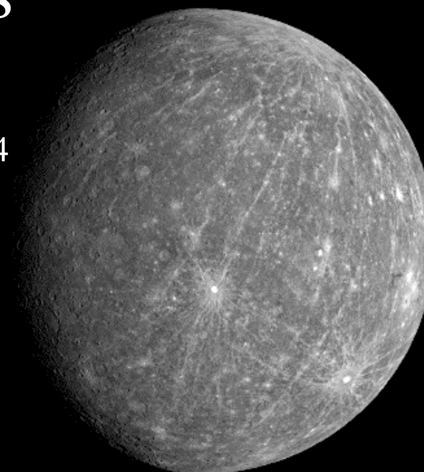
Photophoretic Separation of Metals and Silicates:

The Formation of Mercury-like Planets and Metal Depletion in Chondrites



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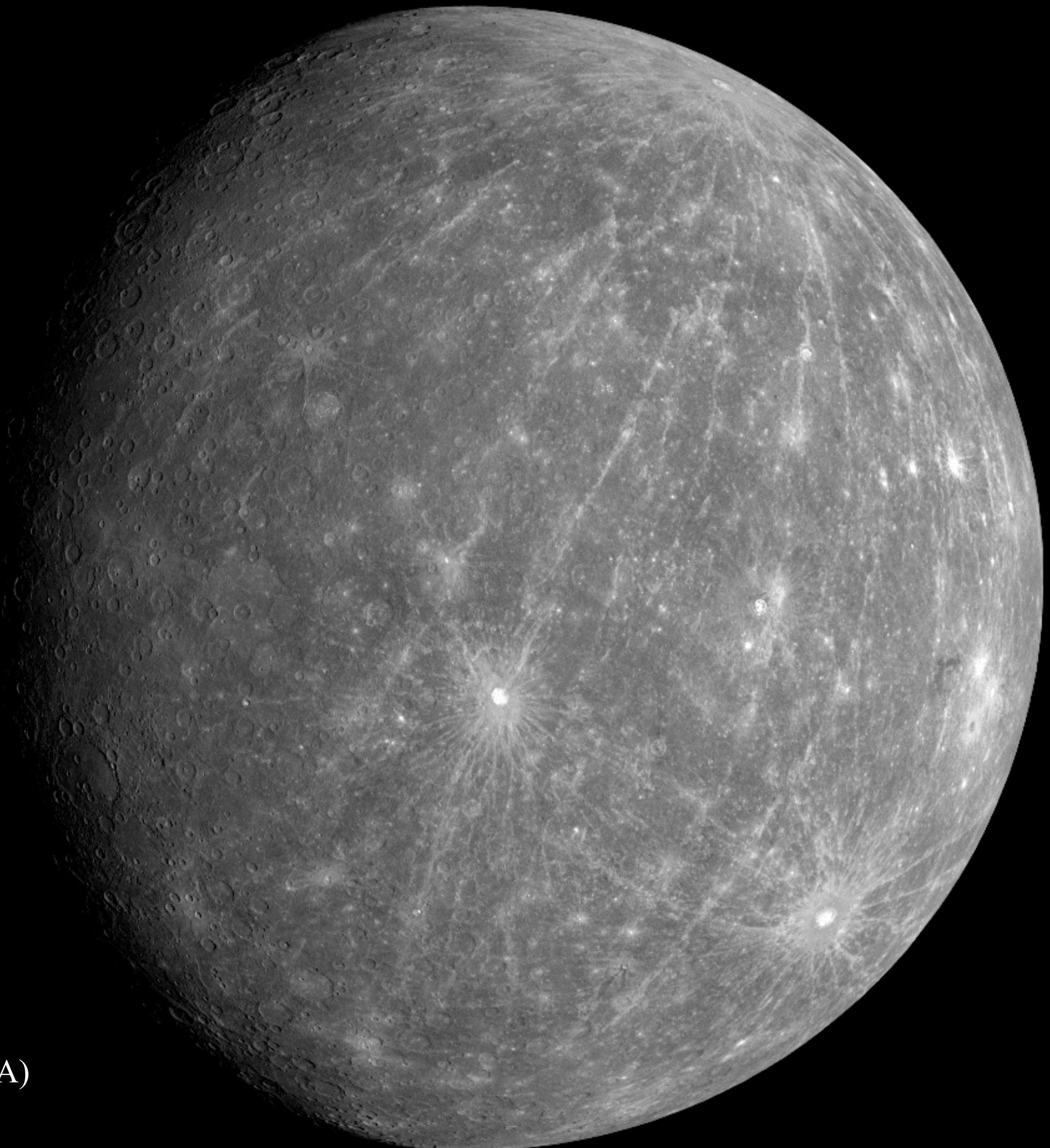
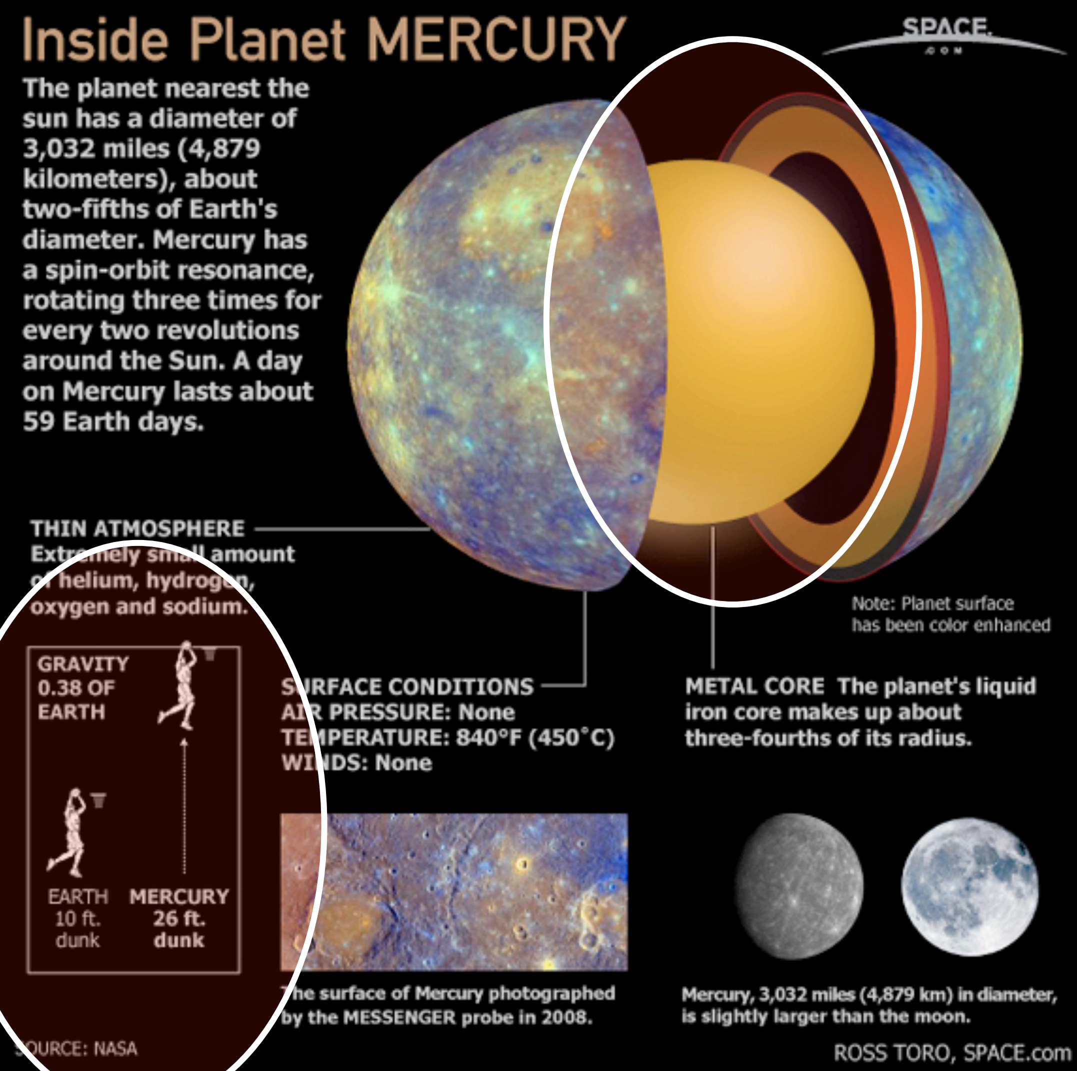


(Mercury, Messenger, NASA)


Inside Planet MERCURY
SPACE.com
The planet nearest the sun has a diameter of 3,032 miles (4,879 kilometers), about two-fifths of Earth's diameter. Mercury has a spin-orbit resonance, rotating three times for every two revolutions around the Sun. A day on Mercury lasts about 59 Earth days.
THIN ATMOSPHERE
Extremely small amount of helium, hydrogen, oxygen and sodium.
GRAVITY 0.38 OF EARTH
EARTH 10 ft. dunk
MERCURY 26 ft. dunk
SURFACE CONDITIONS
AIR PRESSURE: None
TEMPERATURE: 840°F (450°C)
WINDS: None
METAL CORE The planet's liquid iron core makes up about three-fourths of its radius.
Note: Planet surface has been color enhanced
The surface of Mercury photographed by the MESSENGER probe in 2008.
Mercury, 3,032 miles (4,879 km) in diameter, is slightly larger than the moon.
SOURCE: NASA
ROSS TORO, SPACE.com

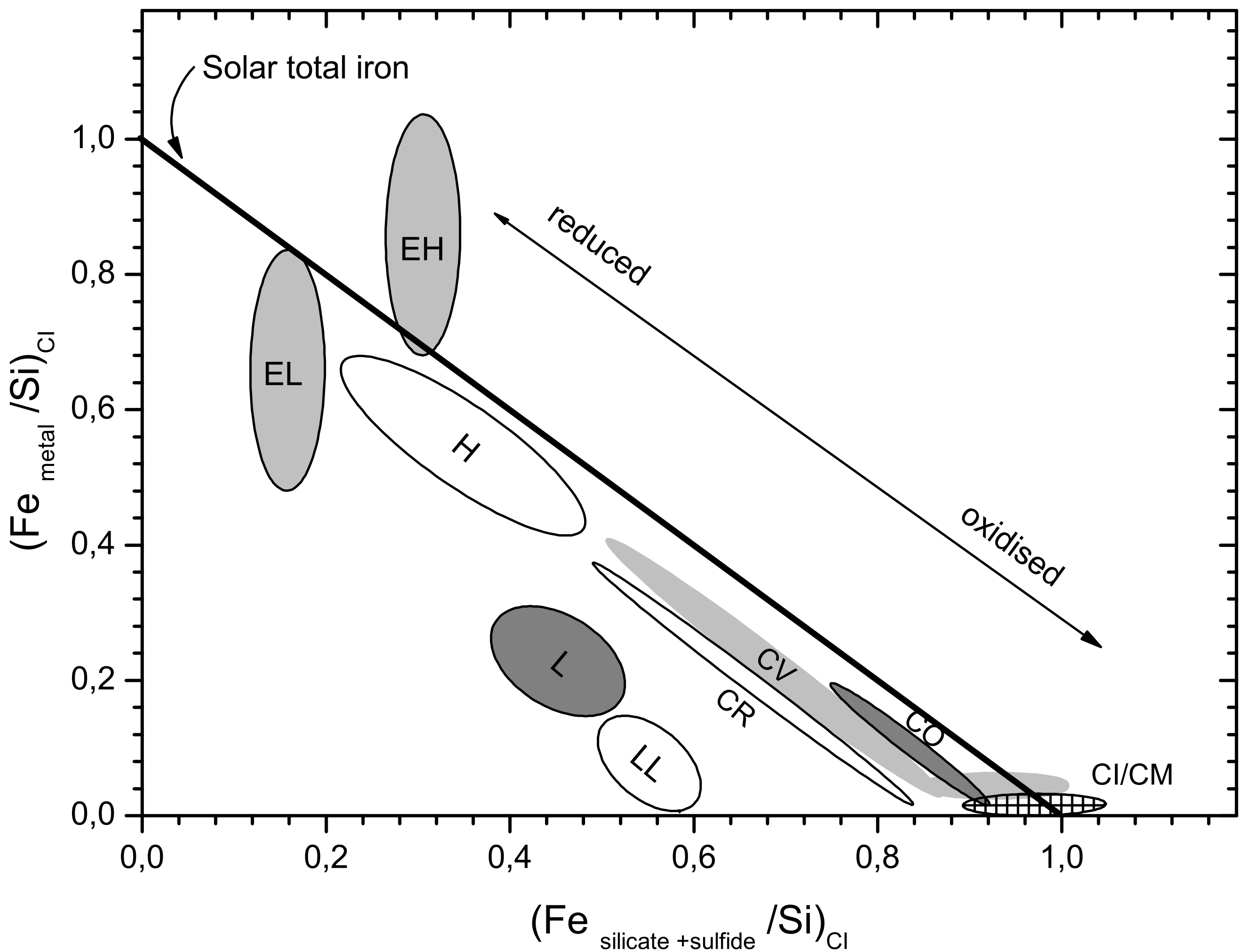
Uncompressed densities of planets (Spohn 2001)

- Mercury: 5.3 g/cm^3
- Earth: 4.4 g/cm^3
- Mars: 3.8 g/cm^3

A trend but most explanations focus on Mercury

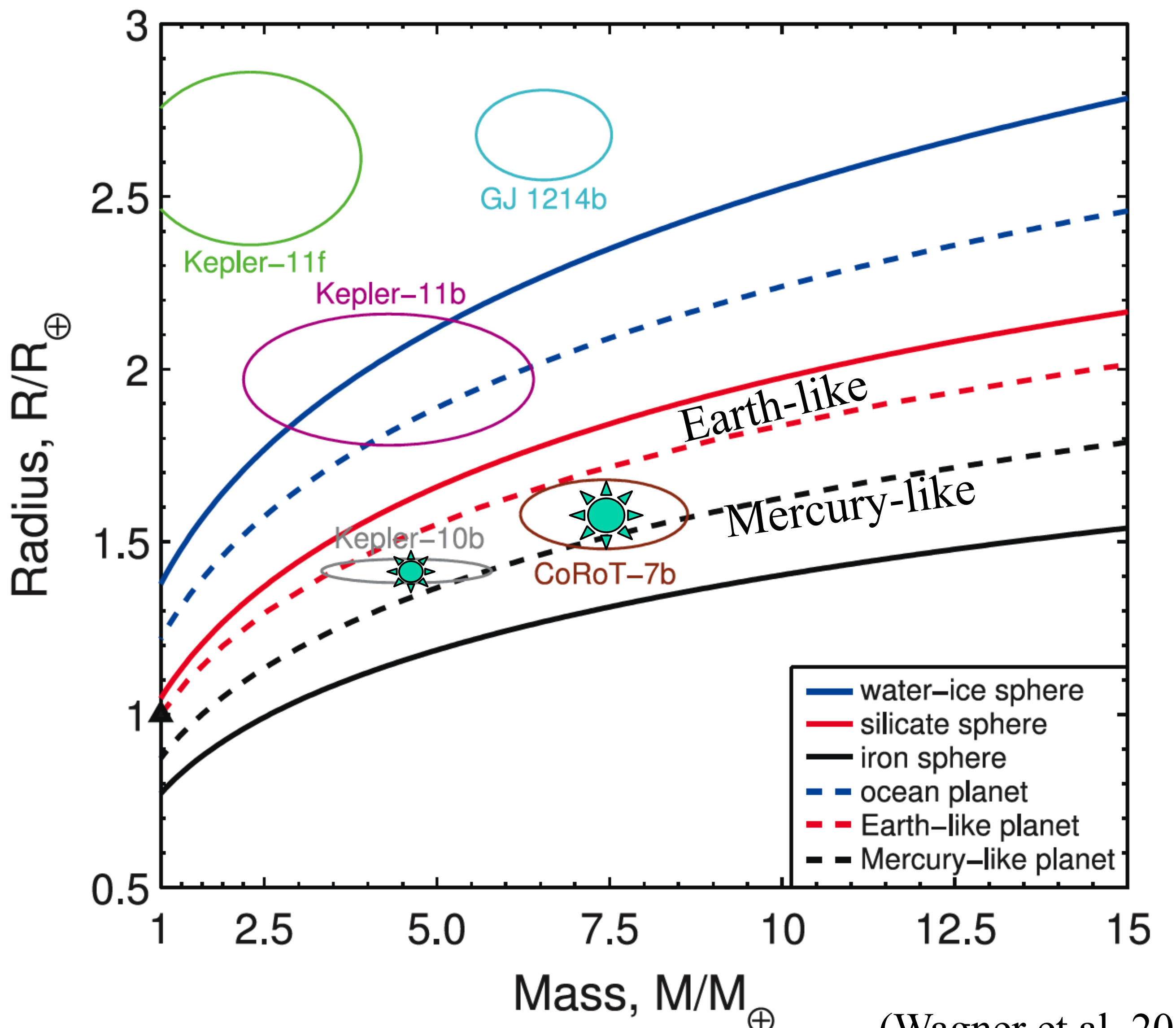
- Impact stripping of mantle proposed (Benz et al. 1988)
- High temperature evaporation of mantle (Cameron 1985)

Radial trend continues in asteroid belt; Chondrites are iron poor



(Trieloff and Palme 2006)

Inner rocky extrasolar planets are Mercury-like



(Wagner et al. 2011)

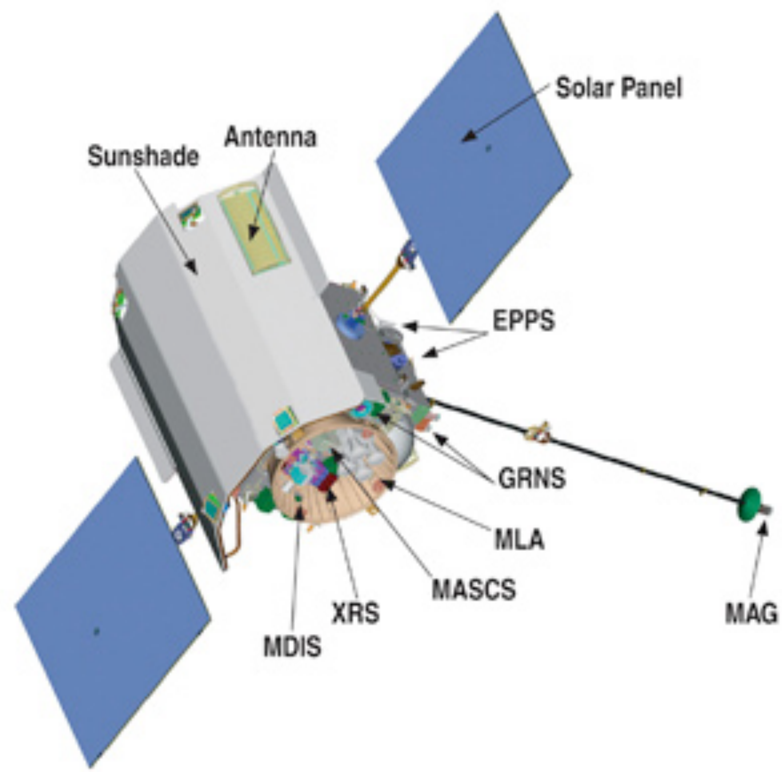
Evidence in planetary systems is

- inner part is metal rich
- outer part is metal poor (silicate rich)

What is the underlying physical mechanism?

Mercury's high density, a surprising revelation from MESSENGER

- Volatile element *K* is still highly abundant (Peplowski et al. 2011)
- This essentially rules out high temperature processes like giant impact or high temperature evaporation



That leaves the high metal content unexplained.

Is there another physical process
which separates metals and silicates
without need for high temperatures?

At what time do planets form?

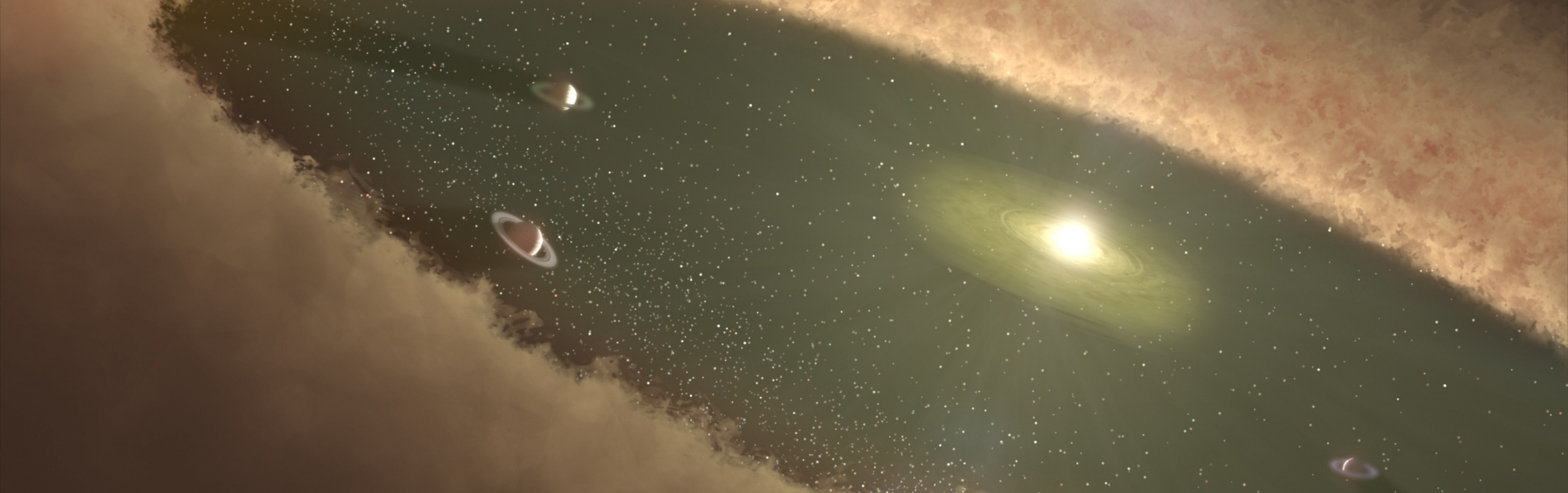
- Standard: sets off in optical thick disk (collisions, particle growth, instabilities, ...)

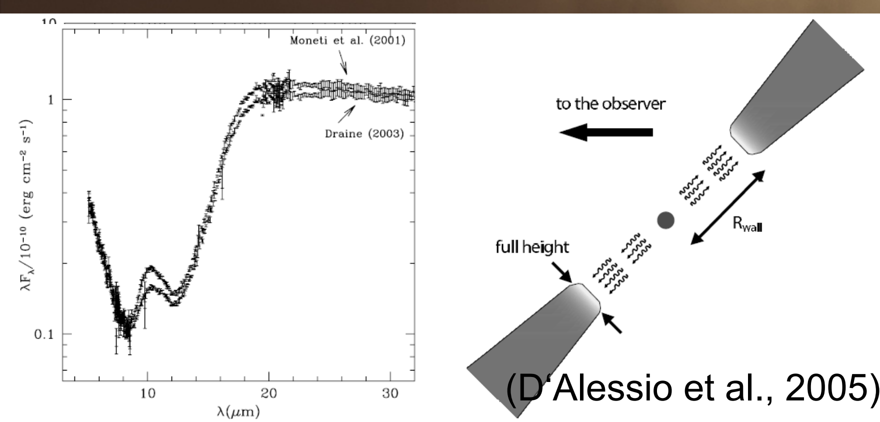
But this cannot be the whole story.

- Asteroids:
  - chondrules, form only 2-3 million years late
  - evidence for rapid assembly afterwards
  - evidence of irradiation effects prior to assembly (**optical thin**)
    - solar flare tracks in carb. chondrite grains (Caffee 1987)
- Earth:
  - solar wind implanted noble gases acquired by small precursor planetesimals (**optical thin**)
    (Trieloff et al. 2000, 2002)

Optical thin inner parts in disks with gas are known
Transition disks

(Sicilia-Aguilar et al. 2008, Najita et al. 2007)

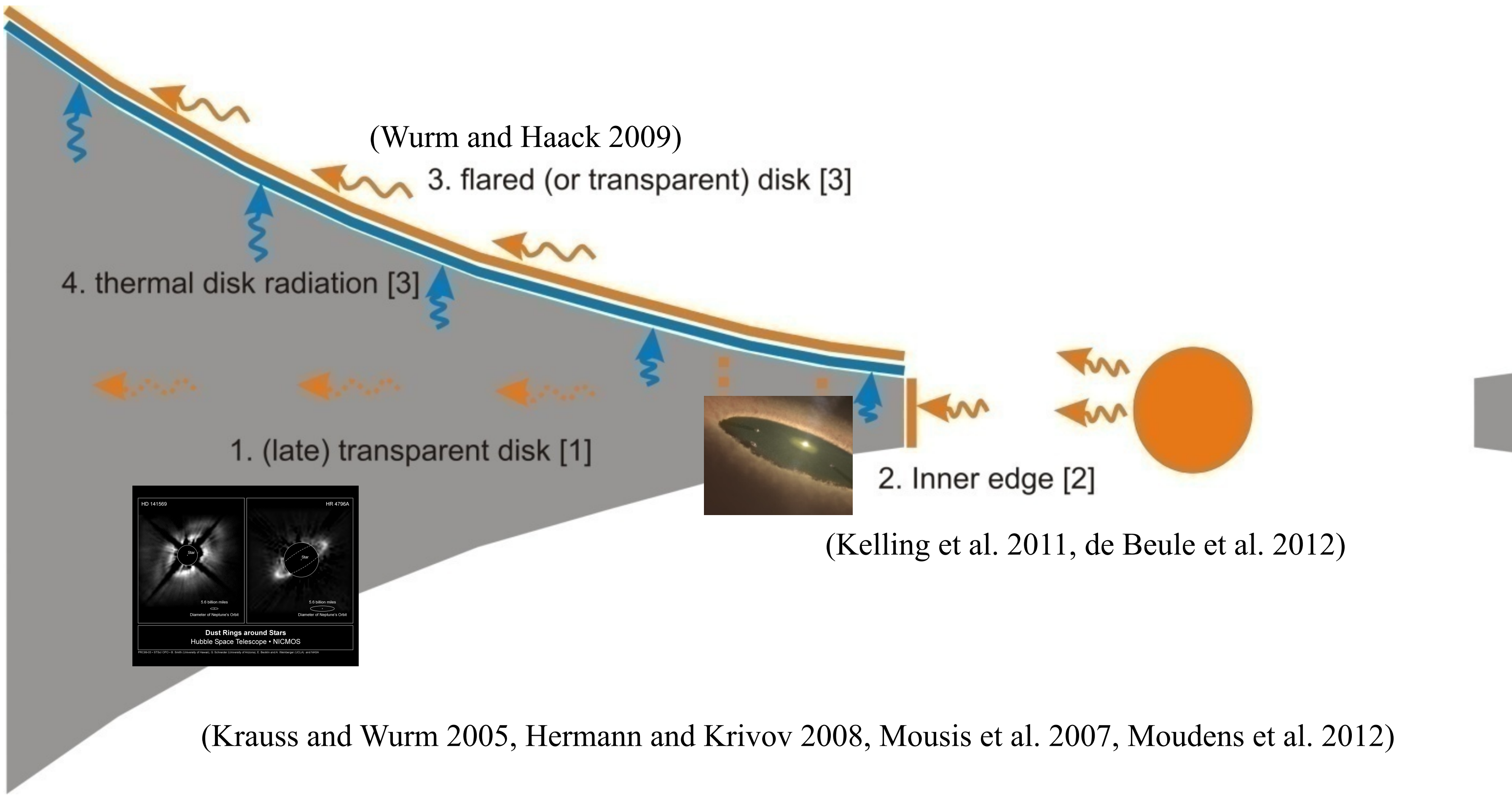




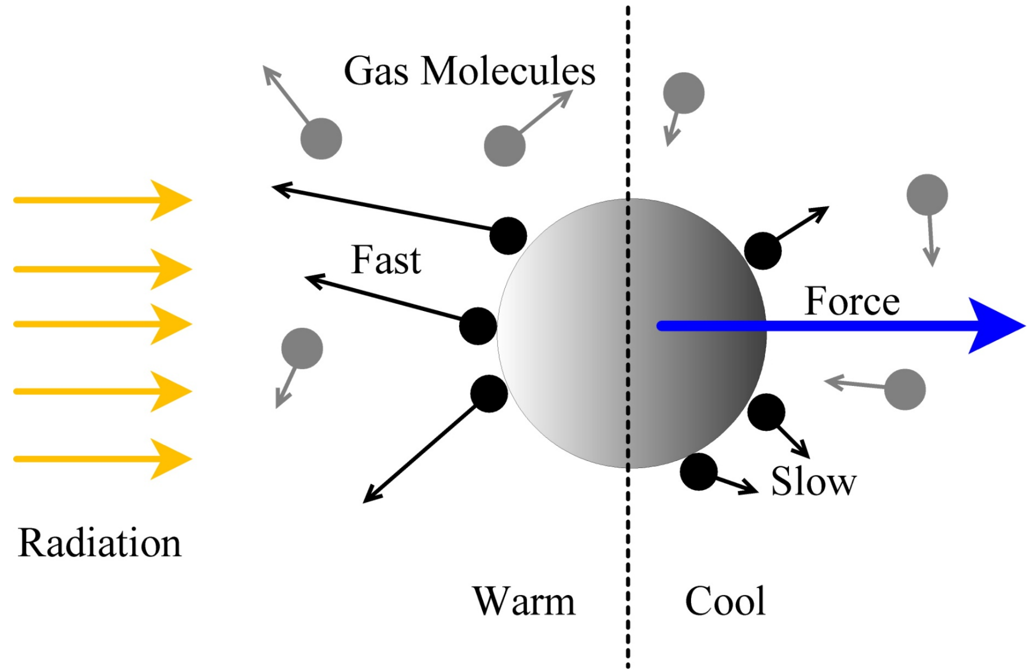
(D'Alessio et al., 2005)

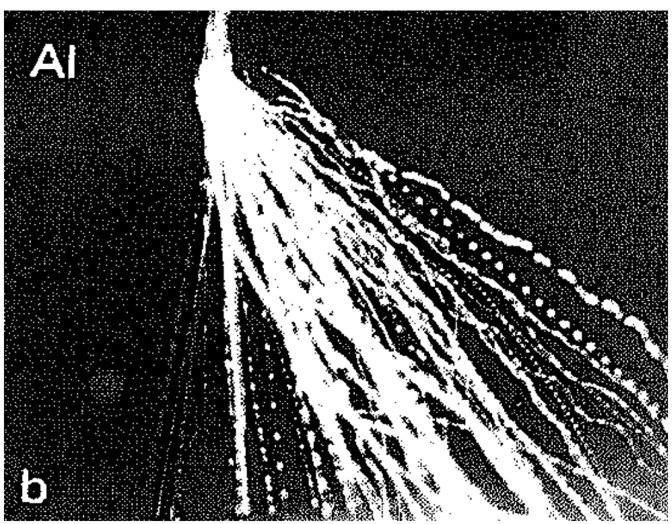
Courtesy NASA/JPL-Caltech / T. Pyle

Potential of photophoretic transport in general in protoplanetary disks



Photophoresis





(Rohatschek 1985)

(Teiser et al. and Loesche et al. in prep)

- Optical thin parts important (observation, meteorites, ...)
- Photophoresis works in these phases
- Can photophoresis separate metals and silicates?

Photophoresis (Approximation for LOW pressure)

Radiation Flux Density

Volume

Gas Pressure

$$F_{Ph} = \frac{\pi a^3 I p}{6 k_{th} T}$$

Temperature

Thermal Conductivity

Thermal conductivities:

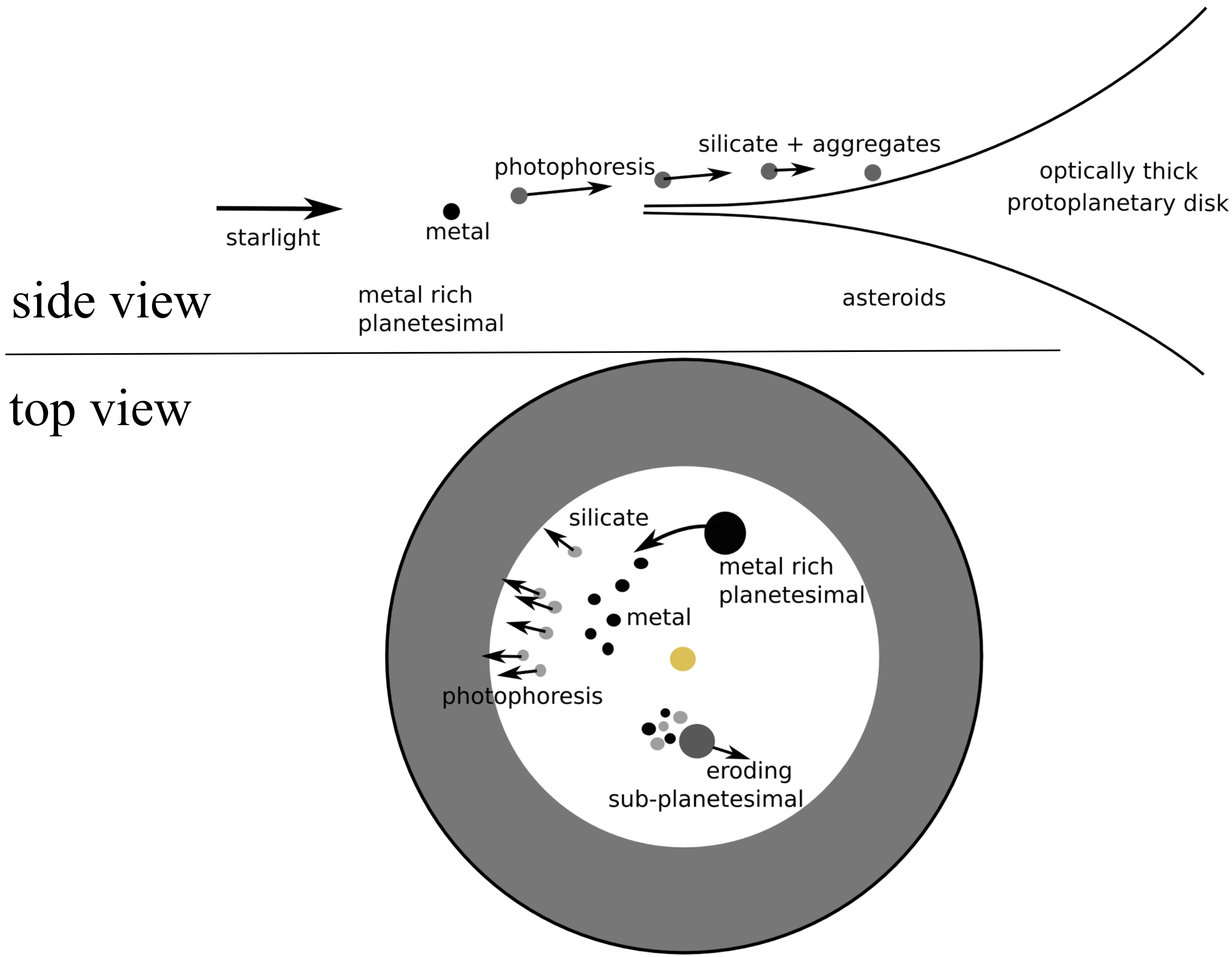
- Iron: > 50 W/(m K)
- Silicates: ~ 1 W/(m K)
- Aggregates: < 0.1 W/(m K)

Photophoretic drift rates (10µm grains):

- Metal: 1 AU / 15 million years
- Silicates: 1 AU / 300.000 years
- Aggregates: 1 AU / 30.000 years

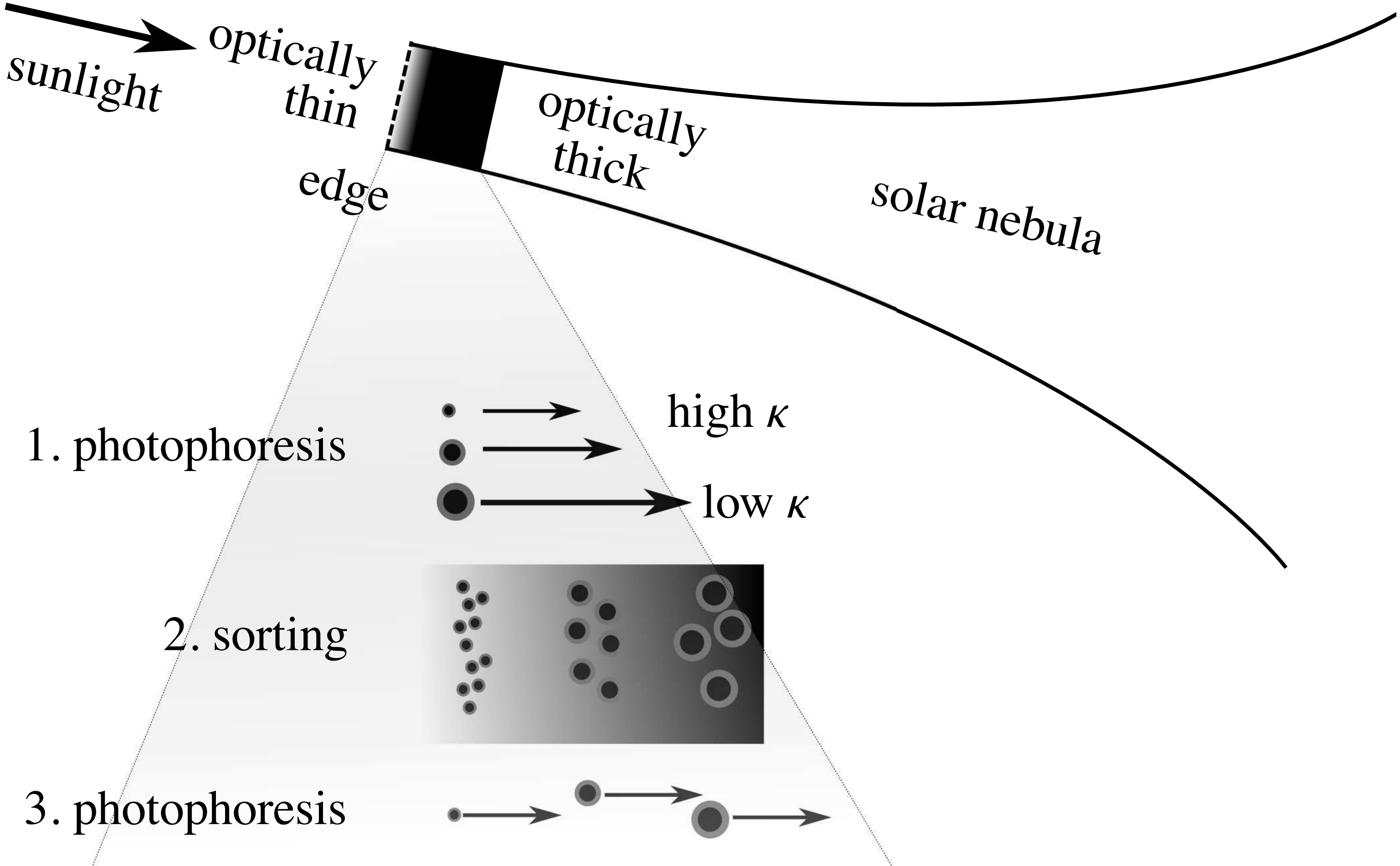
Metals essentially stay where they are (no motion in experiments), while silicates might keep up with outward moving edge.

Photophoresis is one possible physical mechanism with few assumptions
to separate
metals and silicates
without relying on high temperatures



In optical thin parts metals and silicates will be separated

(Wurm, Trieloff, and Rauer, submitted)



(Loesche and Wurm 2012)

Photophoresis separates silicates and metals by preferential outward transport of silicates inside the inner edge of a disk