Reading: Chapter 17, section 17.3; Chapter 18: section 18.2 & 18.4; Chap. 22, through 22.3 for next time
OBAFGKM mnemonics: see Discussions Page on Canvas (small extra credit opportunity)

Last time: **Stellar Motions and vital statistics**

- Stars move among one another - in ways we can measure
- Motions provide more clues to stellar distance
- W/distance we can determine luminosity & do a census of the stars
- Luminosity and temperature ranges

Today: **Stellar Families, Masses and Luminosities**

- Luminosity and temperature correlate - the H-R diagram
- H-RD reveals distinct groups - dominated by the Main Sequence
- Masses of stars can be found using binary star systems
- The Main Sequence is a sequence of Mass
- Mass and Luminosity correlate - the M-L relation as a consequence of fundamental physics

A Census of the Stars

- **Observed Luminosities**

  $L_{sun}/100{,}000 \rightarrow\ > 100{,}000 \times L_{sun}$

- **Observed Temperatures**

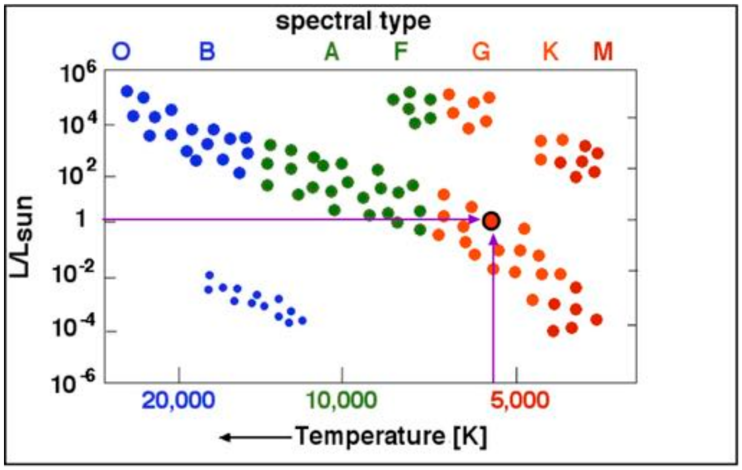
  2000K $\rightarrow$ 200,000K

- **Classification**
  stars of a **given spectral type** (= temperature) can have
  vastly different luminosities ranging over factors of several thousand

- **Need to classify stars by**
  spectral type *and* luminosity

1914: The Hertzsprung-Russell Diagram

spectral type as ‘X’; luminosity as ‘Y’



The H-R Diagram: a device to **classify** stars by **spectral type and Luminosity**
(i.e. T, or color)

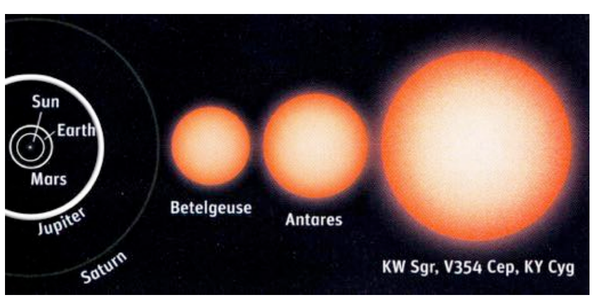
- Radius on the H-R Diagram

$$\frac{L}{L_{sun}} = \left[\frac{R}{R_{sun}}\right]^2 \left[\frac{T}{T_{sun}}\right]^4$$

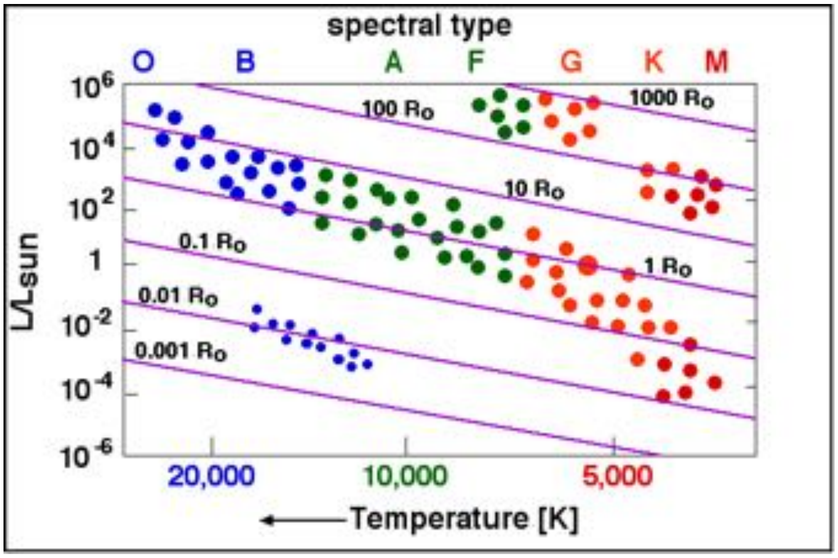
stars at same L:
Higher T → smaller R

stars at same T:
Higher L → Bigger R

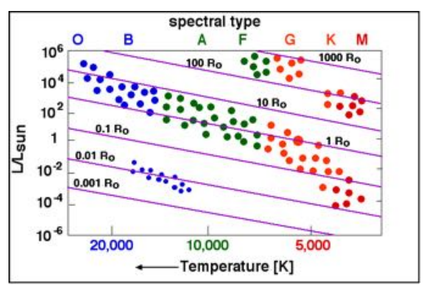
- biggest stars: upper right-hand corner of H-R Diagram



Radius on the H-R Diagram

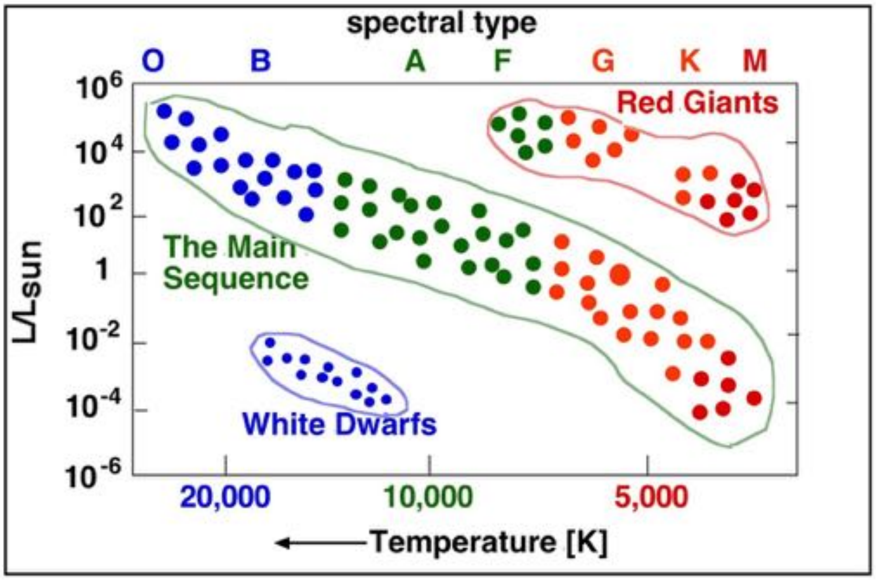


Features on the H-R Diagram

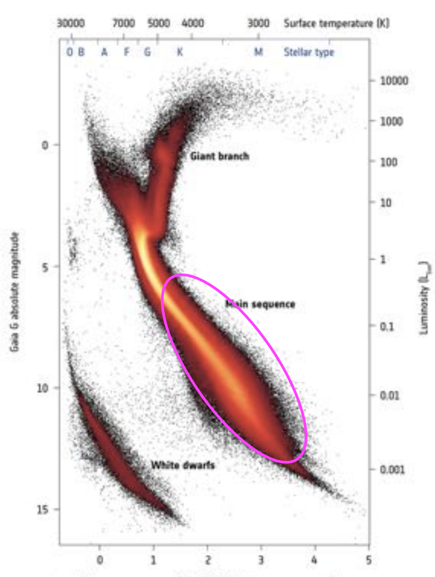


- **The Main Sequence**
  - diagonal band
  - 90% of all stars are Main Sequence stars
- **The Giants**
  - upper right
  - high L, low T -> huge size; 100 R_{sun} and more!
- **White Dwarfs**
  - lower left
  - low L, ~high T -> tiny size; 0.01 R_{sun} and less

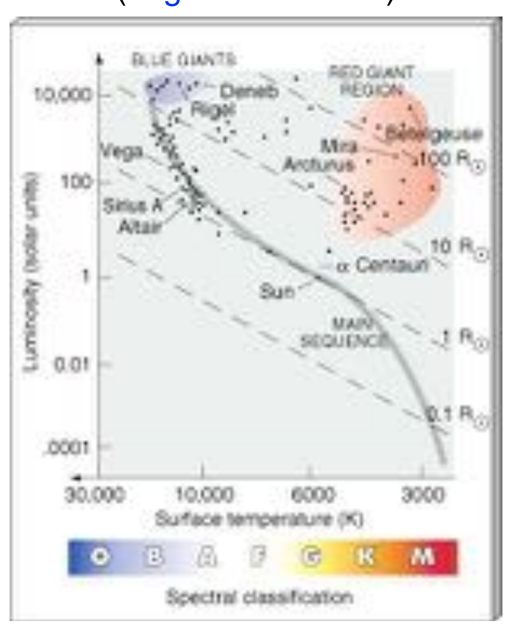
Features on the H-R Diagram



H-R diagram for all stars with Gaia (space) parallaxes (distance limited)



H-R diagram for brightest stars in the sky (brightness limited)

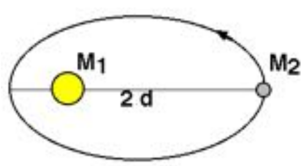


Main Sequence stars
are the most numerous
BUT
The most prominent stars in our sky
are the rare but luminous
blue main sequence, giants and supergiants

- **Why such variety?**
- **What makes stars so different from one another?**
- **What are we missing? MASS!**

Measuring Stellar Masses: Binary Stars

- Kepler's Third Law - for binary stars

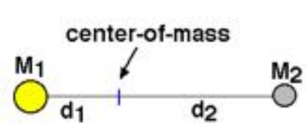


$$\frac{d^3}{P^2} = M_1 + M_2$$

orbital period [yrs]

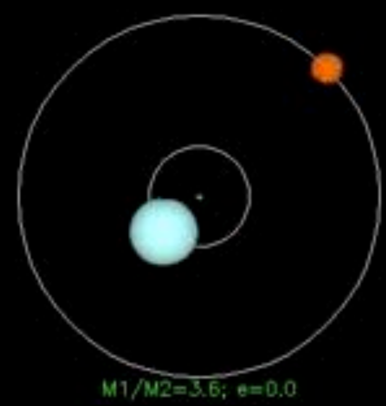
- The See Saw Law

$$\frac{M_1}{M_2} = \frac{d_2}{d_1}$$



- sum *and* ratio of masses allows determination of the individual masses of each star

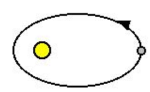
Reflex Orbital Motion



Credit: R. Pogge, OSU

Types of binary stars

- **Visual**
  - widely separated (10-100 a.u. and more)
  - know d_1+d_2, d_2/d_1, P (sometimes)

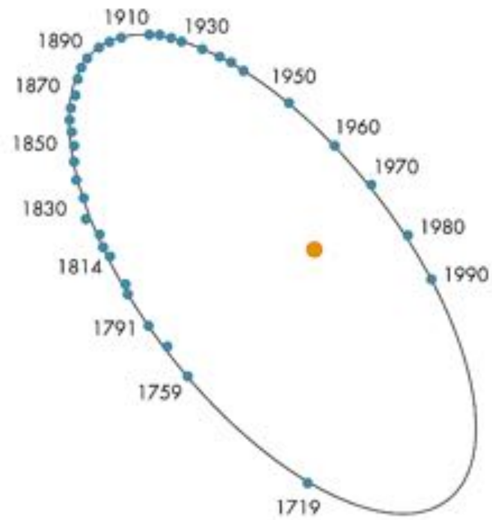


- **Spectroscopic**
  - spectral lines show periodic Doppler shifts
  - too close to see individual stars
  - know d_2/d_1 (from velocities), P

- **Eclipsing**
  - brightness variations as stars eclipse one another
  - know P , shapes of stars, light distribution

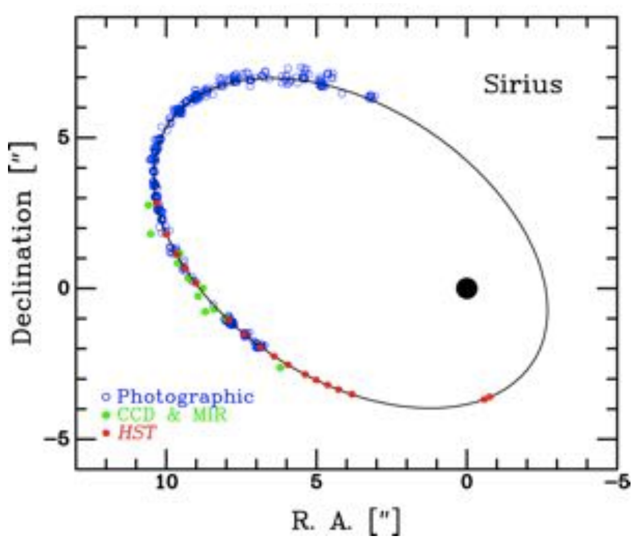
- **Eclipsing spectroscopic - rare**
  - provide d_1+d_2, d_2/d_1, P and so masses
  - radii from eclipses and orbital velocities

Castor - a visual binary



Sirius - a shorter-period visual binary

(Bond et al. 2017)



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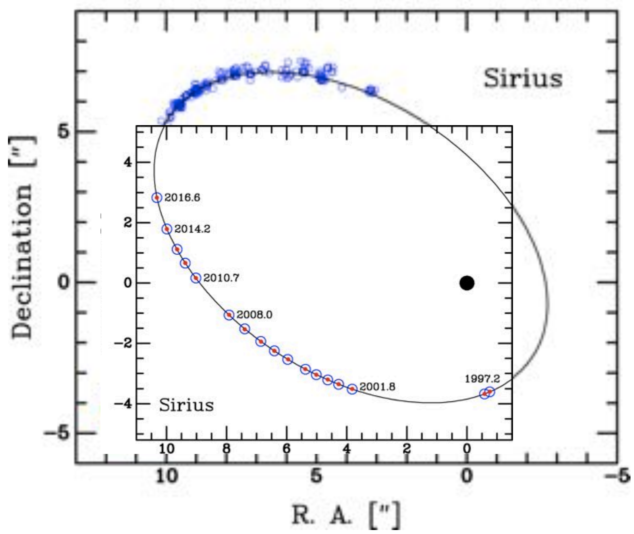
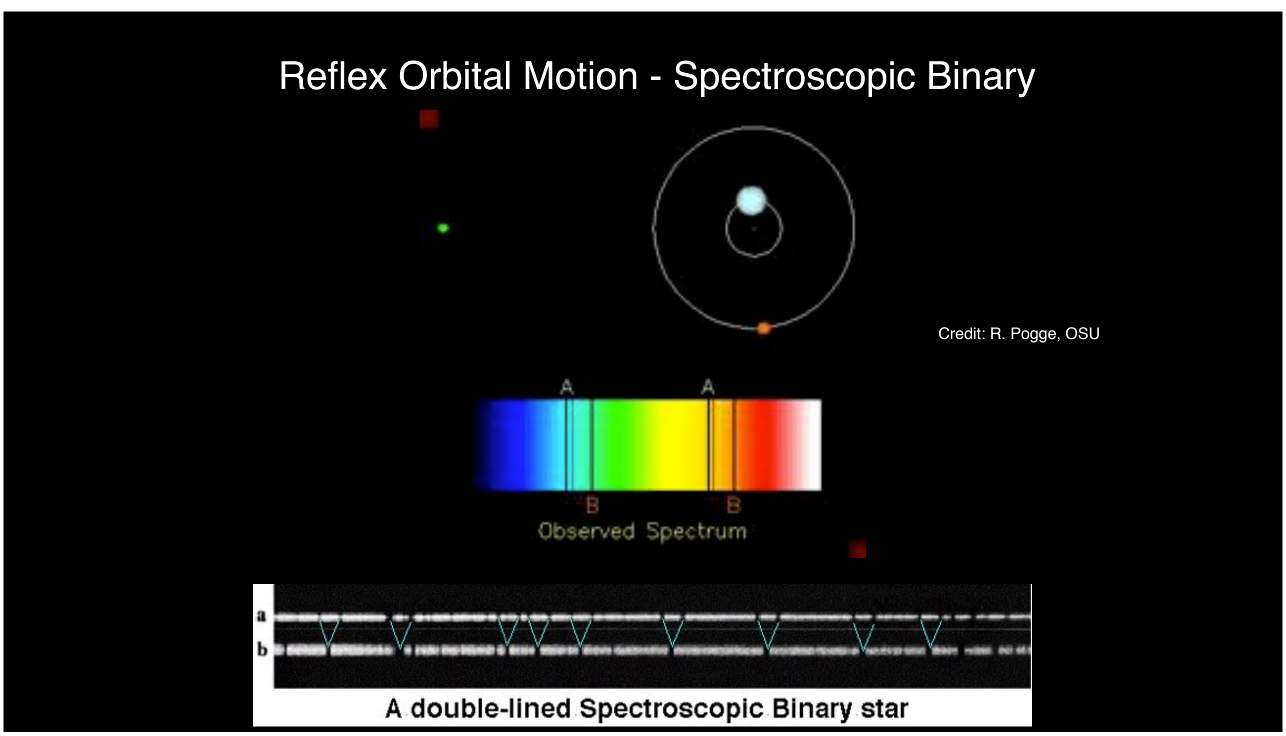
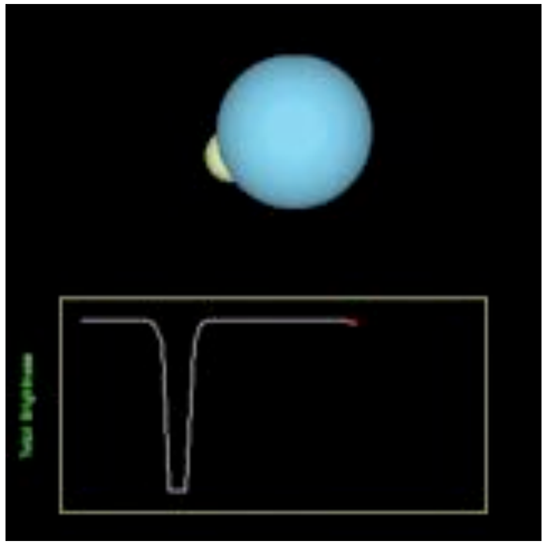




- Eclipsing binary



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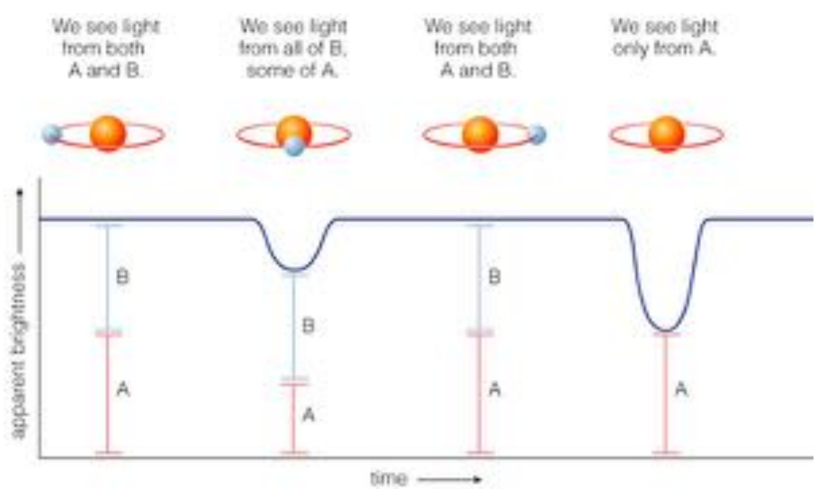

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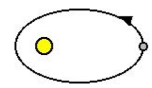

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- **Eclipsing spectroscopic - rare**
  - provide d_1+d_2, d_2/d_1, P and so masses
  - radii from eclipses and orbital velocities

- more than 50% of stars are in binary or multiple systems
- BUT only about **100** can be used to measure accurate stellar masses
- Key Observation:
  Stars with the same mass have the same spectral type... on the Main Sequence

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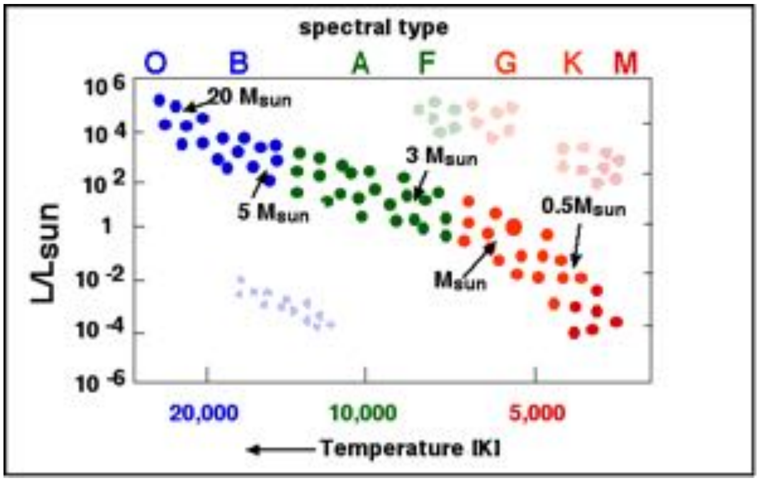


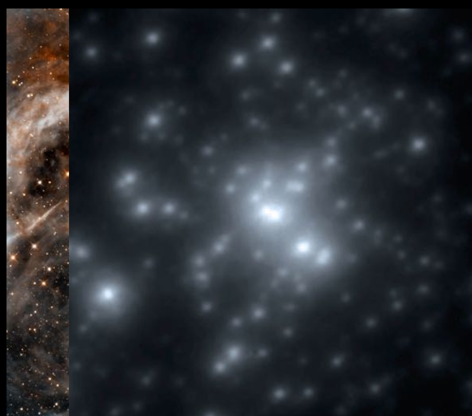
Properties of Main Sequence Stars

# in Galaxy for each O star	L/L_{sun}	M/M_{sun}	R/R_{sun}	Example
1	260,000	20	10	Rigel
100,000	60	3	2.5	Vega
1,000,000	1	1	1	Sun, Capella
5,000,000	0.06	0.4	0.6	Barnard's Star

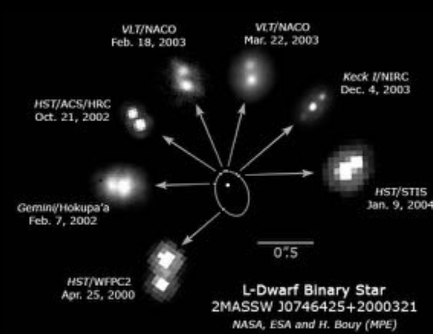
- **Lower mass limit** of Main Sequence: **0.08 M_{sun}**
  - stars less massive don't get hot enough to burn hydrogen
- **Upper mass limit**: **~ 200 M_{sun}**
  - if M > 100 M_{sun}, violently unstable

Main Sequence Extremes

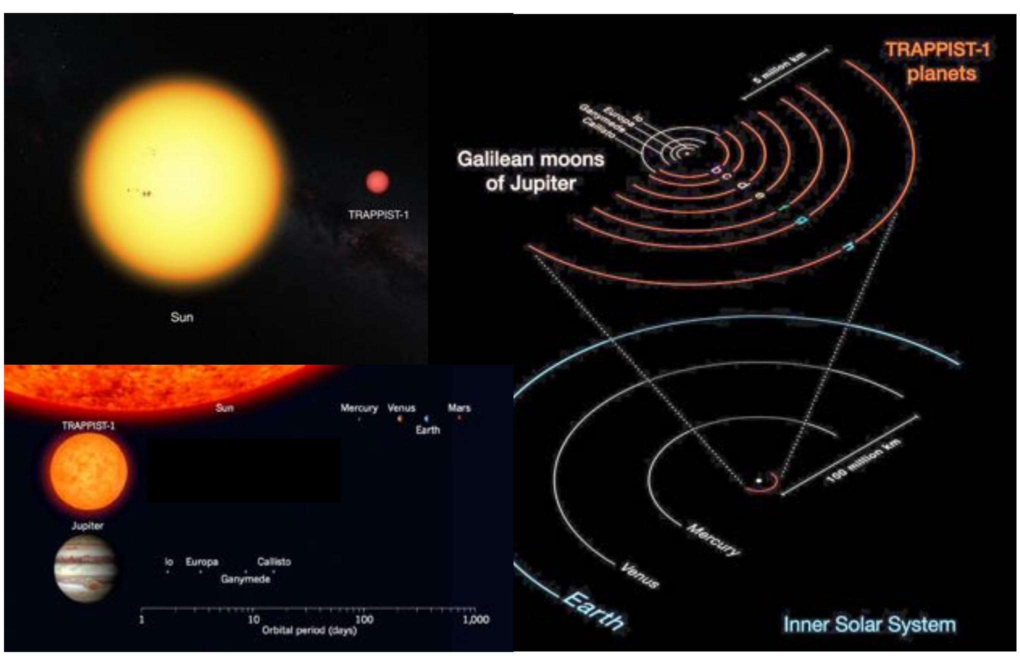
High Mass:
R136a1 at ~300 M_{sun}



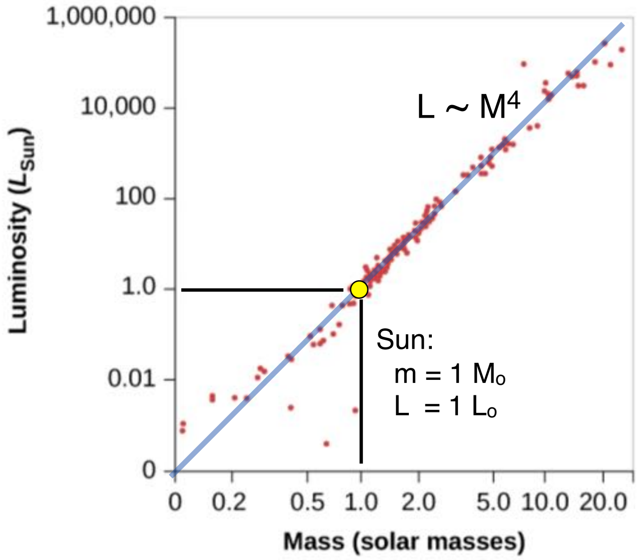
Low Mass:
an 'L' Dwarf at 0.077 M_{sun}



TRAPPIST-1: L =0.0005 L_{sun} M=0.08 M_{sun}



The Mass-Luminosity Relation



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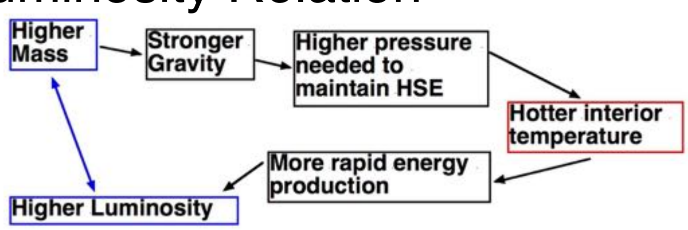

- <u>Eddington</u> (1926):
  $L \propto M^4$ for main sequence stars
- Main sequence is a sequence in MASS
  blue stars are more massive than red stars
- The Sun is a M.S. star
  - <u>The Sun burns hydrogen in its core</u>
- **all M.S. stars burn hydrogen in their cores**