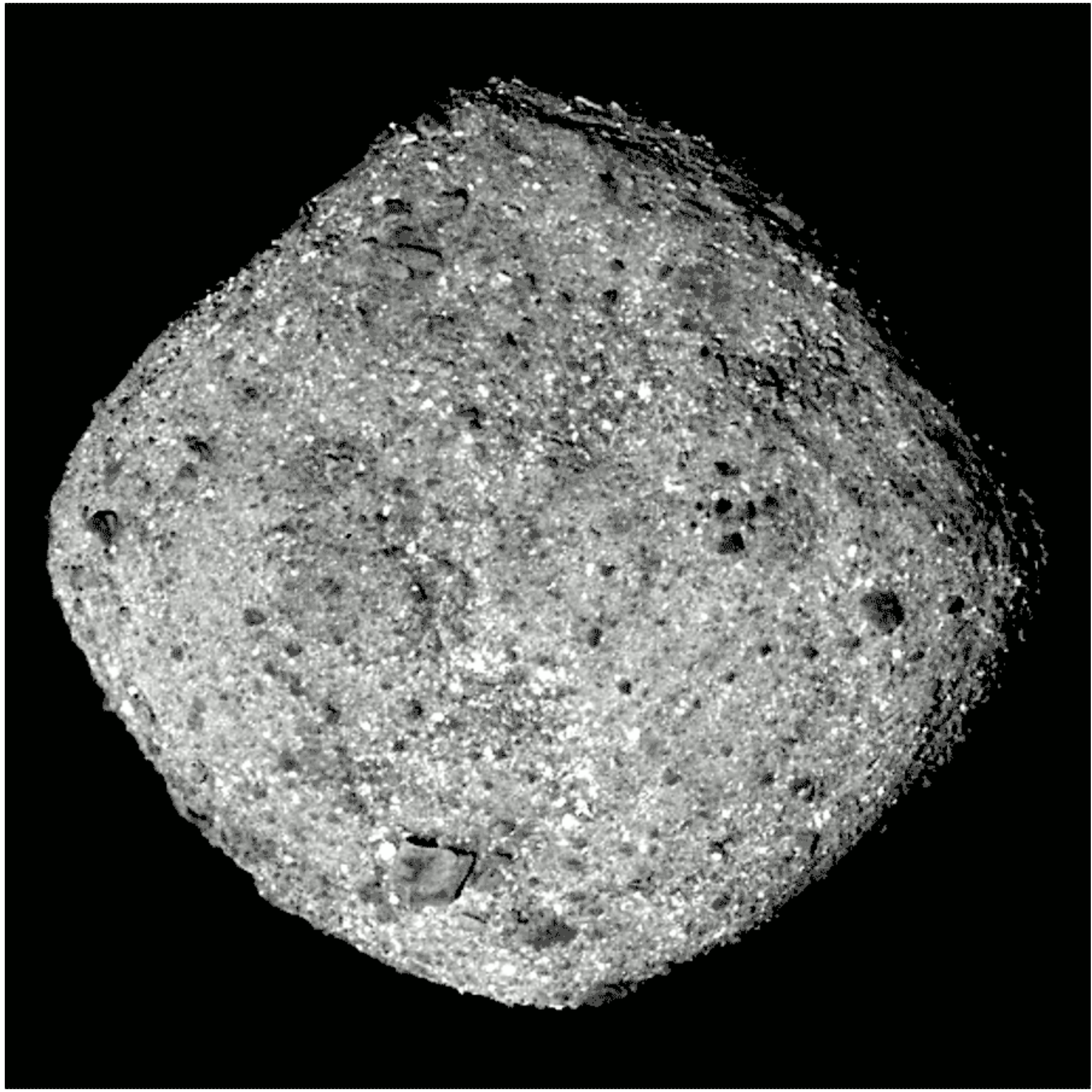
YORP

- Yarkovsky Effect is excess emission from the “sunset” part of the surface changing the asteroid’s orbital path as it rotates

- A second order effect is this emission can also change the asteroid’s rotation:

  - Yarkovsky-O’Keefe-Radzievskii-Paddack effect: YORP



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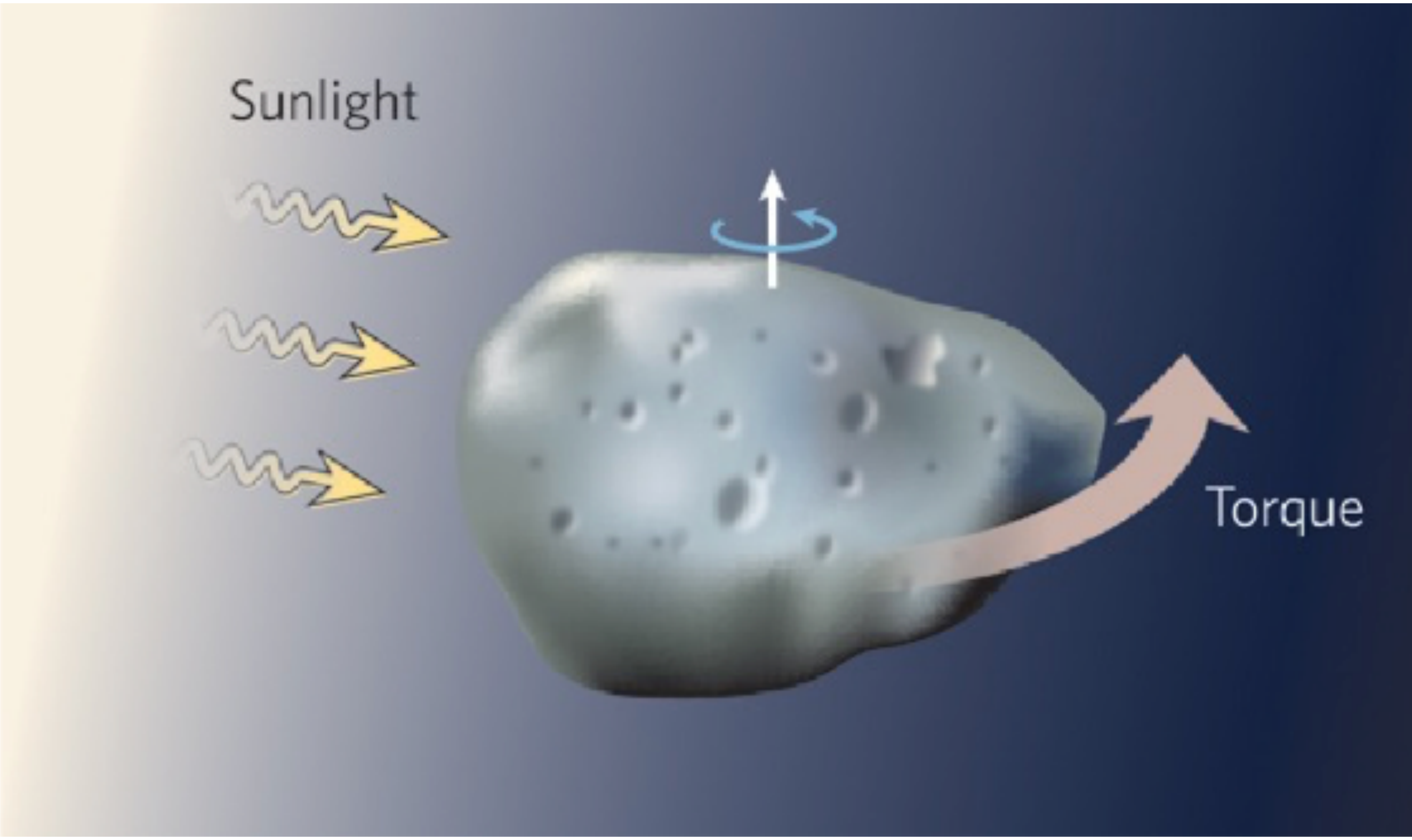
YORP

- Large asteroids have mainly “normal” rotators
- As we move to smaller asteroids, there are fewer and fewer “normal” rotators, and more extremes

Asteroids with D > 125 km	**Asteroids with D ~ 50-125 km**	**Asteroids with D < 50 km**
Rotation rates follow Maxwellian Distribution	**Small excess of fast rotators**	**Strong excess of very fast rotators, strong excess of very slow rotators**

YORP

- Net emission of light is normal to the emitting surface
- If all asteroids were spheres, all emission would be radial to the axis of rotation, and there'd be no YORP
- Asteroids are not spheres, so there is a net torque from the emission due to the irregular shape
- To quantify the amplitude of YORP, need to measure the asteroids shape (imaging, light curves, or occultations)



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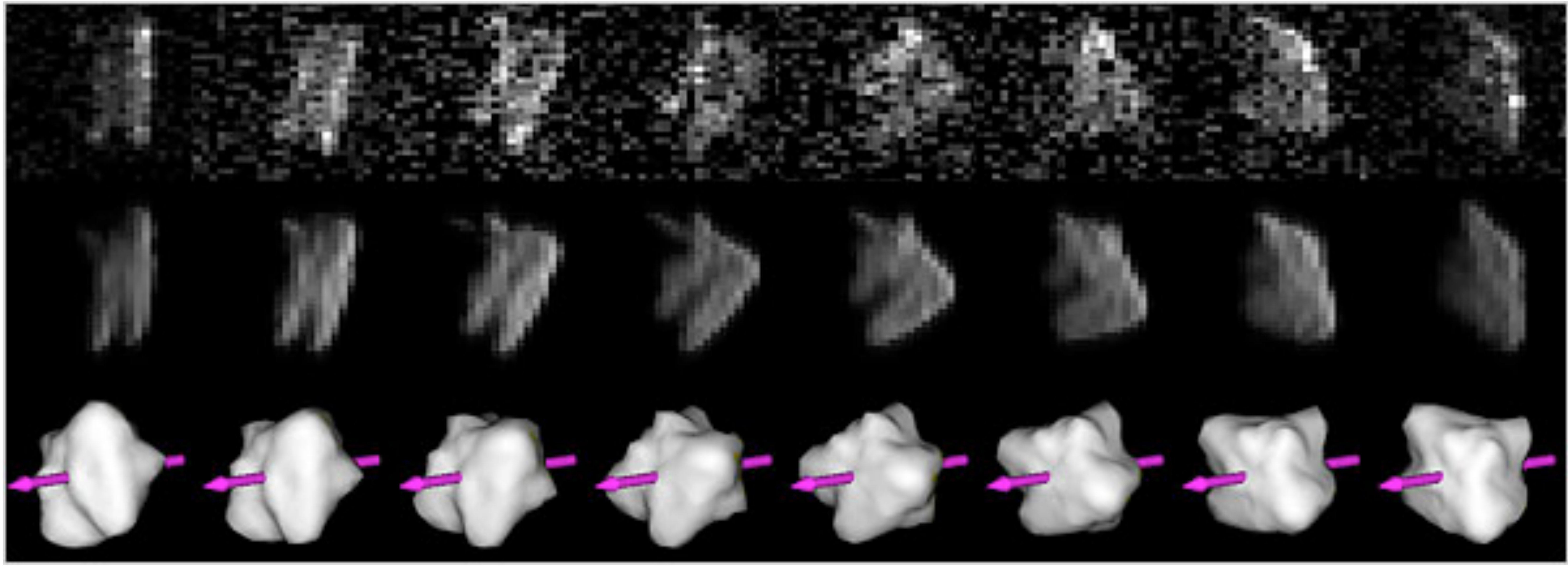
2005 PH5

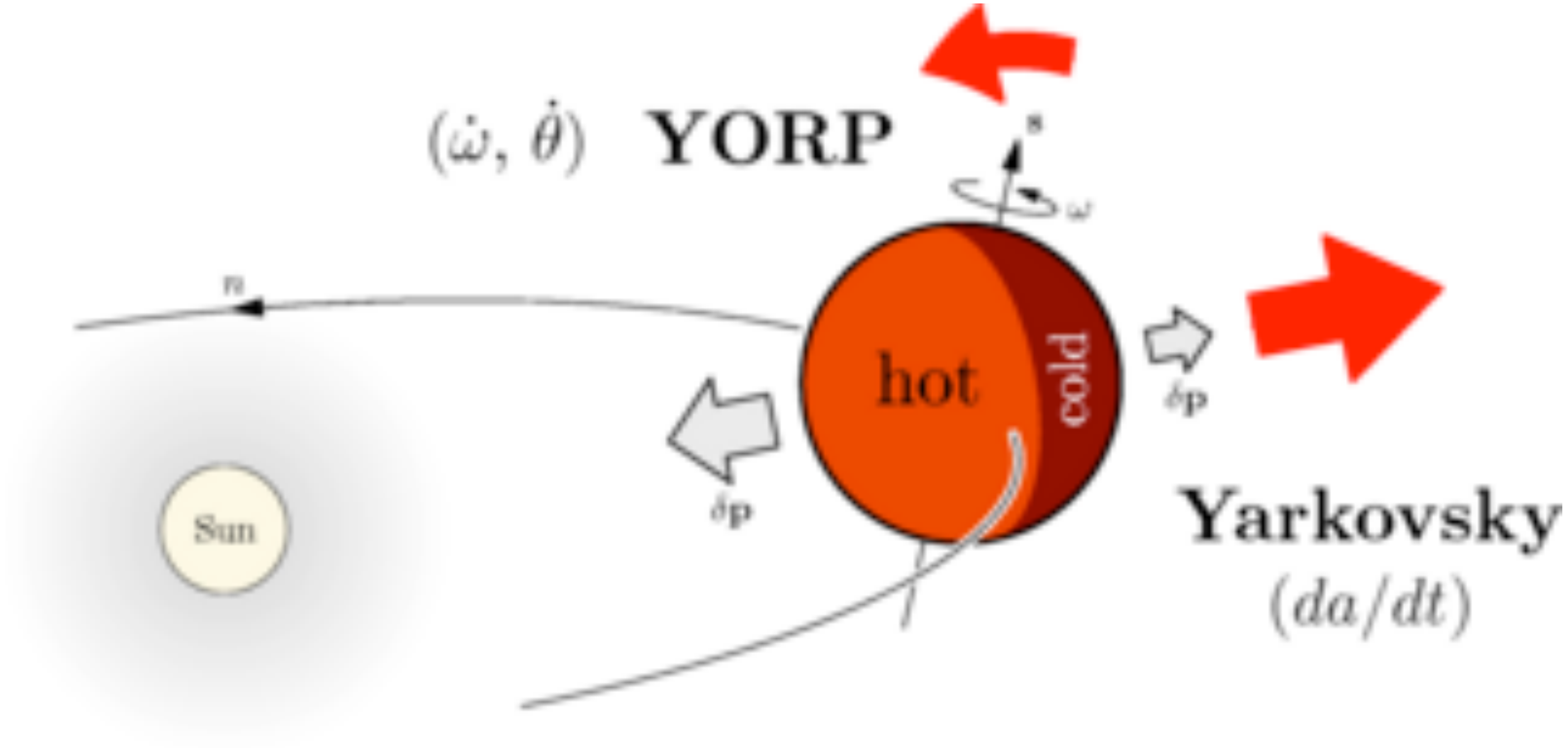
- Radar observations of the surface
- 12 minute rotation period (now)
- 6 minute rotation period (in 0.5 million years)
- 20 second rotation period (in 35 million years)
- Is this why many Near Earth Asteroids (NEAs) have moons?
    - spin so fast that a piece breaks off?



New York Times

Yarkovsky and YORP

- Help move small asteroids (D < 40 km) from source location to Earth-crossing orbits
- Disperse asteroid families
- Modify rotation rates and obliquities of D < 40 km asteroids
- Allow asteroids to enter spin-orbit resonances, affects evolution of spin vectors and semi-major axes
- "Nongravitational forces should now be considered as important as collisions and gravitational perturbations to our overall understanding of asteroid evolution" (Bottke et al. 2006)

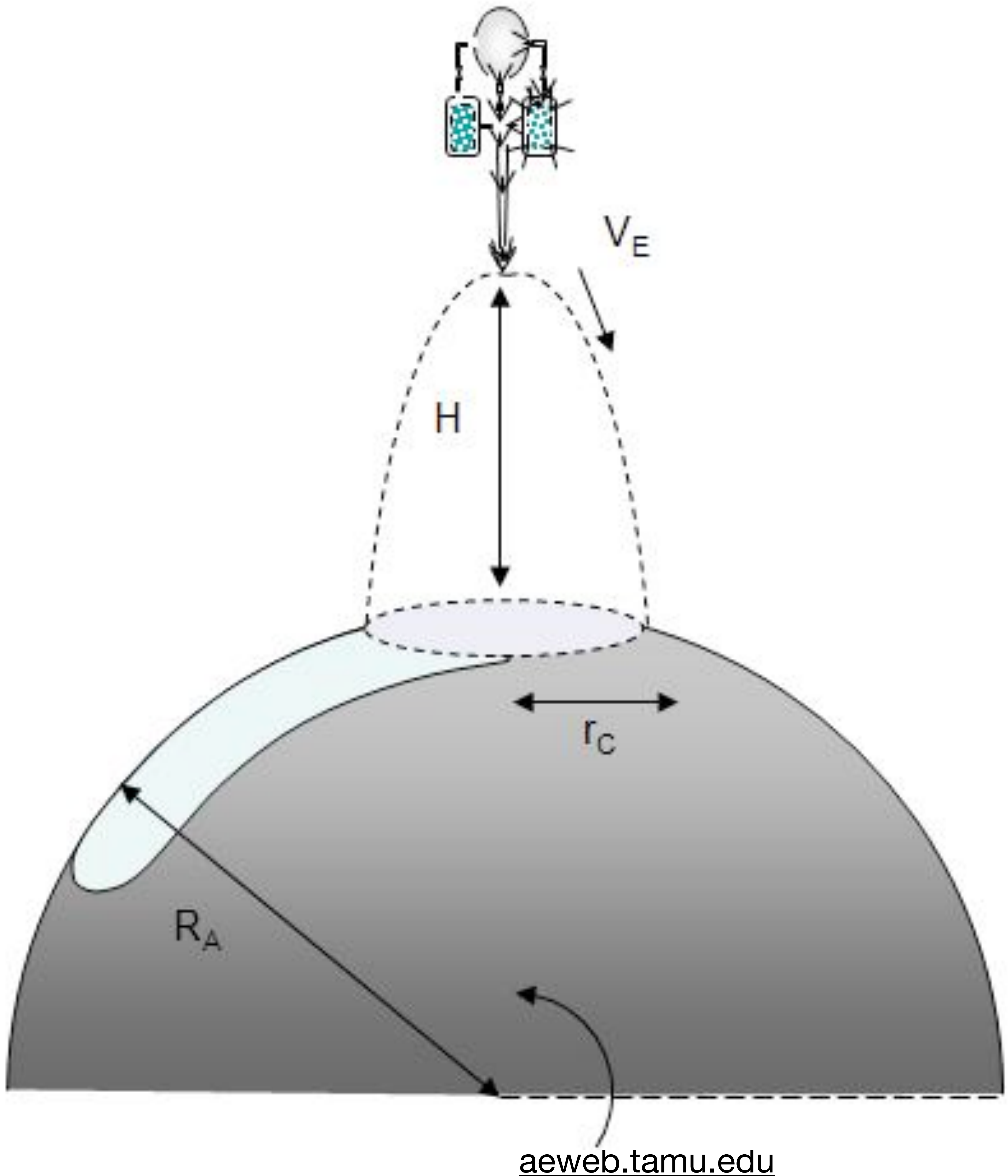


sirrah.troja.mff.cuni.cz

Yarkovsky Effect: How to Save the Earth

- If an asteroid is threatening a future impact on Earth, hiring oil drillers to put a nuclear weapon inside may not be the best move

- Instead, can paint the surface white: changing its albedo, and so altering its trajectory



aeweb.tamu.edu

Response Card Question:

- If I painted an asteroid white, the force from the Yarkovsky Effect would:
  - (A) — get larger
  - (B) — get smaller
  - (C) — stay the same

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

Break

Corpuscular Drag

- Radiation pressure and Poynting-Roberston Drag are due to how a small particle orbiting the Sun interacts with solar photons
- Corpuscular Drag is the interaction of the Solar wind (charged particles from the Sun) and a small particle orbiting the Sun
- Like Poynting-Roberston Drag, this slows particles down so they spiral into the Sun
- Most significant for sub-micron sized particles

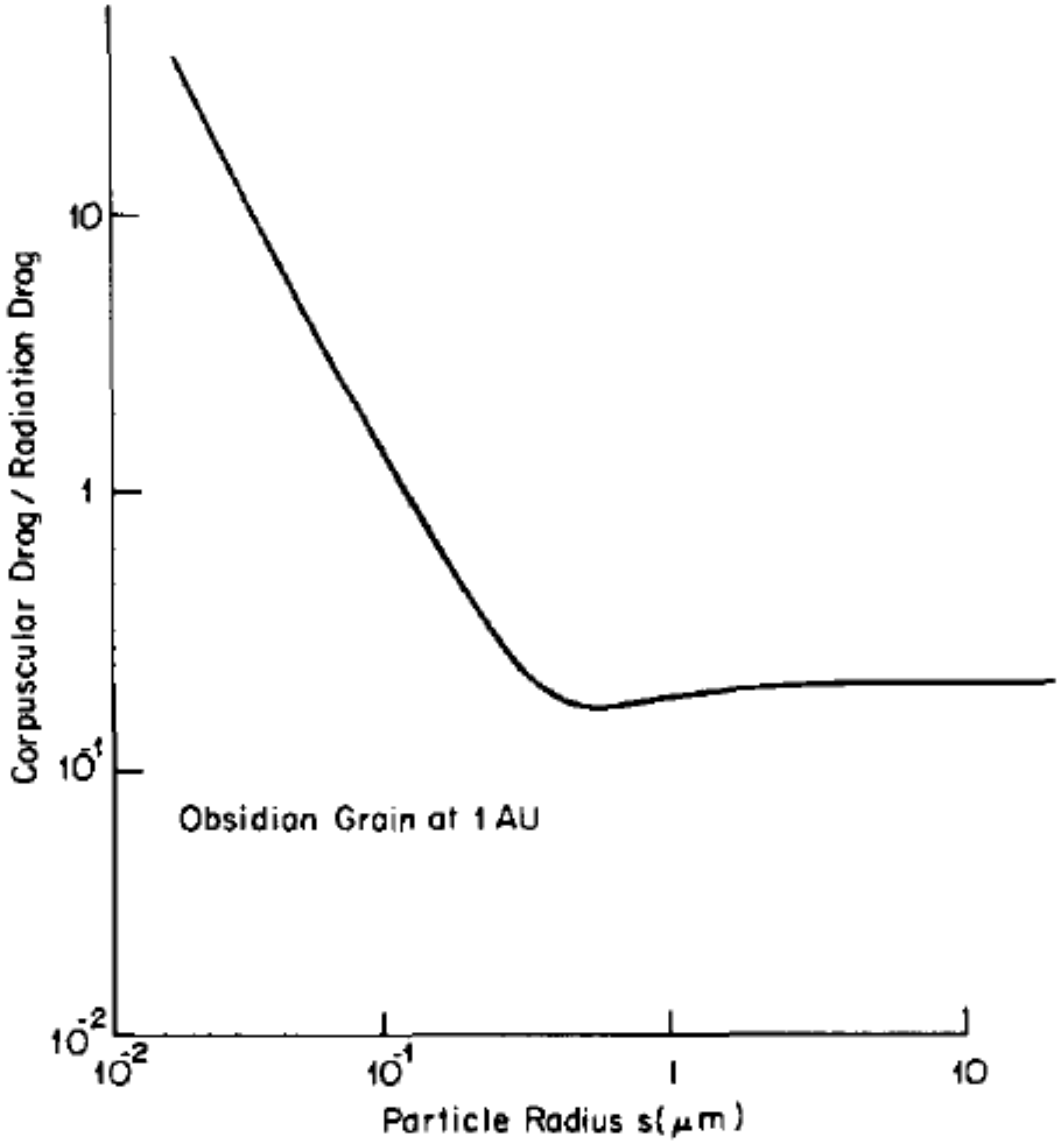


FIG. 11. Ratio of drag caused by the solar wind to hat due to radiation on an obsidian grain at 1 AU. Based on a similar plot given by Lamy (1975).

Burns *et al.* 1979

Corpuscular Drag

- Unlike photons, solar wind particles have mass:

$$E = \frac{1}{2}mv^2 \qquad\qquad p = mv$$

$$p = \frac{2E}{v}$$

- The momentum carried by the solar wind is much less than the momentum carried by solar photons
- BUT: the speed of solar wind particles is much less than the speed of light, so collisions are more "head-on" for the solar wind

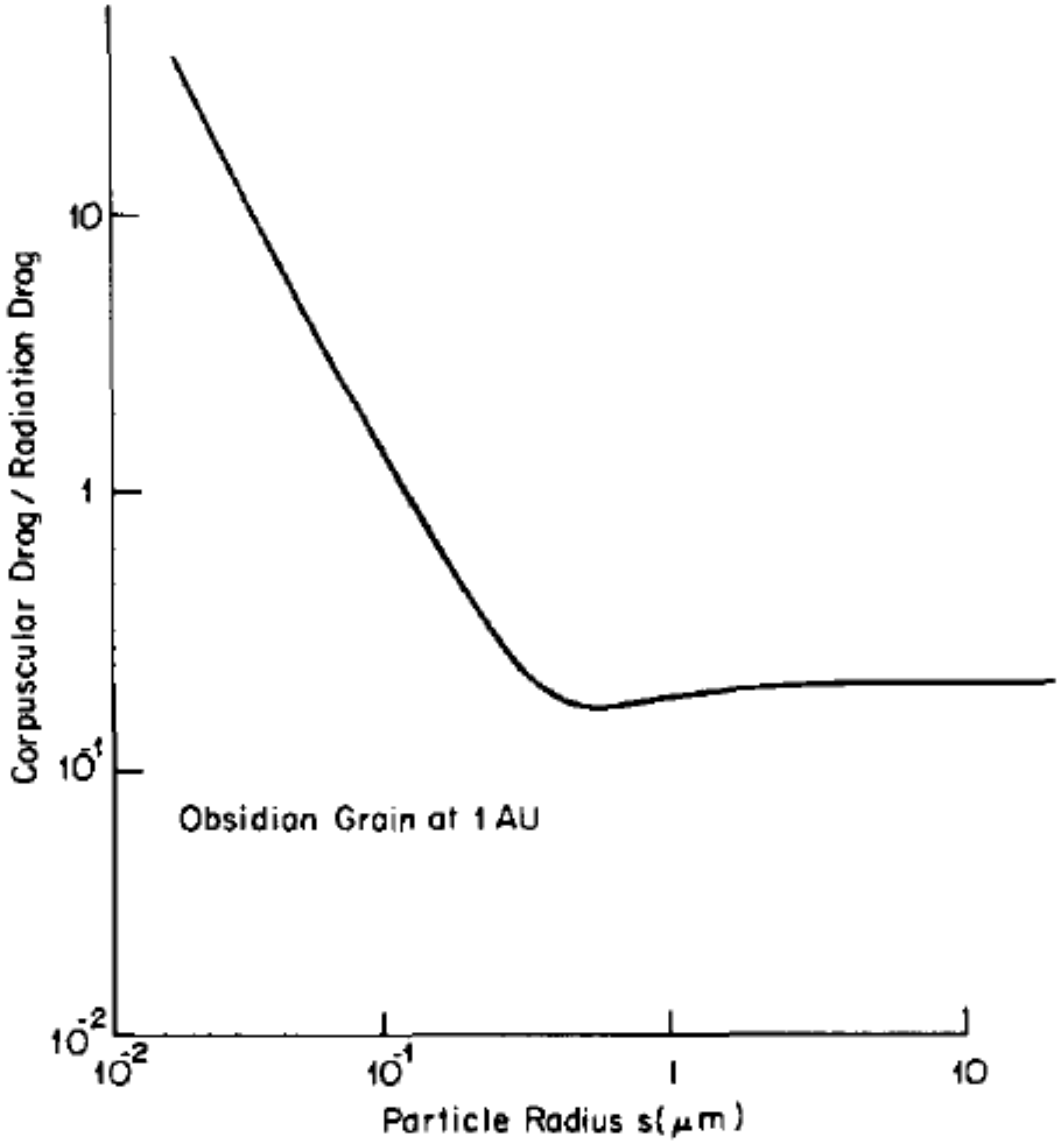
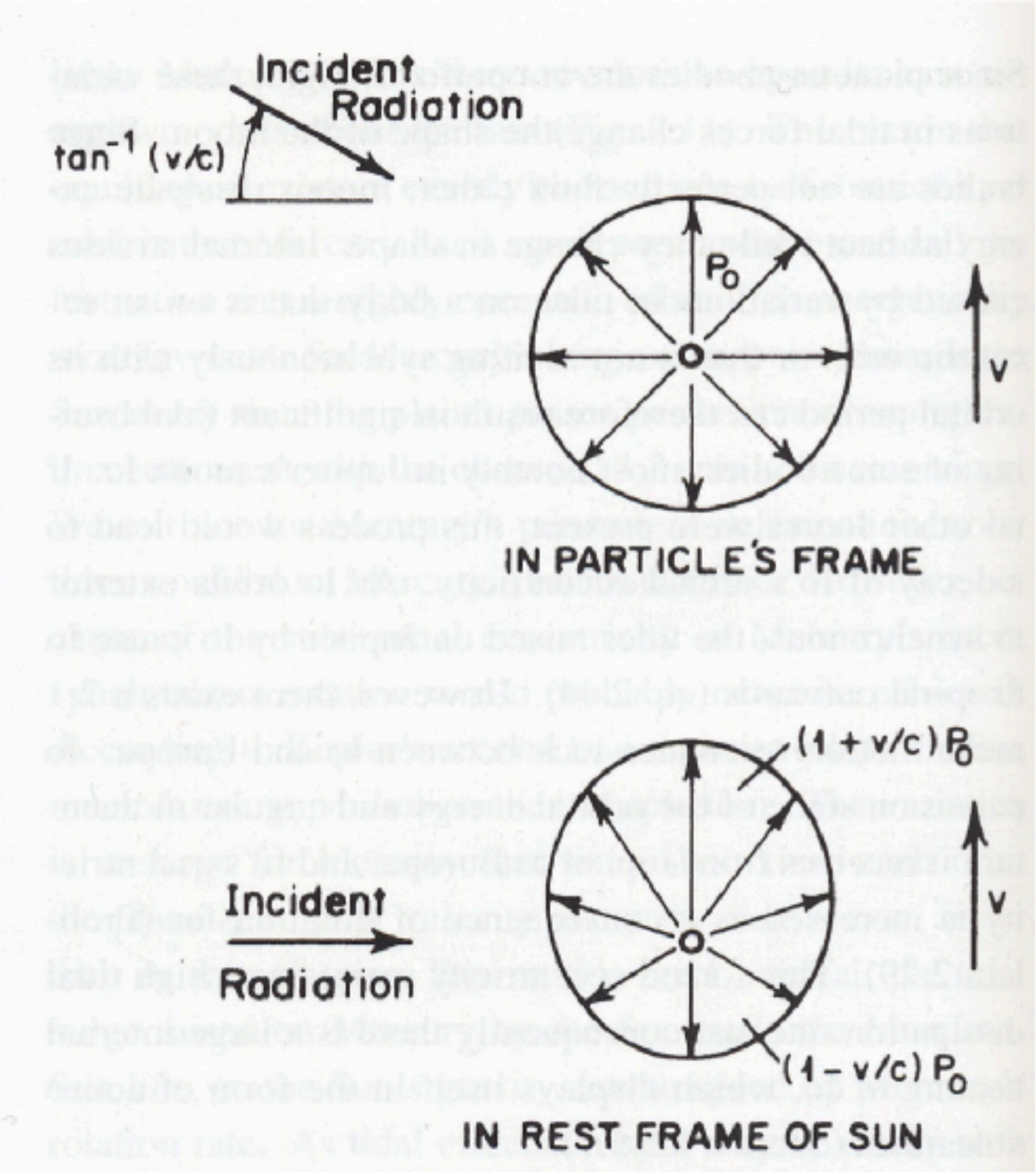


FIG. 11. Ratio of drag caused by the solar wind to hat due to radiation on an obsidian grain at 1 AU. 3ased on a similar plot given by Lamy (1975).

Burns *et al.* 1979

Corpuscular Drag

- PR drag: solar photons have a component of their momentum in the direction of the particle's orbit equal to v/c
- Corpuscular Drag: solar wind particles have a component of their momentum in the direction of the particle's orbit equal to v/v_{sw}
- $v_{sw} \approx 500 \frac{km}{s}$ $\quad c = 3x10^5 \frac{km}{s}$ $\quad v_{orb,Earth} = 30 \frac{km}{s}$
- Aberration of angles for:
  - PR Drag: $\alpha = \tan^{-1}\left(\frac{v_{orb}}{c}\right) = 0.0057°$
  - Corpuscular Drag: $\alpha = \tan^{-1}\left(\frac{v_{orb}}{v_{sw}}\right) \approx 4°$



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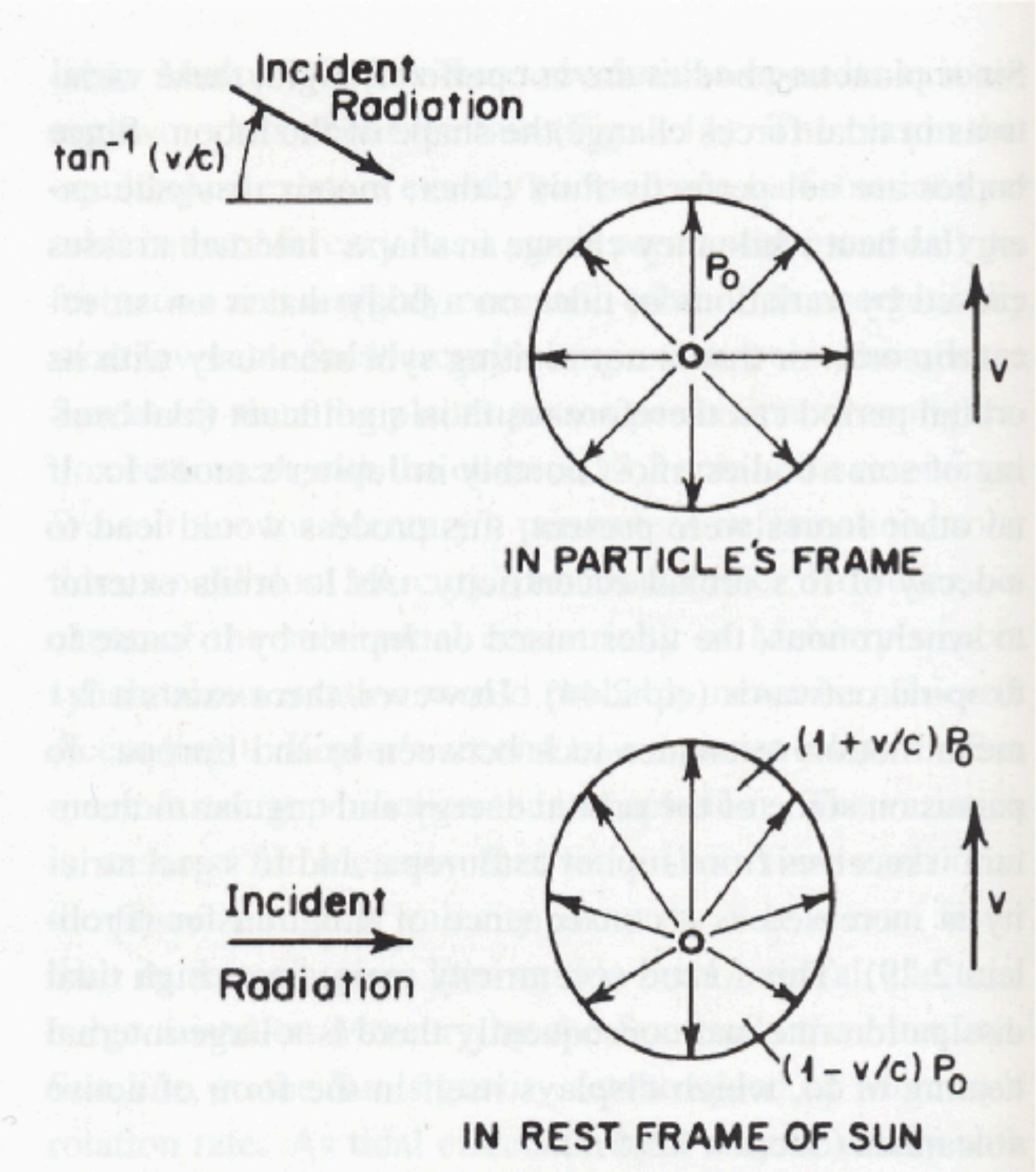
Corpuscular Drag

- PR Drag and radiation pressure depend on Q_{RP}, which approaches 0 for particles smaller than a micron
- Corpuscular Drag becomes more important for sub-micron particles: they migrate into the Sun



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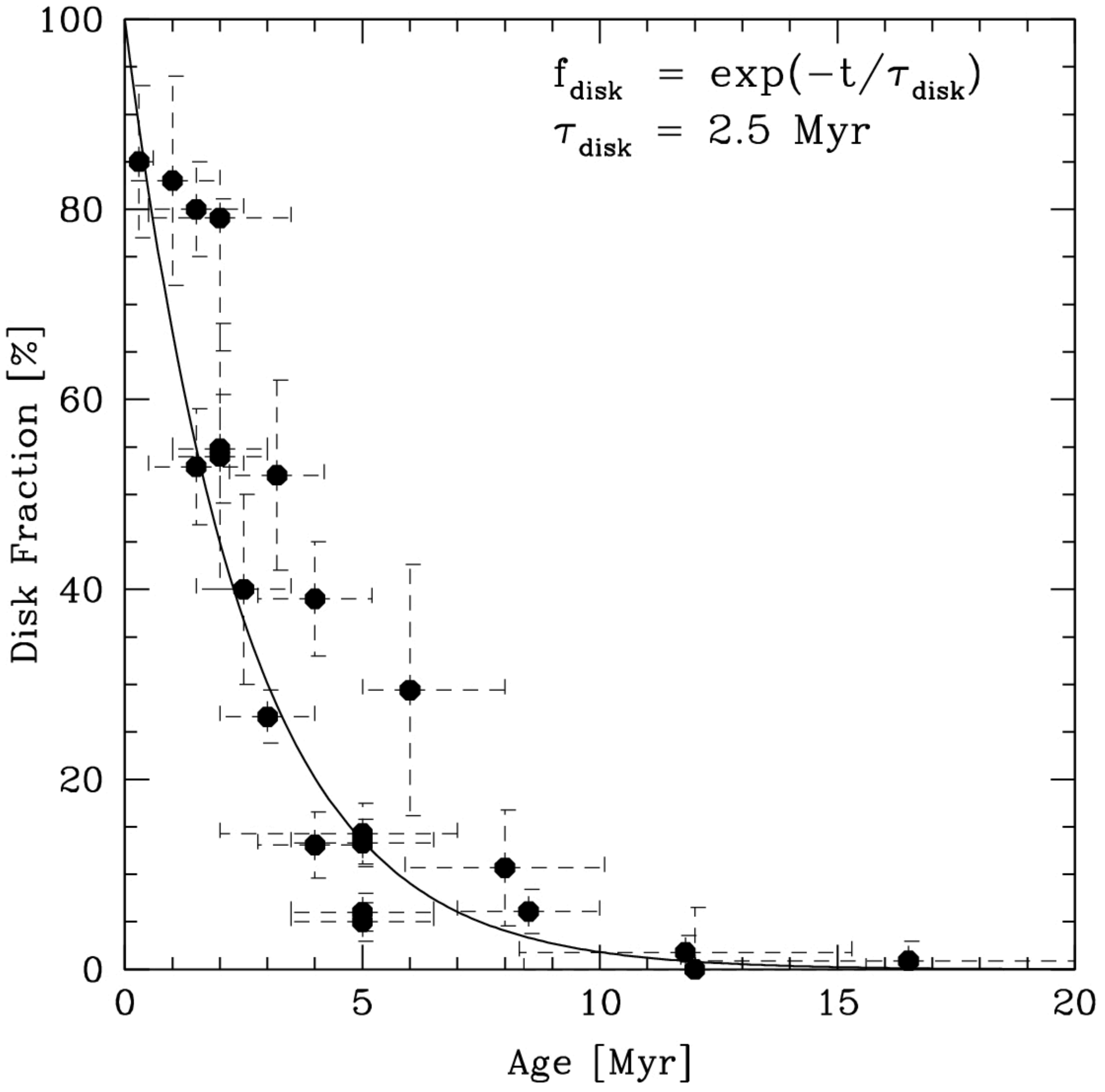
Gas Drag

- Was very important in the gas-rich protoplanetary disk in the first few million years of our solar system's life
- Not so important now for things orbiting the Sun today
- Is important for ring particles or spacecraft orbiting close to a planet with an atmosphere



Mamajek 2009

Gas Drag

- An object that's large enough relative to the mean free path length of the gas in which its immersed experiences a drag force

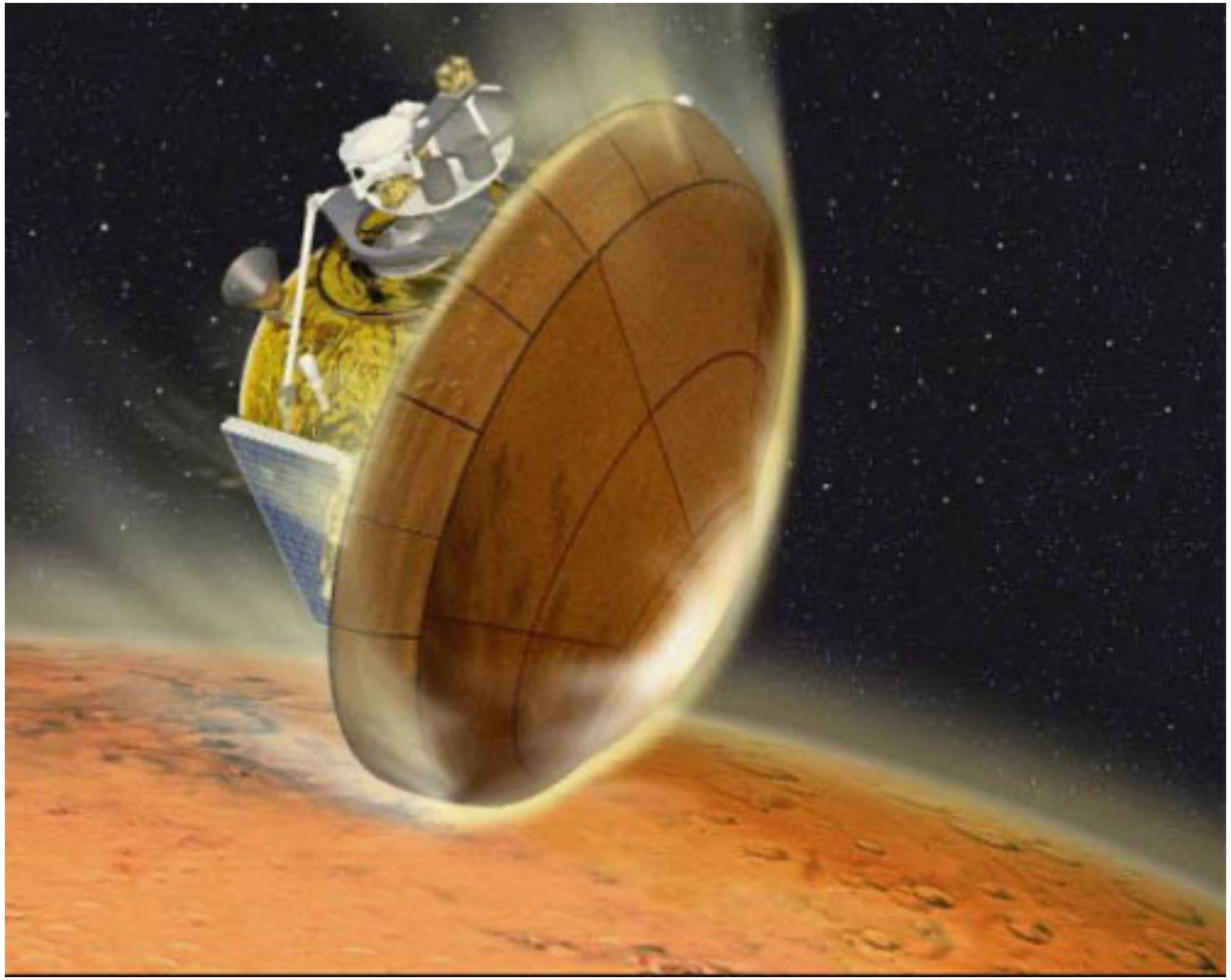
- Drag force depends on cross-sectional area and velocity of the object

$$F_D = -\frac{1}{2} C_D A \rho_{gas} v^2$$

C_D is about 1

Gas Drag

- So long as the object is moving faster than the gas (in the same direction), the object decelerates (loses energy)
- A spacecraft passing through the atmosphere of a solar system body can lose velocity such that it can be gravitationally captured into orbit (aerocapture)



JPL/NASA

Order of magnitude: Parachute

- $F_D = -\frac{1}{2} C_D A \rho_{gas} v^2$ C_D is about 1

- (1) How fast, in m/s, can a person fall without significant injury? (Hint: how many seconds of falling to a hard surface would you be comfortable with?)

- (2) How large an area of parachute on Earth (near the surface) would you need to move down toward the ground at a constant (safe) velocity (hint: without acceleration?)

  (3) How large an area of parachute would you need if you were on Mars, instead?

Order of magnitude: Parachute

- $F_D = -\frac{1}{2} C_D A \rho_{gas} v^2$

- (1) How fast, in m/s, can a person fall without significant injury? (Hint: how many seconds of falling to a hard surface would you be comfortable with?)

- Probably about 1 second of falling, and g = 9.8 m/s/s, so 10 m/s feels like a safe velocity

- (2) How large an area of parachute on Earth (near the surface) would you need to move down toward the ground at a constant (safe) velocity (hint: without acceleration?)

- We want the net acceleration to be 0, which means we want the drag force to equal the force of gravity:

$$F_G = mg = F_D = \frac{1}{2} C_D A \rho_{gas} v^2$$

$$A = \frac{2mg}{C_D \rho_{gas} v^2}$$

- Plugging in numbers, I'm (order-of-magnitude) 100 kg, g = 10 m/s/s, C_D = 1, v = 10 m/s, density of air at sea level is about 1 kg per cubic meter

Order of magnitude: Parachute

- $$A = \frac{2mg}{C_D \rho_{gas} v^2}$$

- Plugging in numbers, I'm (order-of-magnitude) 100 kg, g = 10 m/s/s, C_D = 1, v = 10 m/s, density of air at sea level is about 1 kg per cubic meter

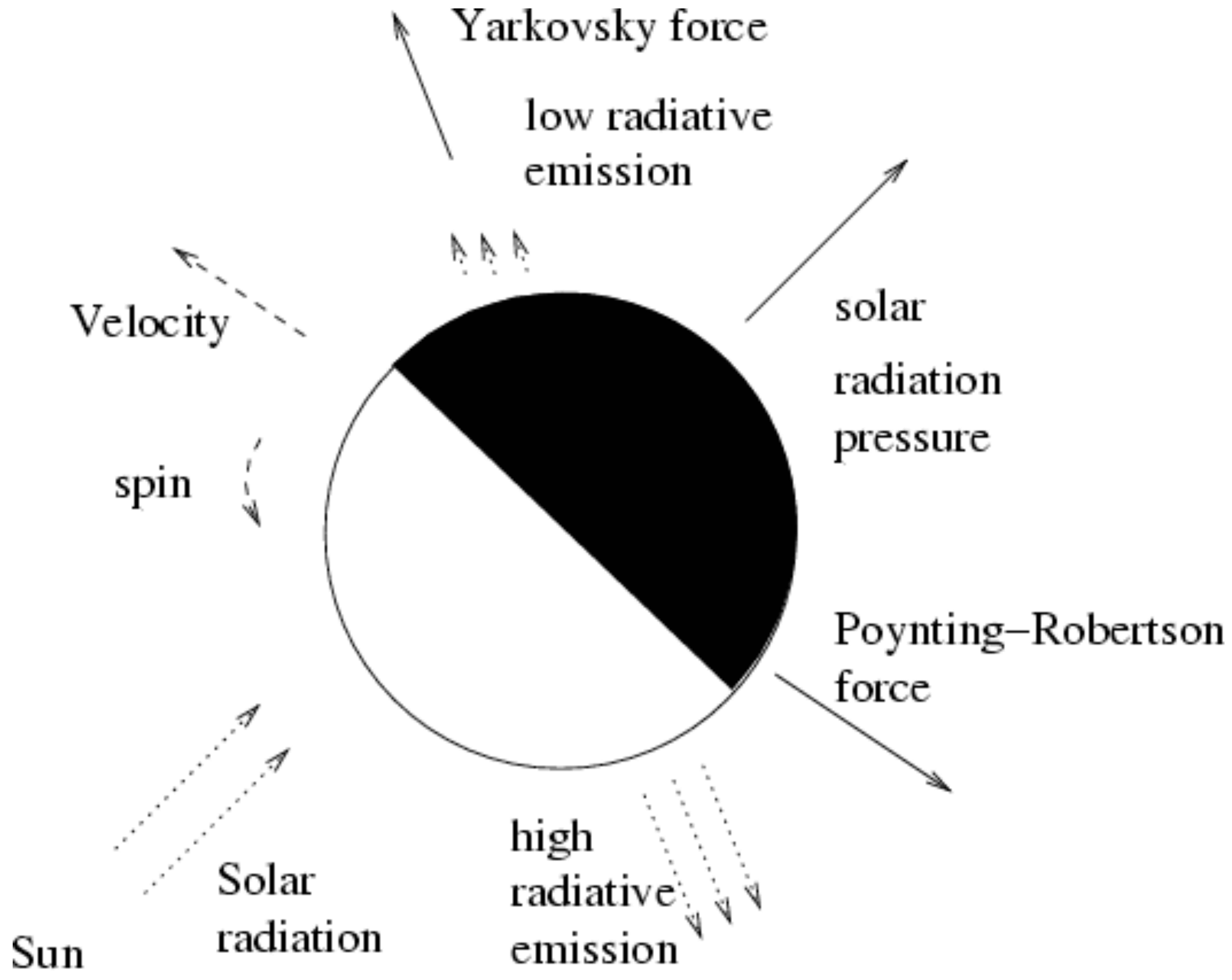
$$A = \frac{2(100kg)(9.8\frac{m}{s^2})}{(1)(1\frac{kg}{m^3})(10\frac{m}{s})^2} = \frac{2000}{100}m^2 = 20m^2$$

(3) How large an area of parachute would you need if you were on Mars, instead?

My maximum safe velocity will stay the same, so will my mass, so will C_D. That just leaves the density of air on Mars (1% that of Earth), and the surface gravity (1/3 that of Earth)

$$A = 20m^2 \frac{g_M}{g_E} \frac{\rho_E}{\rho_M} = 20m^2 \frac{1}{3}(100) = 600m^2$$

Dissipative Processes



Vaubaillon et al. 2005

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

For next time

- Reading: de Pater & Lissaeuer Chaper 5, section 5.4, 5.4.1, 5.4.2, 5.4.2.1
- Homework 2 will be due Wednesday, September 14 at 11:59pm