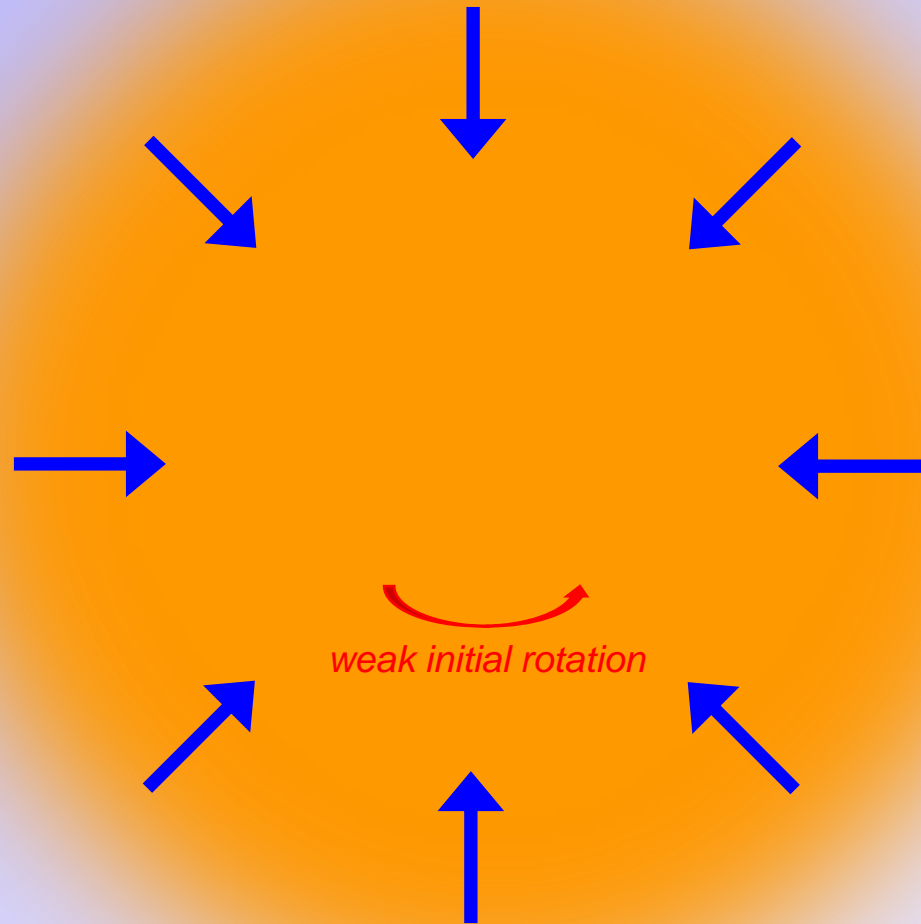


Today's Topics

Wednesday, April 8, 2026 (Week 10, Lecture 27) – Chapter 7, 14.3-4, 30.1-3.

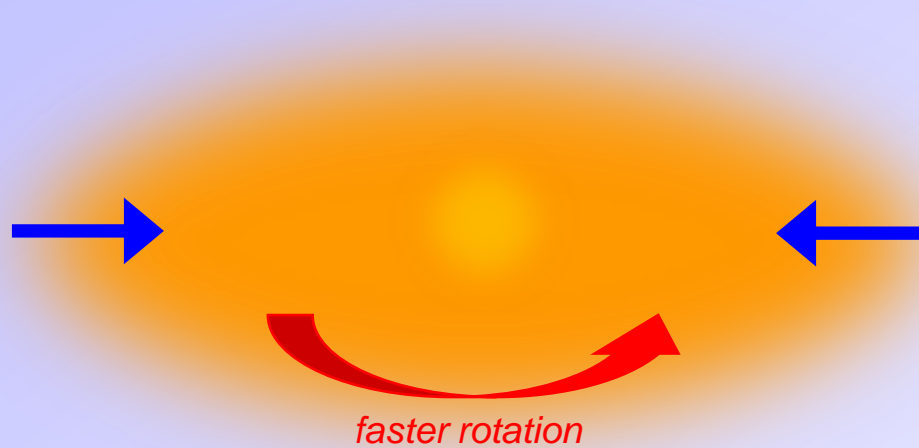
- A. Review: Solar system formation
- B. Examples of Protoplanetary systems
- C. Exoplanets
- D. Exolife?

Step 0: large cloud of gas & dust



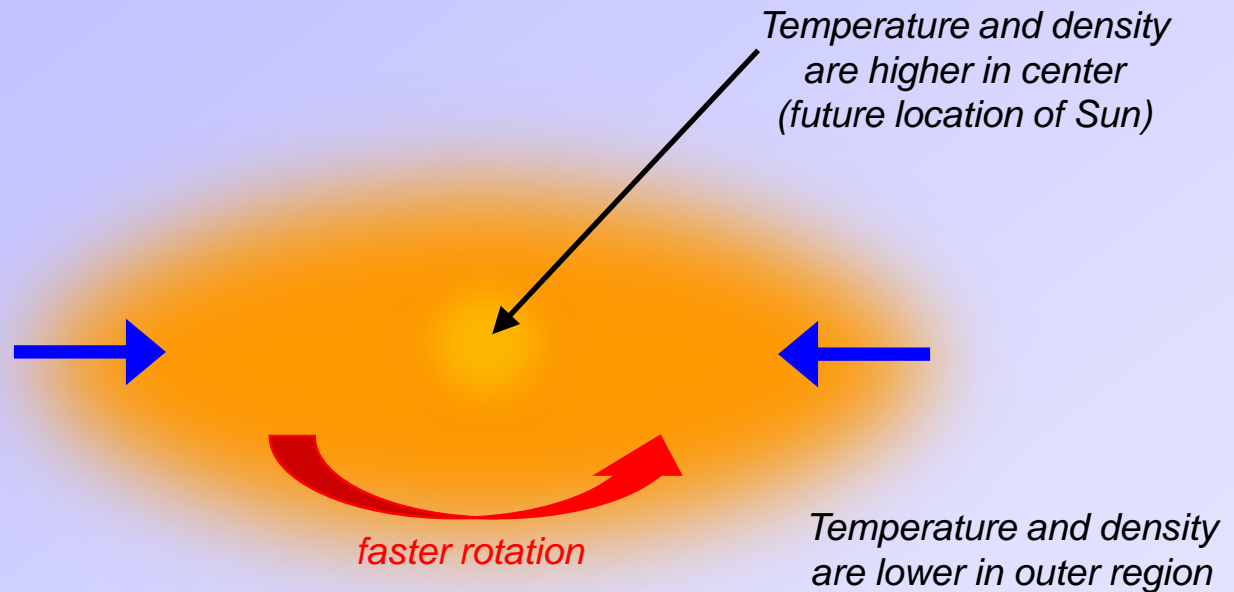
Mutual gravity pulls gas, dust, particles, and material inwards.

Step 1: Contraction



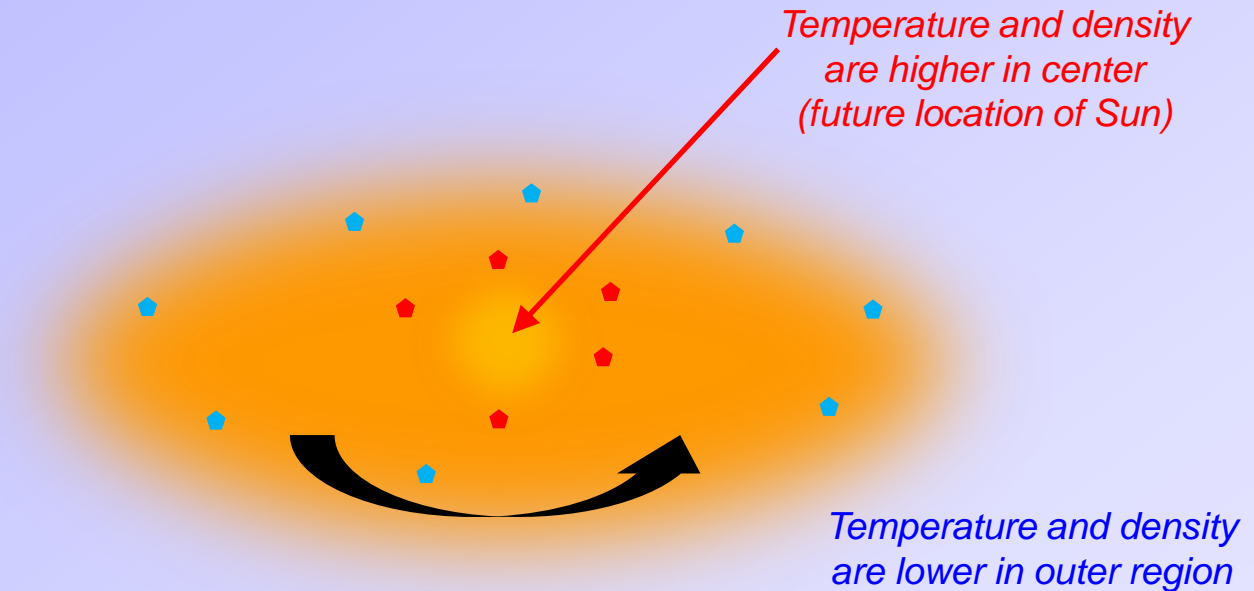
As the solar nebula contracts it **heats up** (energy conservation), spins faster (angular momentum conservation), and flattens out.

Step 1: Contraction



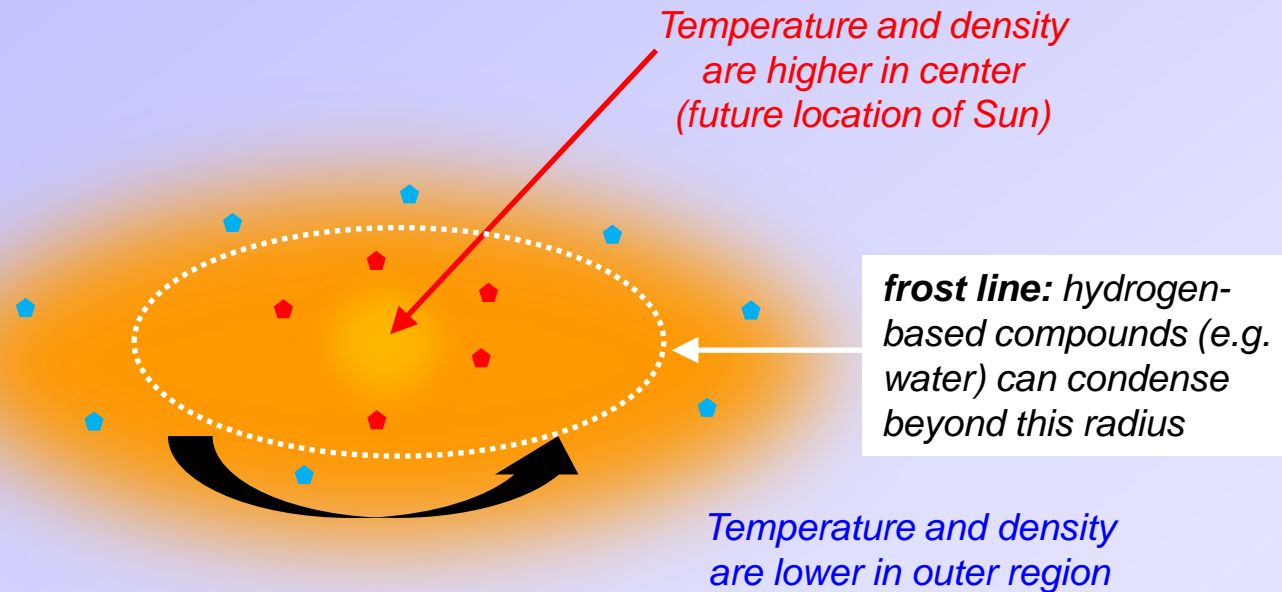
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Step 2: Condensation



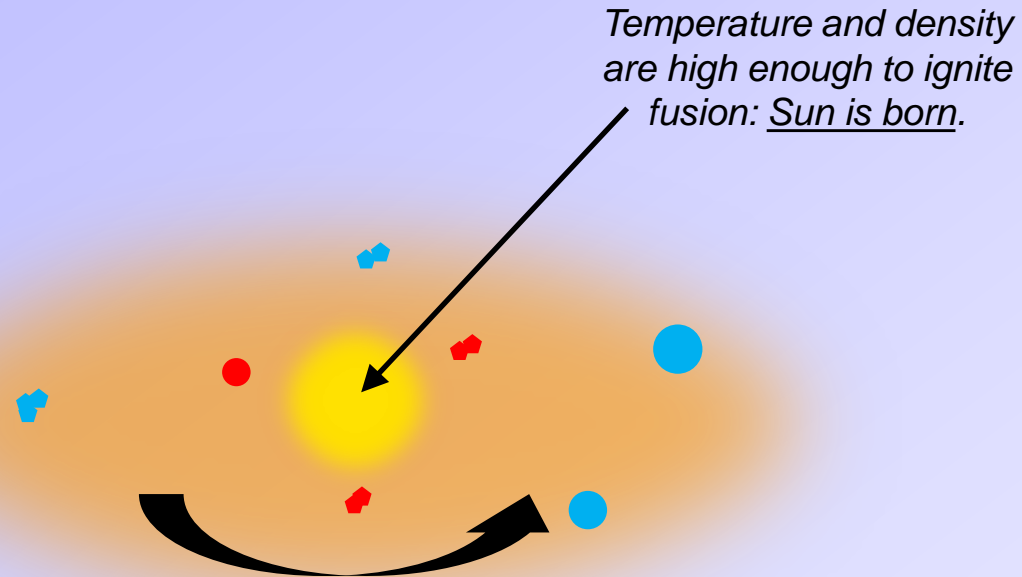
As the nebula cools (blackbody radiation) heavy element gases condense around dust particles. Hydrogen and helium do not condense, but hydrogen-based molecules can in the cooler outer parts.

Step 2: Condensation – “frost line”



As the nebula cools (blackbody radiation) heavy element gases condense around dust particles. Hydrogen and helium do not condense, but hydrogen-based molecules can in the cooler outer parts.

Step 3: Accretion of Planetesimals



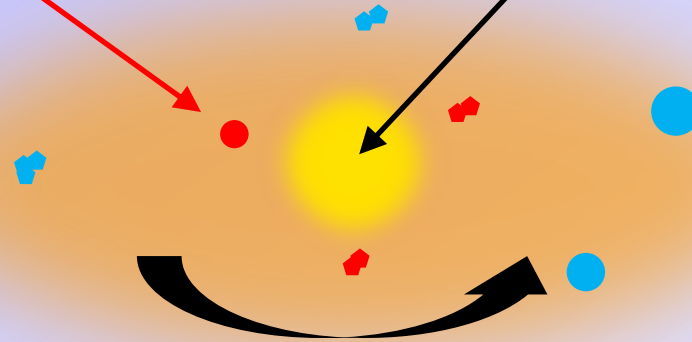
- **Accretion of planetesimals:** Solid particles collide and stick together to progressively start planets. Their gravity becomes strong enough to collect gases.
- **Star ignition:** The central region gets dense enough to **ignite fusion**.

Step 3: Accretion of Planetesimals

Inner planetesimal tend to be richer in heavy elements, which condense at higher temperature.

They tend to be smaller, since they sweep a smaller area (gathering less material).

Temperature and density are high enough to ignite fusion: Sun is born.



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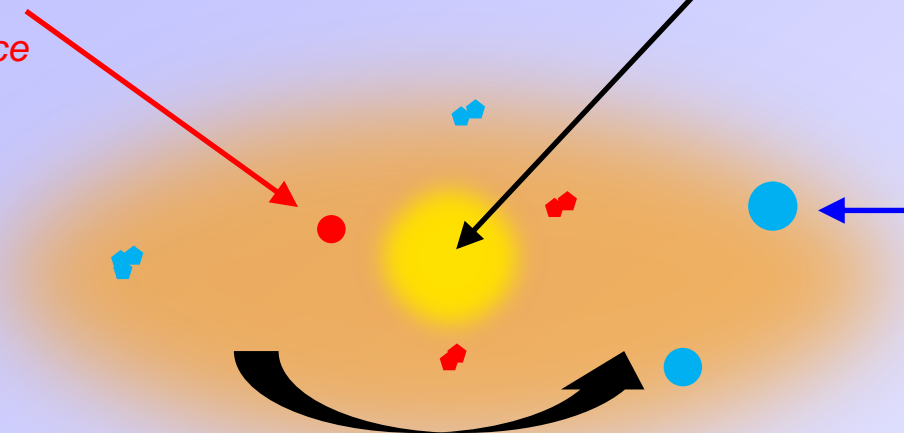
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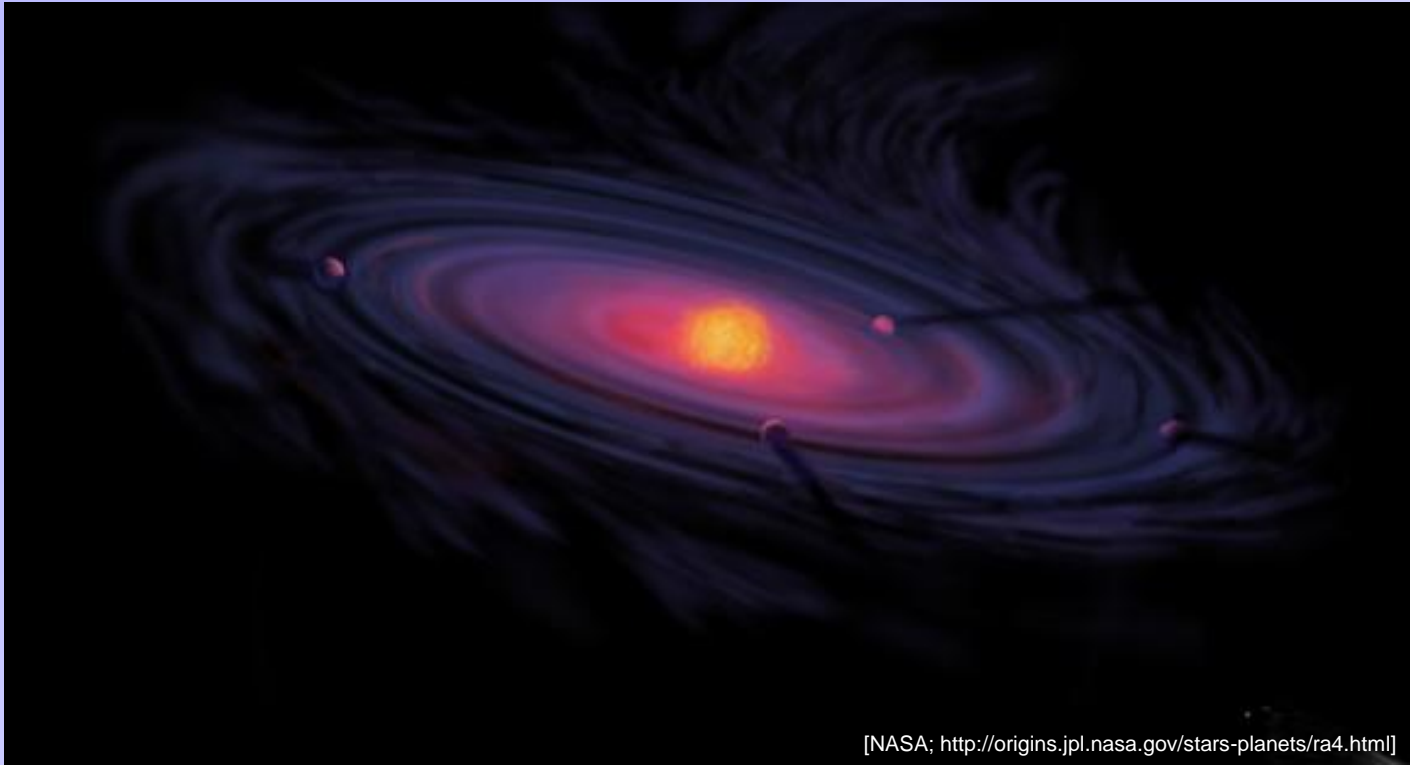
Temperature and density are high enough to ignite fusion: Sun is born.

Outer planetesimals tend to be more icy and hydrogen rich.

They tend to be bigger because they sweep out a larger region, so they can gather more material.

- 
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 - **Star ignition:** The central region gets dense enough to **ignite fusion**.

Step 3: Planetesimals to Planets



- As the planetesimal collide and stick together, they become bigger and evolve into planets. In doing so, they clear out their orbits.
- Near circular orbits are more stable, since more eccentric elliptical ones can lead to collisions between planetesimals/planets.

Nascent Protoplanetary Systems

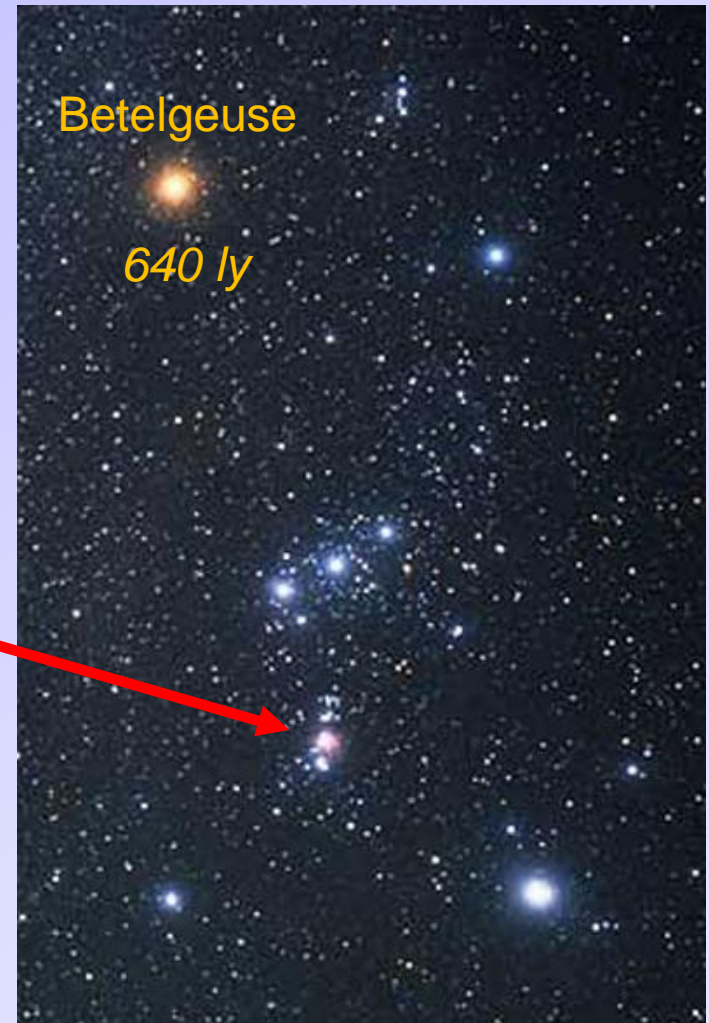


Constellation: **Orion**

Nascent Protoplanetary Systems

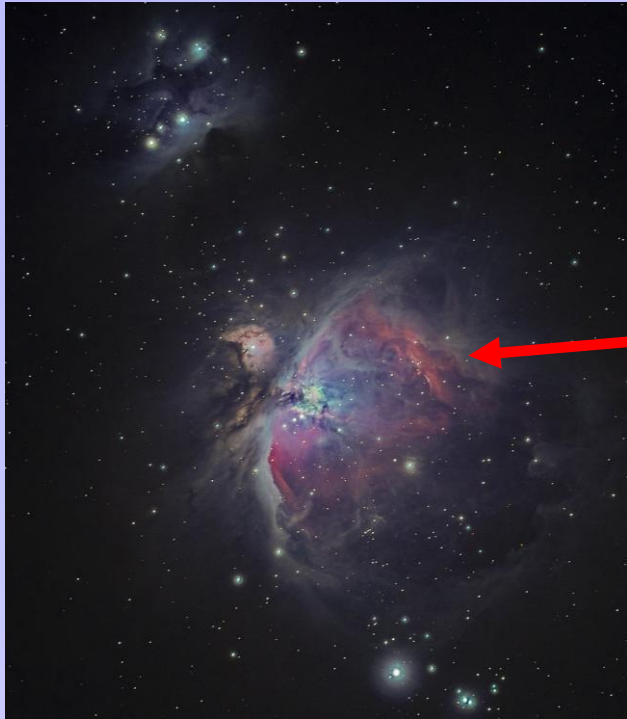


Orion Nebula

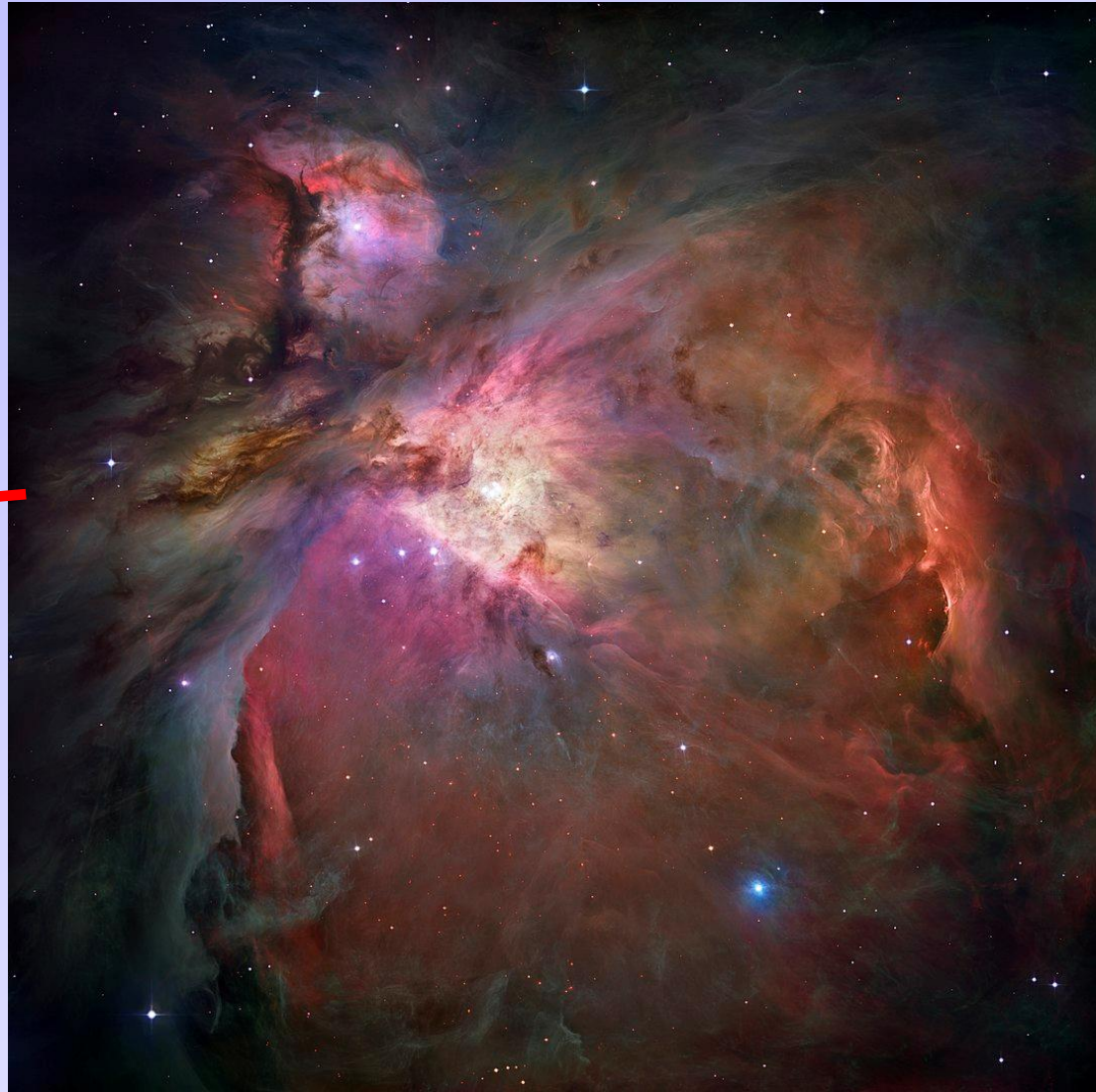


Constellation: **Orion**

Nascent Protoplanetary Systems



Orion Nebula



[NASA, ESA, M. Robberto (Space Telescope Science Institute/ESA) and the Hubble Space Telescope Orion Treasury Project Team]

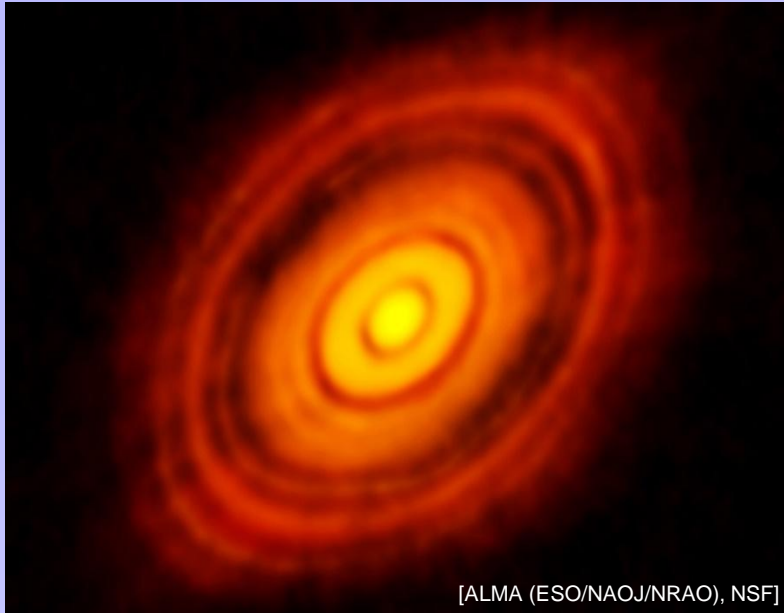
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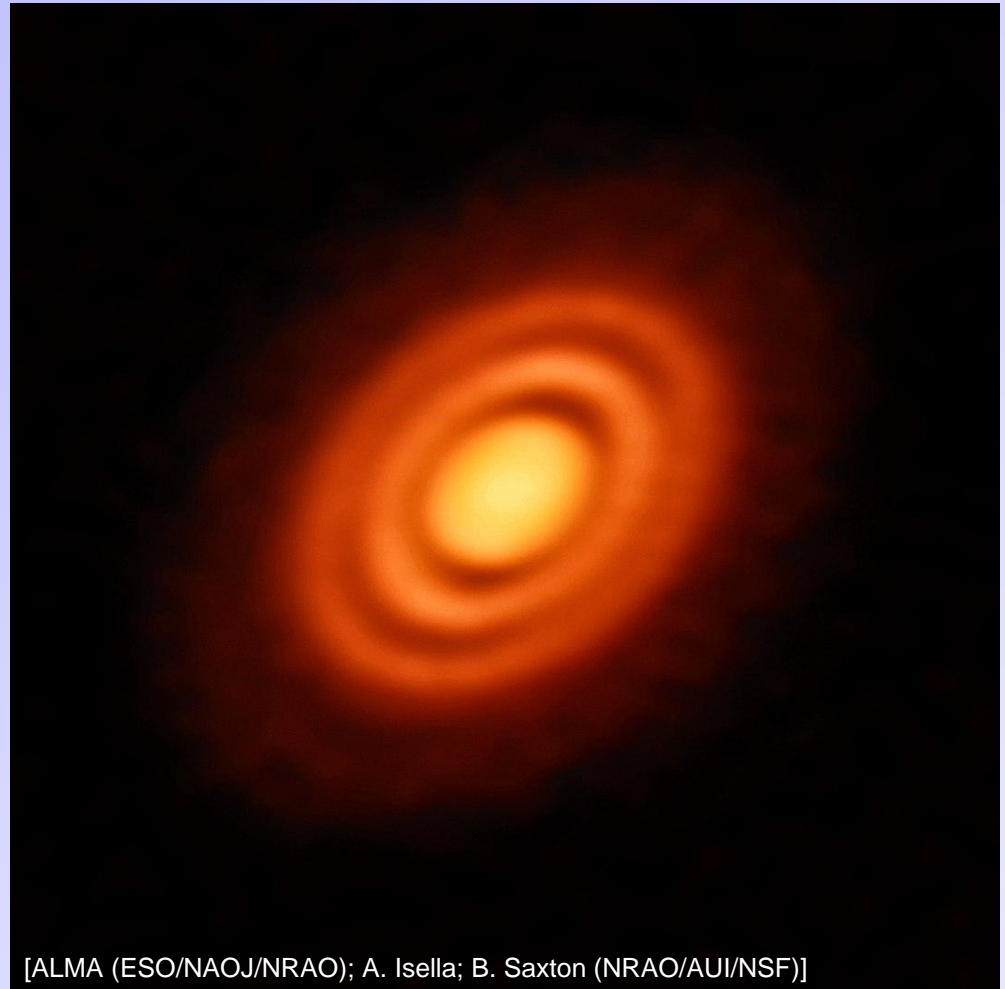


Protoplanetary Disks – mm wave



[ALMA (ESO/NAOJ/NRAO), NSF]

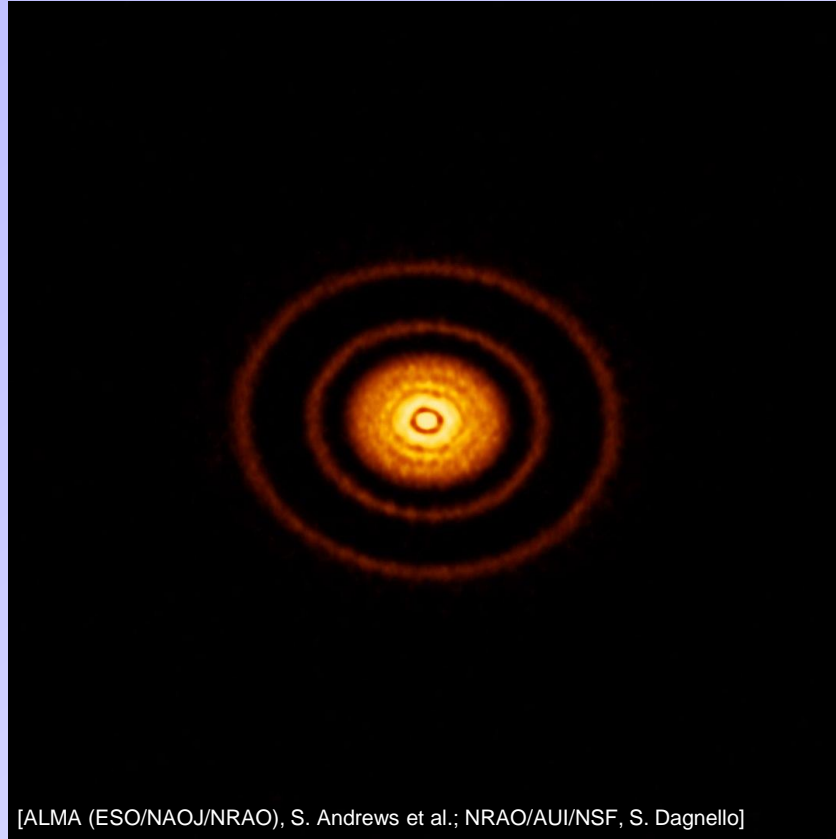
The Protoplanetary Disk of the young star HL Tauri
(in Milky Way galaxy, Taurus constellation)



[ALMA (ESO/NAOJ/NRAO); A. Isella; B. Saxton (NRAO/AUI/NSF)]

Cloud of gas and dust surrounding the young star HD 163296.
(in Milky Way galaxy, Sagittarius constellation)

Protoplanetary Disks – mm wave



Protoplanetary disk around the young star AS 209.

(in Milky Way galaxy, Ophiuchus constellation)

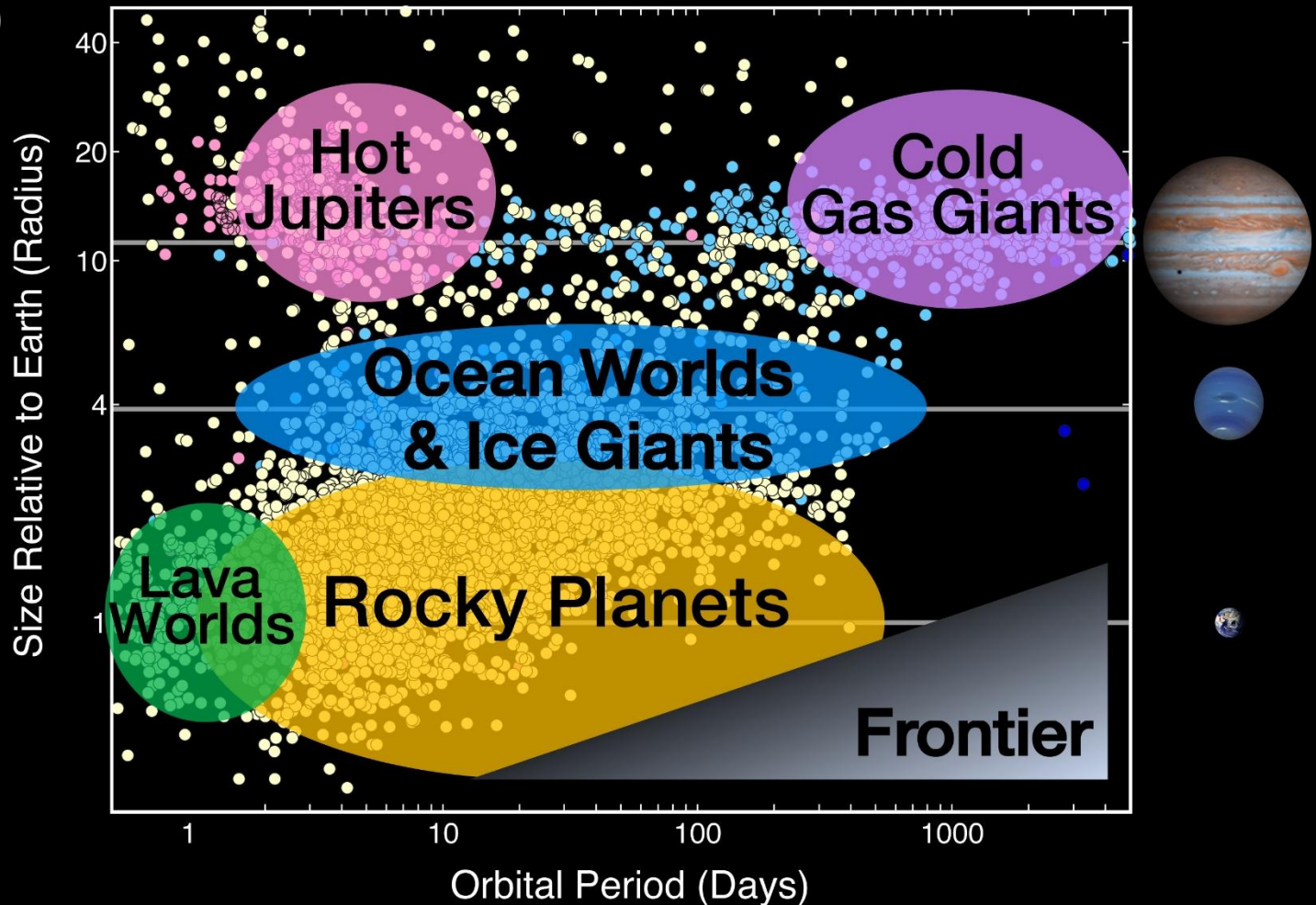
Exoplanets

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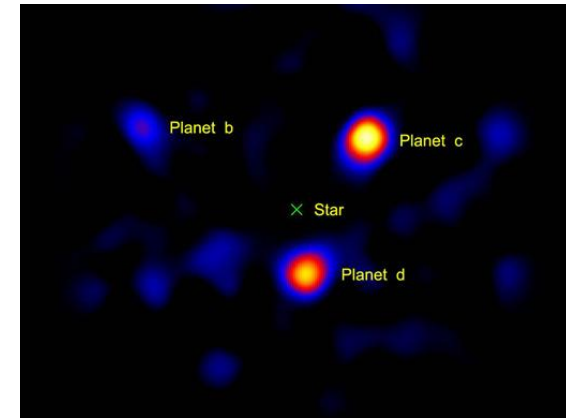
(updated: 2017)



Exoplanets

What we know so far

- **Most stars (possibly all) have planets.**

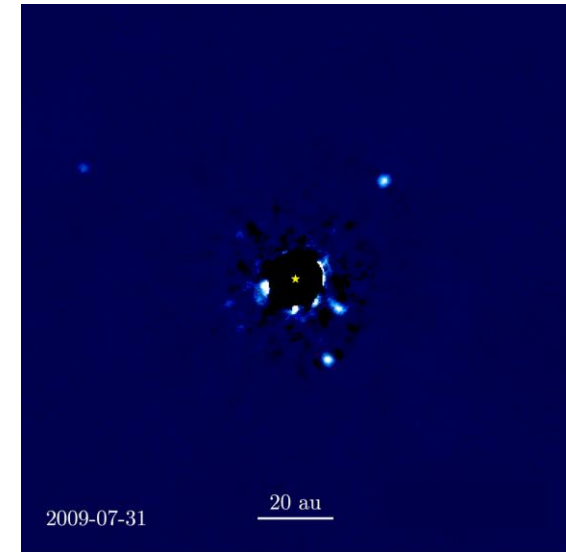


*3 planets around star HR8799 (120 ly)
Orbits: 24 AU, 38 AU, 68 AU.
[Hale telescope, 2010]*

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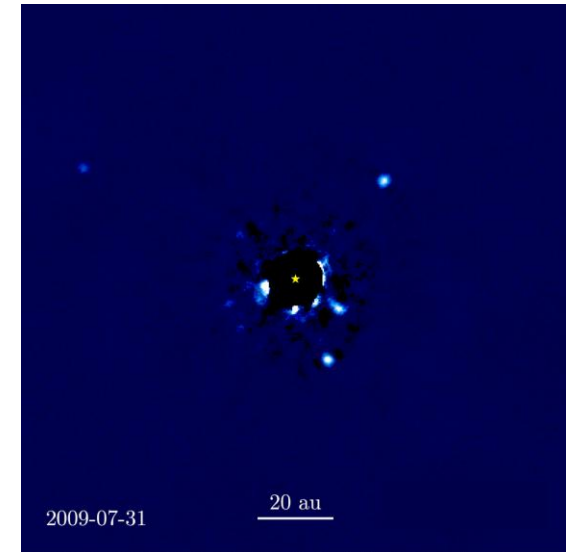


*4 planets around star HR8799 (120 ly)
[Keck telescope, 2009-2016, J. Wang,
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Models of evolution for solar systems show that planets often perturb the orbits of other planets and **move them towards the star** (or shoot them out).

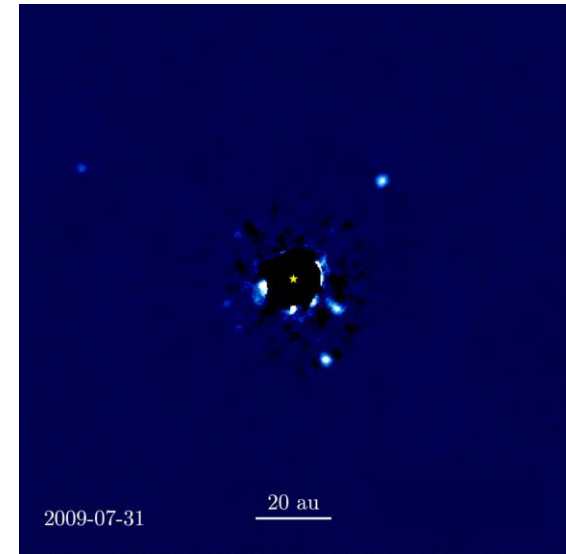


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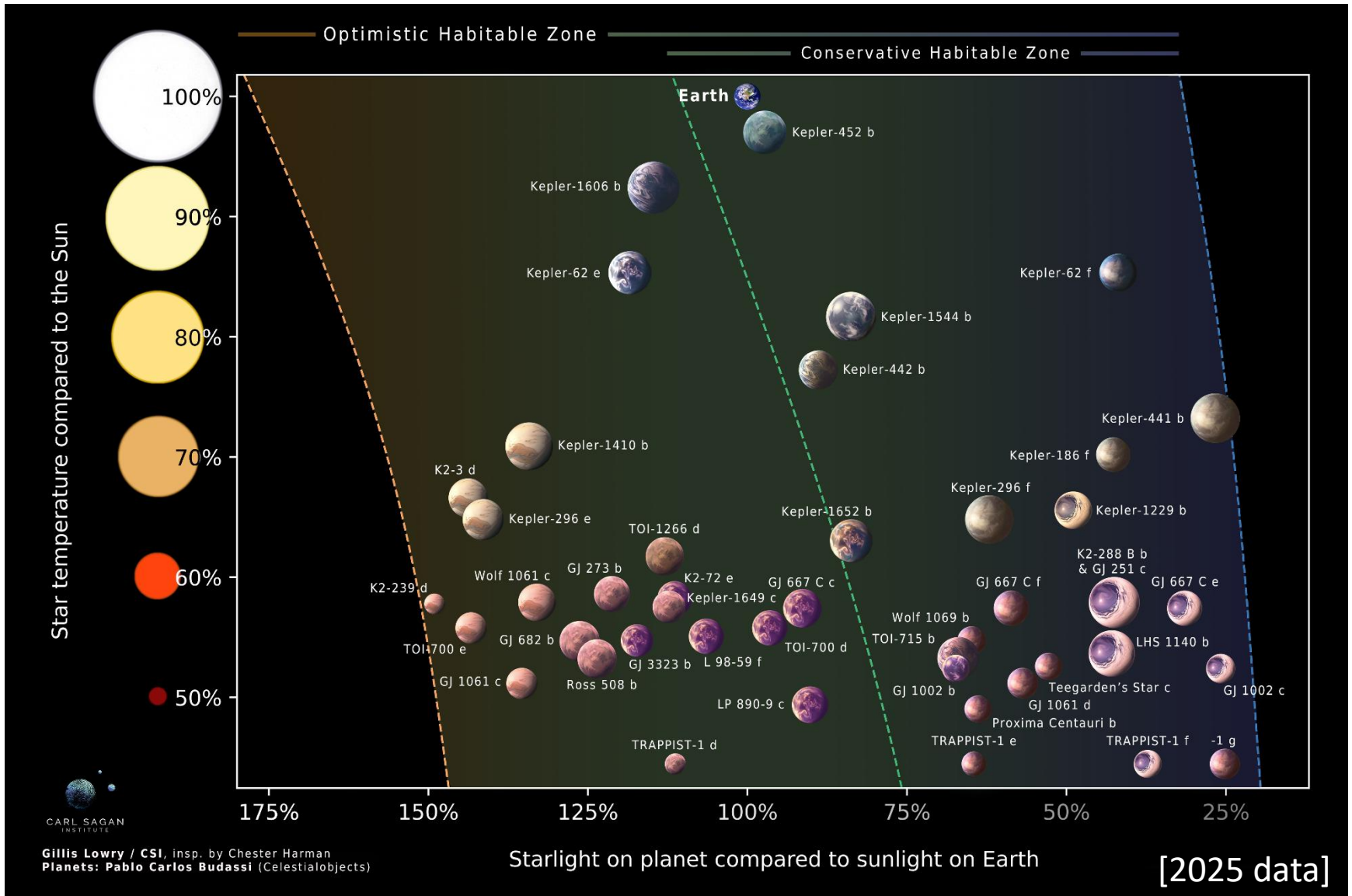
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Models of evolution for solar systems show that planets often perturb the orbits of other planets and **move them towards the star** (or shoot them out).
- Roughly 40% of Sun-like stars have terrestrial planets in the **“goldilocks”** region.
→ Above freezing and below boiling for water.
- **Earth-like** planets are very common
They are harder to detect than larger ones, so we have not seen very many yet.

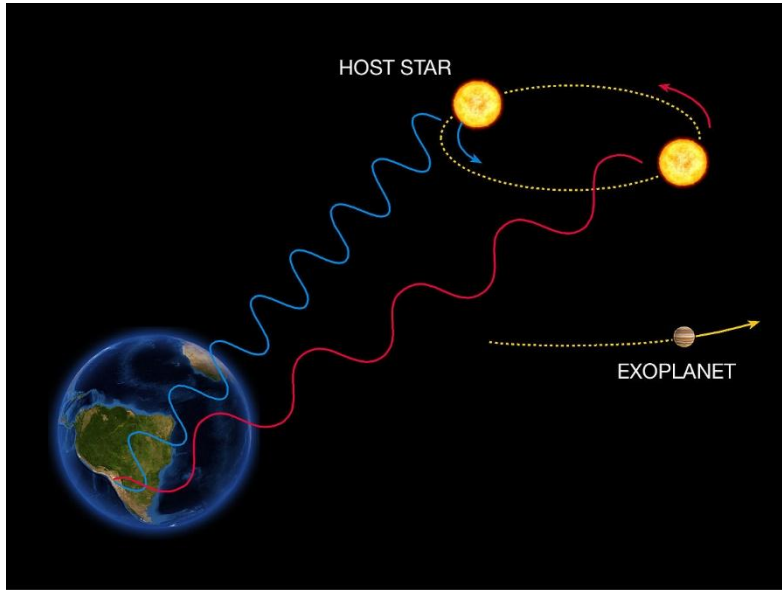


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Earth-like Exoplanets



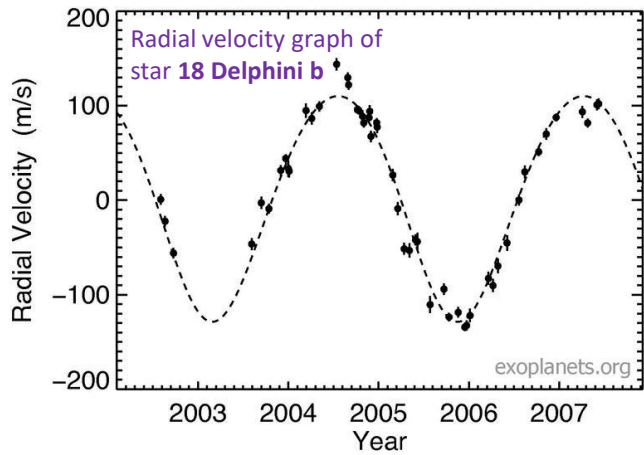
Main Detection Methods



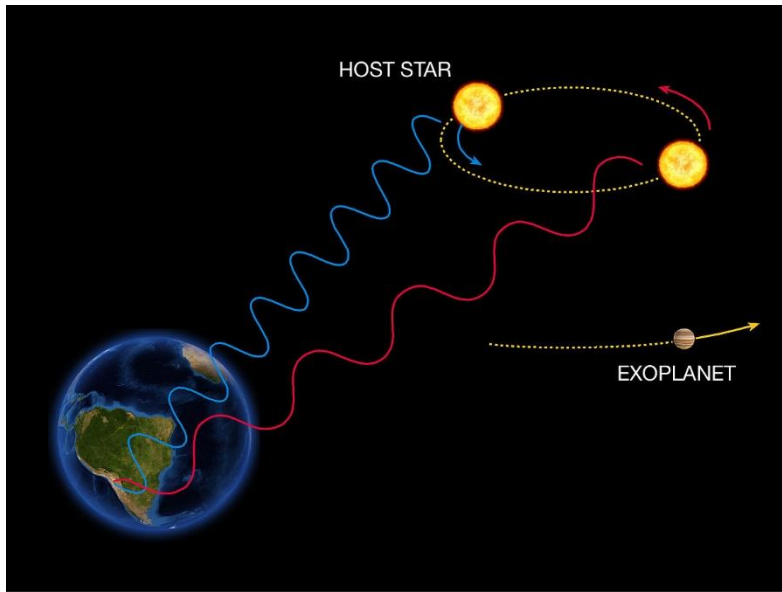
The Radial Velocity Method

ESO Press Photo 22e/07 (25 April 2007)

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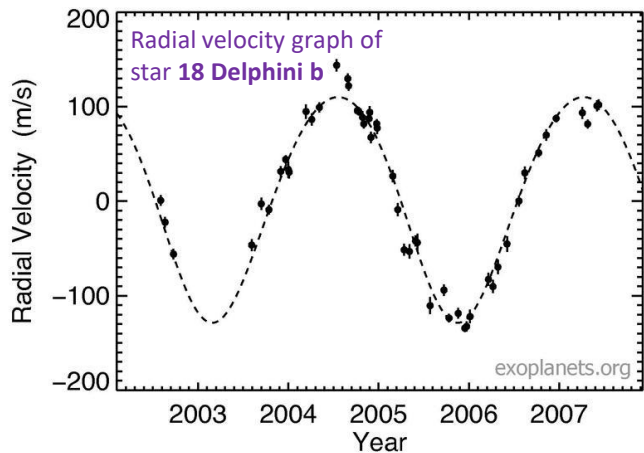
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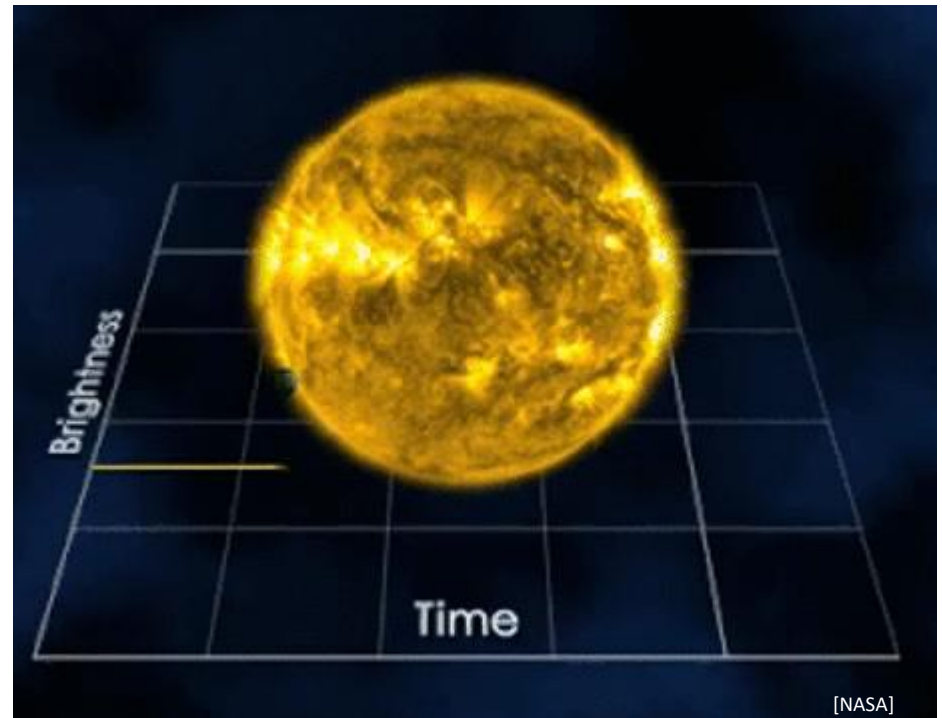
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Transit Photometry



[NASA]

Signal is typically 1 part per 10,000 dimming.

PollEv Quiz: Pollev.com/sethaubin

What is Life ?

Definitions of Life (biology) – *there are many definitions (no consensus)*

Definition 1

Life is considered a characteristic of something that preserves, furthers or reinforces its existence in the given environment *[Wikipedia]*.

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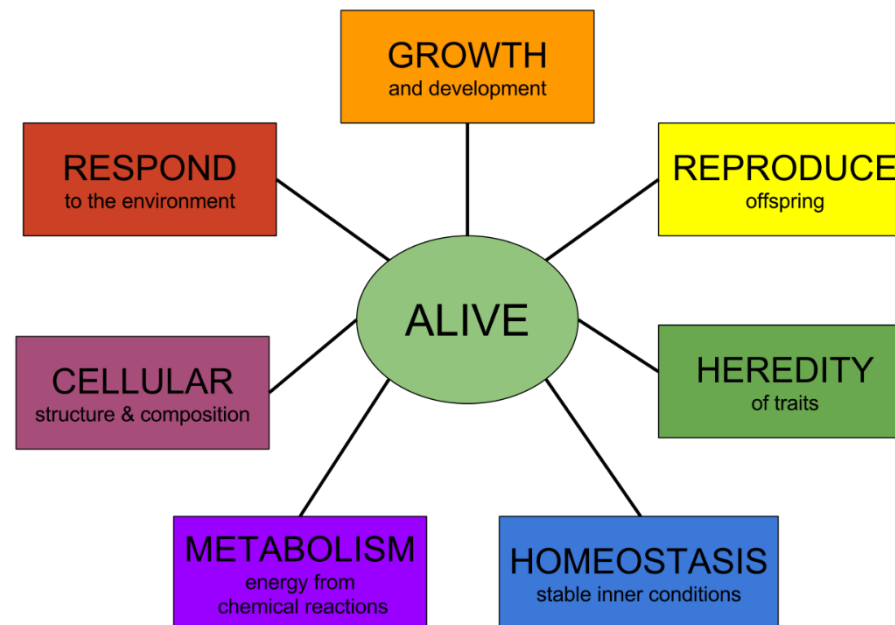
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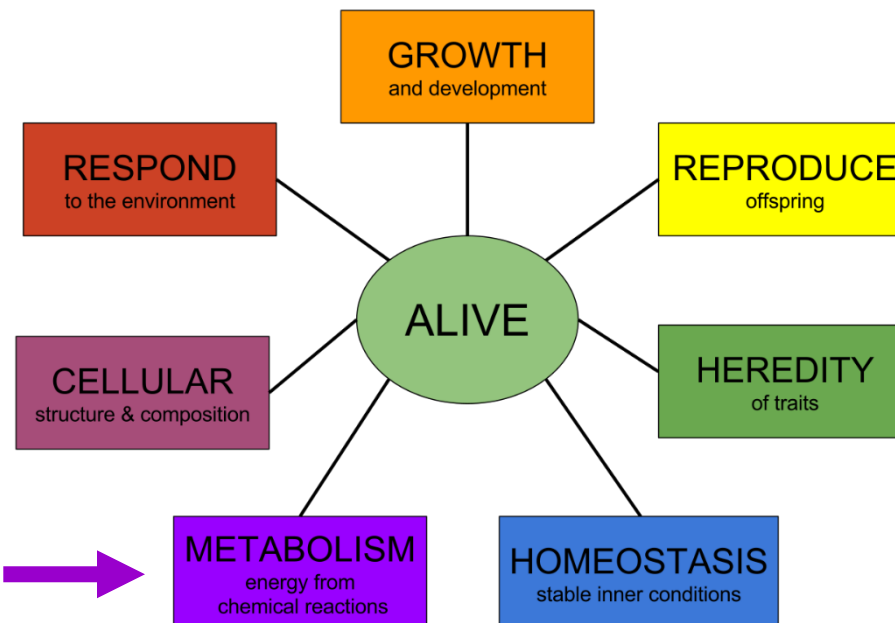
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Life requires specific environmental conditions →
... Also, life can modify its environment.

Life requires an energy source →



What are the environmental requirements for Earth-style Life?

Ingredients for Earth-style life

- **Liquid water** (solvent).
- Carbon, hydrogen, nitrogen, oxygen, phosphorus, and sulfur.
- **Temperature range: -25° C to 120° C.**
- Not too much ionizing radiation.
- **An energy source:** solar energy, chemical energy, heat.

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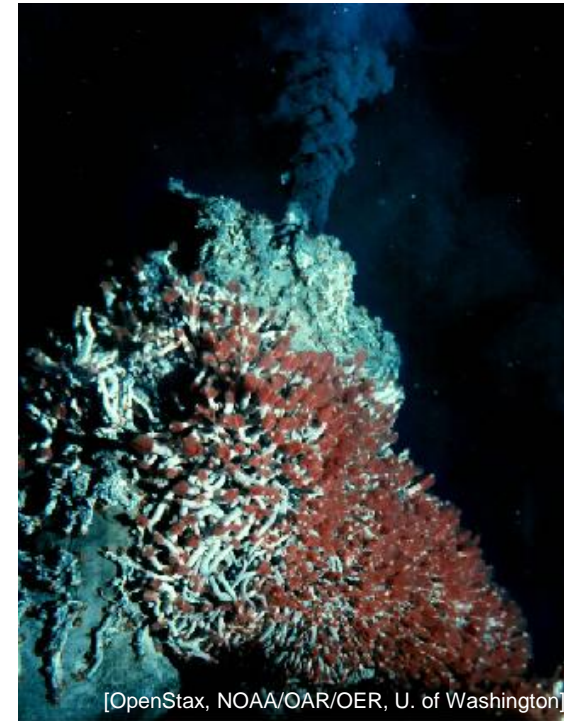
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[OpenStax: Astronomy]

Hot spring (Yellowstone Nat. Park): multi-colored photosynthesizing bacteria (solar energy). Central pool (92°C) bacteria use chemical energy.



[OpenStax, NOAA/OAR/OER, U. of Washington]

Hydrothermal vent: chemical energy (metal sulfides).

Examples of Hardy Life



[Wikipedia: Schokraie E, et al. (2012), PLoS ONE 7(9): e45682. doi:10.1371/journal.pone.0045682]

The Tardigrade (length: ~0.5 mm) can survive

- -270° C to 150° C for a few minutes.
- Vacuum to 1000 bars.
- Years of dehydration.
- 1000x lethal radiation dose of animals.



[NASA: microbes.arc.nasa.gov/images/content/gallery/lightms/publication/unicells.jpg]

Cyanobacteria are photosynthesizing bacteria that have existed on Earth for 2.1 billion years ago (maybe longer)

Where to look for life In the Solar System ?



Mars may have suitable conditions for life just below its surface:

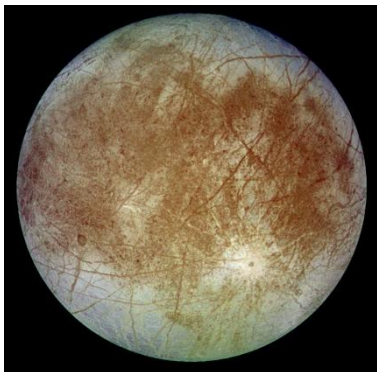
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- **Tidal heating.**
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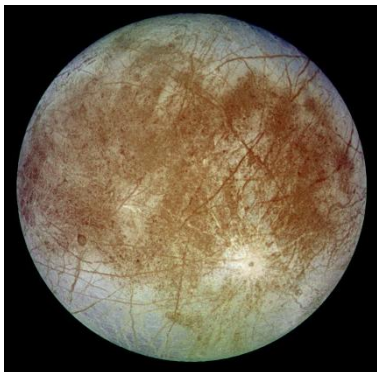
[NASA/JPL/DLR: Galileo mission, 1996]

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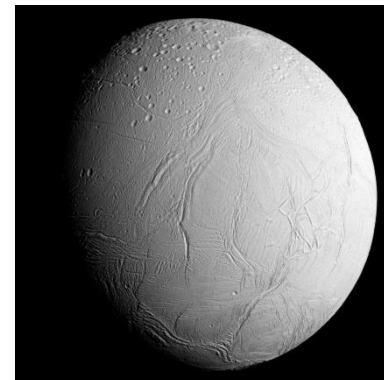
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[NASA: Cassini mission, 2015]

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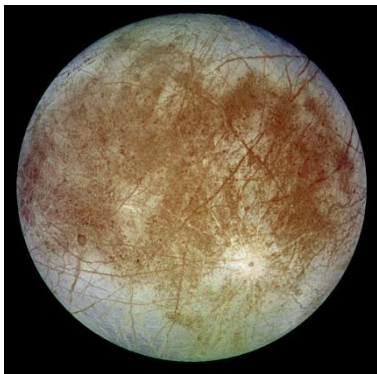
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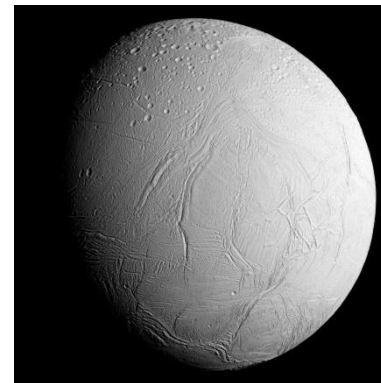
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More speculative: Ganymede sub-surface water, upper atmosphere of Venus.