

Habitable Planets

Chapters 10.1-10.4; 11.1

Lectures Sept. 11, 16. Exam is Sept 18 (Thursday)

Conventional requirements for habitability

Planet -- difficult to get very complex and *stable* molecules elsewhere. We will come back to question of whether habitable exoplanets are common.

Continuous **liquid water** (main requirement for conventional habitable zone) *on surface*.
This is the main subject of Ch. 10.

Thick atmosphere -- protection, stabilizes climate, pressure holds in the liquid water

Planet mass large enough for radioactive Heating → plate tectonics, other geol. activity.

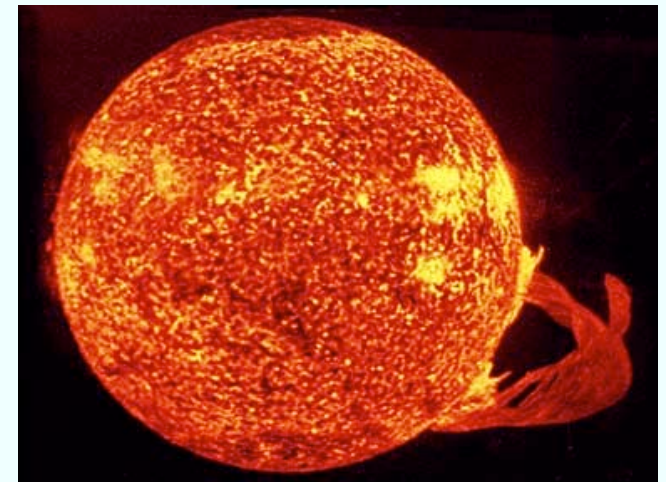
Star that lives long enough (~ 1 Gyr)

(main sequence star: Sun or smaller), and

other properties... No flare stars? →

Magnetic field? Protection from cosmic rays.

Large moon? Stabilizes rotation, ...



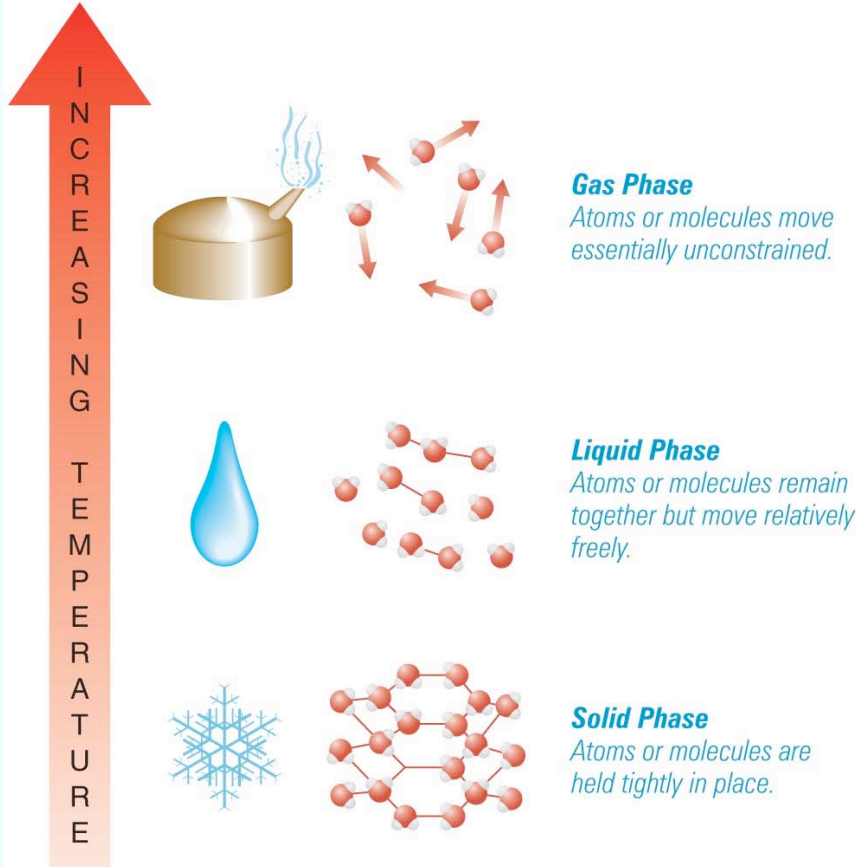
→ Our view of habitable planets appears highly Earth-o-centric!

Critical temperatures for phase changes of various substances









As temperature rises, all materials undergo *phase changes* between solid, liquid, and vapor, at certain critical temperatures.

Memorize *critical temperatures of water*.

Where will such temperatures be likely to arise?



The four types of materials present in the protoplanetary solar nebula (Table 3.1 in textbook)

	Examples	Typical Condensation Temperature	Relative Abundance (by mass)
Hydrogen and Helium Gas	hydrogen, helium in nebula 	do not condense	 98%
Hydrogen Compounds	water (H ₂ O) methane (CH ₄) ammonia (NH ₃) 	< 150 K	 1.4%
Rock	various minerals 	500–1,300 K	 0.4%
Metals	iron, nickel, aluminum 	1,000–1,600 K	 0.2%

Critical temperatures for phase changes and relation to HZ in words

- Every substance can exist in different “phases” --- gas, liquid, solid. Which one occurs depends almost entirely on the temperature T.
- As it cools, the substance will undergo a transition from the gas, to liquid, to solid phase at certain critical temperatures. (Think ice cubes.) At low pressures, transition can be from gas directly to solid, with no liquid phase possible.
- Each substance has its own critical temperature for the gas-liquid (or gas-solid in the case of rocks) transition, called its “evaporation” or “condensation” temperature.
- To get rocky (minerals) planets like ours, T must be $< 1000\text{-}1500\text{K}$. If T higher than this, rocks will “sublime” or “vaporize” back to the gaseous state.
- For life, T must be low enough for complex molecules to form, so this requires temperatures below $\sim 400\text{ K}$. But it is difficult to imagine life without a *liquid* to serve a large number of functions. And there are very strong arguments that *water* is an amazingly unique liquid for this purpose.
- Liquid water requires T between 273K (freezing of water 0 C) and 373K (boiling of water, 100 C). The range of distances from a given star for which a planet is in this temperature range is called the “**liquid water habitable zone**” or just “**habitable zone**”, which we abbreviate **HZ**.
- However other liquids are possible--see table on later slide. And there are several environments outside the conventional HZ that might support liquid water or life.

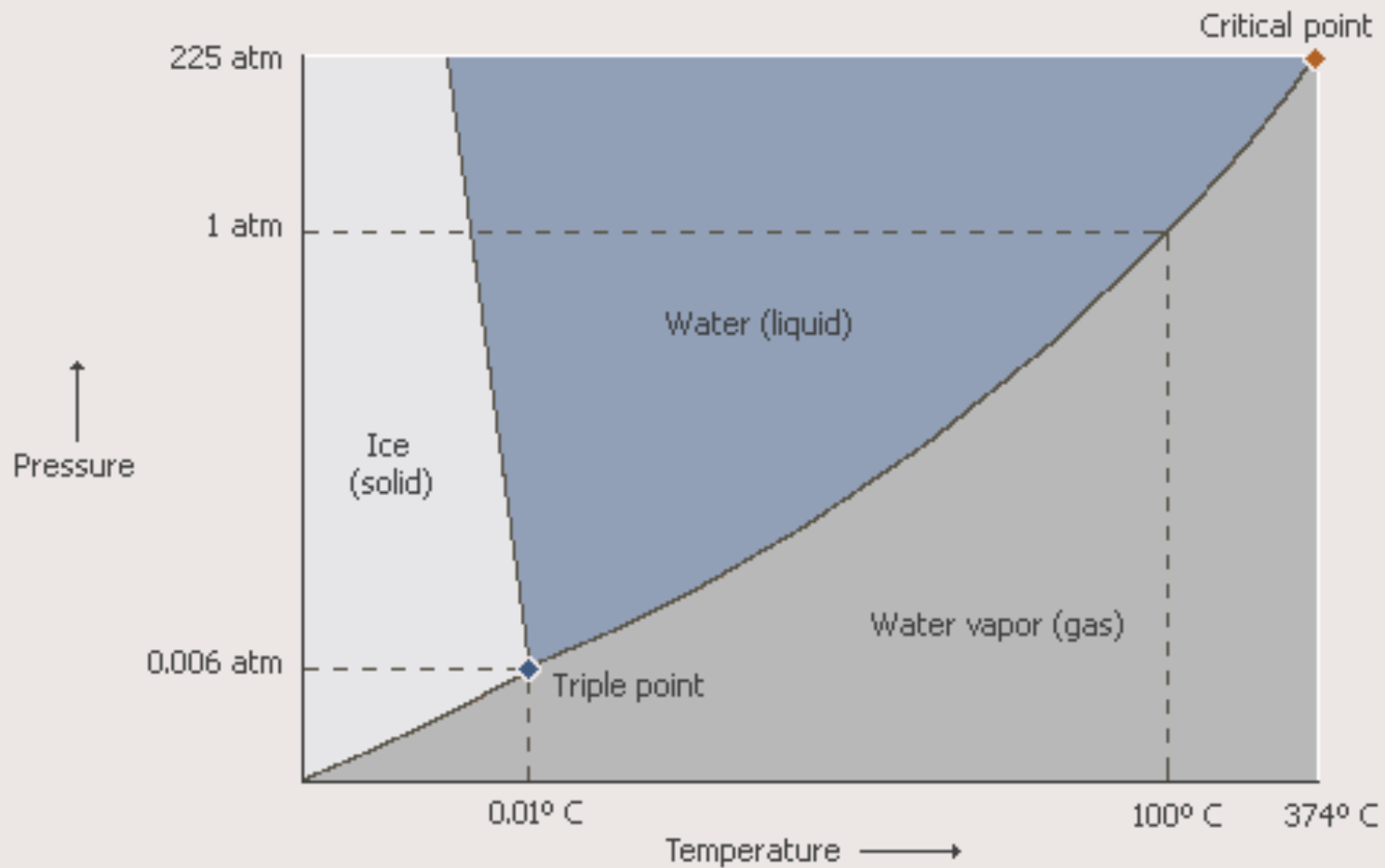
Several substances remain liquid over a fairly large temperature range and are abundant enough so that they might form oceans.

(This is why Titan, a moon of Saturn, is of such great interest.)

But water is the hands-down winner in several other respects...

Liquid	Melting temp.	Boiling temp.	Range for liquid
Water (H ₂ O)	0 °C	100 °C	100 °C
Ammonia (NH ₃)	-78 °C	-33 °C	45 °C
Methane (CH ₄)	-182 °C	-164 °C	18 °C
Ethane (C ₂ H ₆)	-183 °C	-89 °C	94 °C

Water Phase Diagram

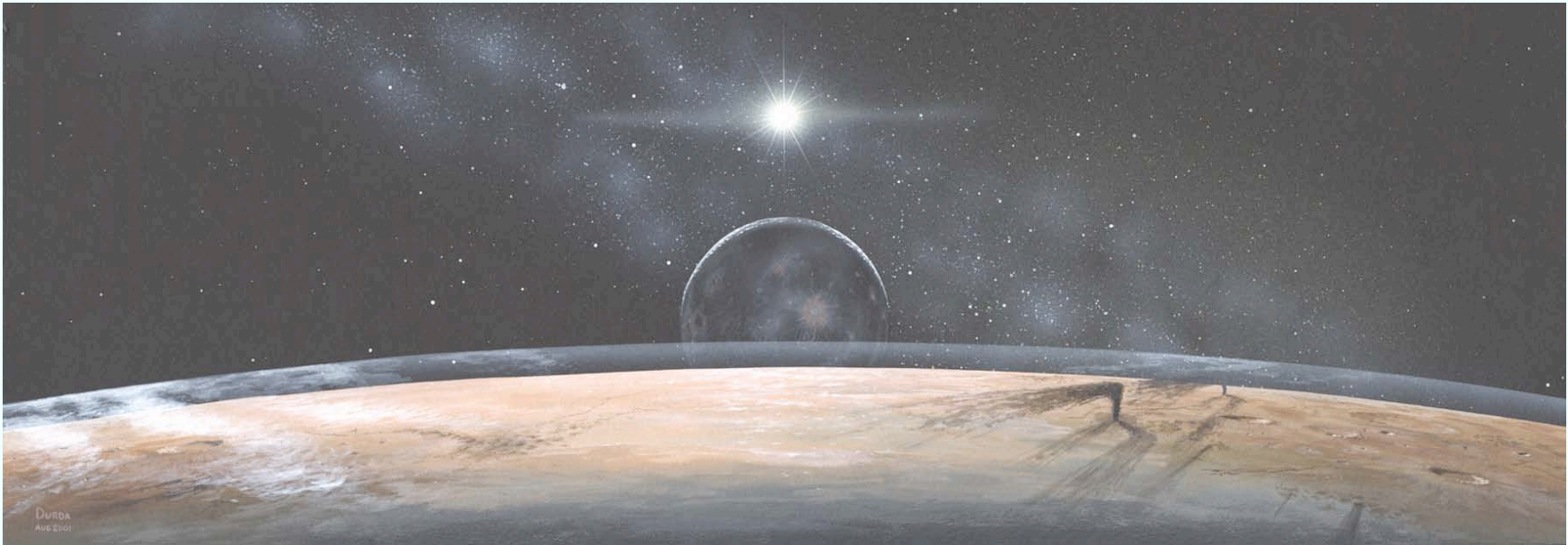


Drawing is not to scale

What controls a planet's surface temperature?

The temperature of a planet's surface is mostly controlled by its **distance** to its parent star, *and* its parent star's **luminosity**, because that determines how much energy it receives.

The illustration below shows the Sun as it would appear from Pluto:
Way too cold for *liquid* water (but plenty of water ice)
→ Pluto is far outside the "habitable zone."



Planetary Surface Temperatures--how to calculate them

[The factor left out of this is **climate**: greenhouse effect, cooling by clouds and ice, ...]

Quantitatively: An object's surface temperature reflects an equilibrium between

1. The rate at which it receives energy (per second, and per unit area). If planet is at distance d from star of luminosity L (energy per sec), then this is the received flux: $L/4\pi d^2$,

and

2. The rate at which it emits energy (per second, and per unit area). You may remember that for a black body this is given by the Stefan-Boltzmann law: $E = \sigma T^4$ (σ = Stefan-Boltzmann constant, don't worry about it).

Equating 1 and 2 gives $T^4 \sim L/d^2$ or

$$T \sim L^{1/4}/d^{1/2}$$

This merely says temperature will increase if brighter star or smaller distance, as you know intuitively, but the formula gives you a way to calculate temperatures *quantitatively*.

Now is a good time to understand what determines a planet's temperature

Your textbook gives a detailed discussion of the climate effects that dominate estimates of the width of the HZ, in particular how they affected Venus and Mars (which is also affected by its tiny mass). We discussed these in class, but read the text in detail, and especially:

Assignment at textbook web site:

Tutorial: *Surface temperature of terrestrial planets.*

At the end, you should be able to answer the three major questions listed:

- 1. What are the three main factors that determine a terrestrial planet's surface temperature?*
- 2. Explain how each factor affects a terrestrial planet's temperature.*
- 3. Discuss the main reason why Venus is so much hotter than Earth, and Mars so much colder.*

Inside, outside, and within the liquid water habitable zone



(a)



(b)

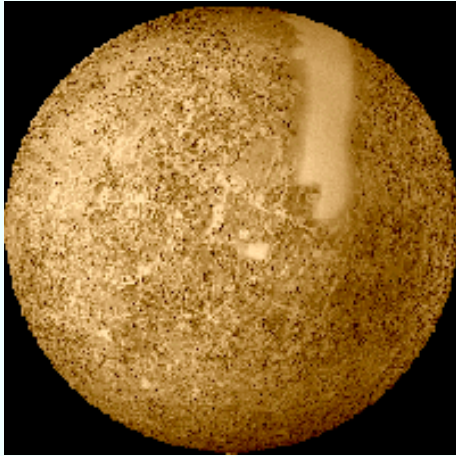


(c)

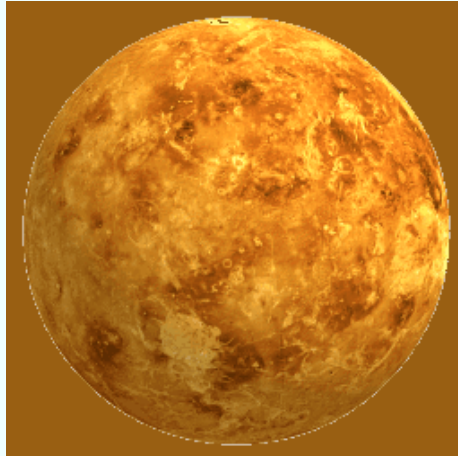
Too hot, too cold, and just right. Scenes on imaginary planets emphasize that many extrasolar planets may not have conditions suitable for life. **(a)** The surface of this planet, close to a pair of hot, massive stars, is a sun-blasted desert. **(b)** On this world, far from a red and white pair of stars, all water is frozen. **(c)** Some worlds may exist in which liquid water persists and life forms have evolved.

(SOURCE: Paintings by Don Dixon, Ron Miller, and WKH, respectively.)

Planets in our Solar System

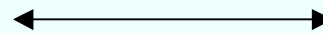


Mercury



Venus

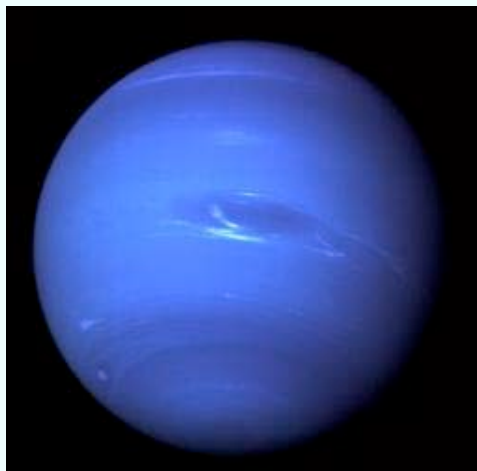
Habitable zone here



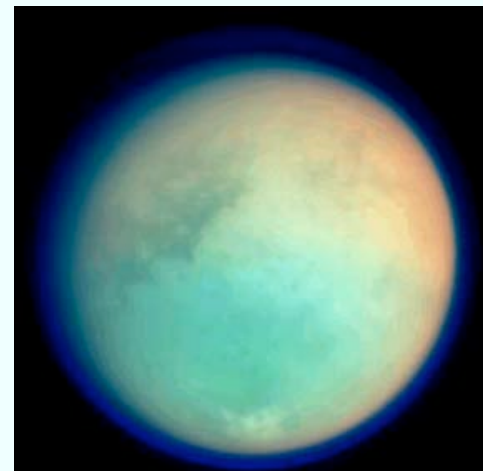
Mars



Jupiter

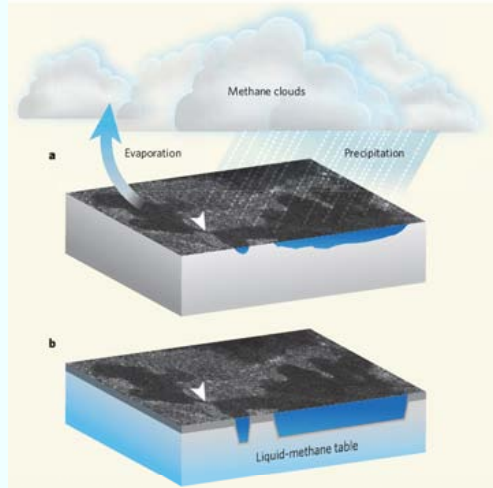
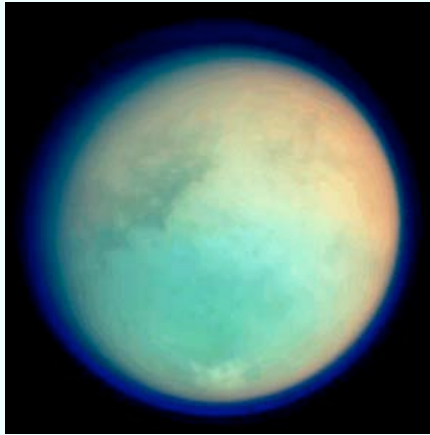


Uranus



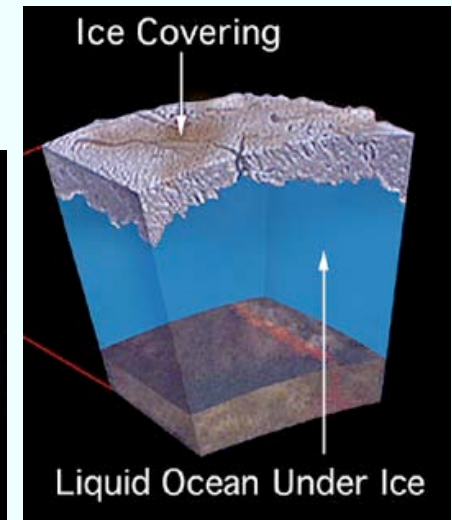
Titan

Outside the HZ: Moons of giant planets?



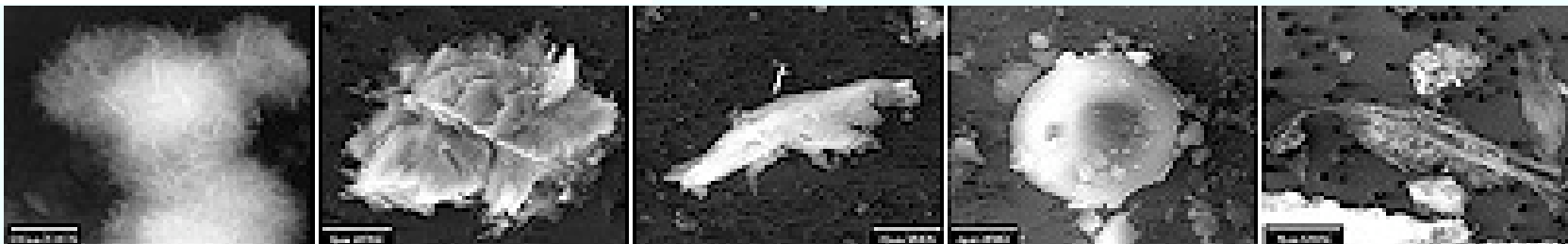
Europa

- ◆ Tidally heated icy moon of Jupiter
- ◆ Cracks and other features suggest
- ◆ Liquid water beneath surface?



Titan

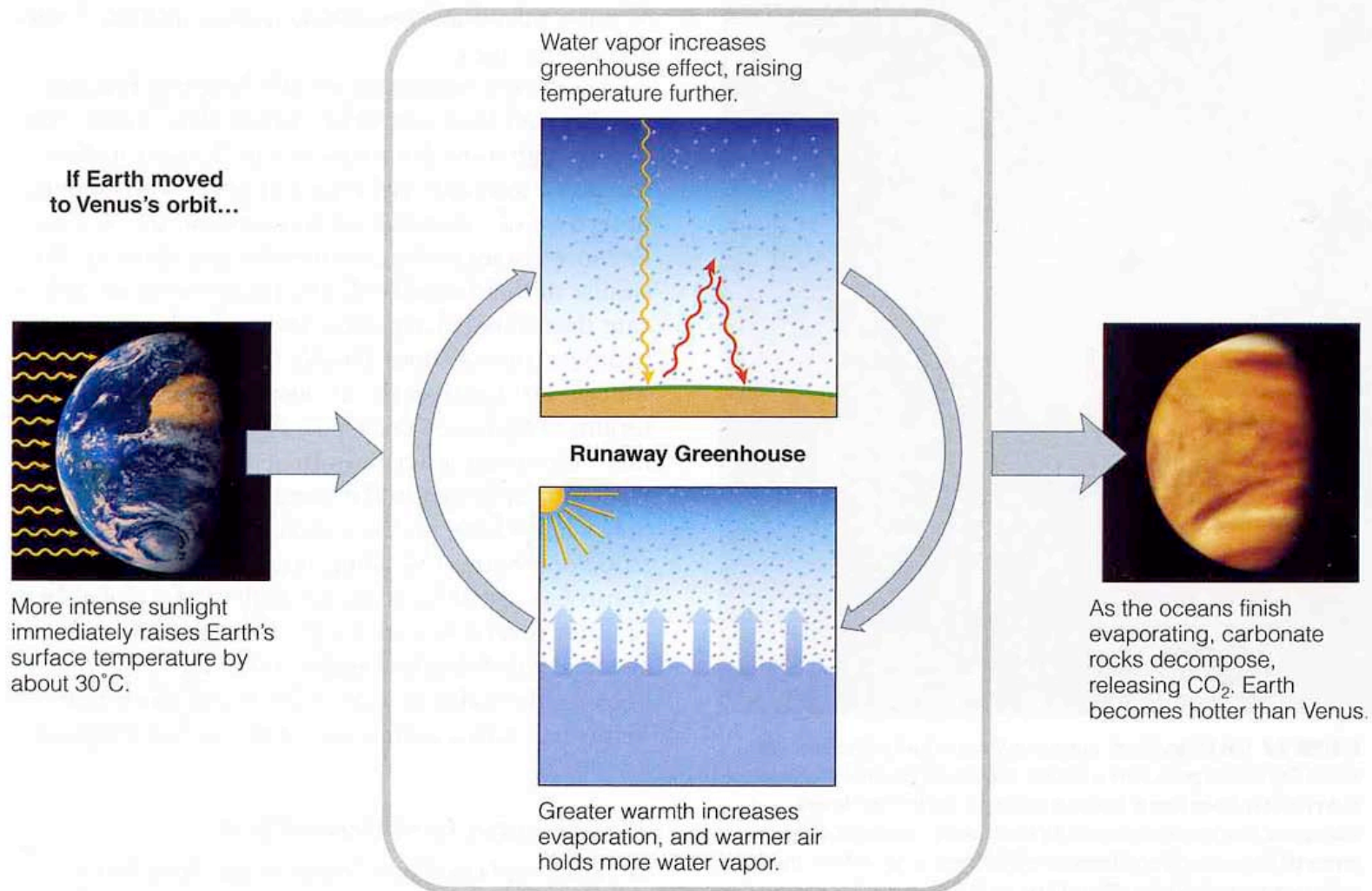
- ◆ Only moon with atmosphere (methane, ammonia)
- ◆ Cold analogy to early Earth?
- ◆ Evidence for rain cycle (right) finally discovered by Cassini



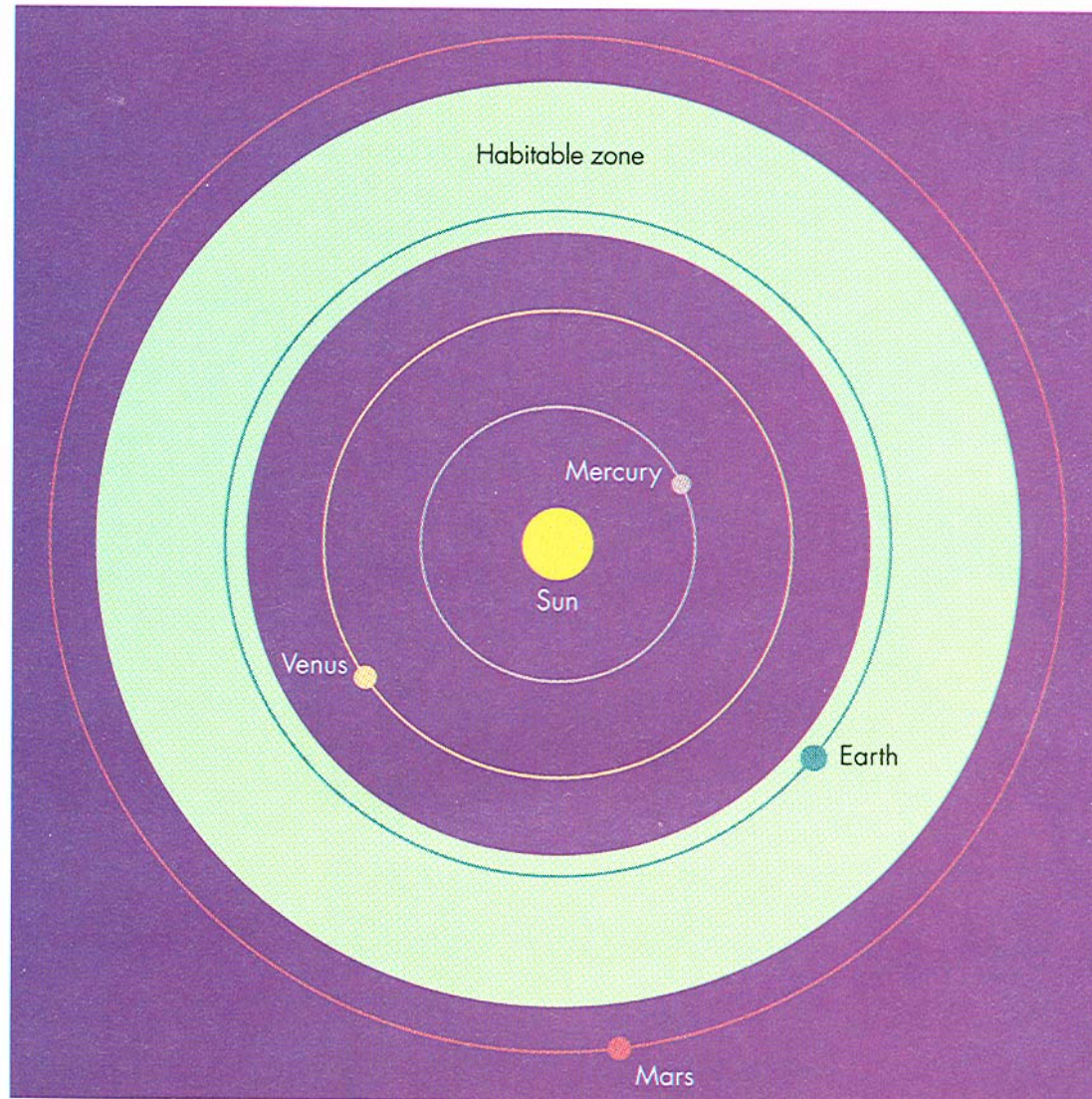
Some organisms found in ancient Antarctic ice 1250 meters beneath Vostok Station

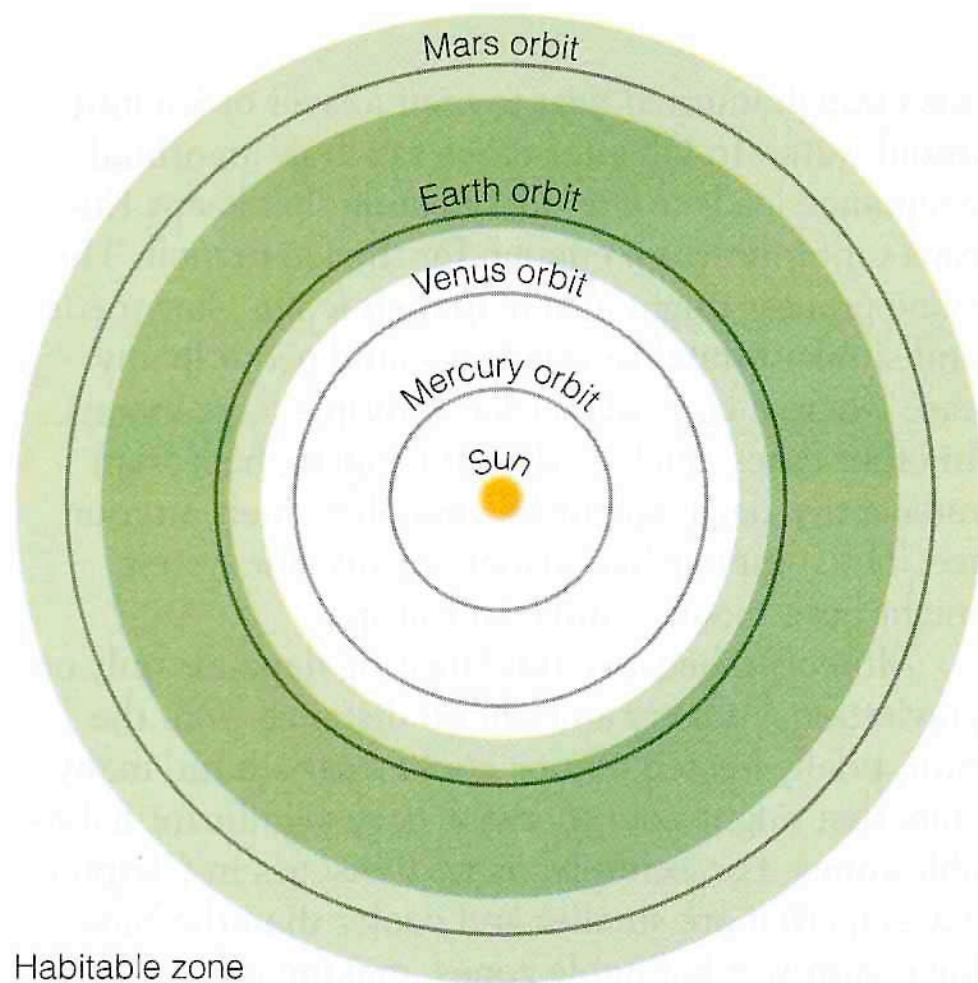
Inner and outer boundaries of habitable zone (HZ) in solar system

We can see the main effects related to the habitable zone here in our Solar System: Consider what happened to **Venus** → runaway greenhouse. (Fig. 10.3 in text) Consider how reversed has occurred on Mars.



A calculation of the continuously habitable zone for the Sun. Notice that the Earth barely is barely within HZ. This is for “moist greenhouse” inner boundary of HZ, where water vapor *might* be destroyed by UV and H escape.





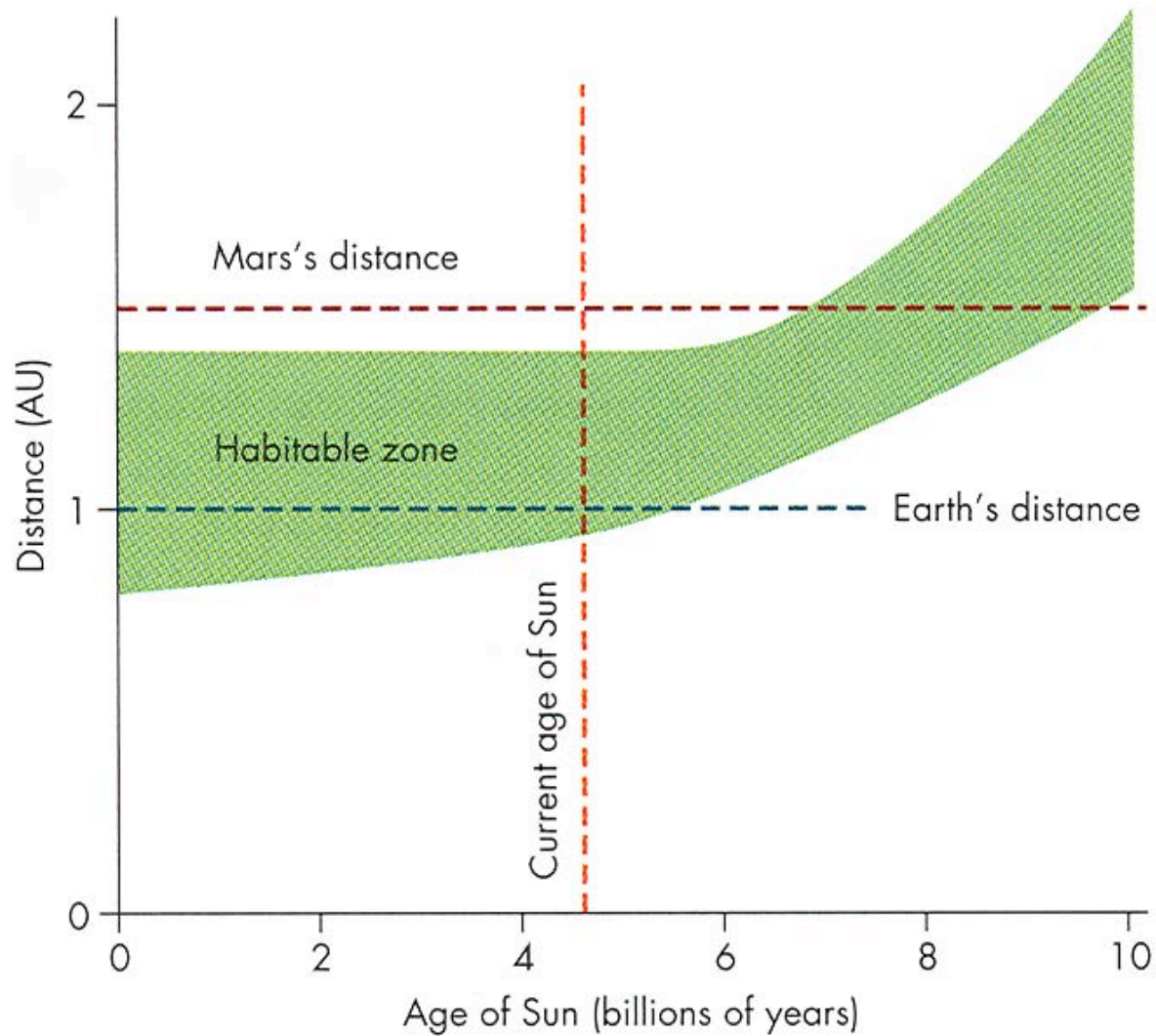
Habitable zone

- conservative estimate
- optimistic estimate

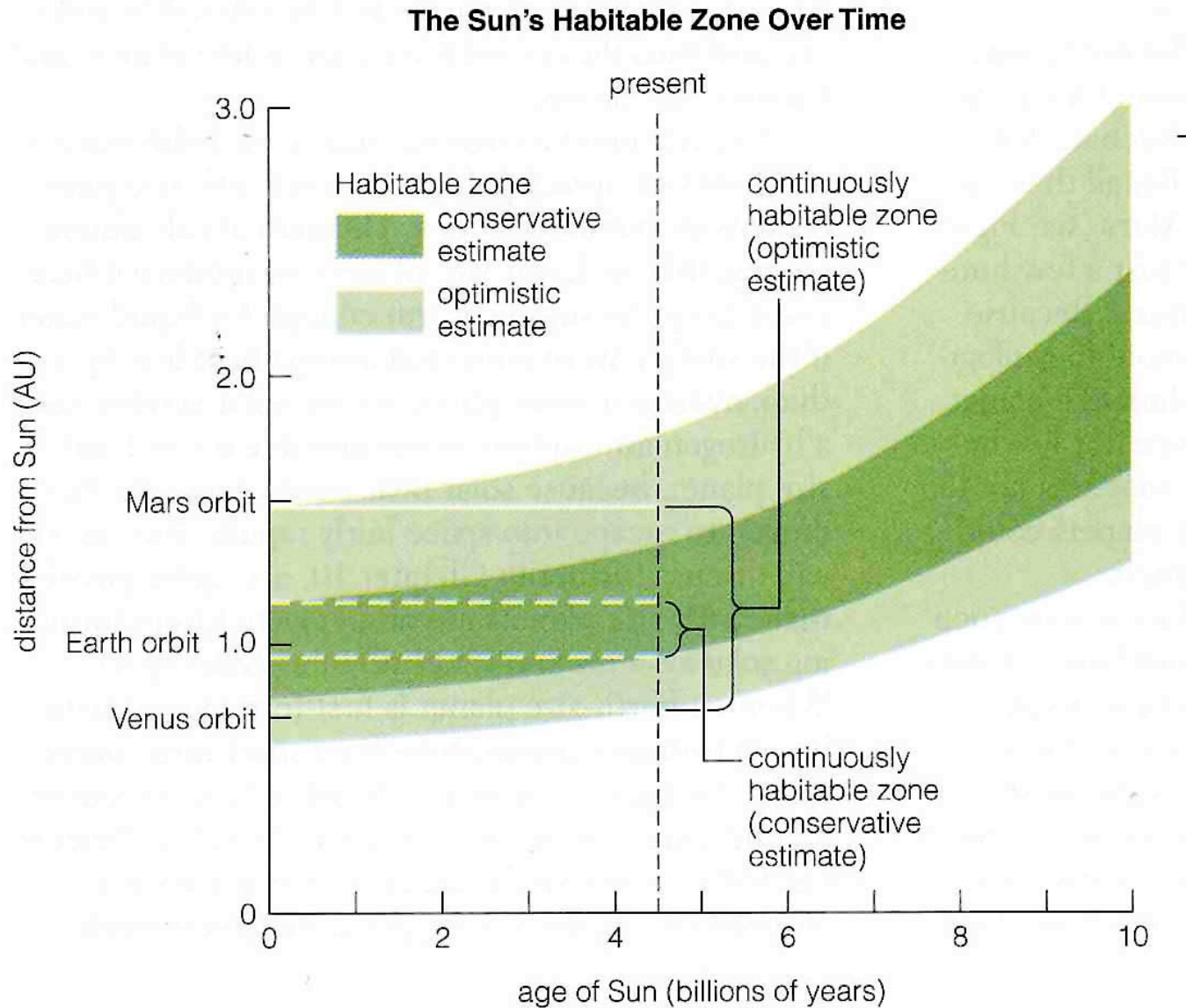
FIGURE 9.4 Boundaries of the Sun's habitable zone today. The narrower set of boundaries represents a model based on the more conservative assumptions, while the wider set represents the most optimistic scenarios.

Actually the answer is not so clear--depends a lot on the climate model and the assumptions. This illustration shows the results for two choices of assumptions (Fig. 10.4 in textbook).

Time evolution of the Sun's habitable zone--moves further from Sun as the Sun ages and *brightens*, leaving the Earth behind. Probably not for at least ~ 1 Gyr



More complicated version from your textbook (Fig. 10.5). Notice that in the “optimistic” choice, Earth will remain in the habitable zone for 3-4 more billion years.



There is more to habitability than water...

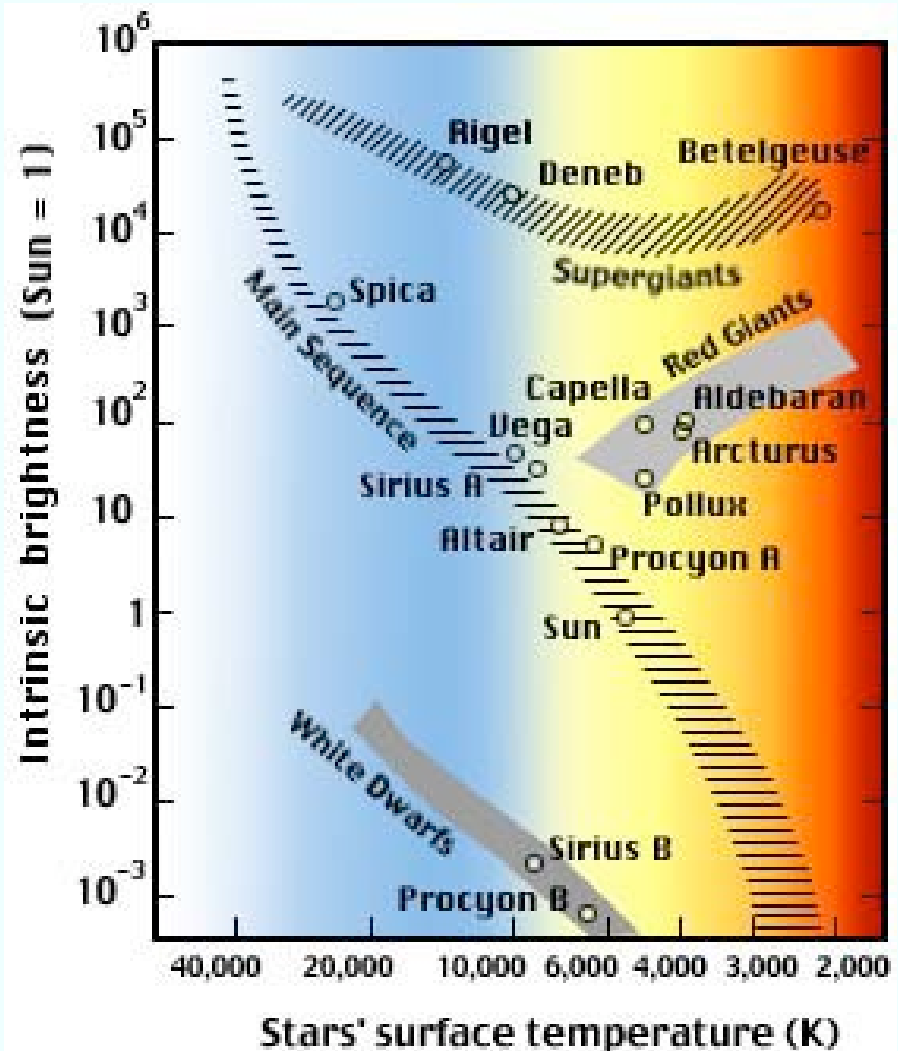
What types of stars might harbor habitable planets with life?

Recall the H-R diagram (illus.right). We think we can rule out just about *all* the types of stars shown, *except* for those on the main sequence around the Sun's spectral type and cooler. To understand why, we need to understand *masses* and *lifetimes*.

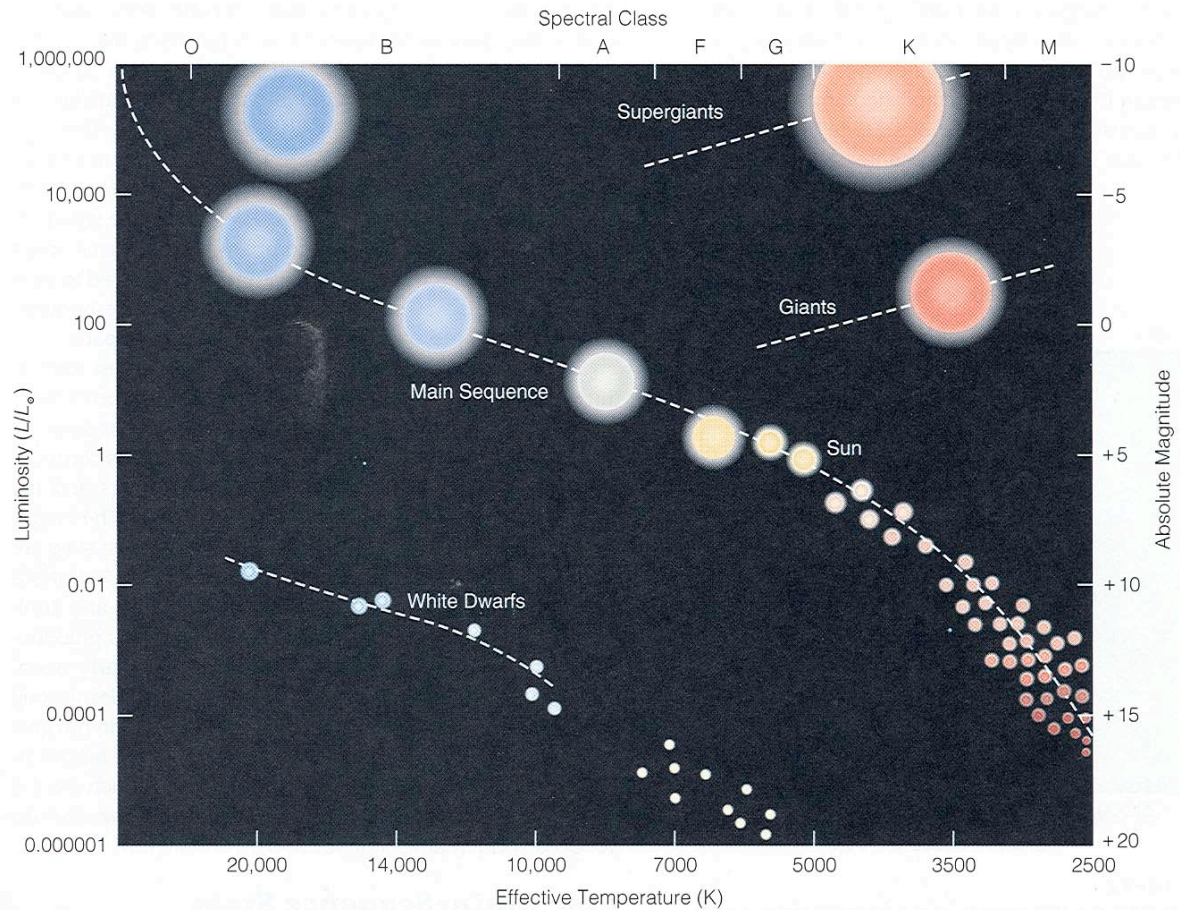
For now, notice the *main sequence*, the *giants* and *supergiants*, and the *white dwarfs*.

Why do most people think only stars on the main sequence are serious contenders for life-bearing planets?

The crucial factor: We think it took about 0.5 to 1 Gyr for life to arise on Earth. So we assume it may take that long elsewhere.



Stars come in many varieties--how should the habitable zone look for each of these classes of stars? How long do these different classes or phases last? Which type of star is the most or least numerous?



An H-R diagram for a selection of different types of stars. Stars are plotted schematically to show colors and relative sizes, but they are not to true scale. (This would require much larger red giants and much smaller white dwarfs.) Main-sequence stars, which release energy by fusing hydrogen into helium, run diagonally across the diagram.

Some properties of main sequence stars of different spectral types (masses). Notice the huge variation in luminosity and lifetime. These quantities control our decisions about which stars we should inspect for terrestrial-mass planets and biomarkers.

Table 10.1 Typical Properties for Hydrogen-Burning Stars of the Seven Major Spectral Types

Numbers given in "solar units" are values in comparison to the Sun; for example, a mass of 60 solar units means 60 times the mass of the Sun. Note that the Sun is a G star. (More specifically, the Sun's spectral type is G2.)

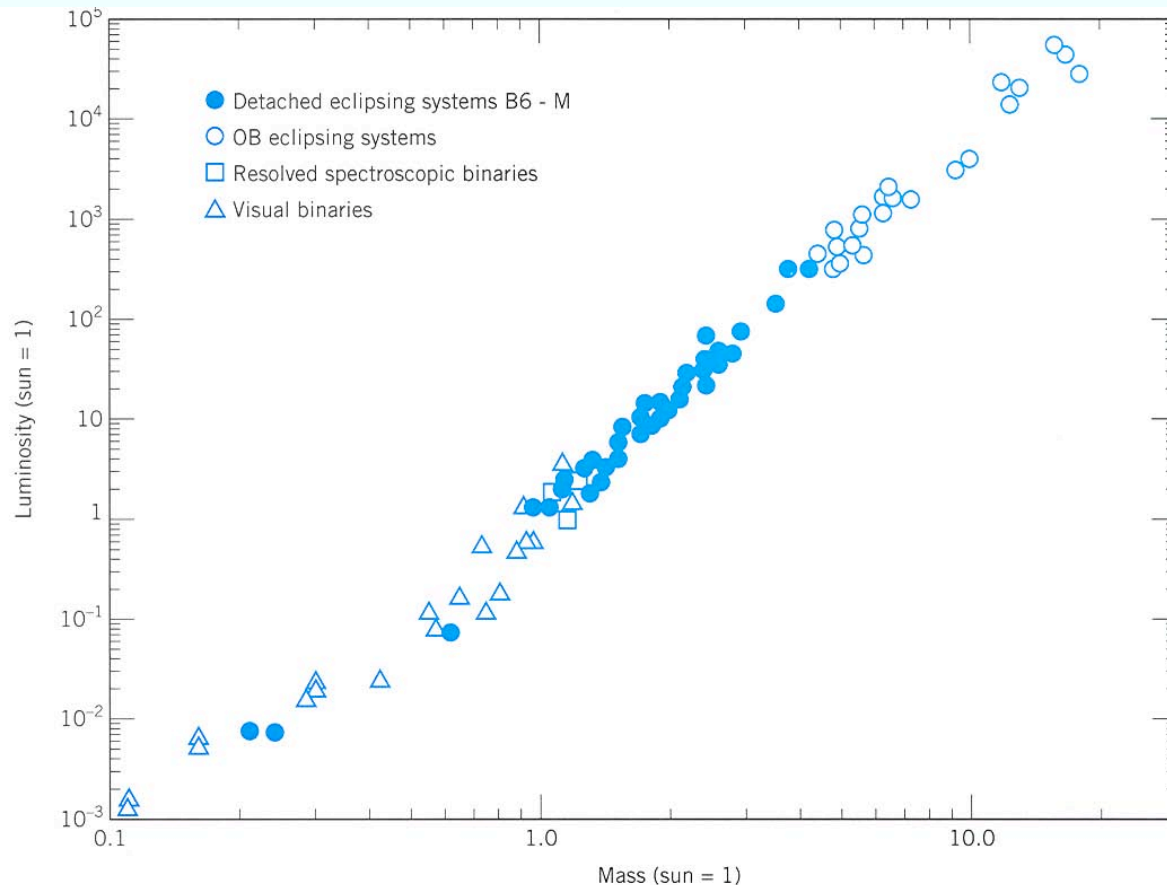
Spectral Type	Approximate Percentage of Stars in This Class	Surface Temperature (°C)	Luminosity (solar units)	Mass (solar units)	Lifetime (years)
O	0.001%	50,000	1,000,000	60	500 thousand
B	0.1%	15,000	1,000	6	50 million
A	1%	8,000	20	2	1 billion
F	2%	6,500	7	1.5	2 billion
G	7%	5,500	1	1	10 billion
K	15%	4,000	0.3	0.7	20 billion
M	75%	3,000	0.003	0.2	600 billion

The stellar luminosity-mass relation.

Mass is fundamental stellar property. Graph below shows that *luminosity* increases very rapidly with increasing mass. Two implications:

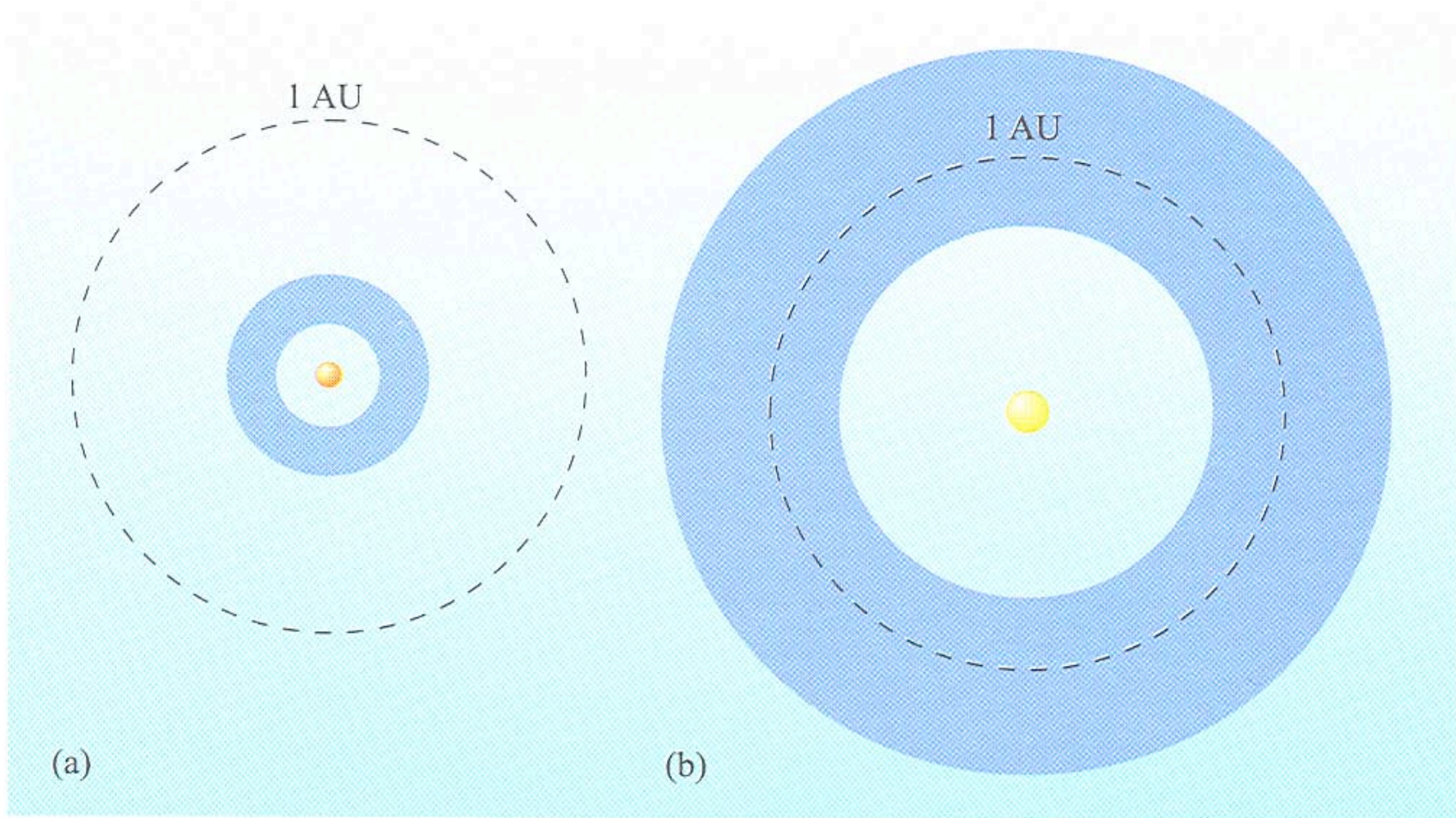
1. HZ will be further from star if significantly more massive than Sun. (Not a problem, just a result)
2. Main sequence lifetime will be small for higher-mass stars: *This is a problem!*

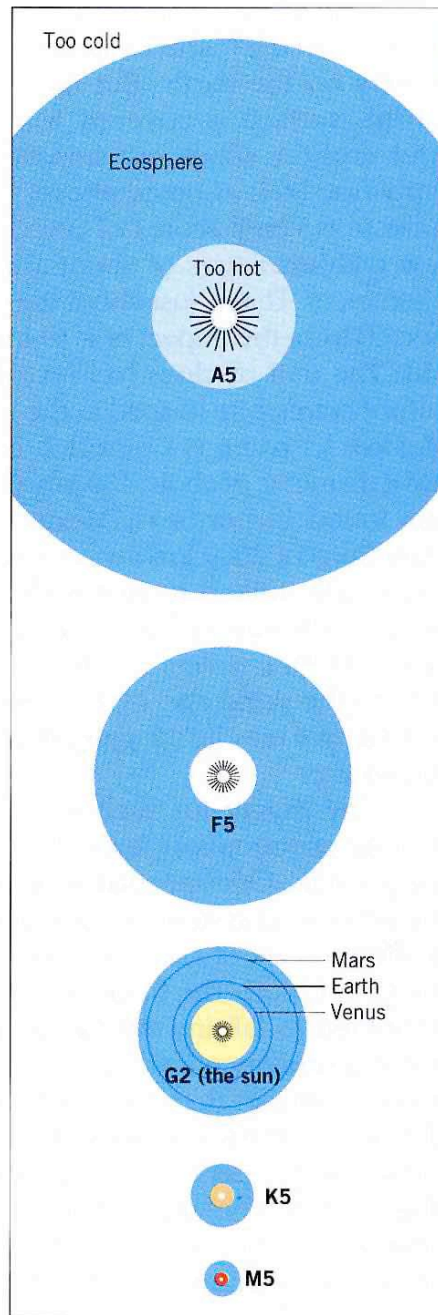
Not enough time for life to develop? We assume this is correct and so do not search stars more than about 1.5 times the Sun's mass.



M star (low-mass, low-luminosity) habitable zone compared to that of a G-type (solar-like) star: Smaller, narrower.

But so close to star that planet will not rotate: "Tidal synchronization". Will atmosphere freeze out on "dark side"? After years of concern, answer appears to be *NO*. So we keep M stars on our lists, but continue to worry about their violent flares...



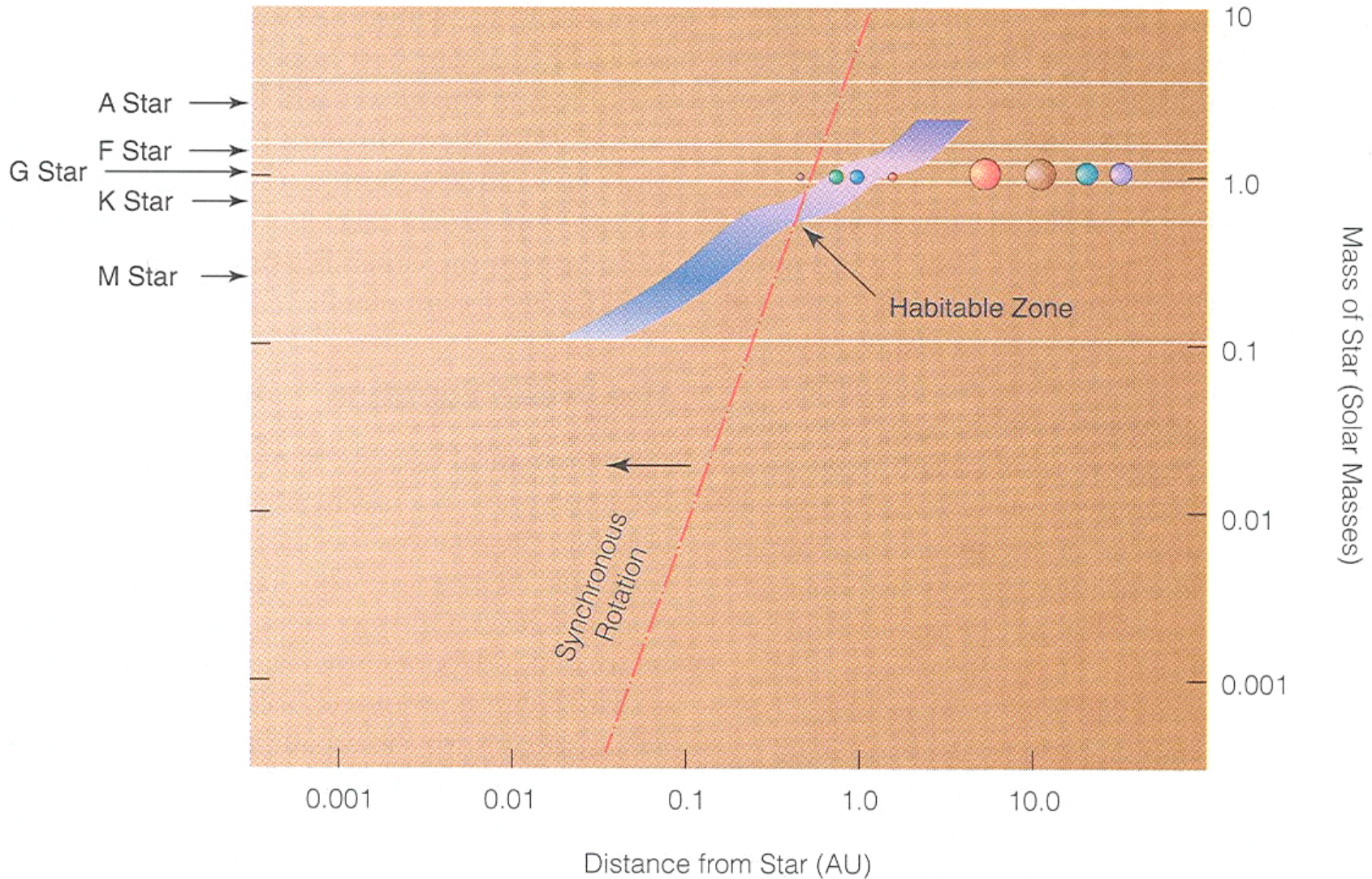


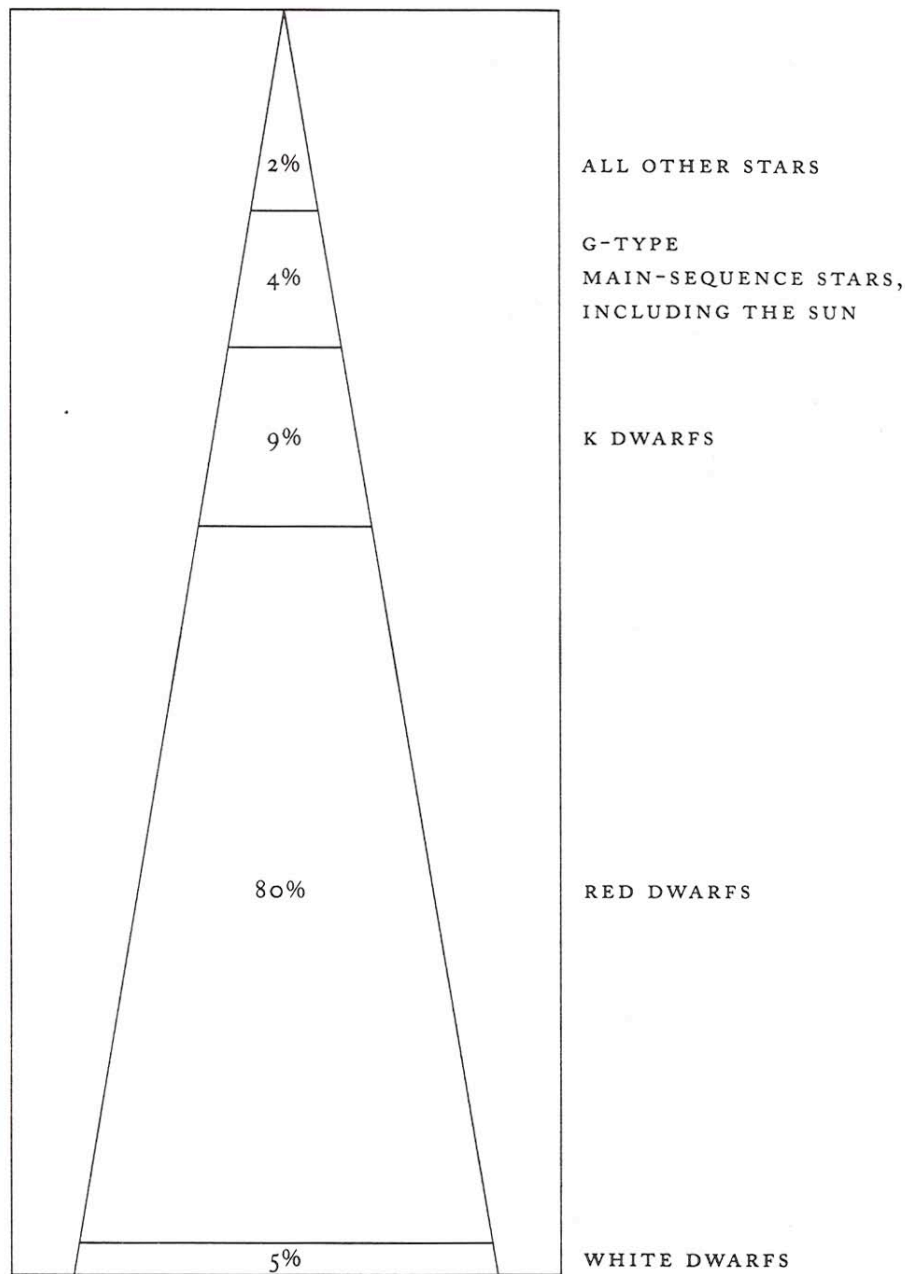
Liquid water habitable zone for stars of different masses (spectral types, *luminosities*)

Understand why HZ is so much further from star for the higher-mass star (top) and so close to the star for the lower-mass star (bottom). Why is the higher-mass star's HZ also *thicker*?

Habitable Zone (blue band) for different stellar masses (vertical axis).
Note line for “synchronous rotation” (tidal locking)

Note: This may be a difficult graph to understand, but is well worth the attempt; *you will encounter such graphs again*





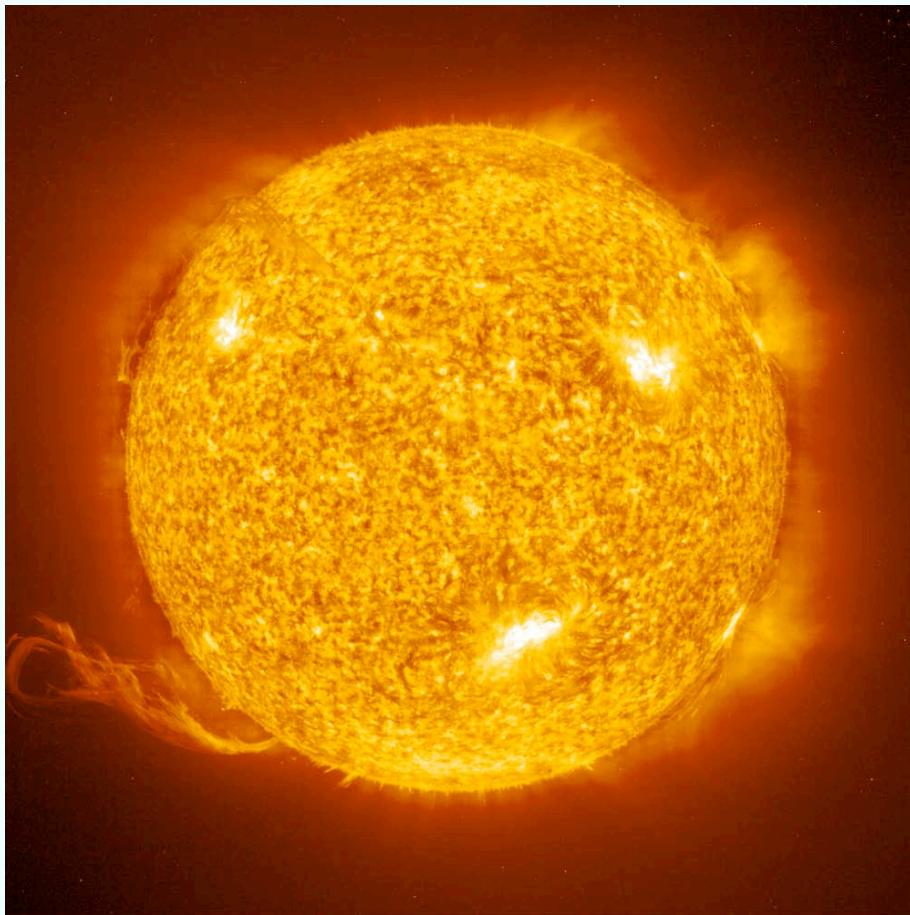
Relative fraction of different types of stars.

Why not search for life around M stars since they are the most numerous?

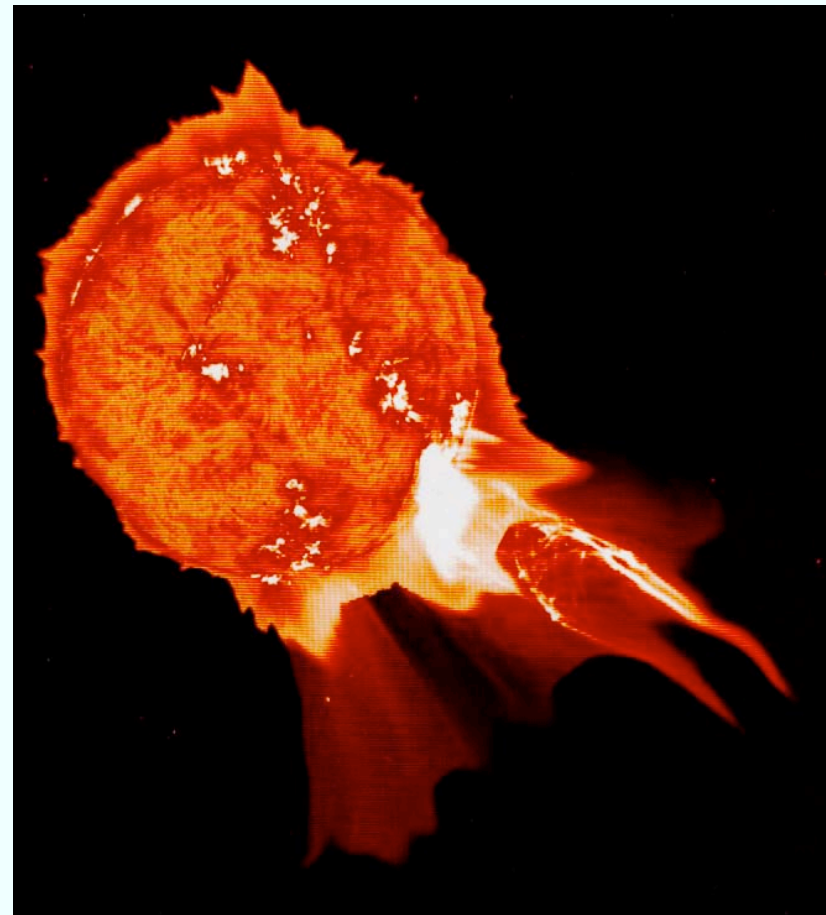
Choice seems obvious, but there are severe problems with searches for Earth-like planets around spectral class M main sequence stars, all because they are extremely faint. (See Mass-luminosity relation graph From earlier.)

M star planets: No longer worried about synchronous rotation/tidal locking/atmospheric freezout, but many M stars are thousands or even millions of times more active (in flares, etc.) than the Sun

Active Sun in X-rays

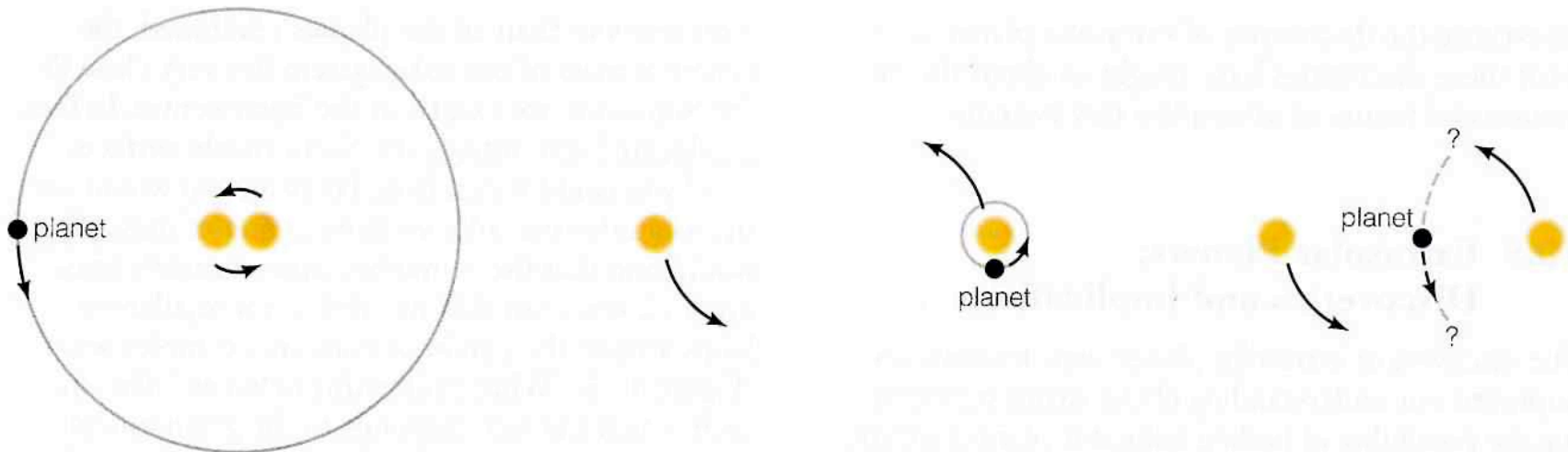


M star flares?



Binary stars--should we search for signs of life there?

Should we search for life, or signals, from **binary star** systems? There is a potential for unstable planetary orbits, and intolerable climate variation. The so-called “five-to-one” rule is illustrated below



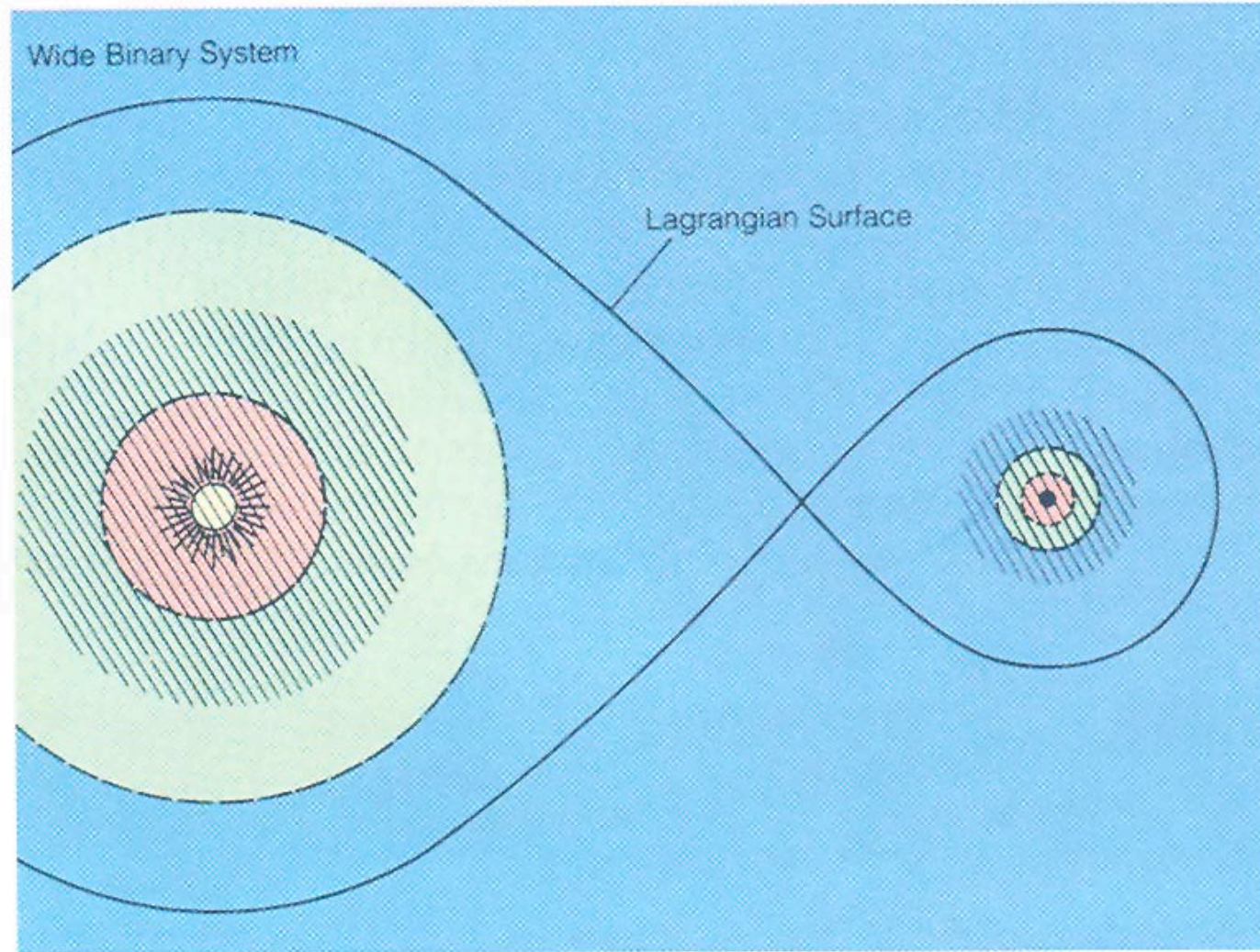
a *Potentially stable:* The planet orbits both stars; the radius of the planet's orbit is much larger than the separation between the stars.

b *Potentially stable:* The planet orbits one star; the radius of the planet's orbit is much smaller than the separation between the stars.

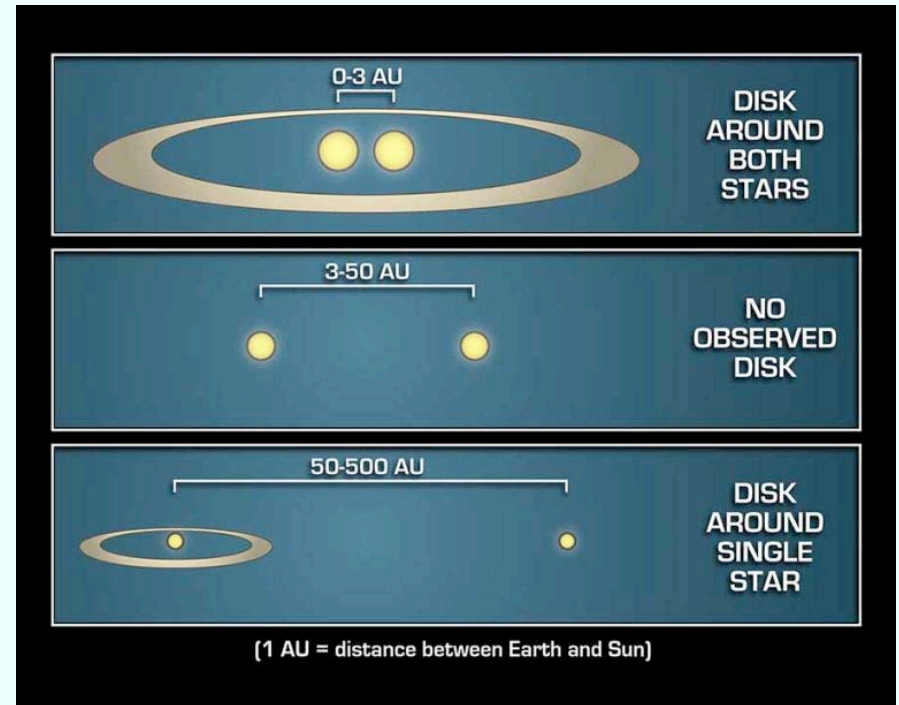
c *Not stable:* The orbit of the planet is neither much larger nor much smaller than the separation between the stars.

FIGURE 10.4 Three orbital possibilities in a binary star system.

Binary parent stars again: The “five-to-one rule”--orbits outside the hatched regions will be greatly perturbed by the companion, leading to irregular, eccentric orbits, or even ejection



Habitable planets orbiting binary stars?



In March 2007 astronomers were surprised to discover that protoplanetary disks exist around binary star systems.

Assignment: Using the "Links" in your textbook web site, find out what telescope was used to make this discovery? What is it about this telescope that makes it perfect for detecting disks?

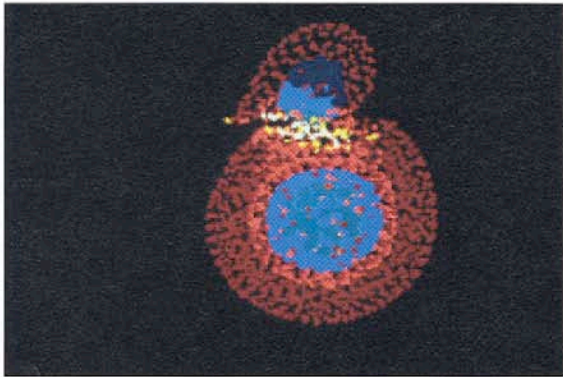
What if habitability requires a stabilizing large satellite, like our Moon? Chances are small it would happen twice. Could instead end up with catastrophic destruction of both bodies as shown below.

When worlds collide: Final stages of planet formation

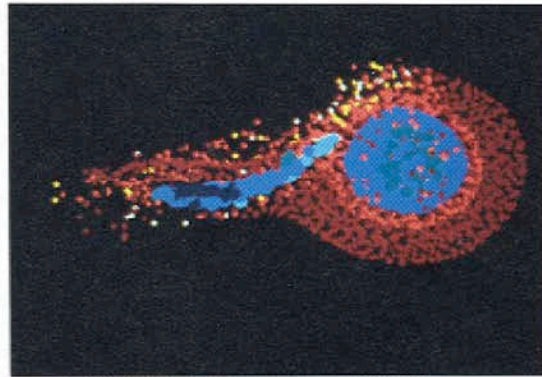


Movie of this simulated collision of two planetesimals can be found in the Links portion of the textbook web site

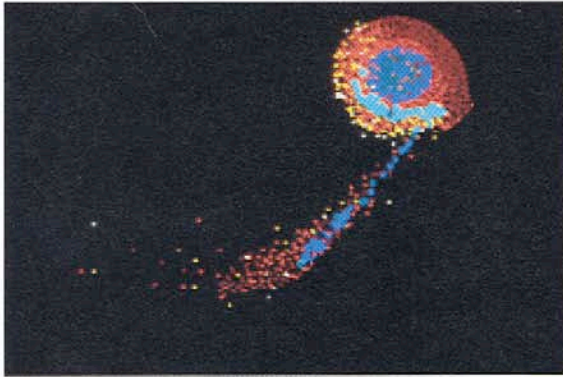
Simulation of lunar formation event



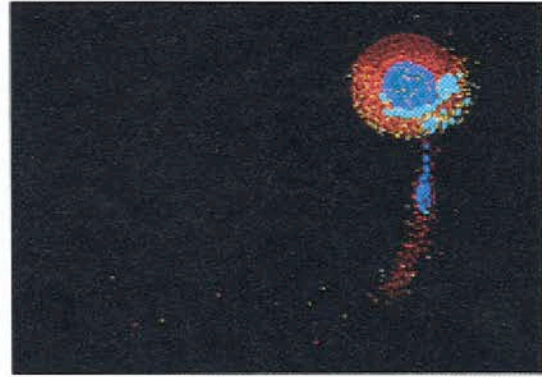
a



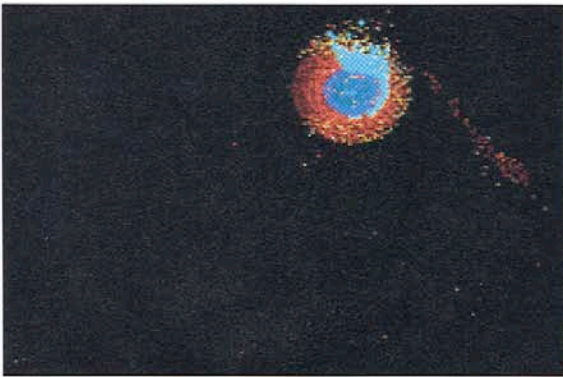
b



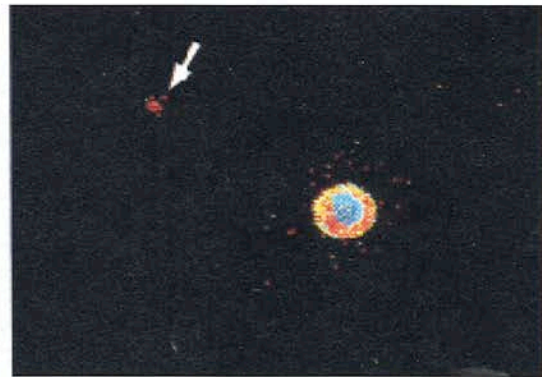
c



d



e



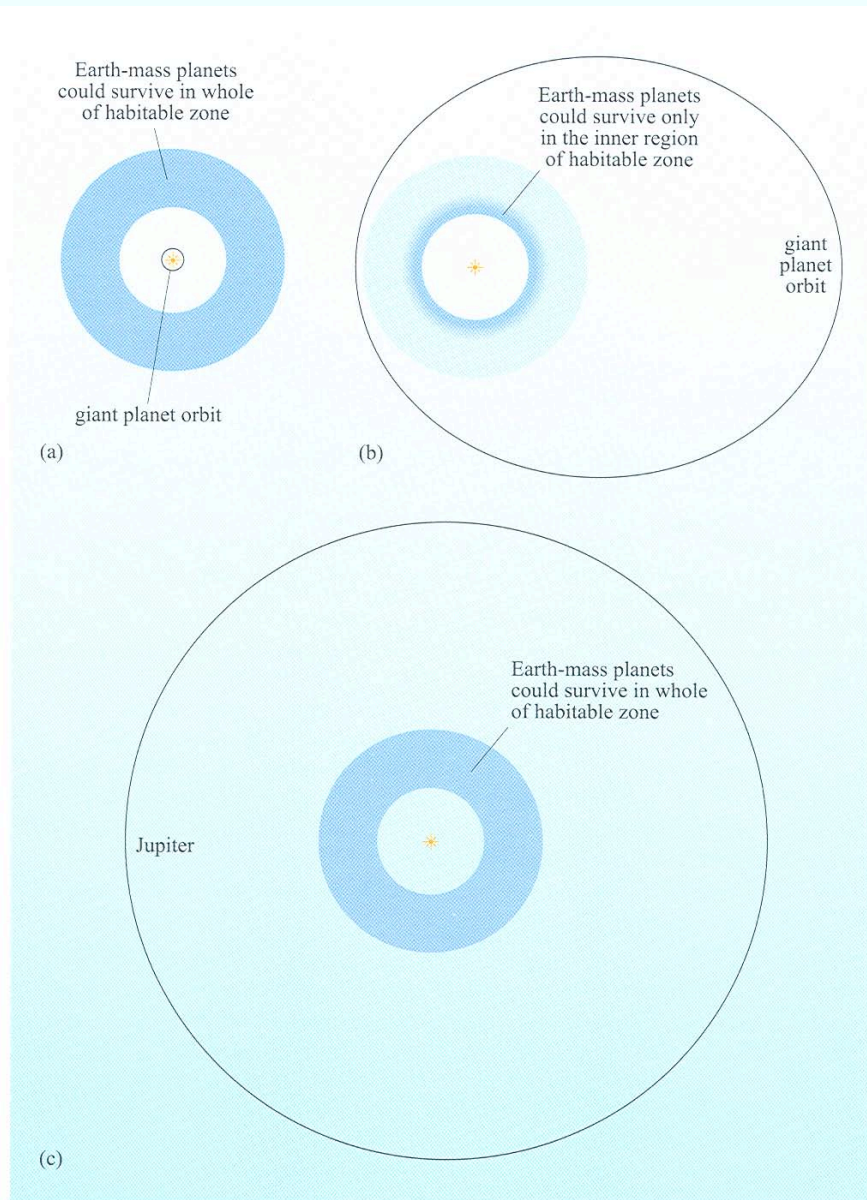
f

Don't forget the potential influence of our large moon on habitability (be able to name a couple of its most important effects). But if formed by impact, probably a very freakish event, so this would greatly reduce the chances for life-bearing planets.

Effect of a giant (Jupiter-like) planet

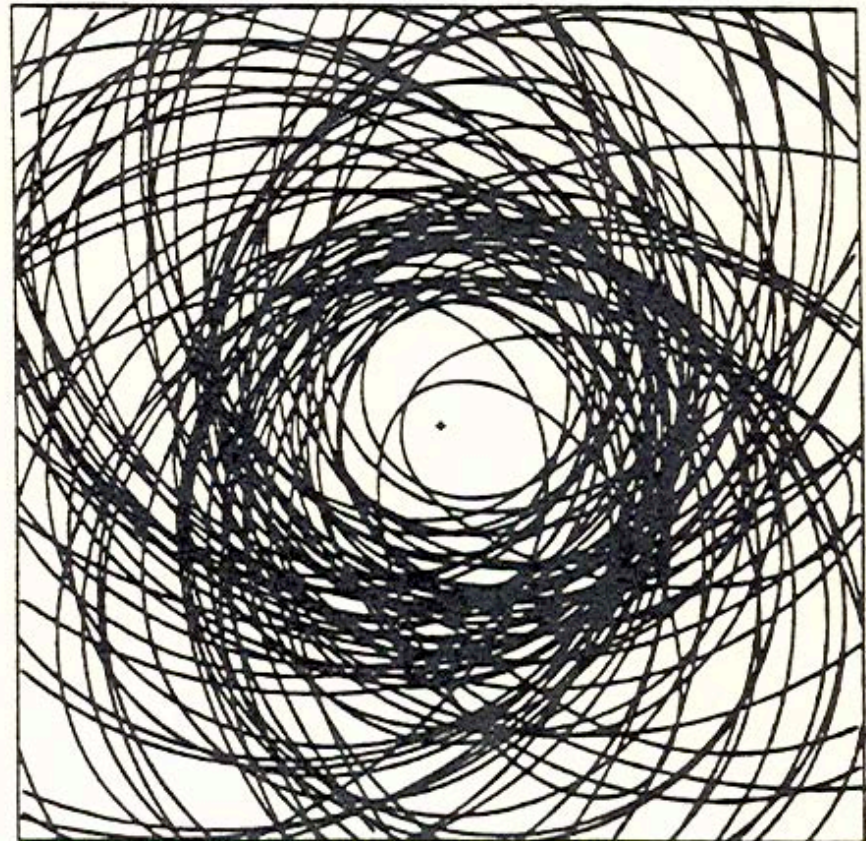
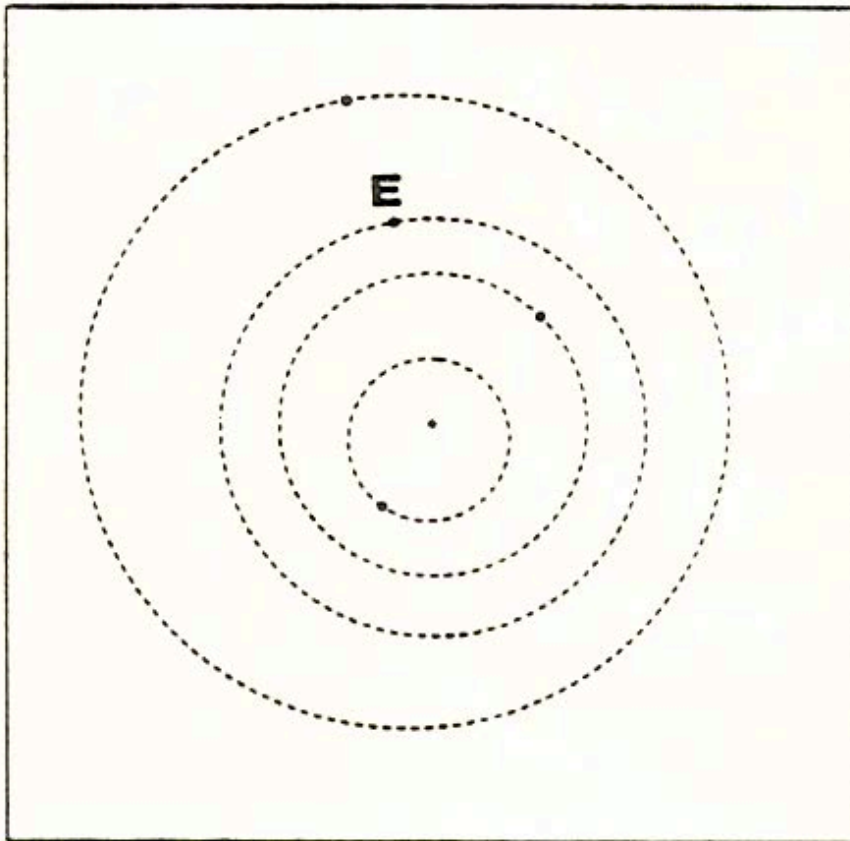
The presence of a giant planet affects the stability of the orbit of a terrestrial-like planet in the habitable zone, *if* the giant planet orbit is sufficiently eccentric.

(But recall that an outer giant planet can also protect inner terrestrial-like planets by keeping most of the comets away, reducing the number of sterilizing impacts.)

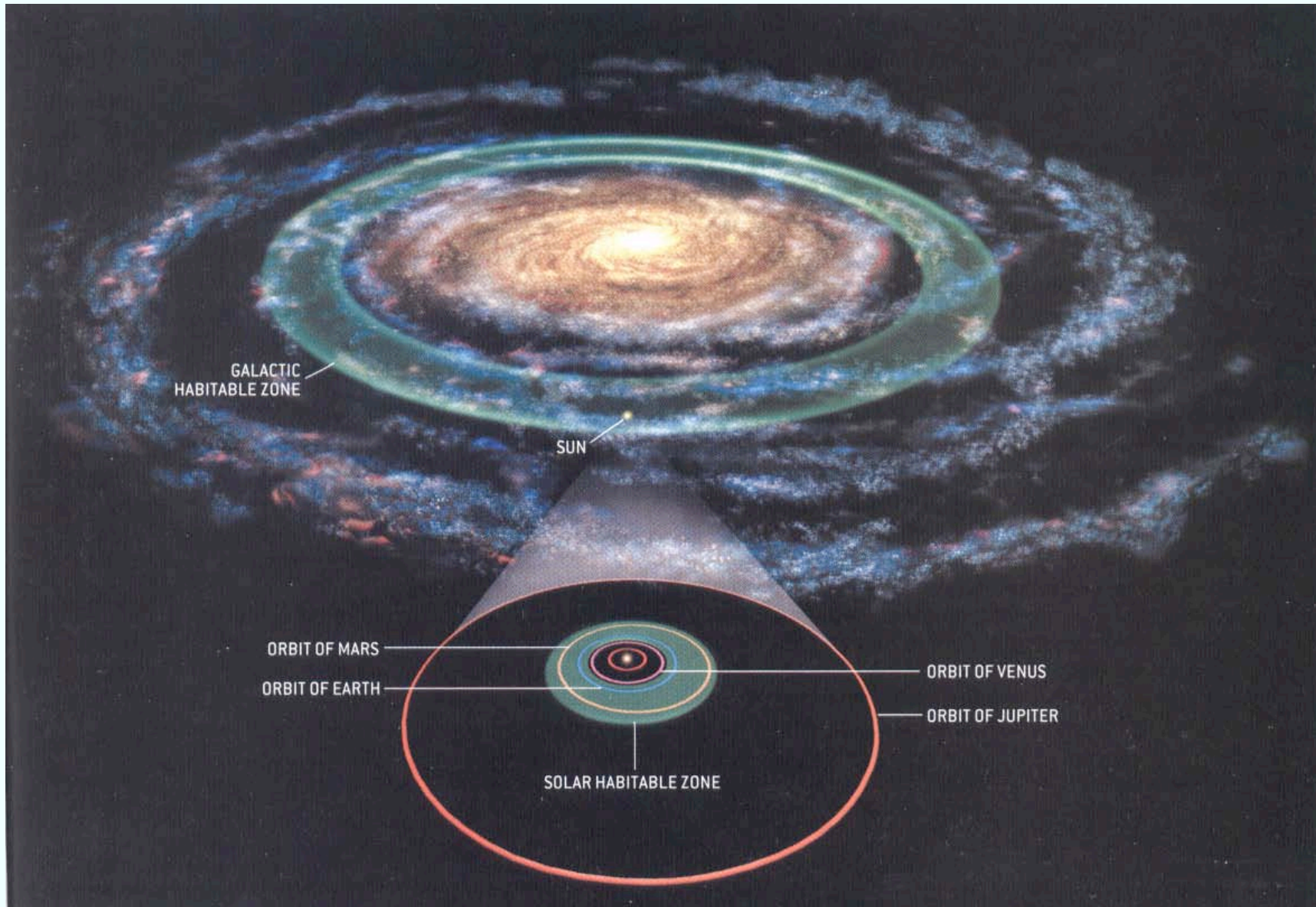


Survivable orbits for Earth-mass planets in the habitable zone where (a) the giant is very much interior to the habitable zone, (b) the giant is not far outside the habitable zone, (c) the giant is well outside the habitable zone as is the case with Jupiter in the Solar System.

An outer giant planet can also affect the rate at which asteroids or comets invade the inner parts of the planetary system. This is a picture of asteroid orbits in our Solar System--if not for Jupiter's strong influence, their eccentricities would be much smaller. But Jupiter also keeps *comets* OUT of the inner solar system, protecting us from too many mass extinctions! So the presence of a giant planet, and its properties, may play a large role in determining habitability.



A “galactic habitable zone?”--maybe some parts of our Galaxy are more favorable to planet formation or life than others. (Very speculative).



Some ways in which certain locations in our Galaxy *might* have low probabilities of planet formation or *might* be hazardous for life.

Globular Cluster M22



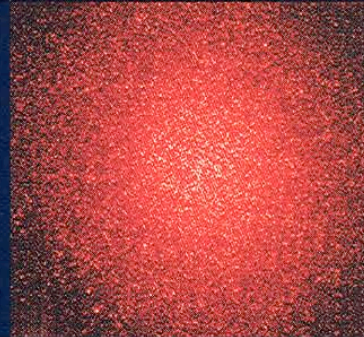
Few heavy elements

Eagle Nebula



Being evaporated by giant stars

Globular Cluster Omega Centauri



Few heavy elements

O-type Star G339.88-1.26



Too bright, too short-lived

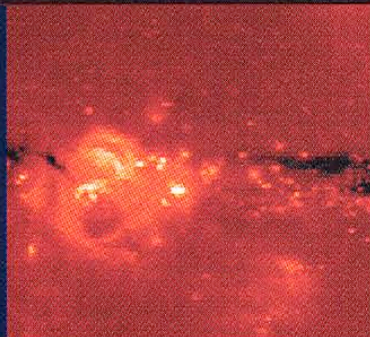
WHAT IS BEAUTIFUL is often dangerous, in space as on Earth. Some of the most renowned sites in the galaxy are hostile to planets, let alone living things. The safest places in the galaxy tend to be the most boring ones.

Trifid Nebula



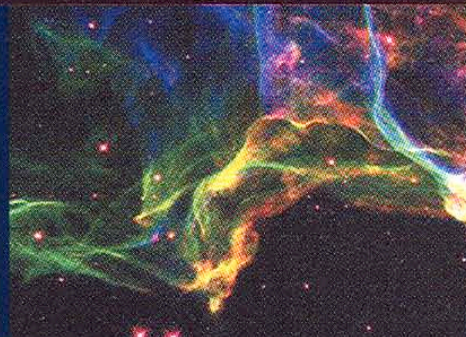
Ionized gas

Galactic Center



Intense radiation, unstable orbits

Cygnus Loop



Debris from stellar explosion

Proplyds in Orion Nebula



Being evaporated by giant stars