Habitable Planets

n_e Number of planets, per planetary system that are suitable for life

$$n_e = \underset{\substack{\nearrow \\ \text{planetary}}}{n_p} \quad \underset{\substack{\nwarrow \\ \text{stellar}}}{f_s}$$

$n_p = n_e$ for stars like Sun

$f_s =$ fraction of stars with suitable properties

n_p, n_e could be greater than 1

$f_s \leq 1$

Key requirement Liquid for solvent

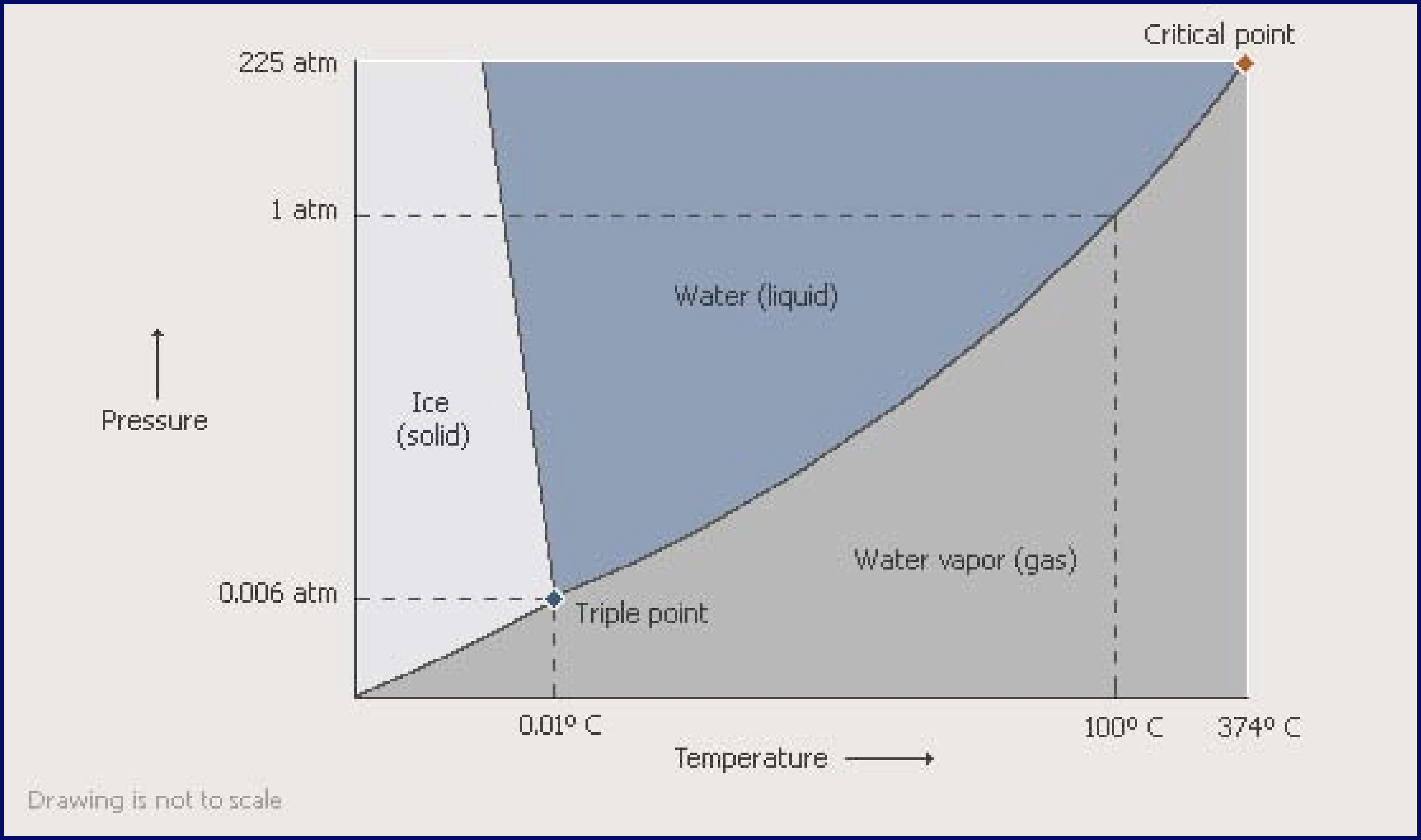
H_2O 273 - 373 K at Earth pressure
→ 647 K at higher pressures
→ 330 K protect proteins, membranes
smaller range at lower pressure

CH_4 (methane) 91-109 at Earth pressure

NH_3 (ammonia) 195 - 240 K at Earth pressure

Pressure, Gravity → size of planet

Water Phase Diagram



What sets the temperature?

In space, absorption and emission of electromagnetic radiation (light)

Energy in = Energy out

(L/d^2) (T^4)

$$\square \quad T \quad \left(\frac{L}{d^2}\right)^{1/4}$$

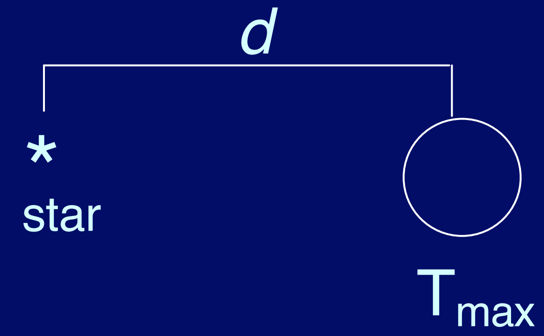
$$d^{-1/2}$$

$$\frac{1}{\overline{d}}$$

4 □ as far from star, T is half as high

Planet Temperatures

1st approximation: A blackbody at a distance *d* from a star of luminosity L



Maximum temperature

$$T = 394\ \mathrm{K}\left(\frac{L}{d^2}\right)^{1/4}$$

L in $L_\odot$
d in AU

2nd approximation: A fraction of the light is reflected (not absorbed)

Call this fraction the albedo (A)

$$T = 394\ \mathrm{K} \left[\frac{(1-A)\,L}{d^2} \right]^{1/4}$$

e.g. Moon $A = 0.07$ $T_{max} = 387$

$L = 1\ L_{\odot}$ correct to few %

But Earth : $A = 0.39$ □ $T_{max} = 342$ K predicted

$T_{max} \leq 313$ K

3rd approximation:

Account for rapid rotation - T_{max} less

T_{min} more

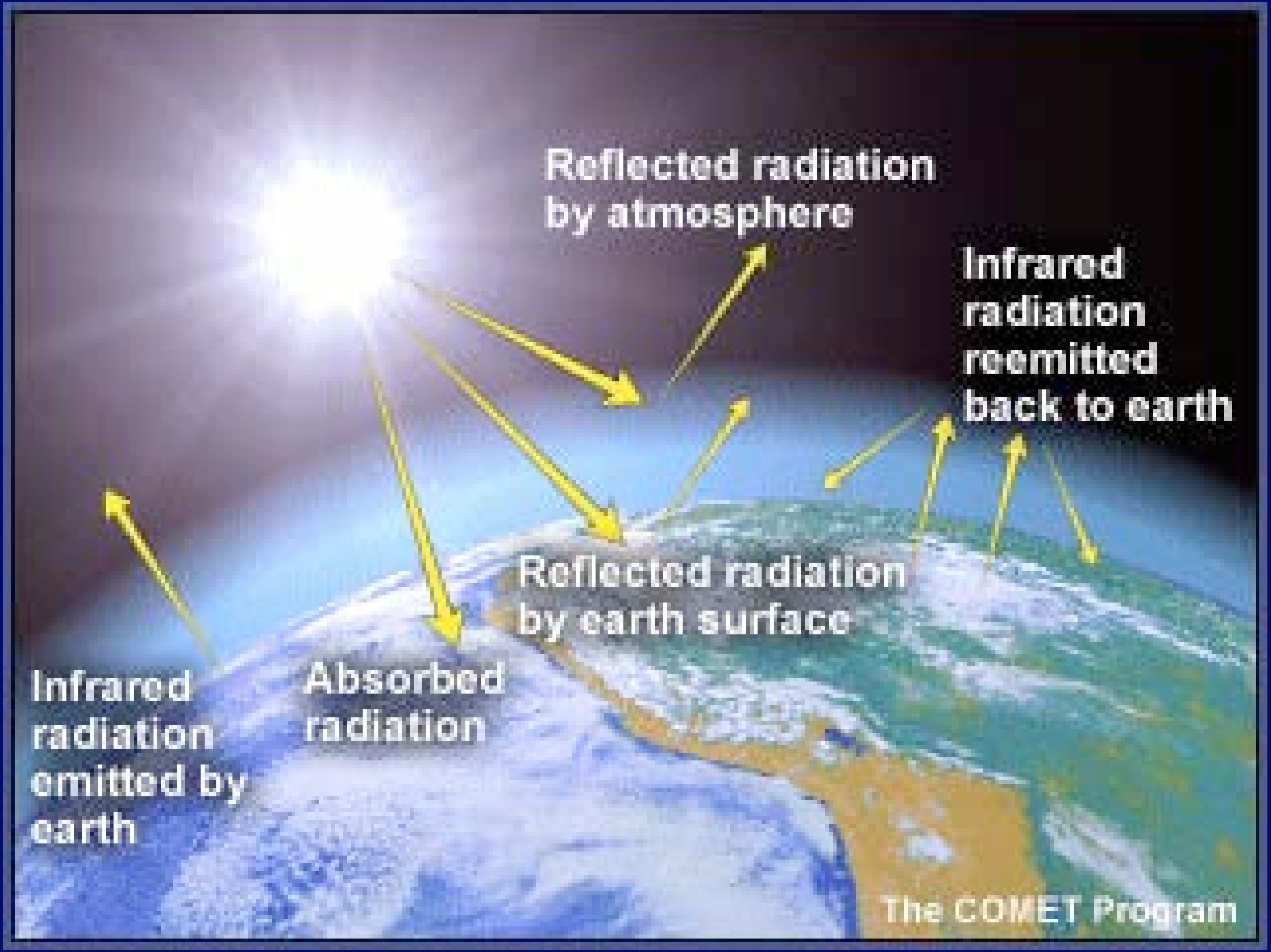
close to T_{avg}

$$T_{avg} = 279\ \mathrm{K} \left[\frac{(1\text{-}A)\ L}{d^2} \right]^{1/4}$$

Earth: $A = 0.39$ □ $T_{avg} = 246\mathrm{K}$

<u>Actual</u> $T_{avg} = 288\mathrm{K}$

4th approximation: Greenhouse effect



Consequences of Greenhouse Effect:

Raises T_{avg} (Earth) by about 40K

Otherwise $T_{avg} < T_{freeze}$

□ Frozen Planet

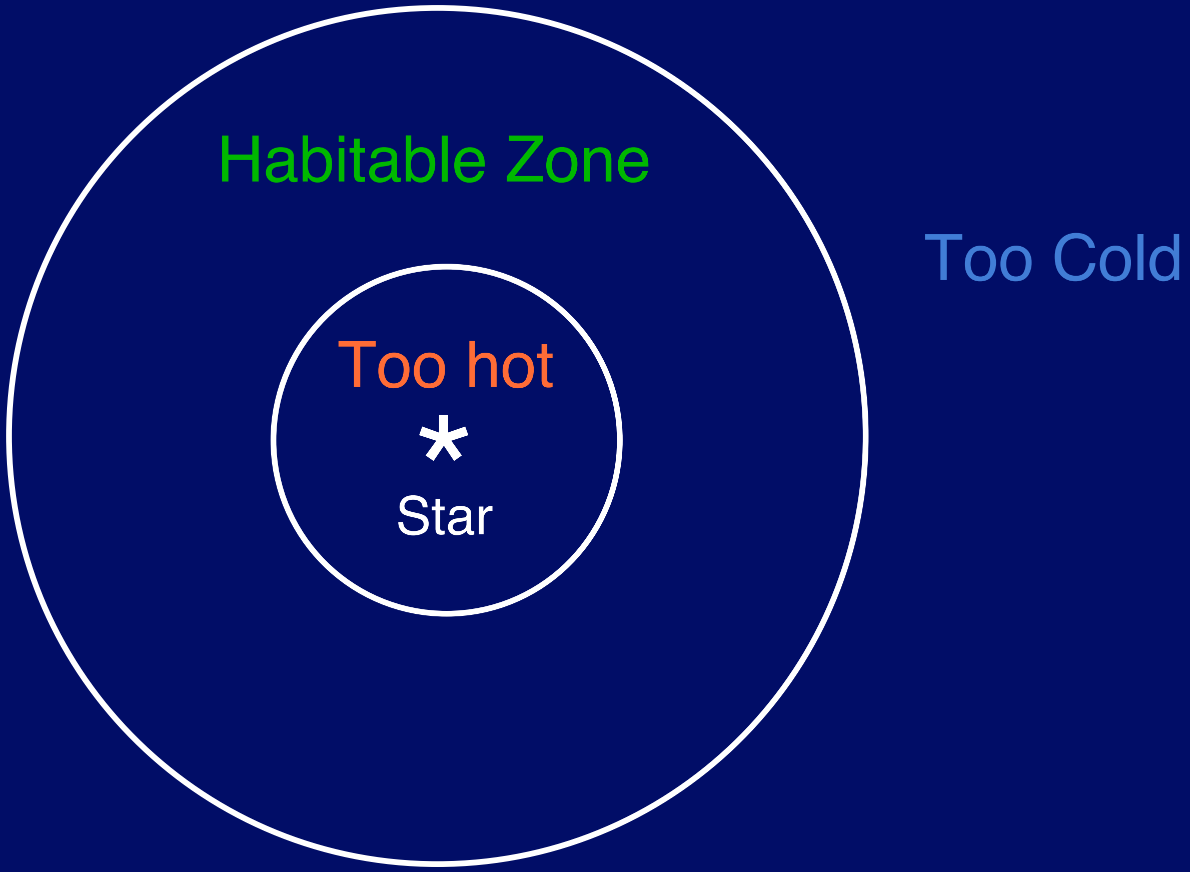
Habitable Zone (HZ)

For fixed luminosity, Greenhouse Effect

a required temperature range

translates to a required

range of distances from star



But Greenhouse Effect could have a big impact on the size of HZ

Continuously Habitable Zone (CHZ)

Need ~ 5 □ 10^9 years for intelligent life?

But Sun’s L increases slowly

T_{Earth} constant to few degrees (mostly)

(decreasing Greenhouse)

HZ moves out as L rises

□ CHZ smaller than HZ

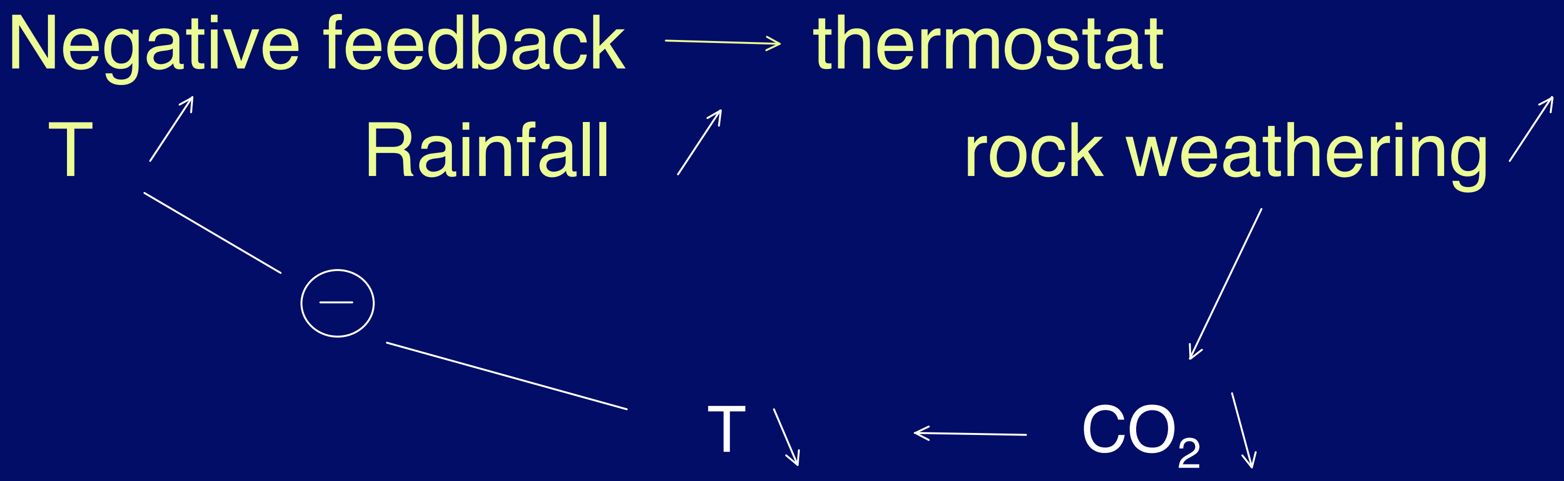
Pessimist

Computer Models

Hart CHZ 0.95 - 1.01 AU

$\Rightarrow$ $n_p \lesssim 0.1$

Middle of the Road



Negative feedback → thermostat

T ↗ Rainfall ↗ rock weathering ↗

$\ominus$

T ↘ ← CO_2 ↓

Whitmire et al. CHZ 0.95 - 1.5 AU

$\Rightarrow$ $n_p \sim 1$

The Carbon Cycle without Life

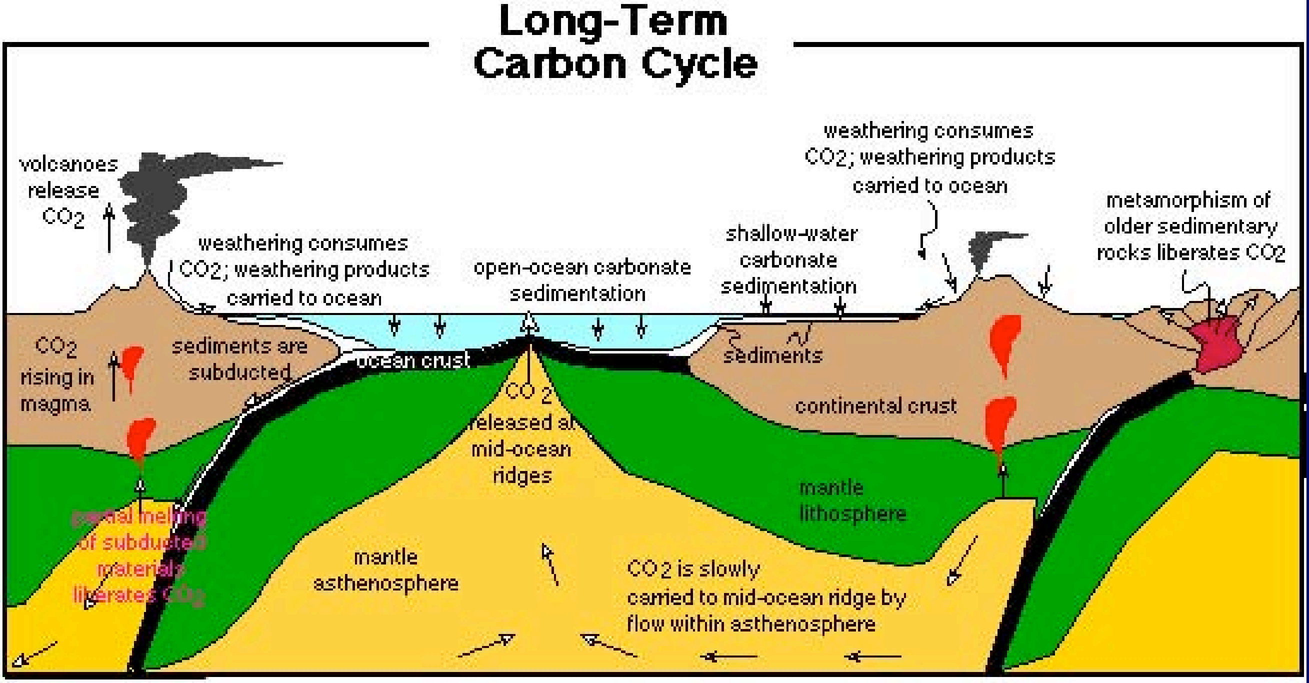
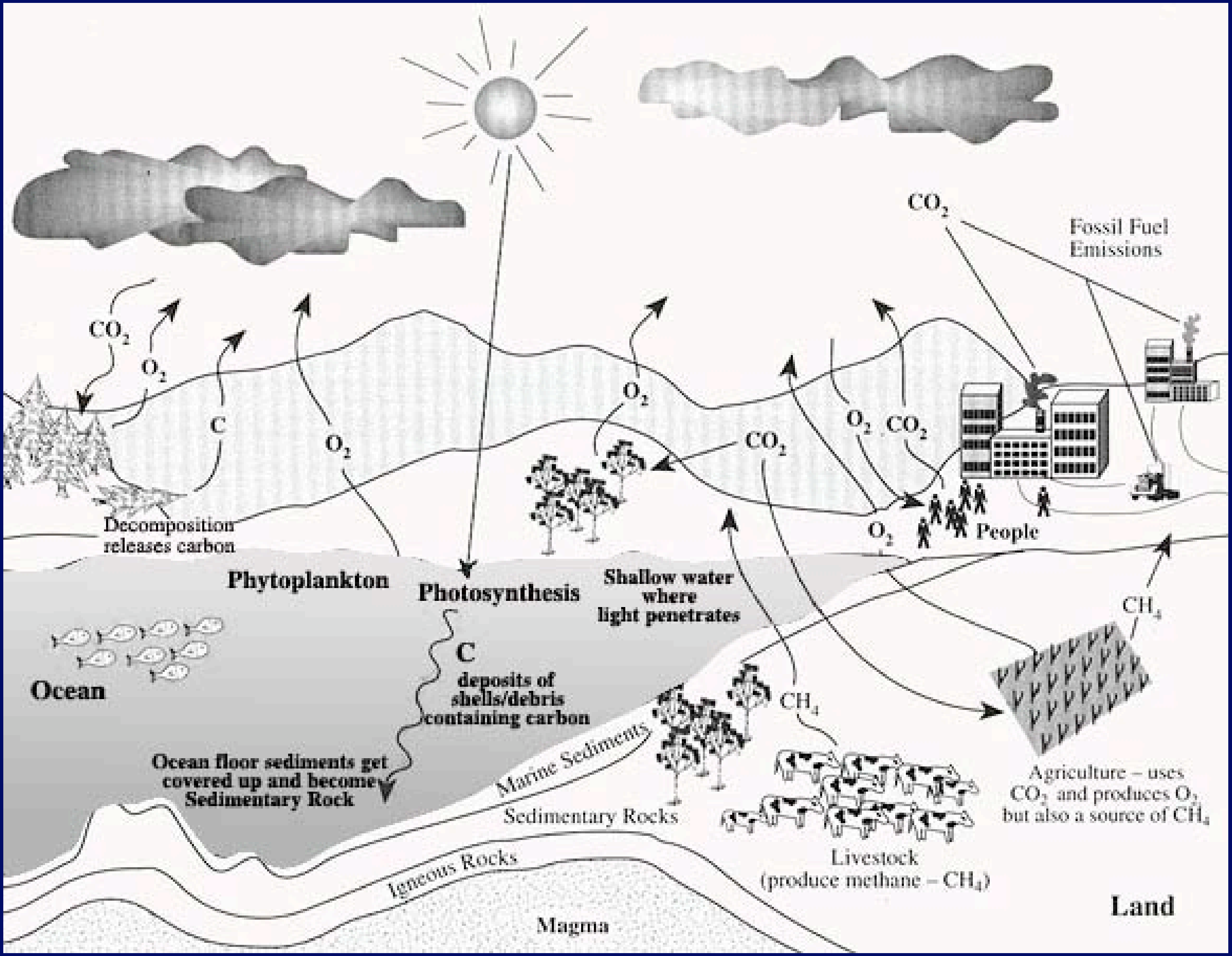
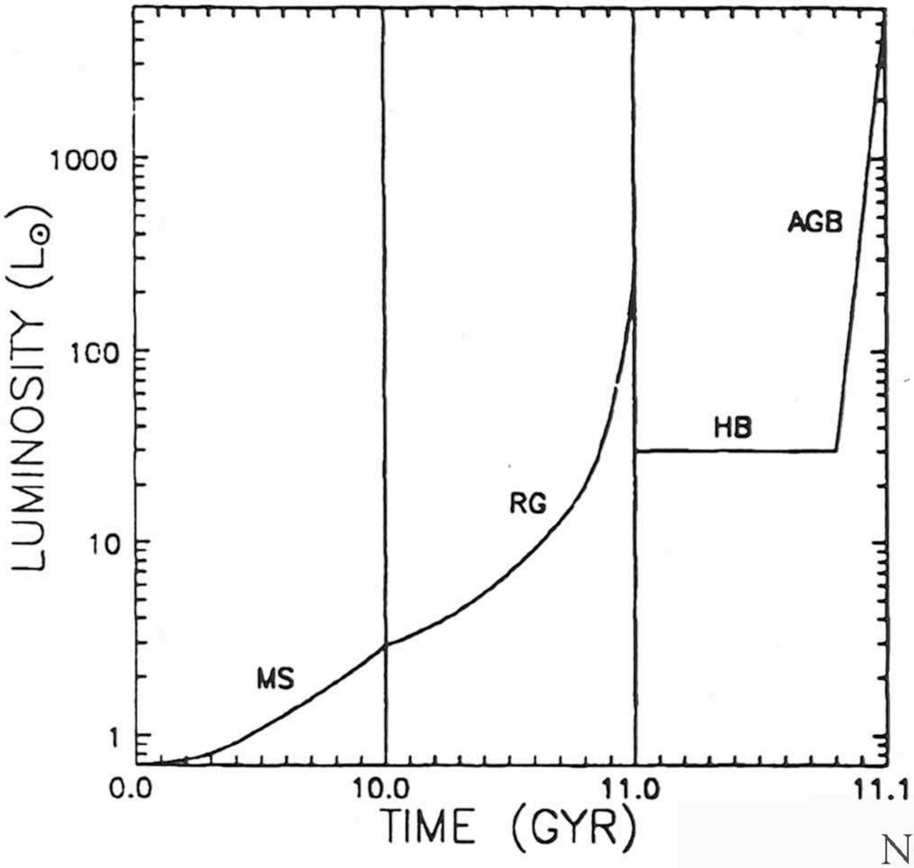


Figure 7.3. Schematic representation of the long-term global carbon cycle showing the flows (hollow arrows) of carbon that are important on timescales of more than 100 Kyr. Carbon is added to the atmosphere through metamorphic degassing and volcanic activity on land and at mid-ocean ridges. Atmospheric carbon is used in the weathering of silicate minerals in a temperature-sensitive dissolution process; the products of this weathering are carried by rivers to the oceans. Carbonate sedimentation exracts carbon from the oceans and ties it up in the form of limestones. Pelagic limestones deposited in the deep ocean can be subducted and melted. Limestones deposited on continental crust are recycled much more slowly — if they are exposed and weathered, their remains may end up as pelagic carbonates; if they get caught up in a continental collision, they can be metamorphosed, liberating their CO_2.

The Carbon Cycle on Earth Now





Note Changing Scale

FIG. 1. *Luminosity evolution of a 1 $M_\odot$ star of solar composition. Note that the scale is broken at 10 and 11 Gyr. The discontinuity at 11 Gyr is real and is due to the helium flash. The phases are: MS = main sequence, RG = red giant, HB = horizontal branch, and AGB = asymptotic giant branch. The final white dwarf phase is not illustrated. Details of the evolution during the HB and AGB phases are omitted.*

$$r_2 = \sqrt{\frac{L(t)}{S_2(T)}}$$

Cold Starts?

- As Habitable Zone moves out
  - Can you unfreeze a frozen planet?
  - Will it become suitable for life?
  - If not, HZ will shrink
  - CHZ is smaller

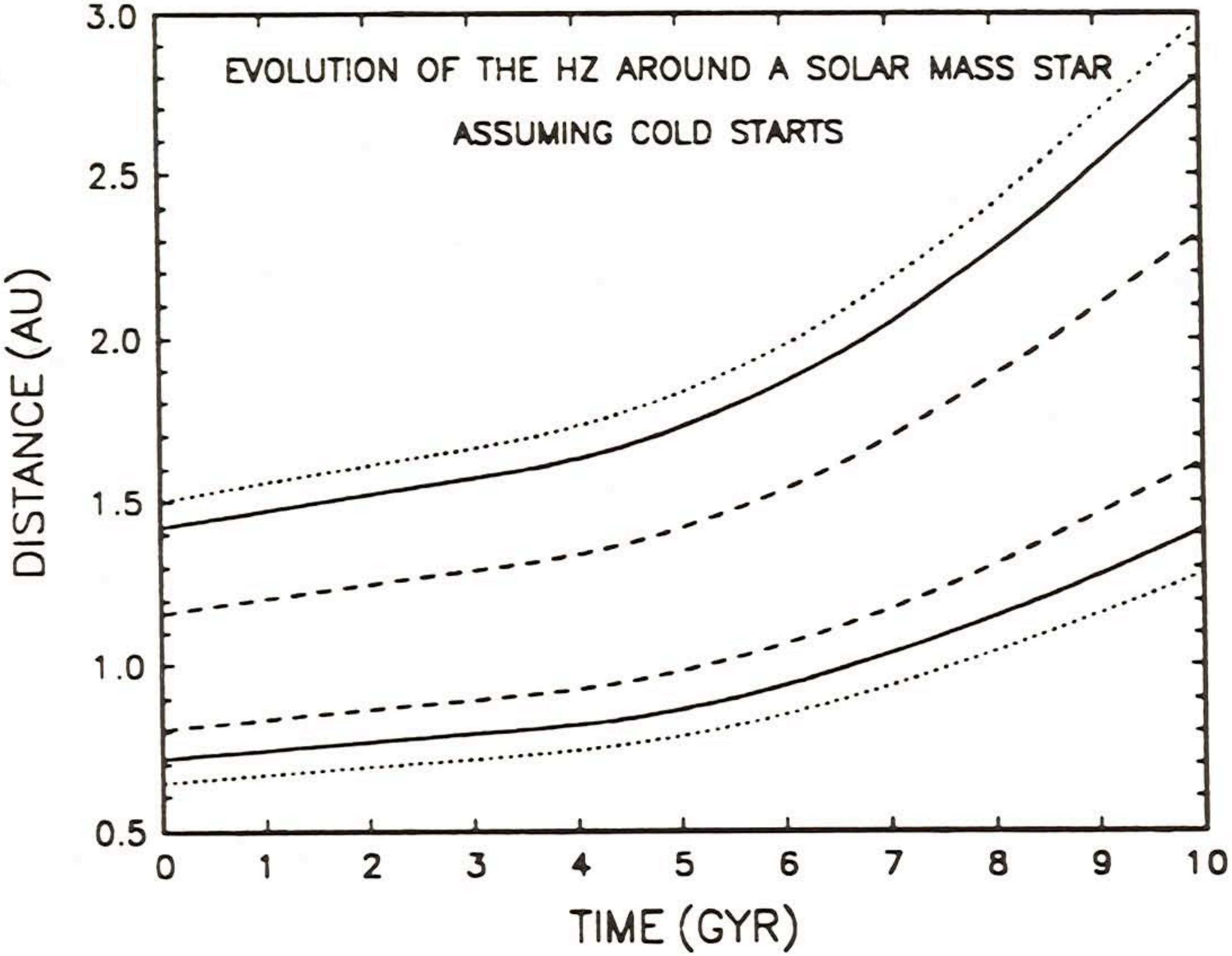


FIG. 2. *Evolution of the HZ around a 1* M$_\odot$ *star assuming that an ice covered planet that was initially beyond the outer HZ boundary can be cold started. The three cases shown are discussed in the text and correspond to the most conservative Case 1 (long dashes), the intermediate Case 2 (solid curves), and the least conservative Case 3 (short dashes).*

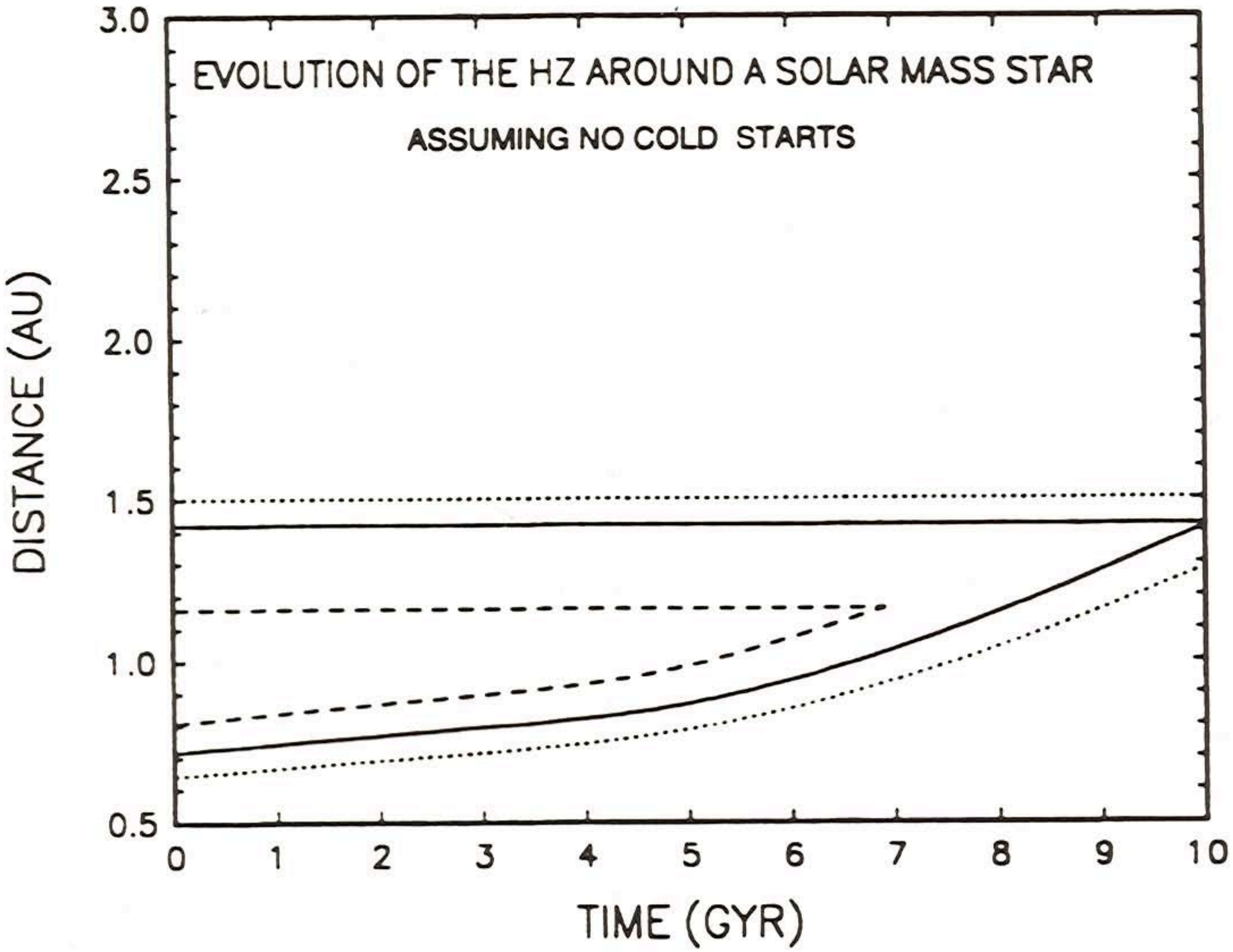


FIG. 3. *Evolution of the HZ around a 1 M$_\odot$ star assuming that an ice covered planet that was initially beyond the outer HZ boundary cannot be cold started until the stellar flux is greater than the critical greenhouse value. The three cases shown are discussed in the text and correspond to the most conservative Case 1 (long dashes), the intermediate Case 2 (solid curves), and the least conservative Case 3 (short dashes).*

Temperatures for Life on Earth

Lower limit?

Some microbes survive for long periods in Antarctic ice

e.g. Lake Vostok - 2.5 miles below glacial ice in Antarctica
Microbes found ~ 400 feet above lake in an ice core

Freeze-dried for ~ 10^6 yrs?
Revive when exposed to liquid
Lower limit is probably about -20° C (253 K)

Upper Limit?

We have learned that some microbes can survive in pressurized water at T up to 400 K (120° C)!

Such microbes have special adaptations to protect their heat-sensitive molecules

For complex life, upper limit seems to be ~ 325K

~52° C or 126° F

But is this limit just an accident of evolution on Earth?

Other Habitable Zones

Microbial Habitable Zone (MHZ)

Fixed by Range of T microbes can withstand

“Animal” Habitable Zone (AHZ)

“Animal” = complex, differentiated, multicellular life

Ward + Brownlee in *Rare Earth* note AHZ much smaller than MHZ

They also argue that parts of our Galaxy unsuitable for animal life

We will consider this point under f_i

Snowball Earth

Increasing evidence that Earth nearly froze over twice

2.4 billion years ago & 650-800 Myr ago

Climate can have dramatic changes

Apparently - these were ended by volcanic eruptions that put much more CO_2 in atmosphere

Other Considerations

1. Sub-surface Water?

   If you don’t need photosynthesis, no need to be on surface

   T increases with depth into Earth

   □ liquid water under “ground”

	e.g. Mars?	Europa (Moon of Jupiter)
HZ $\longrightarrow$	1.5 AU	5 AU
n_p	~ 2	~ 3

2. Other Solvents

e.g. Titan (moon of Saturn) could have liquid methane (CH_4) or ethane (C_2H_6)

HZ $\longrightarrow$ 10 AU

$n_p \longrightarrow \sim 4$

3. Other planetary systems

Jupiter-like planets ~ 1 AU (in HZ)

Life on Moons?

Other requirements?

Pressure? Bacteria on deep sea floor up to 1000 atmospheres

But not “animal” life

Not too salty? - halophilic bacteria

up to 33% salt solution

pH? - LOG [H ions]

pH 1	7	ph 14
acid	normal H_2O	alkali

Almost all cells regulate pH to 7.7

1 ← microbes → 13

Again microbes have adapted to just about any environment of Earth

Importance of Heavy Elements

Planetary systems found so far

Are found more commonly around stars with a lot of heavy elements

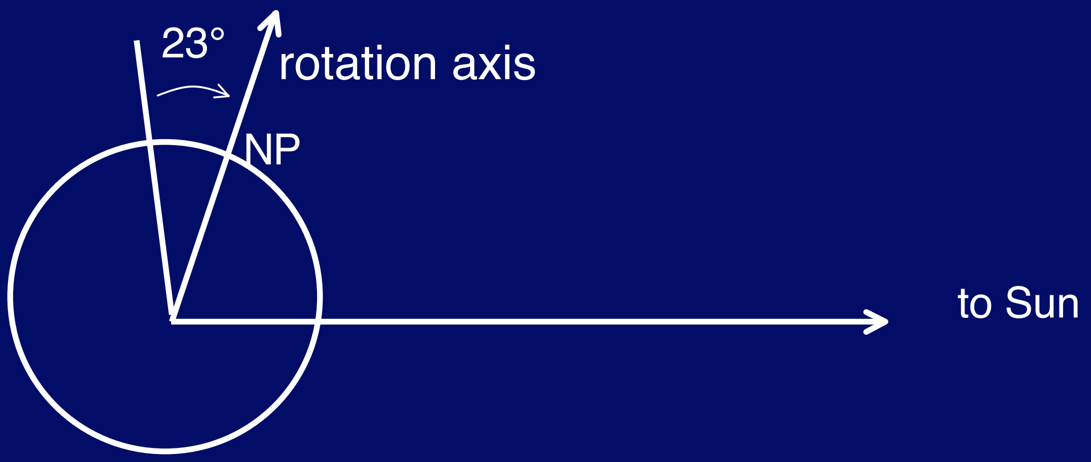
Does this apply to systems more like ours?

The Importance of the Moon

The Moon makes the tides bigger than if only the Sun caused tides

May be important in the origin of life

The Moon stabilizes the Earth’s obliquity



Varies regularly from 22.1 to 24.5 over 41,000 yrs.

Without the Moon, tugs from other planets could make it vary chaotically

Large obliquity could cause snowball Earth

Ward & Brownlee

Only if a large supercontinent at the poles

Williams, Kasting, Caldeira

Issues Raised by Discovery of Other Planetary Systems

1. We know that not all planetary systems are like ours

   But, searches so far could not find systems like ours □ most could be like ours

2. Exotic possibilities for life

   Europa-like moons around giant planets orbiting ~ 1 AU

Stellar Requirements (f_s)

1. Sufficient Heavy Elements

Terrestrial planets, bioelements

1st generation   - ruled out

Population II - ruled out

No significant loss

2. Main Sequence

(Stable L □ Stable T possible)

e.g. Sun will increase L by 10^3

5 □ 10^9 yr from now

Red Giants - ruled out

0.99 OK

3. Stellar Mass Not Too High

(Main sequence Life $\geq$ 5 □ 10^9 yr)

Roughly, L M^4 Fuel M

Lifetime $\frac{\text{Fuel}}{\text{L}}$ or $\frac{1}{M^3}$

Stellar Lifetimes

M ($M_\odot$)	Lifetime (yrs)
30	2×10^{6}
10	3×10^{7}
3	6×10^{8}
1	1×10^{10}
1/3	2×10^{11}
1/10	3×10^{12}

If $t > 5$ □ 10^9 yrs

$M < 1.25\ M_\odot$

$M > 1.25\ M_\odot$ - ruled out if we require 5×10^9 yr for intelligent life to evolve

Most stars are low mass, so

0.90 OK

4. Stellar Mass Not Too Low

a) Do terrestrial planets form?

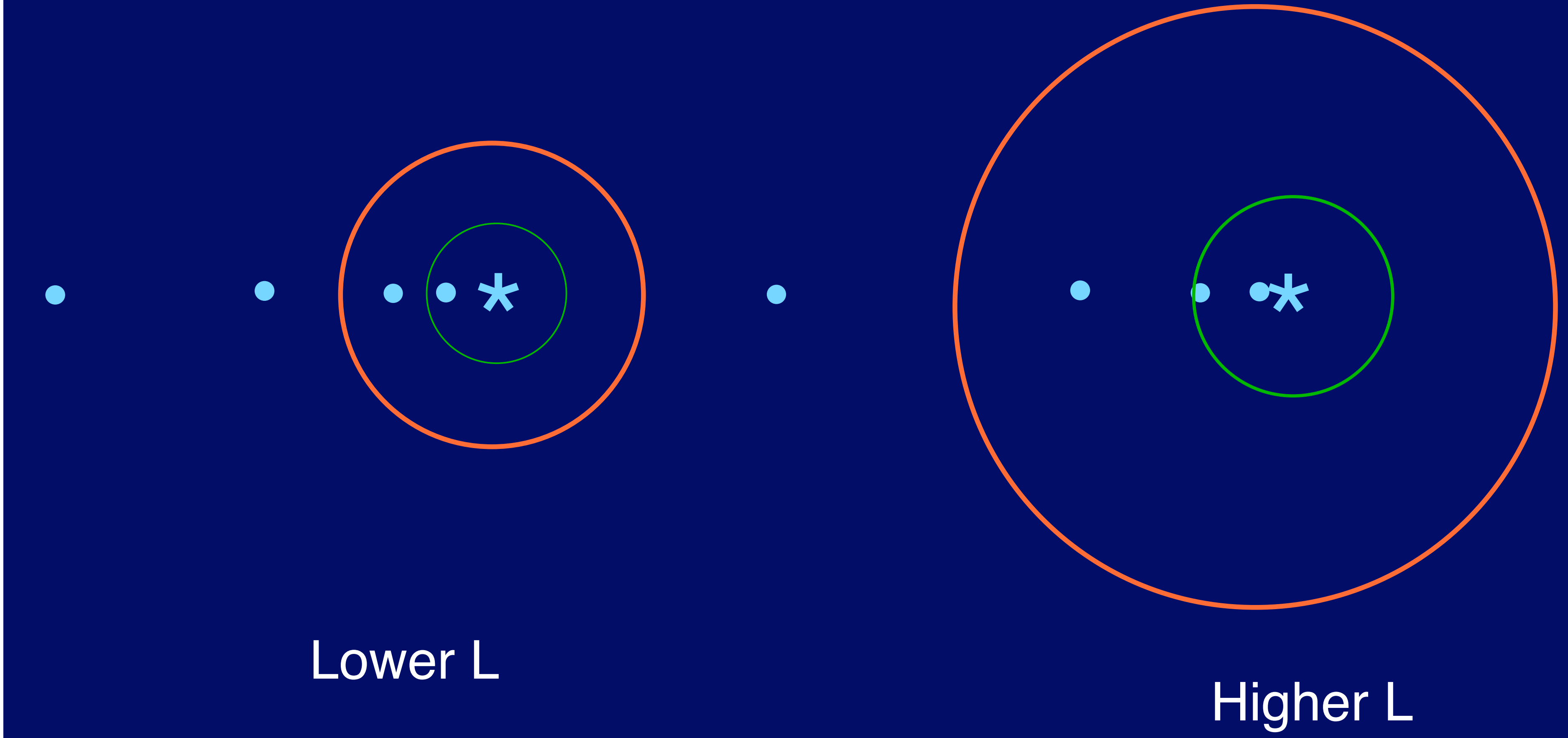
“Jupiters” should form closer to low mass star

Prevent formation of terrestrial planets?

b) Chance of having terrestrial planet in CHZ?

CHZ smaller for Low L

For Logarithmic Spacing, n_p independent of size



Lower L

Higher L

But if planet spacing as in Solar System
and
CHZ not smaller than innermost planet orbit

Chances are the same

c) Low mass stars have strong flares

High energy particles?

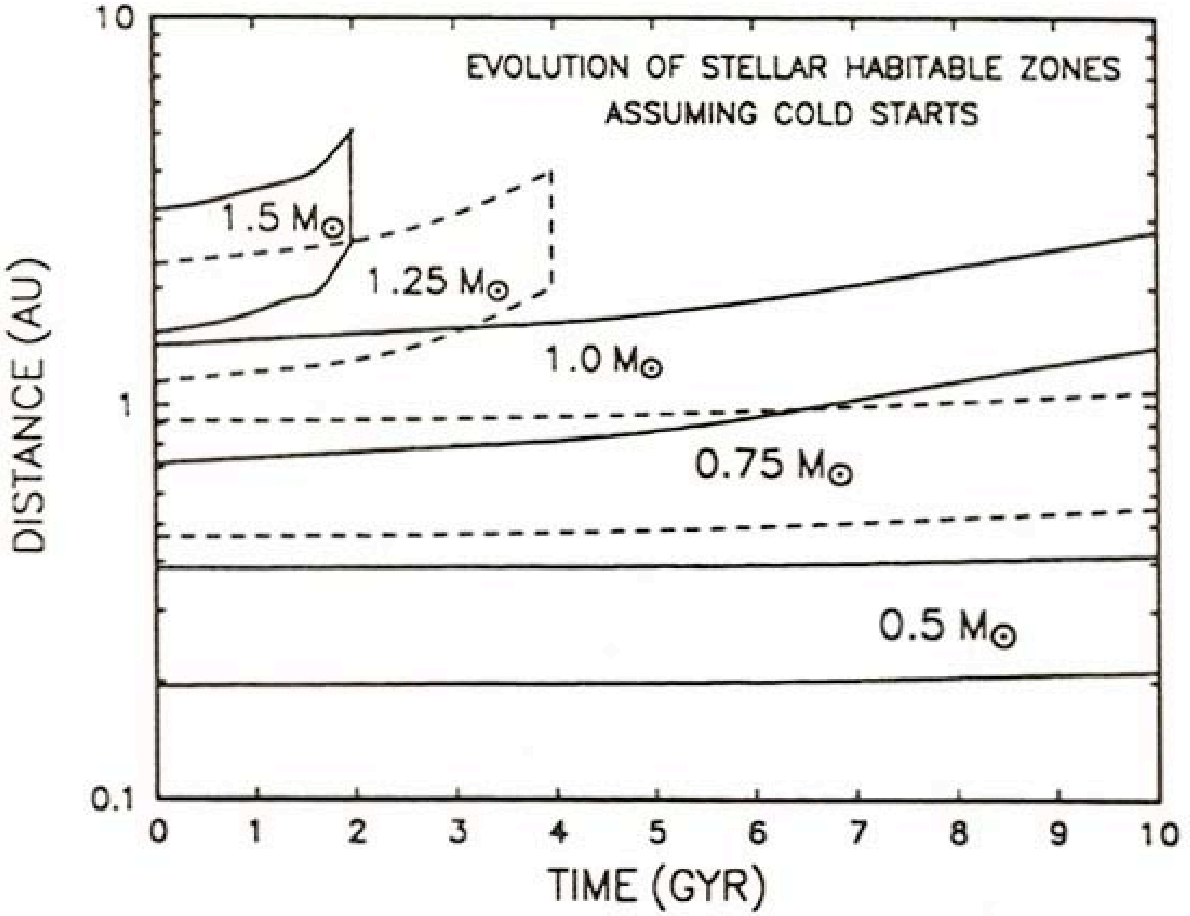


FIG. 5. *Evolution of the around stars of different masses assuming that co starts are possible. Case critical fluxes were use and the evolution was truncated at the end of t main sequence phase.*

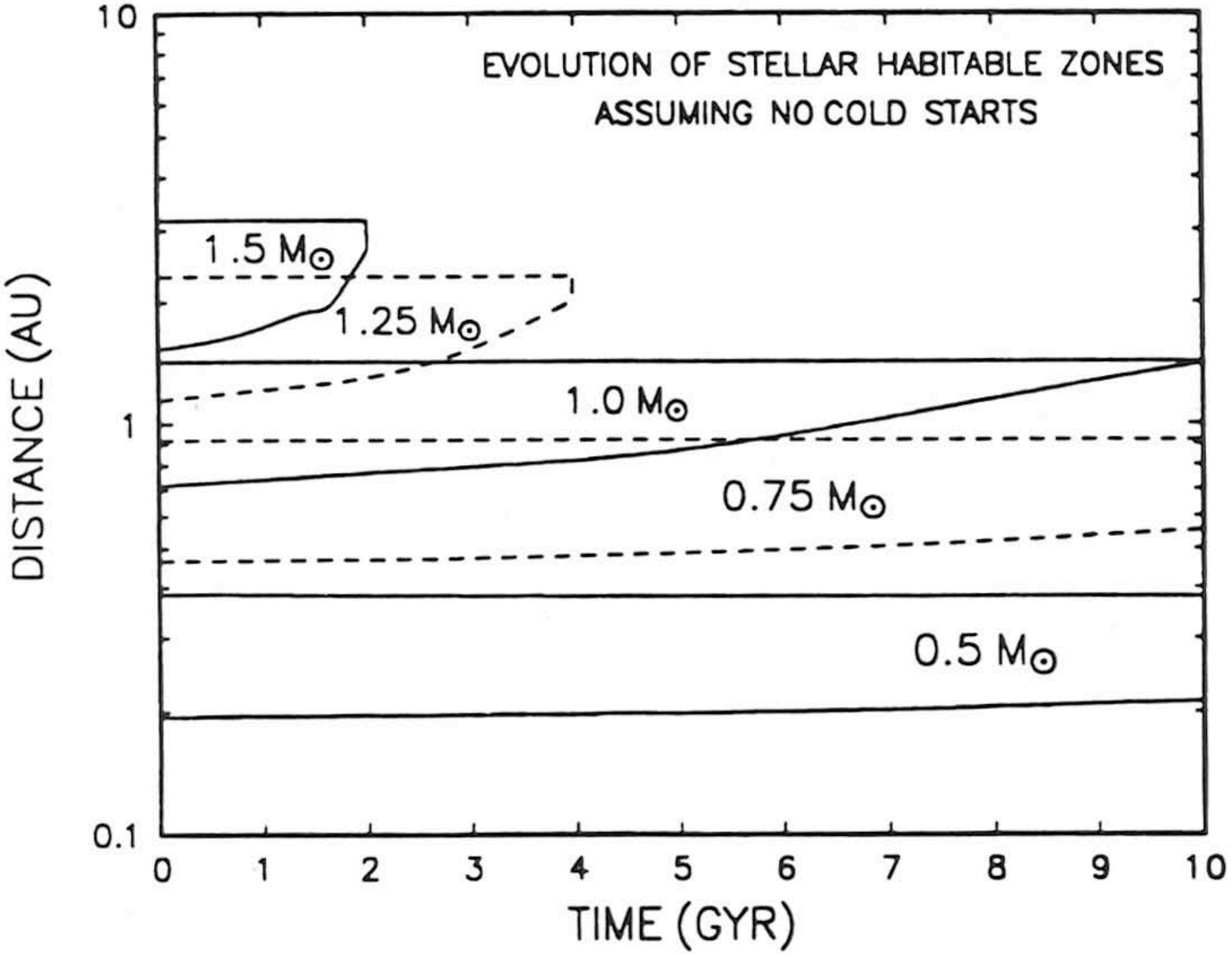


FIG. 6. *Evolution of the HZ around stars of different masses assuming that cold starts are not possible. Case 2 critical fluxes were used and the evolution was truncated at the end of the main sequence phase.*

d) Synchronous Rotation
(Same side always faces star)

$T \qquad \left(\frac{L}{D^2}\right)^{1/4} \qquad \frac{L^{1/4}}{D^{1/2}}$ Tidal Forces $\frac{1}{D^3}$

□ As D decreases, Tidal forces become much more important

Cause synchronous rotation

Gravity greatest on side closest

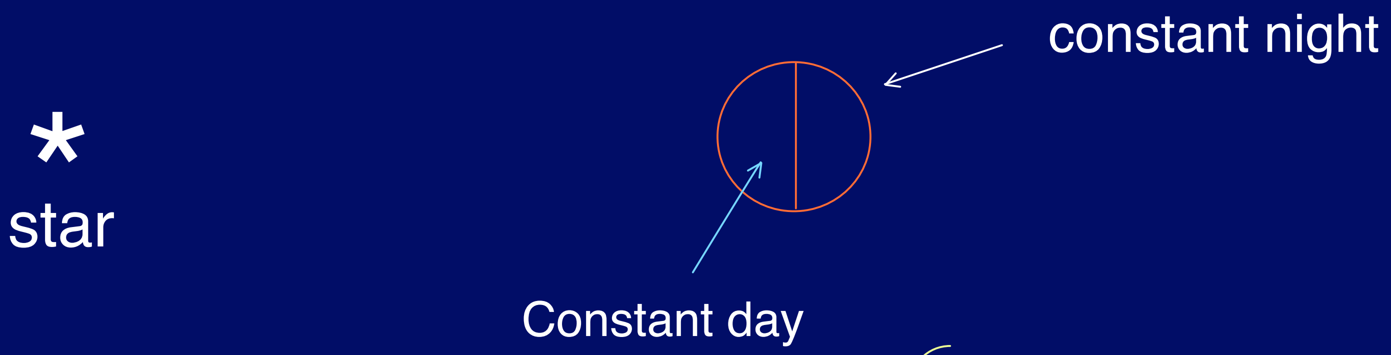
□ Bulge

+ Rotation = Tides

If Rotation ≠ orbital period, friction

→ tends toward synchronous rotation

(but effect of other planets may prevent this)



*

star

constant night

Constant day

□ Atmosphere freeze-out?

May not happen if
atmosphere thick enough

(0.1 Earth pressure)

$M > 0.5\ M_\odot$ □ 0.25 OK

$M < 0.5\ M_\odot$ - ruled out (maybe)

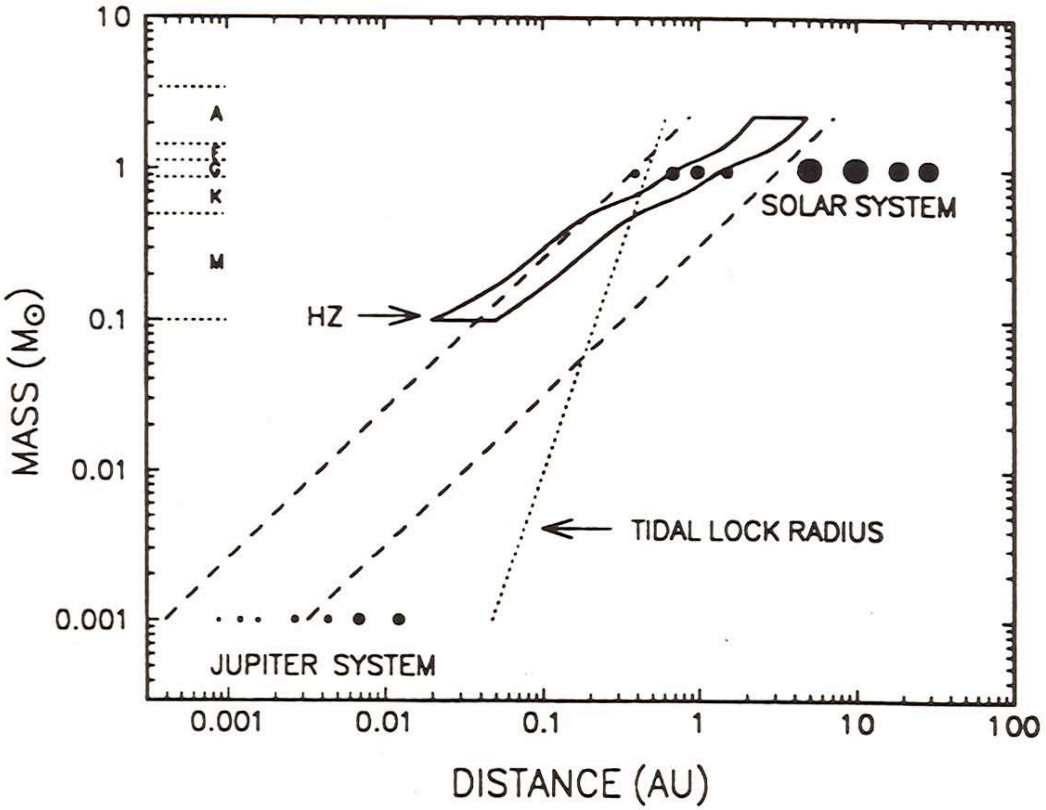
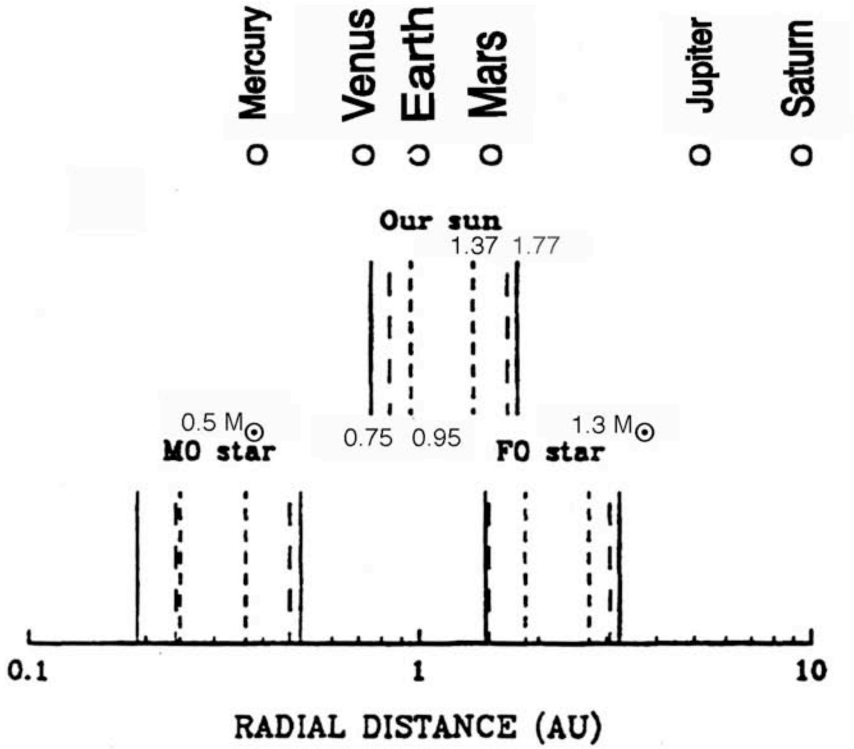
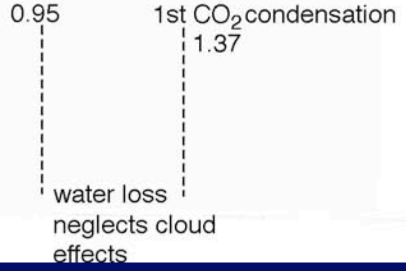


FIG. 8. *The ZAMS HZ (dark solid curve) as a function of stellar mass for Case 2 fluxes. The long-dash lines delineate the most probable terrestrial planet formation zone. The short-dash line is the radius for which an Earthlike planet in a circular orbit would be synchronously or slowly rotating as a result of tidal damping. Note that all such planets in the HZ around M stars are within this radius.*



. **1.** *Habitable zone limits for the three stars listed in Table 2. The solid lines esent the "recent Venus" and "early Mars" limits; the long-dashed lines esent the "runaway greenhouse" and "maximum greenhouse" limits; and hort-dashed lines represent the "water loss" and "1st CO_2 condensation" s. "Recent Venus" and "early Mars" limits for the M0 and F0 stars were d to our own Sun using the S_{eff} values for "water loss" and "maximum nhouse," respectively. The circles at the top represent the six innermost ets in our Solar System.*



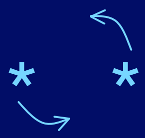
5. Binary Stars

a) Unstable orbits

Unless two stars widely separated

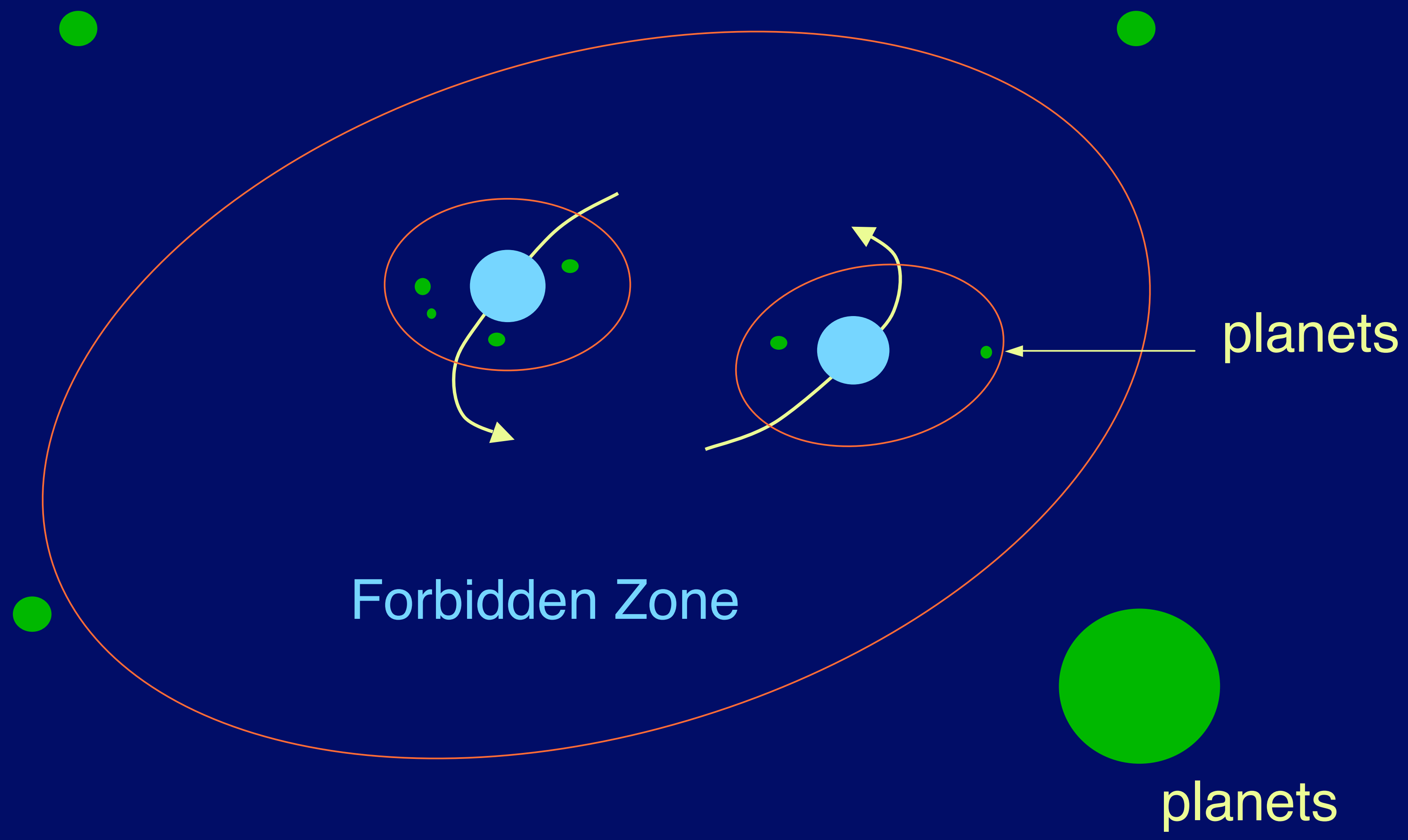
or very close

$$\text{Need} \quad \frac{\text{Distance to Second Star}}{\text{Distance to Planet}} > \frac{7}{1} \text{ or } < \frac{1}{7}$$



or

* (more likely)



Stable orbits around a Binary Star

b) Varying temperature in orbit
also need $\sim 7:1$

c) Both stars on main sequence,
$M < 1.25\ M_\odot$, …

2/3 of all stars are binaries
2/3 ~ “wide enough”

Binaries ruled out? $f_s < 1/3$ (if you kept them for f_p)
Not > $7:1$ ruled out? $f_s < 1/2$

Summary

	Requirement	Fraction OK	Cumulative
	1. Heavy Elements	1.0	1.0
	2. Main Sequence	0.99	0.99
	3. $M<1.25\ M_{sun}$	0.90	0.89
?	4. $M>0.5\ M_{sun}$	0.25	0.22
?	5. Not binary	0.3	0.07
?	5. 7:1 Separation	0.5	0.11

Bottom Line

- Points 1 to 3 are pretty clear
- Points 4 and 5 are less established
- Room for different estimates for f_s
  - Range 0.07 to 0.89 OK
- Then final step:
  - $n_e = n_p f_s$