# Part 2: Stars

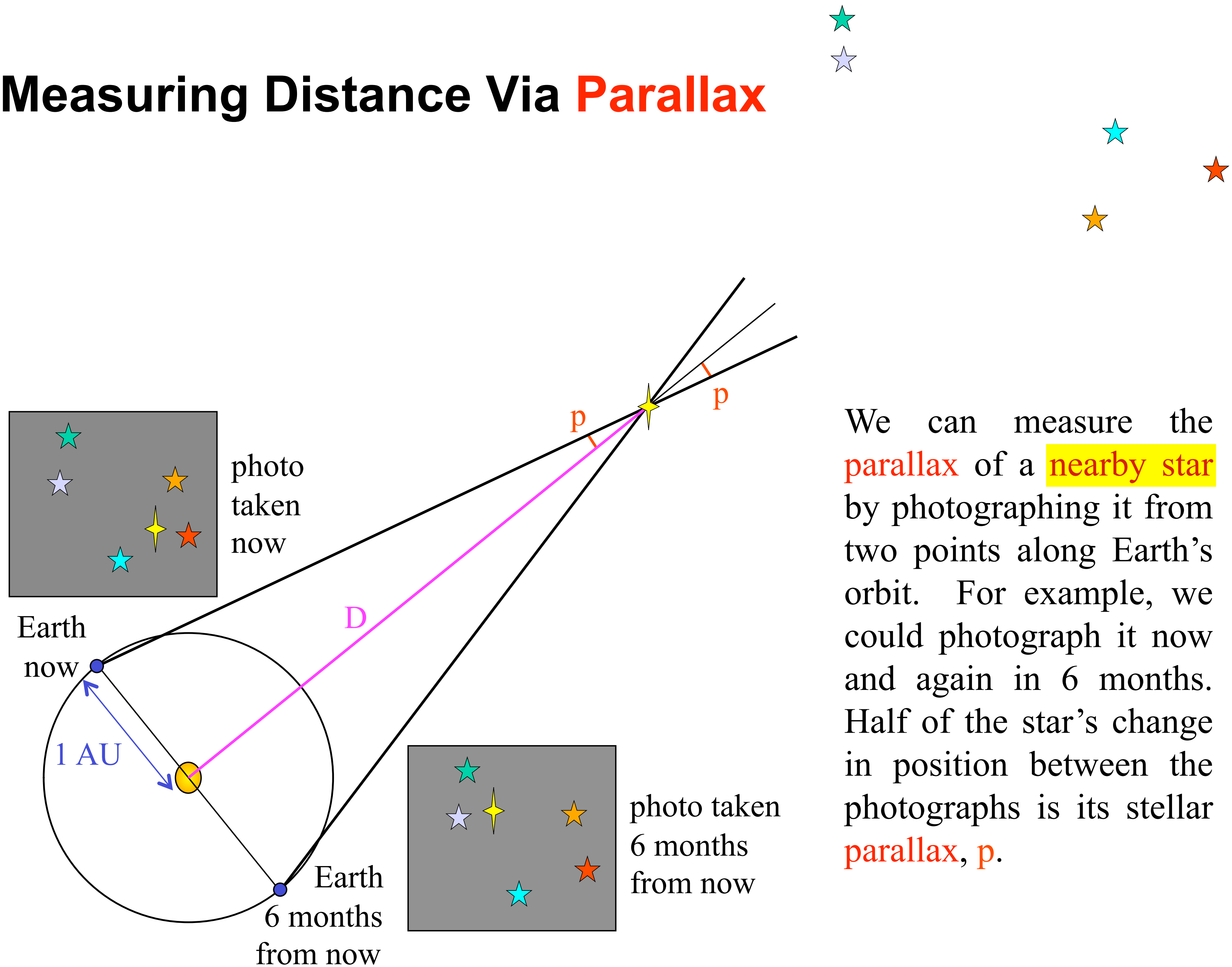
- Thursday, February 9 Reading: Chapter 6 [Ed. 9, 10, 11, 12]
  - The nature of light: How we use spectra to measure the properties of stars
- Tuesday, February 14 Reading: Chapters 8, 9.1, 9.5 or Orion Nebula
  - Stars: distance, luminosity, mass, composition. Star formation. HW2 assnd
- Thursday, February 16 Reading: Chapter 7.1 — 7.2 or 7.3 on the Sun
  - Stars: Our Sun.
- Tuesday, February 21 Reading: Chapters 7 or 9 on fusion, 9.2 — 9.5
  - Stars: Stellar models, energy generation, main sequence life
- Thursday, February 23 Reading: Chapters 10.1 — 10.3
  - Stars: Evolution from main sequence to white dwarf or Type II supernova
- Tuesday, February 28 Reading: Chapters 10.4, 11 HW 2 due
  - Stars: Type I supernovae; white dwarf stars, neutron stars, black holes
- Wednesday, March 1 Help session from 4 — 6 PM in Welch 3.502
- Thursday, March 2 Exam 2 (Part 2)
- Monday, March 6 Help session from 4 — 6 PM in RLM 4.102
- Tuesday, March 7 Exam 3 (Parts 1 + 2)
- Thursday, March 9 Exam 4 (Parts 1 + 2)

**Homework 2 is assigned today.**
**It is posted on the class web site.**

**Note 1: It is OK to discuss the homework problems with your friends. It is not OK to copy their answers. You will get 0 if this happens.**

**Note 2: Please show your work. If you get the right answer but don't show us that you understand how to get the right answer, then I am sorry, but you will get only 1/2 of the full marks.**

# Measuring Distance Via Parallax

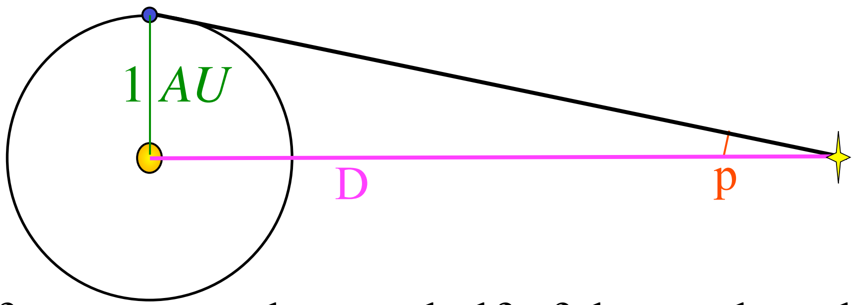



We can measure the parallax of a nearby star by photographing it from two points along Earth's orbit. For example, we could photograph it now and again in 6 months. Half of the star's change in position between the photographs is its stellar parallax, p.

# Parallax as a Measure of Distance

Parallax shifts can be used to measure the distances of nearby stars. A smaller shift implies a larger distance.

$$\frac{1\ AU}{2\pi D} = \frac{p}{360^\circ}$$




We define the parallax of a star, p, to be one-half of the total angle by which the star's position shifts as the Earth travels around its orbit. Then the distance to the star is

$$D = \frac{1}{2\pi}\frac{360^\circ}{p}\, AU = \frac{1''}{p}\, pc,$$

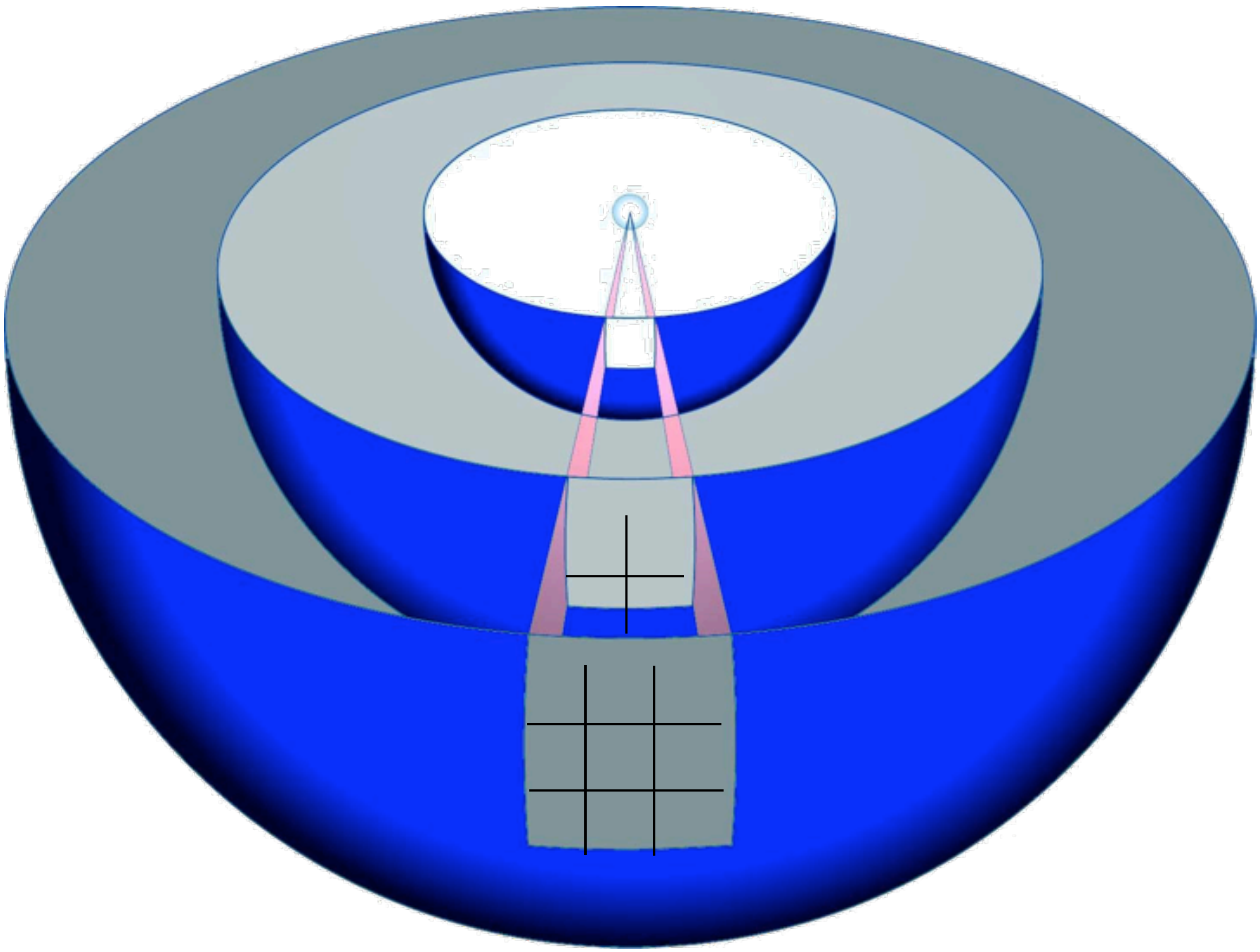
1 pc = 3.26 light years. This defines "parsec" as a new unit of distance.

Here (set p = 1")

$$1\ pc = \frac{360 \times 60 \times 60}{2\pi}\, AU = 206265\ \ AU.$$

Ground-based observations can measure shifts as small as 0.01". The Hipparcos satellite measured angles as small as 0.002". So the biggest distances that so far have been measured using parallaxes are about 100 parsecs (~ 300 ly) from Earth and about 500 parcecs (~ 1500 ly) from space. The Gaia satellite is now measuring ~ 1 billion stars throughout our Milky Way galaxy <u>much</u> more accurately.

# Apparent Brightness Decreases As Distance$^2$



# Absolute and Apparent Luminosity

Absolute luminosity measures how much energy an object radiates in a given time.

Apparent luminosity or apparent brightness is a measure of how much energy we receive from an object per unit time. The apparent brightness of an object depends on its distance. If L is the absolute luminosity and d is the distance, then

$$\text{apparent brightness} \propto \frac{L}{d^2}.$$

## The Horrible Magnitude System

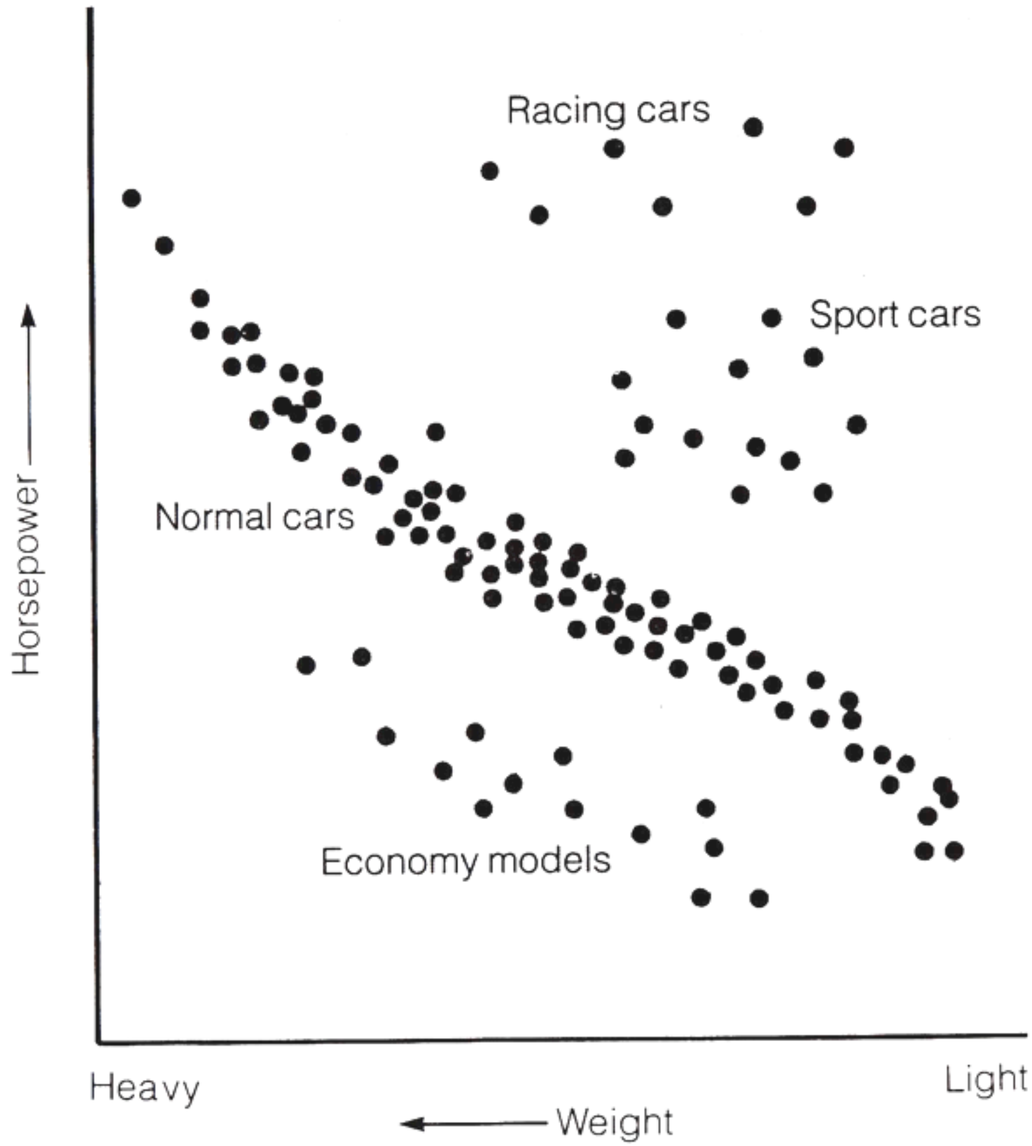
Traditionally, astronomers use "magnitudes" to talk about the luminosity of objects. The magnitude scale is logarithmic; 5 magnitudes are a factor of 100 in luminosity. It is also backwards; brighter stars have smaller magnitudes.

The absolute magnitude of an object is defined to be the apparent magnitude that it would have at a distance of 10 parsec.

# Apparent Magnitudes and Brightnesses

| Object | Apparent Magnitude | Apparent Brightness (Relative to Vega) |
|---|---|---|
| Sun | -26.5 | $4.\times10^{10}$ |
| Full Moon | -12.5 | 100,000 |
| 100 watt light bulb at 100 m | -11.1 | 27,700 |
| Venus (at brightest) | -4.4 | 58 |
| Mars (at brightest) | -2.7 | 12 |
| Jupiter (at brightest) | -2.6 | 11 |
| Sirius (brightest star) | -1.4 | 3.6 |
| Vega | 0.0 | 1.0 |
| Spica | 1.0 | 0.4 |
| Naked eye limit in urban areas | 4 | 0.025 |
| Uranus | 5.5 | 0.0063 |
| Naked eye limit in rural areas | 6.5 | 0.0025 |
| Limit for typical binoculars | 10 | $1.\times10^{-4}$ |
| Limit for 15-cm (6-in) telescope | 13 | $6.\times10^{-6}$ |
| Pluto | 15 | $1.\times10^{-6}$ |
| Visual limit for large telescopes | 19.5 | $2.\times10^{-8}$ |
| CCD limit for large telescopes | 28 | $6.\times10^{-12}$ |
| Hubble Space Telescope limit | 29 | $3.\times10^{-12}$ |

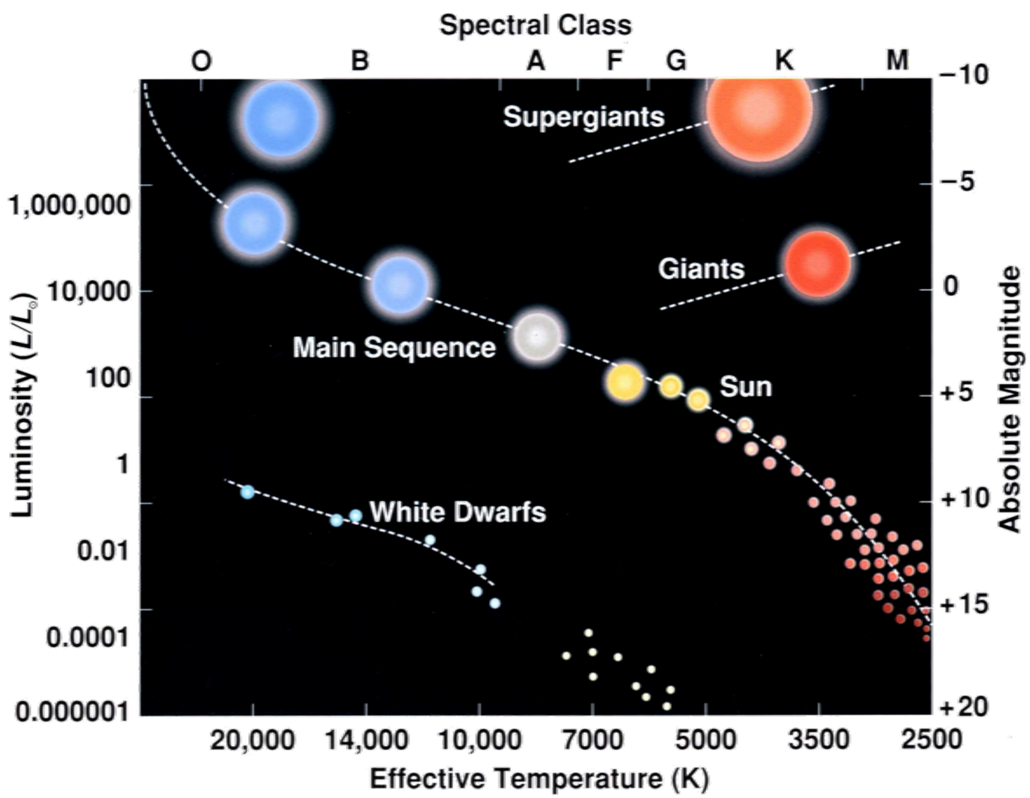
# A Hertzsprung-Russell Diagram For Cars



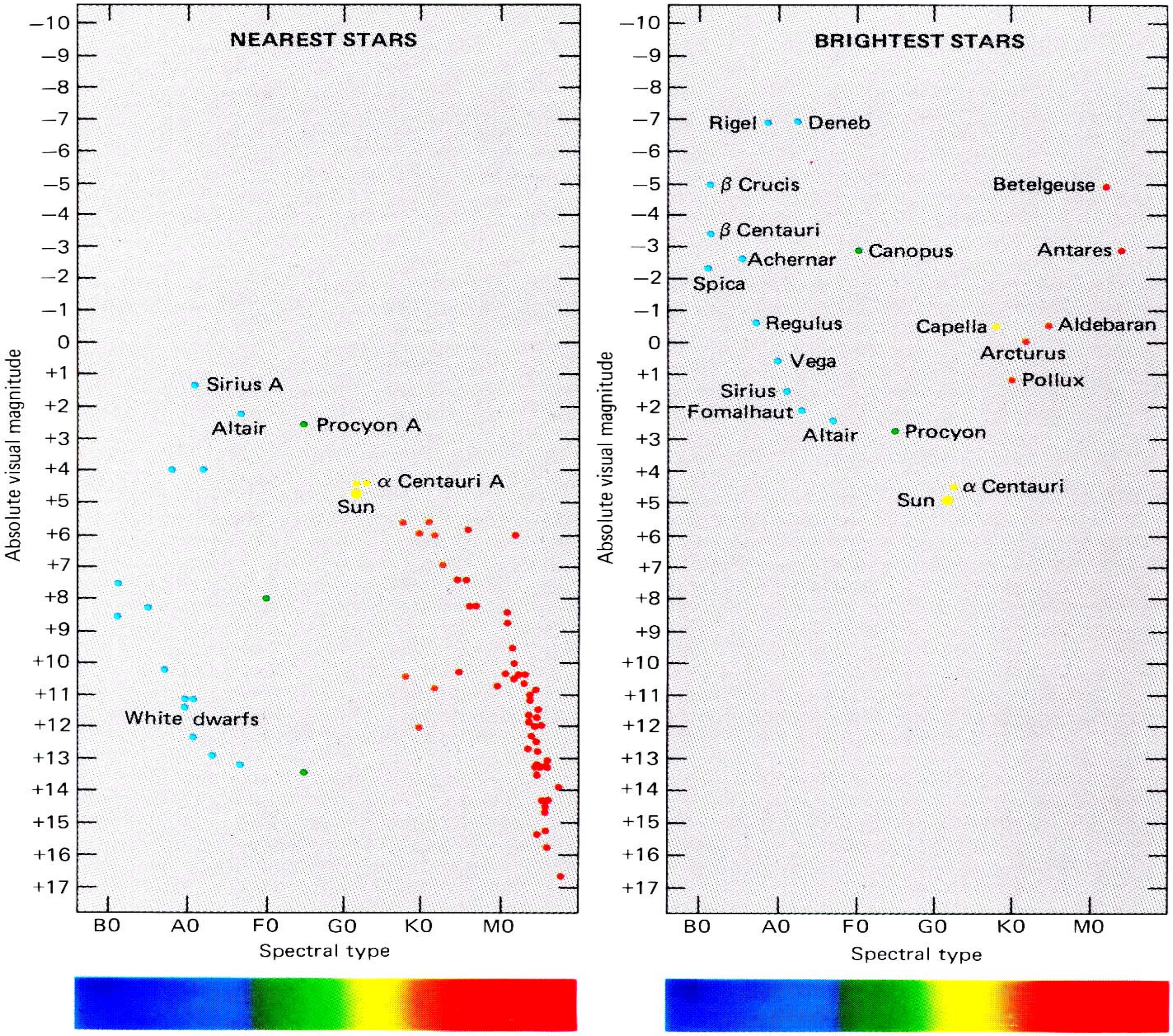
# The Hertzsprung-Russell (HR) Diagram

By the end of the 19th century, absolute luminosities and temperatures were known for many stars. It turns out that these two properties are related. An effective way to classify stars and to learn about their evolution is to plot each star's luminosity against its temperature. This is called a Hertzsprung-Russell or HR diagram.

When many stars are plotted, they fall into distinct patterns:

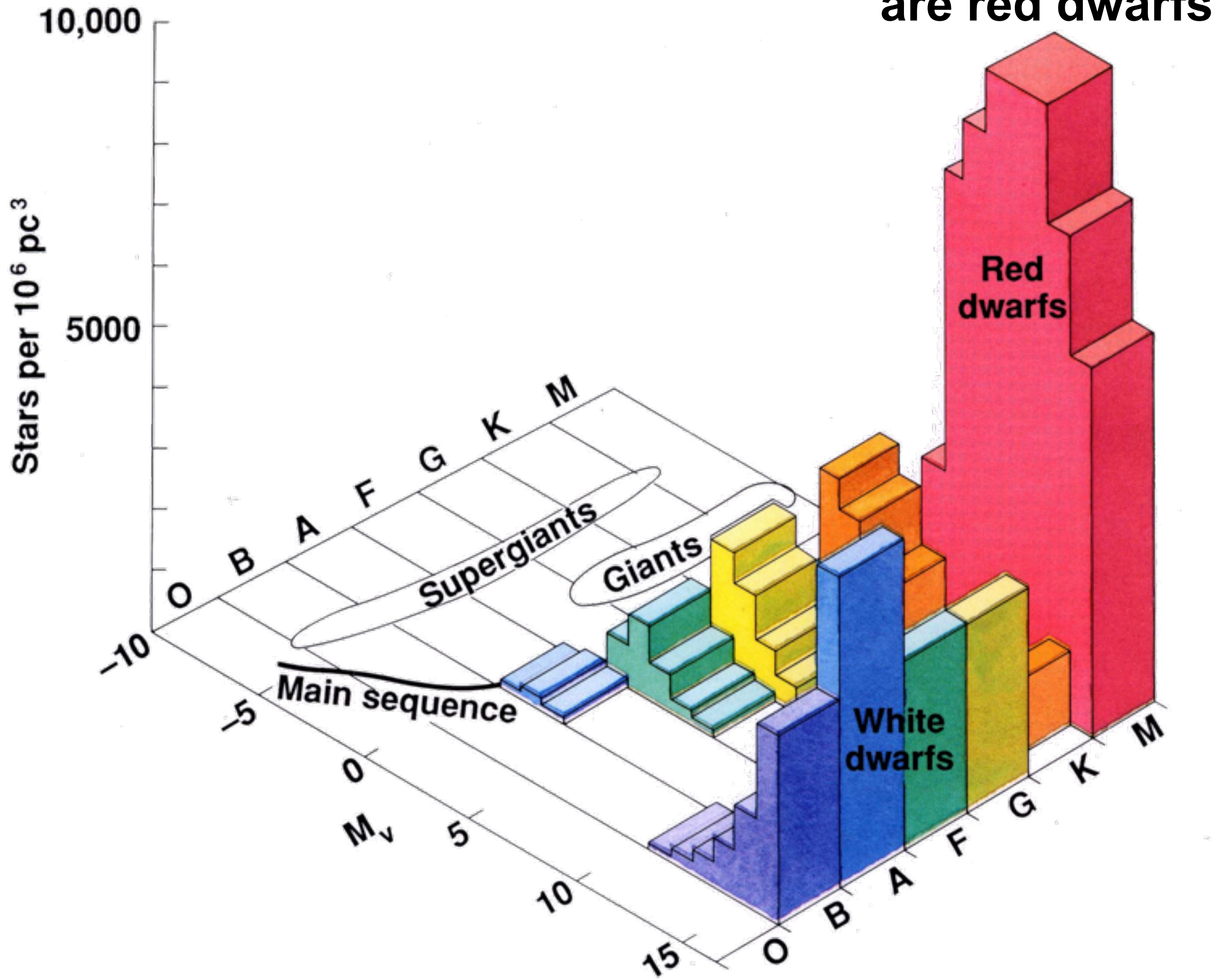


# Nearest Stars versus Brightest Stars



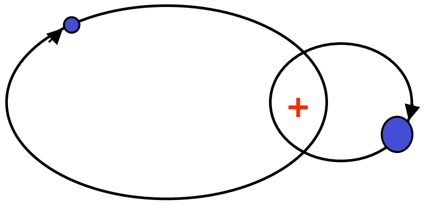
# Numbers of Stars

**The most numerous stars near the Sun are red dwarfs.**



# Measuring Stellar Masses Using Double Stars

The Sun is a solitary star. This is unusual. Most stars are members of binary systems: two stars orbit around a common center of gravity.



If the stars are far enough apart to be seen separately with a telescope, the system is called a visual binary. Depending on the orbital period, we may be able to plot the orbits of the stars.

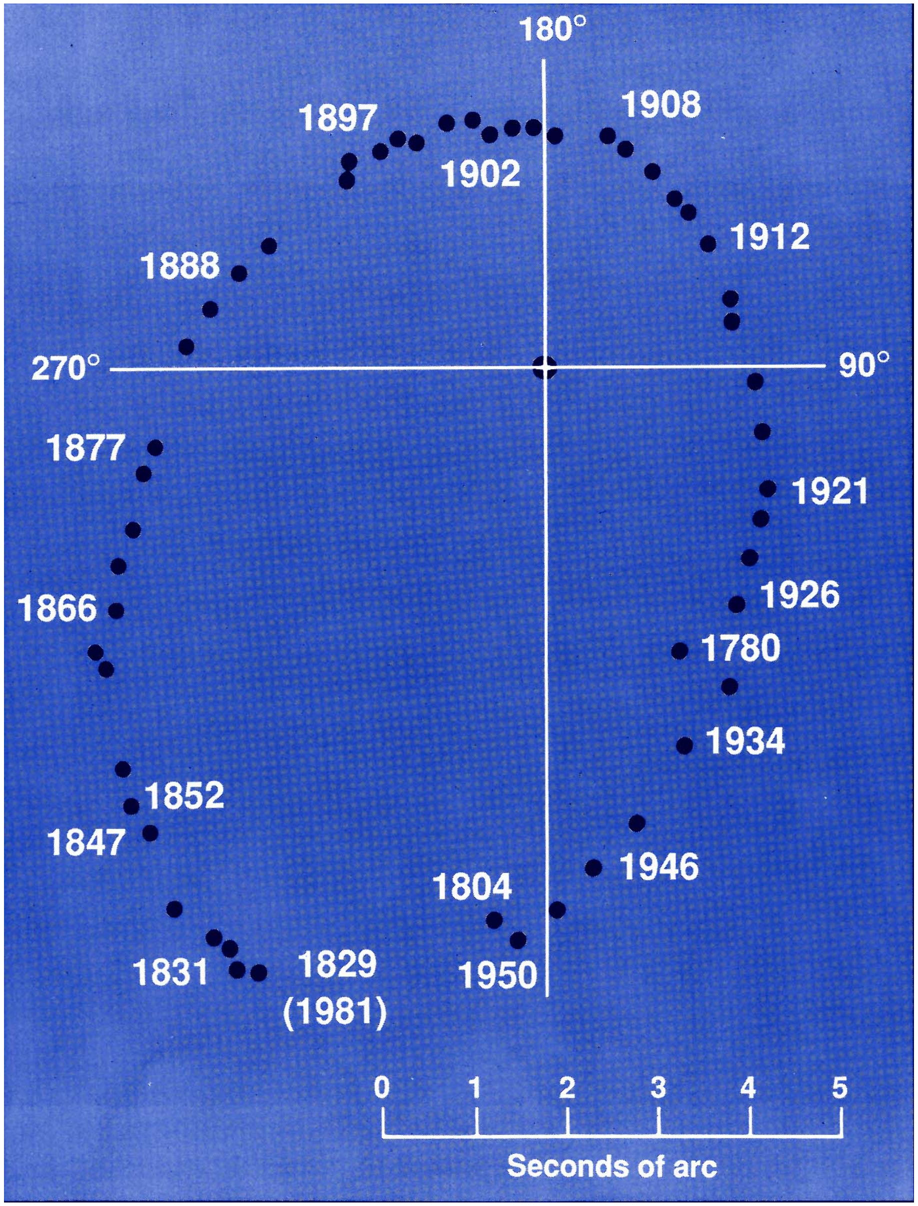
If the stars are too close to be separated with a telescope, we can still recognize that the system is a binary if we can observe wavelength shifts in spectral lines caused by the doppler effect. Such systems are called spectroscopic binaries.

If the stars are close together and we see their orbit plane edge-on, then the stars may eclipse each other. These systems are called eclipsing binaries.

**We can use binary stars to measure stellar masses.**

**We can use eclipsing binary stars to measure stellar radii.**

# Observed Relative Positions of the Visual Binary Xi Bootes



# Measuring Stellar Masses

Kepler's laws need a slight modification to describe the motions of double stars:

1. Each star moves in an elliptical orbit;
   the center of mass is the common focus of the two ellipses.
2. Each star sweeps out equal areas in equal times.
3. The quantity $a^3/P^2$ gives the total mass of the two stars.

A straight line drawn between the stars always passes through the center of mass. Each star's distance from the center of mass is inversely proportional to its own mass.

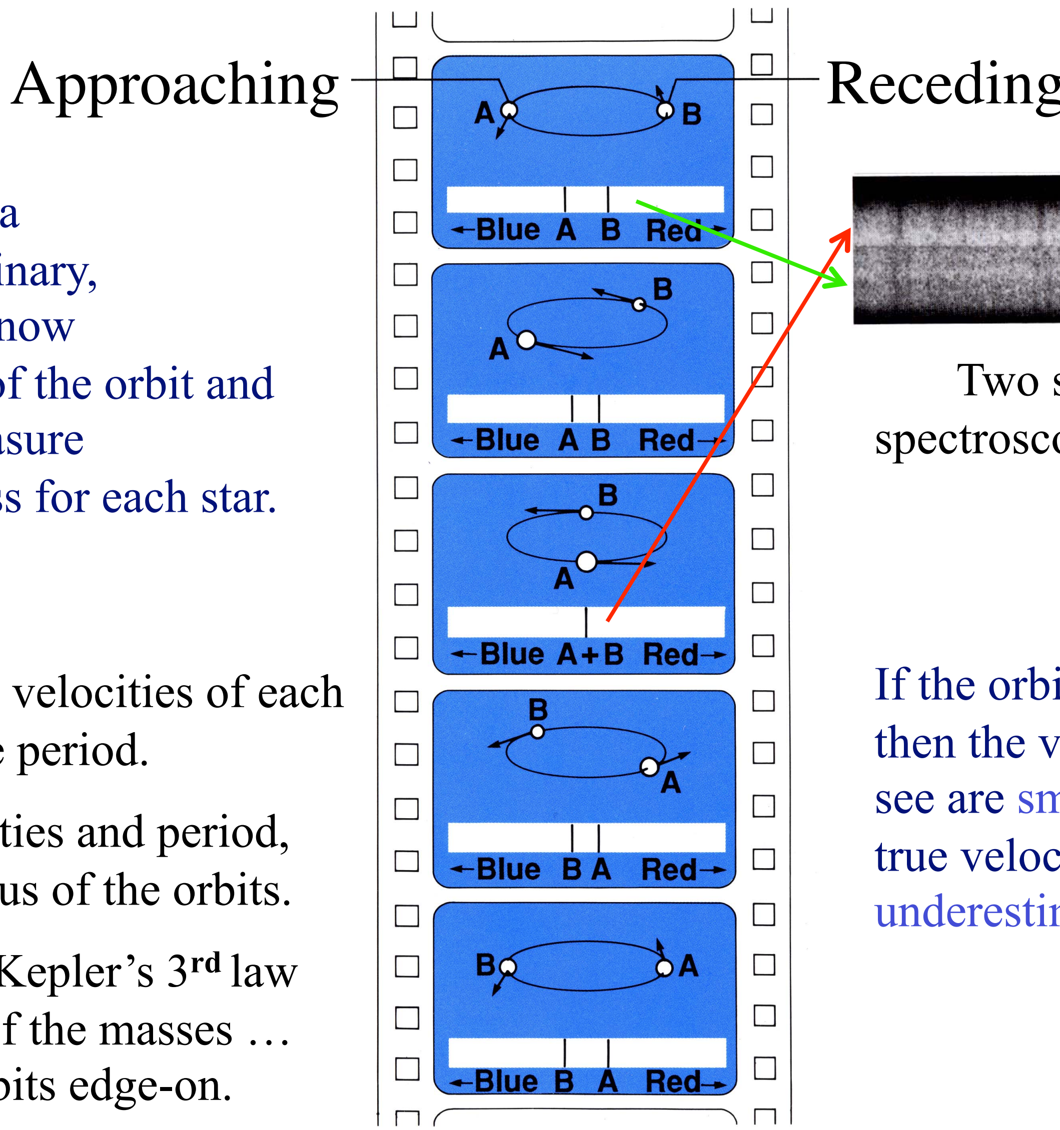
The semimajor axis of the relative orbit, $a$, is one-half of the maximum distance between the stars. If $a$ is measured in AU and P is measured in years, then

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

is the total mass in units of the Sun's mass. Combing this with the distance of each star from the center, the masses of the two stars, $M_1$ and $M_2$, can be determined.

<u>Note that we have to know how far the binary is from the Sun.</u>

# Spectroscopic Binaries



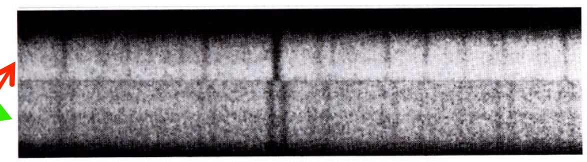

If the system is a spectroscopic binary, then we don't know the inclination of the orbit and so can only measure a minimum mass for each star.

Method:

We measure the velocities of each star and find the period.

From the velocities and period, we find the radius of the orbits.

Then we apply Kepler's 3rd law to get the sum of the masses … if we see the orbits edge-on.



Two spectra of the spectroscopic binary Mizar

If the orbits are not edge-on, then the velocities that we see are smaller than the true velocities and we underestimate the masses.

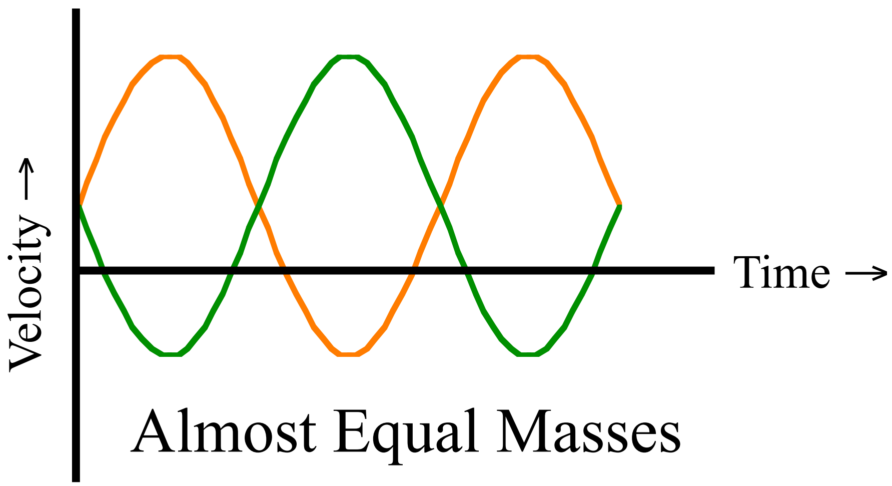
# <u>Note</u>

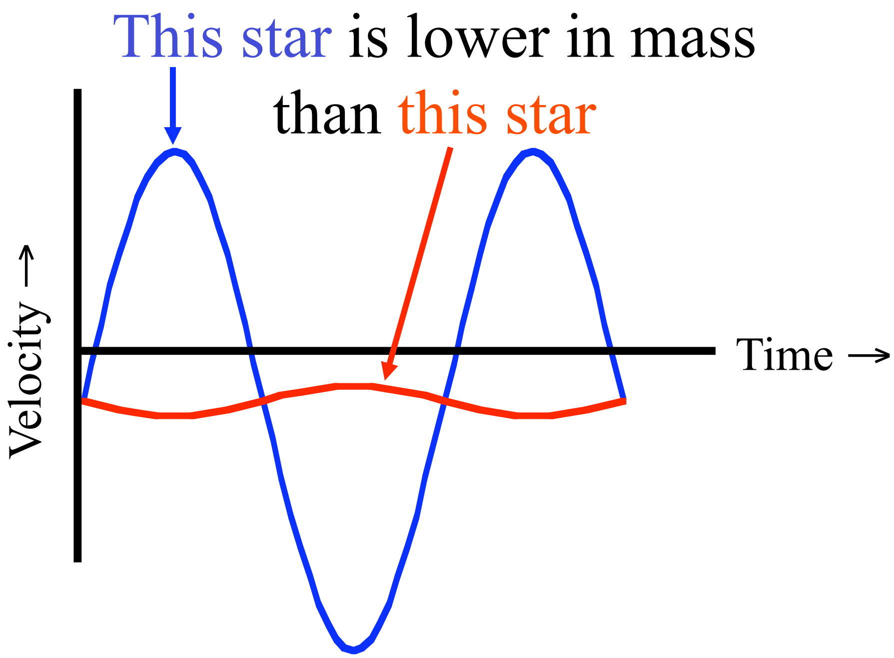
**There is both a binary star applet**

**and**

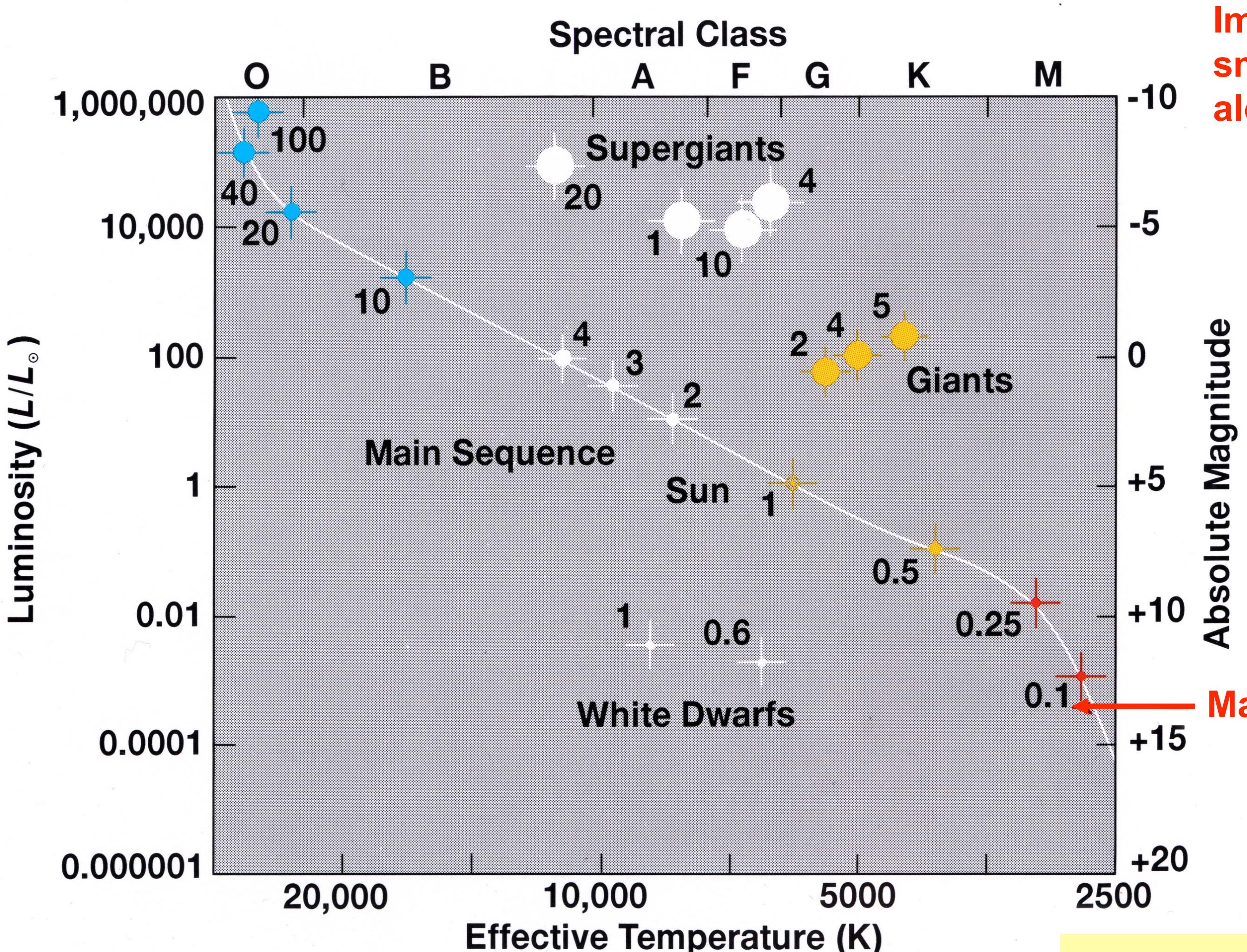
**a minilecture on deciphering the orbits of binary stars posted on the class web site.**

# Weighing Binary Stars



# Stellar Masses




**Important: there is a smooth progression in M along the main sequence.**

**Important: masses of giant stars are a mixture of small and large because stars of different M evolve to the same part of the HR diagram.**

**Mass in $M_{\odot}$**

Stellar Masses
20←in $M_{\odot}$

**0.08 $M_{\odot}$ is the lower limit for hydrogen "burning"**

# Mass — Luminosity Relation

more luminous

Higher-mass stars are <u>much</u> brighter.

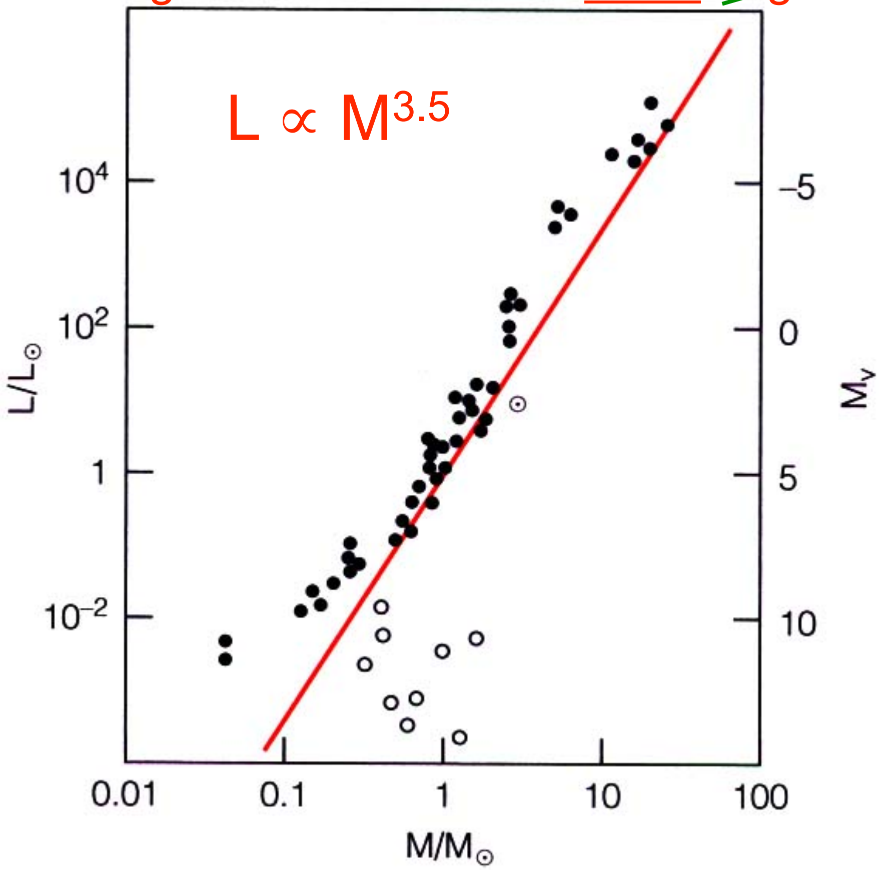



**Figure 8-21**
The mass–luminosity relation shows that the more massive a main-sequence star is, the more luminous it is. The open circles represent white dwarfs, which do not obey the relation. The red line represents the equation in By the Numbers 8-5.

# Stellar Radii

Only the Sun is close enough to show an easily measurable disk.  Most other stars appear as unresolved points of light.  The radius of the Sun is measured to be $R_\odot$ = 0.7 million km.

**Photometric radii**

The temperature T and absolute luminosity L of a star tell us its radius r:

1. The total amount of black-body radiation emitted per unit surface area is given by the Stefan-Boltzmann law, L/area = $\sigma T^4$.

2. So the total luminosity is $L = 4\pi r^2 \sigma T^4$, since $4\pi r^2$ is the surface area of a sphere of radius r.

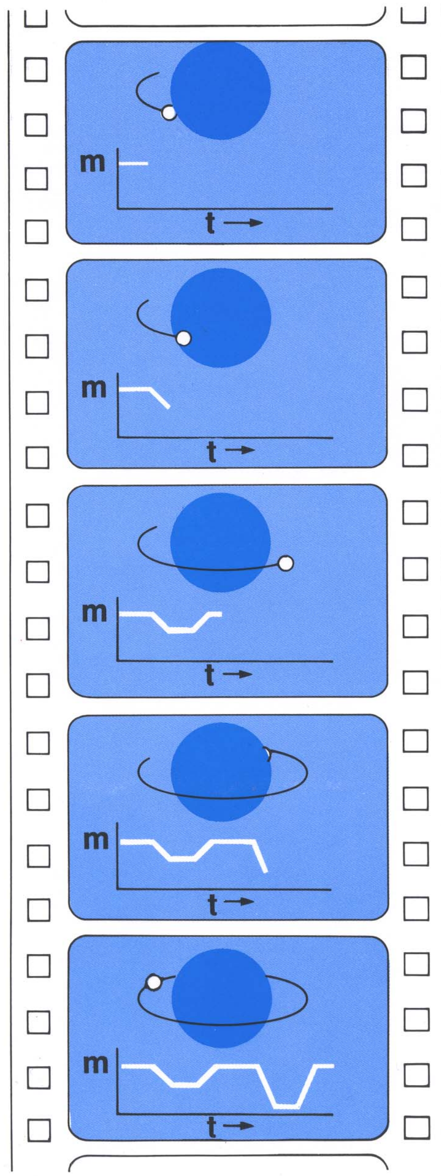
Note that luminosity is proportional to the square of the radius of the star and the fourth power of its temperature.  For example, suppose that two stars have the same absolute luminosity, but one is 2 times hotter than the other.  Then the cooler star must have $2^4 = 16$ times the surface area, and so it must have 4 times the radius of the hotter star.

Eclipsing binary stars give us another way to measure stellar radii:

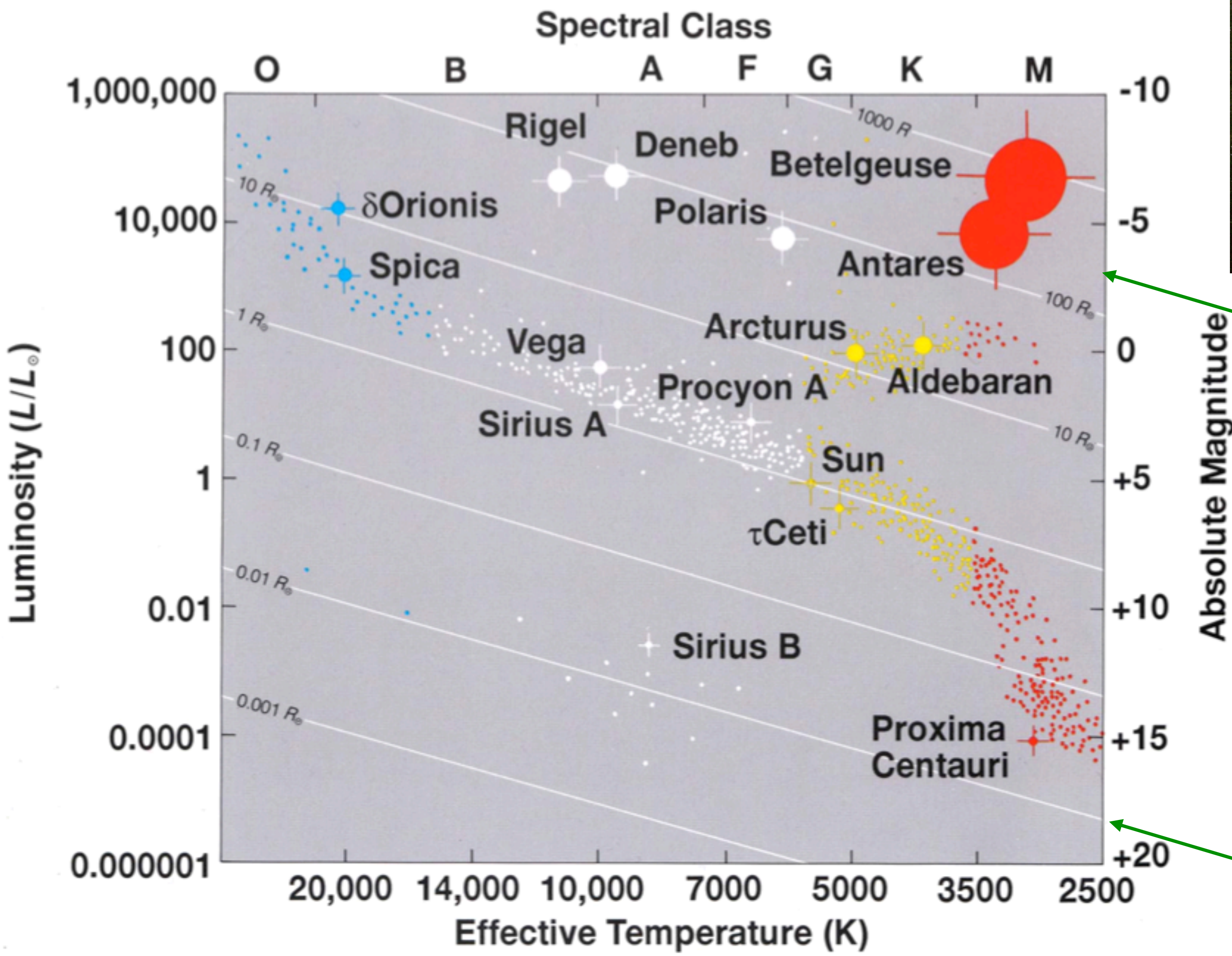
# Eclipsing binary stars are used to measure stellar radii.

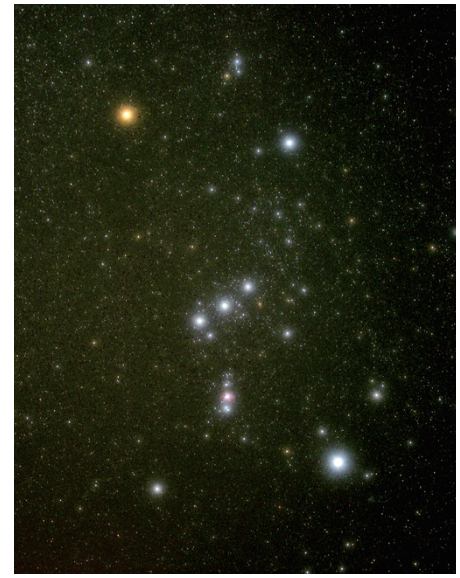
If we know
the orbit velocities and the period,
then
observing how long the eclipses take
tells us the radii of the stars.

There are lots of complications:
we don't know the inclination;
the stars may be distorted
by each others' gravity, etc.



# Stellar Radii in the HR Diagram



Radius of Earth's orbit around the Sun

Earth's radius

# Giants, Dwarfs, and Main Sequence Stars

Combining these measurements, we can describe the stars in different parts of the HR diagram:

### Giant and Supergiant Stars

Stars in the upper right of the HR diagram are very luminous but rather cool. They must have enormous radii in order to radiate so much energy. Some are as big as the orbit of Mars. But most of these stars are only a few times more massive than the Sun.

### White Dwarf Stars

Stars in the lower middle and left of the HR diagram are relatively hot but very dim. They must be tiny. These stars are about the size of the Earth, but they are comparable to the Sun in mass. Therefore they are incredibly dense.

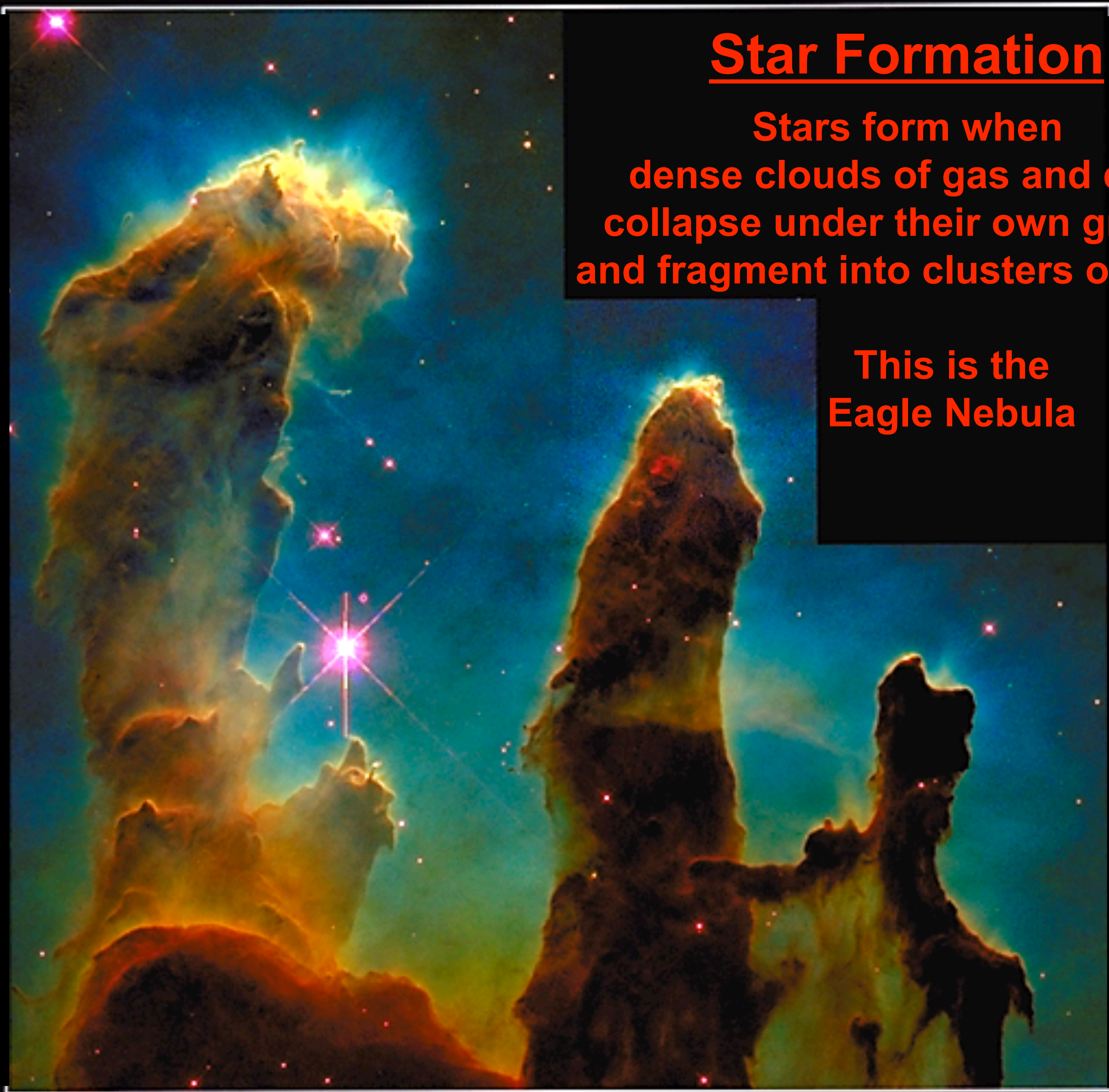
### Main Sequence Stars

Extending from upper left to lower right is a band of stars known as the **main sequence**. The Sun is a typical main sequence star. The masses, radii, temperatures, and absolute luminosities of main sequence stars increase smoothly from right to left in the HR diagram.

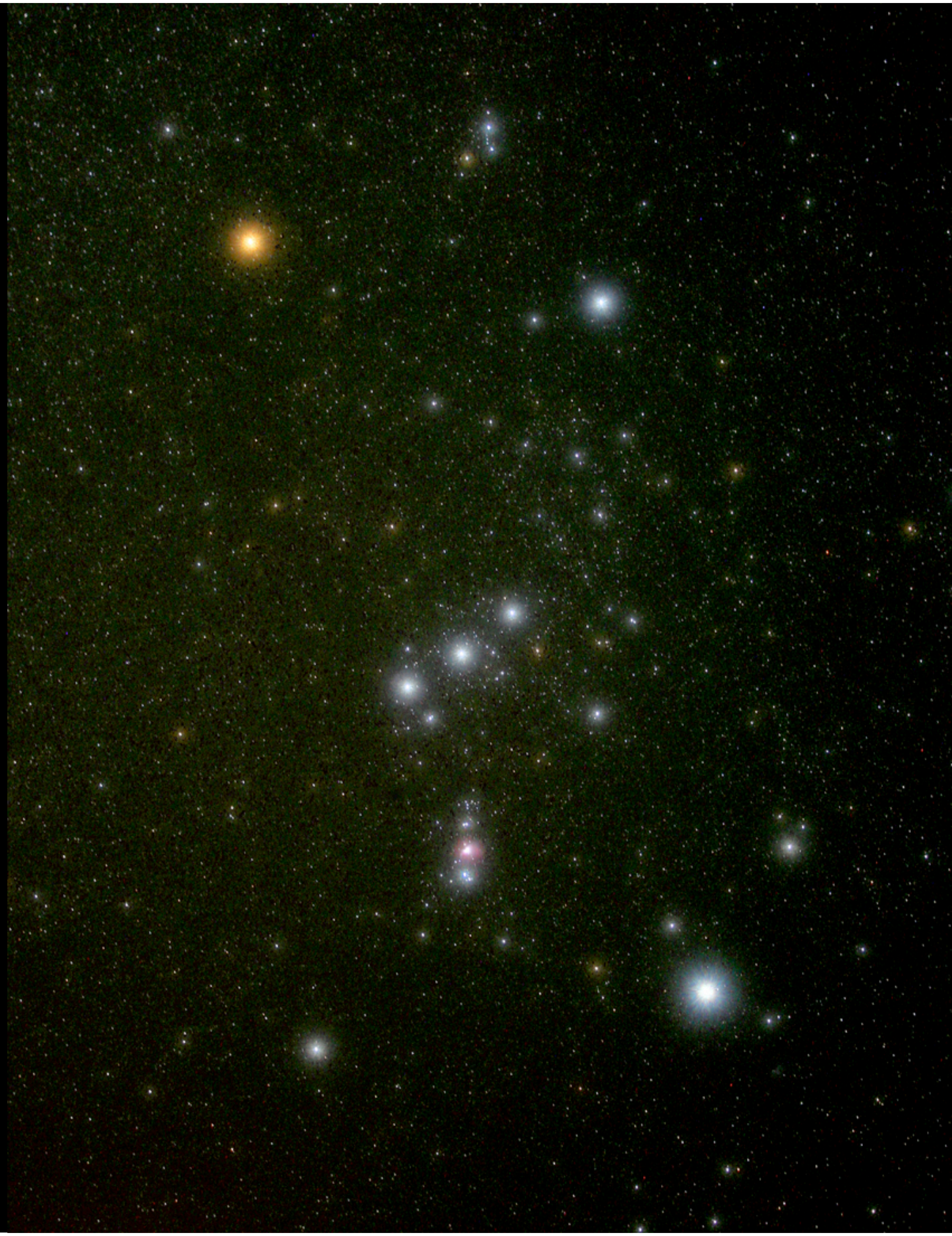
# Star Formation

Stars form when
dense clouds of gas and dust
collapse under their own gravity
and fragment into clusters of stars.

This is the
Eagle Nebula



Gaseous Pillars in M16 · Eagle Nebula



# Horsehead Nebula

Distance ≈ 1500 ly. The neck of the horsehead is ≈ 1 ly across.
The bright star is the easternmost star in the belt of Orion.

# Star Formation

Stars form in clouds of gas and dust:
gravity pulls the raw materials together and makes the clouds collapse.

## Interstellar Gas and Dust

The space between stars is not empty; it is filled with low-density gas and dust. By mass, ~ 3/4 is hydrogen, 1/4 is helium, and the rest is carbon, nitrogen, oxygen, and heavier elements. About 1 % of the mass is in carbon and silicate dust particles that are about the size of particles of smoke. Dust particles are about 150 m apart, on average.

### Emission Nebulae

Low-density gas that is ionized by nearby hot stars emits an emission-line spectrum and is called an emission nebula. The Eagle and Horsehead slides contain emission nebulae. Many are pink because they are dominated by hydrogen Balmer lines.

### Reflection Nebulae

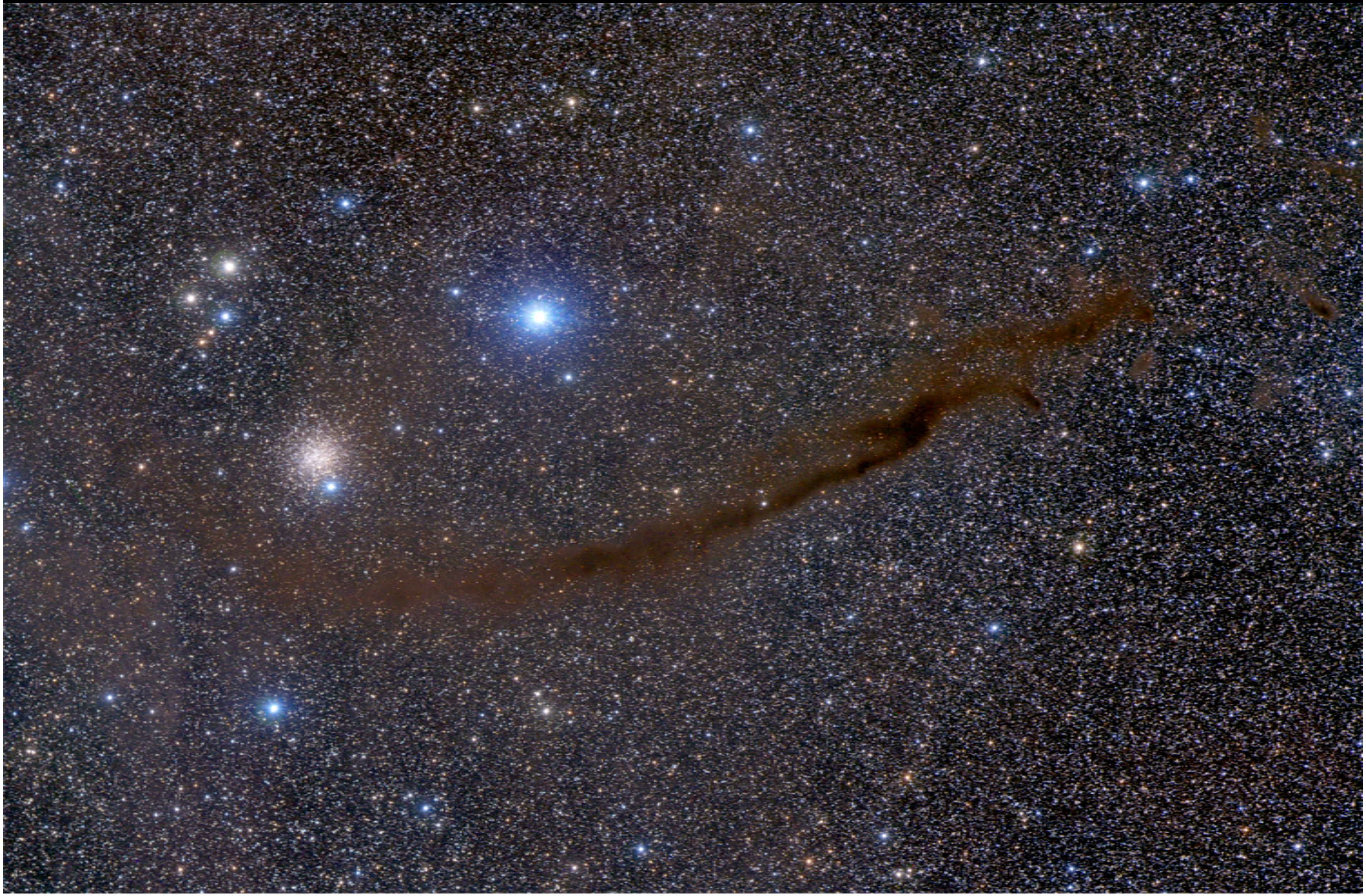
Reflection nebulae emit mostly light that is reflected from dust grains. They are blue, because blue light is scattered more than red light if the scattering particles are similar in size to the wavelength of visible light. Earth’s sky is blue for the same reason.

### Absorption Nebulae

These are dense clouds of gas & dust that absorb and redden light from stars that are behind them.

# Reflection Nebula and Rigel

# Absorption Nebula



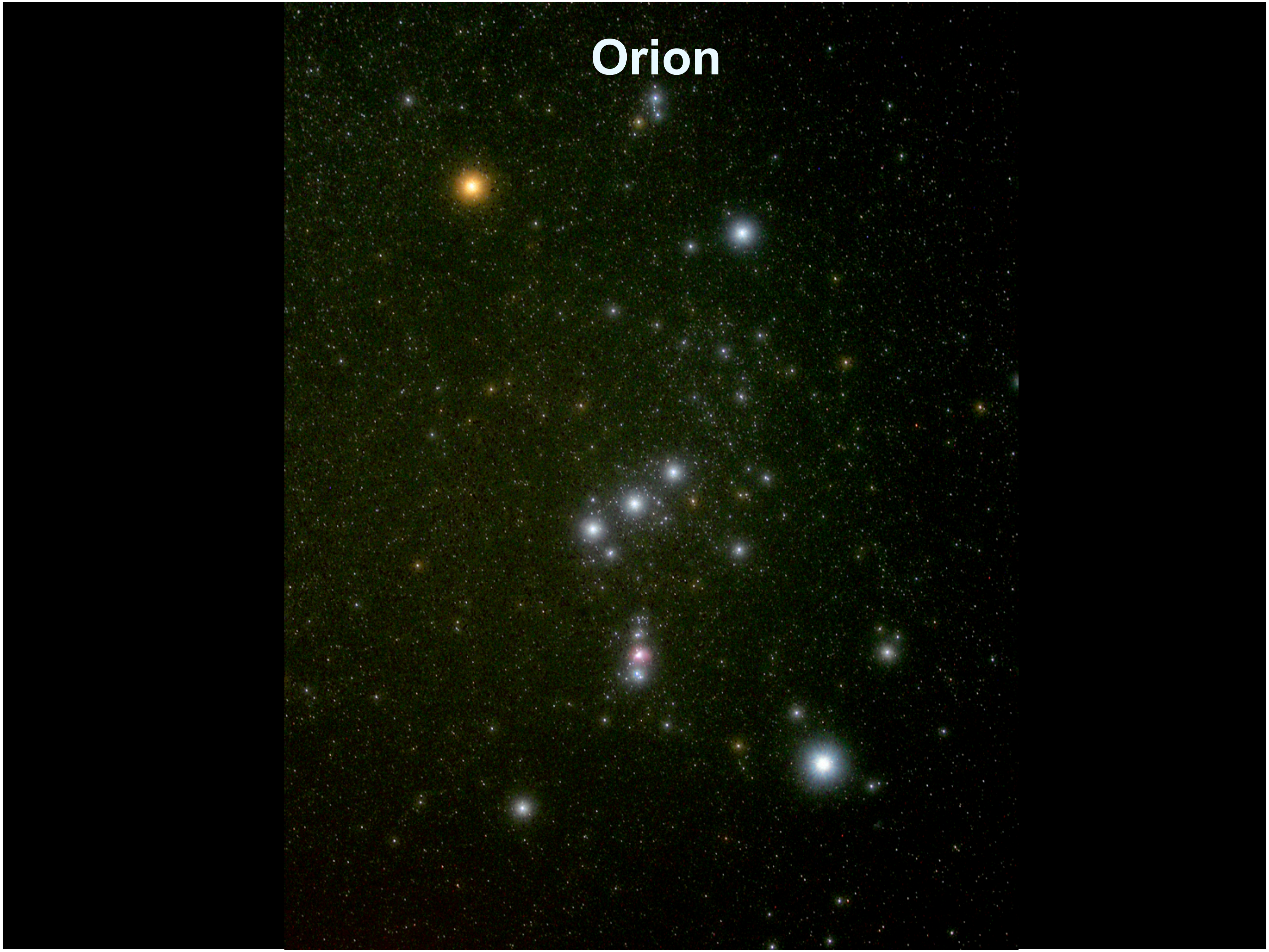
# Star Formation

## Molecular Clouds

In some places, we find enormous clouds of gas and dust. A typical cloud complex may be 50 pc in diameter and have a mass of several million $M_{\odot}$. The gas and dust are not smoothly distributed — the clouds are clumpy.

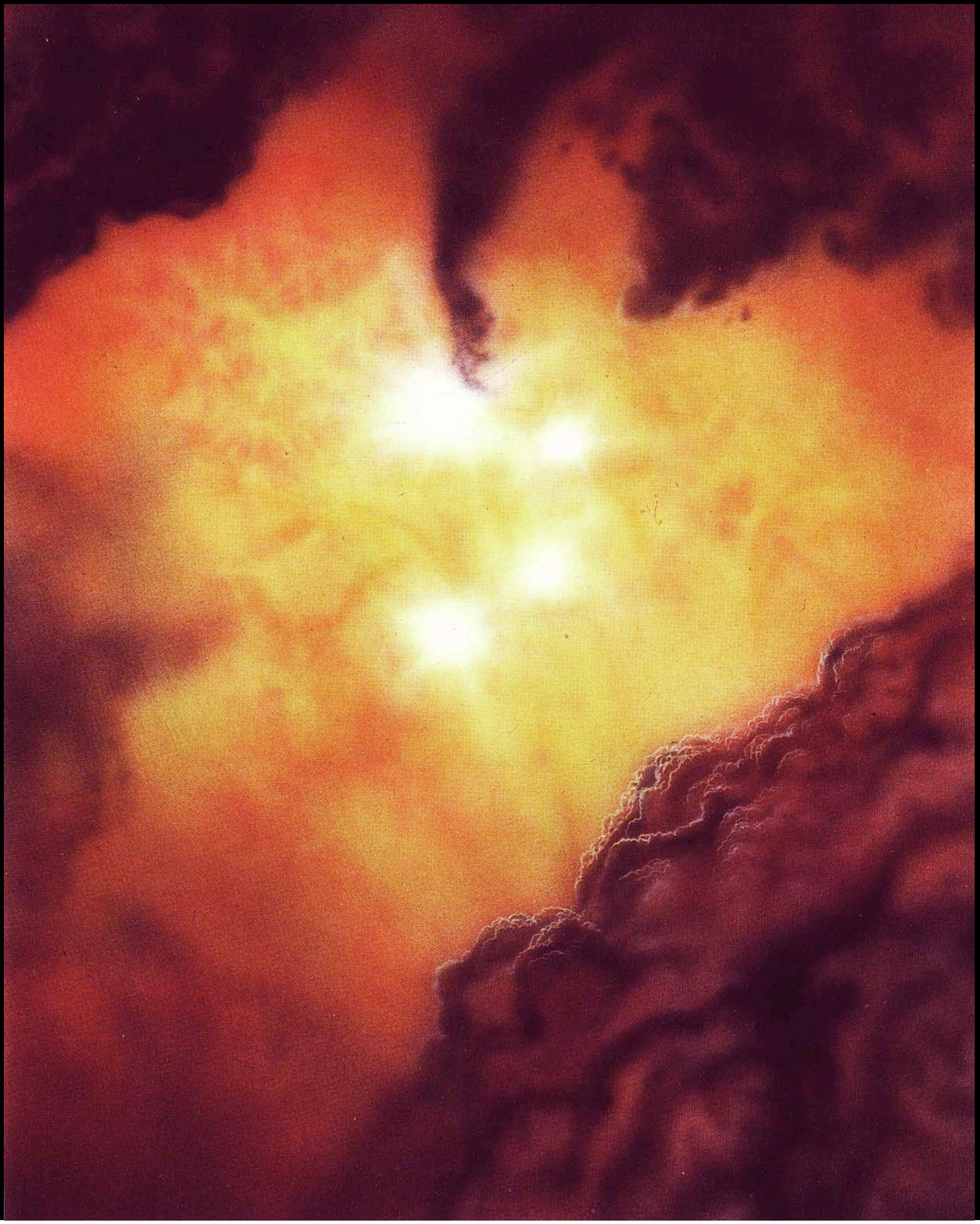
Stars form in the smallest and densest subclumps. When the density gets high enough, the clouds become unstable and collapse under their own gravity.

# Lagoon Nebula


Orion

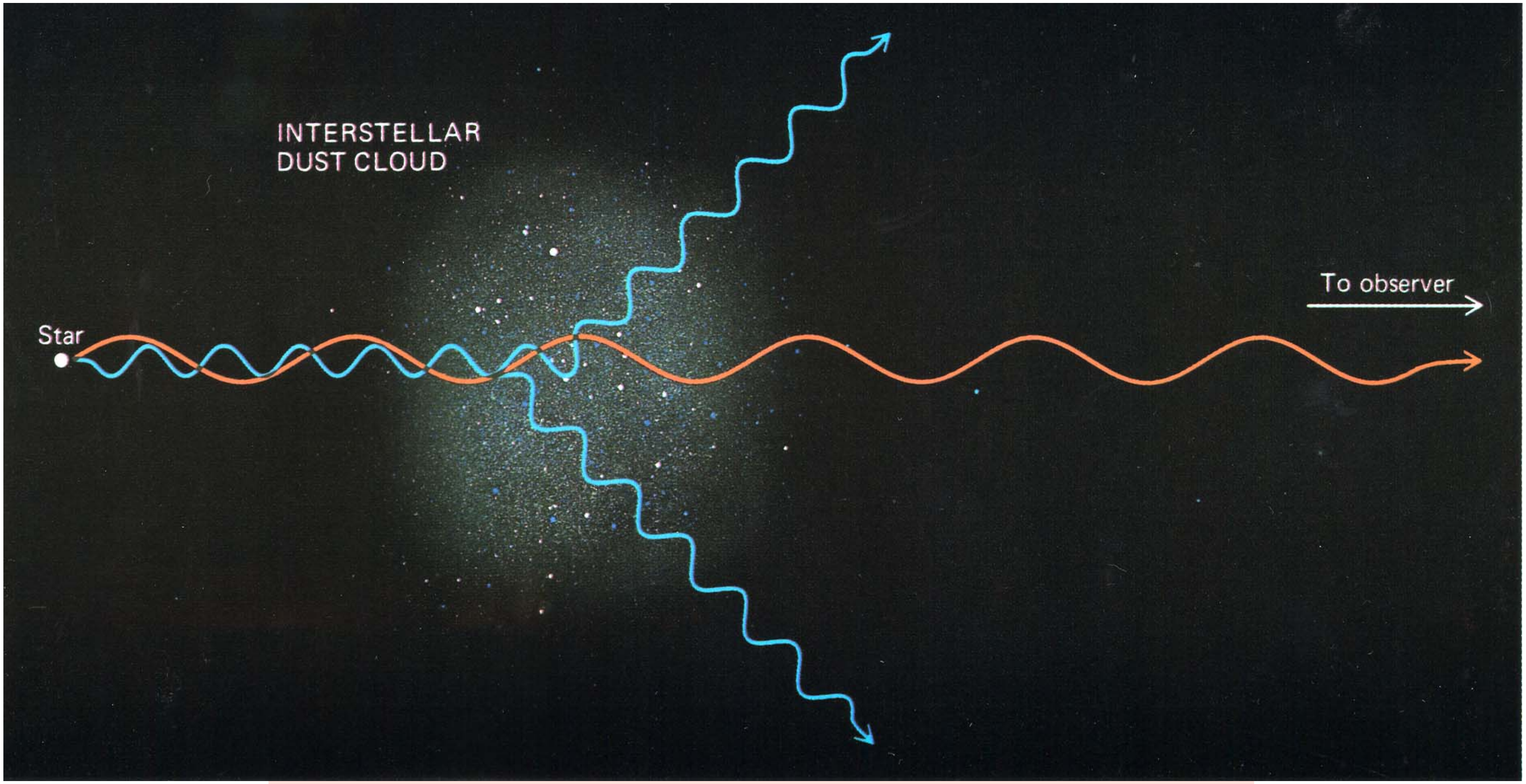

Orion Nebula

# Trapezium Star Forming Region



# Interstellar Dust Clouds

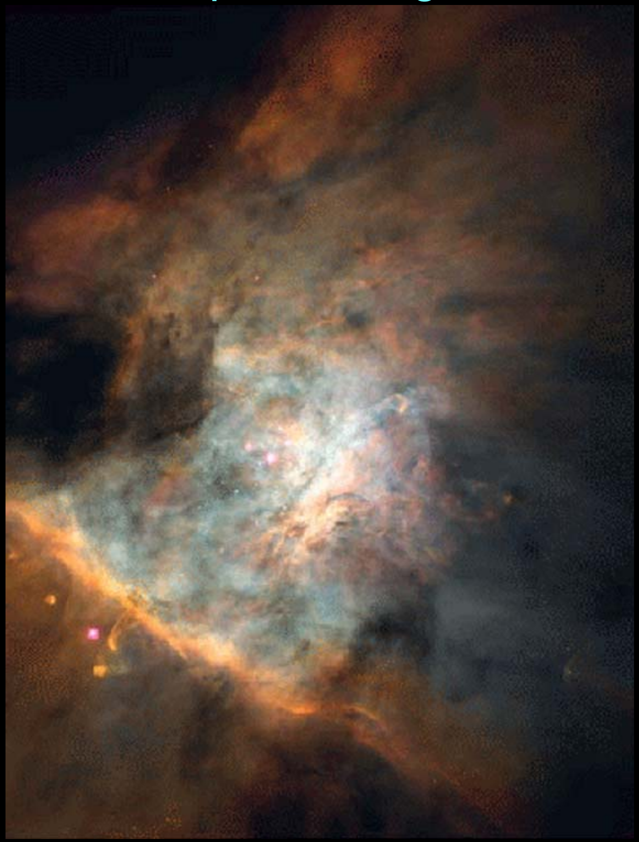
Interstellar dust {absorbs / scatters & / reddens} the starlight that passes through it.



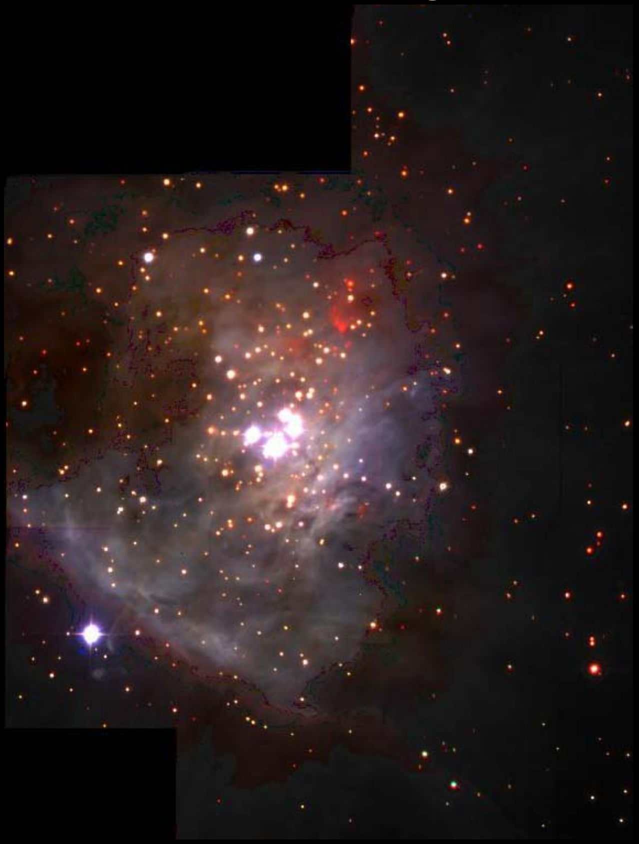

**Absorption is much less important in the <u>infrared</u>.**

# Center of the Orion Nebula

Optical Image



Infrared Image



Trapezium stars: four young OB stars (separation ~ 0.13 ly) ionize the Orion nebula and make it glow.

Dust absorption prevents us from seeing into the current star formation region in visible light.

In the infrared, we see through the dust to the cluster of young stars that is forming behind the trapezium stars.

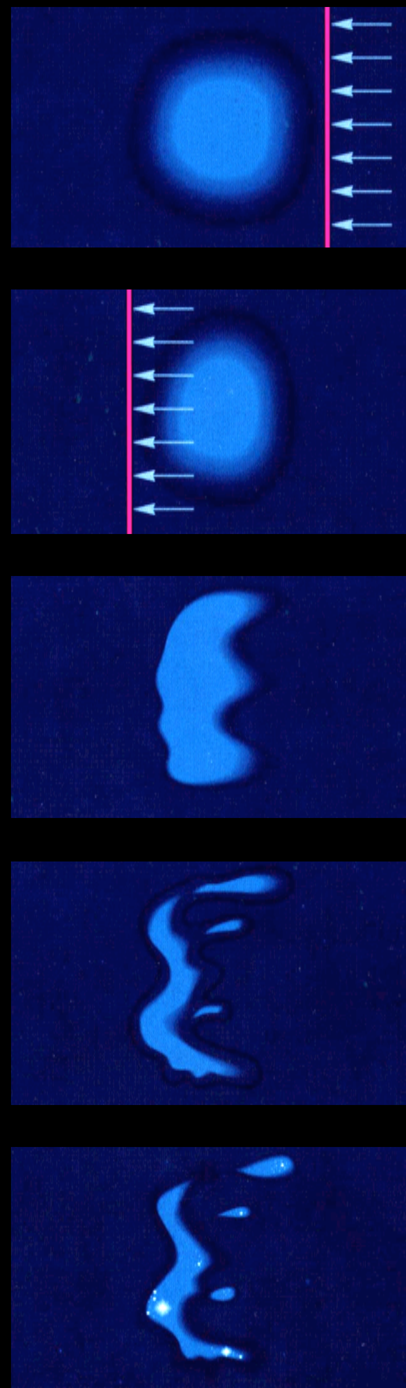
Giant molecular cloud ≈ 500,000 $M_\odot$.

# Star Formation

Shocking a molecular cloud helps persuade it to collapse.

Shocks can be provided by winds and radiation pressure from young stars, blasts from supernova explosions, or the gravitational compression caused by the spiral structure of our Galaxy.

We think.



Eventually, the hot young stars burn through the dust cloud and blow away the rest of the gas and dust.

A young “open cluster” is left behind.

The 5 frames at left might take about 6 million years.

# Protostar Formation

### Gravitational Collapse

Star formation starts when a cloud of diameter ~10,000 AU and a mass of several $M_\odot$ begins to collapse under its own weight. Cooling by infrared light emission keeps the temperature at about 10 K. At such low temperatures, gas pressure is too small to slow the collapse.

### Disk Formation

At the start of the collapse, the cloud rotates slowly, but as it gets smaller, Kepler's $2^{nd}$ law demands that its rate of rotation increase. By the time the cloud has collapsed to a diameter of ~ 100 AU, it has flattened out into a rotating disk. At this point, the cloud is spinning so fast that it can collapse no farther.

### Accretion and Outflow

Somehow, the spin of the inner part of the disk is slowed, allowing gas to collect at the center into a protostar. The protostar and its surrounding disk interact and fire jets of gas that flow outward along the rotation axis at speeds of about 100 km/s.

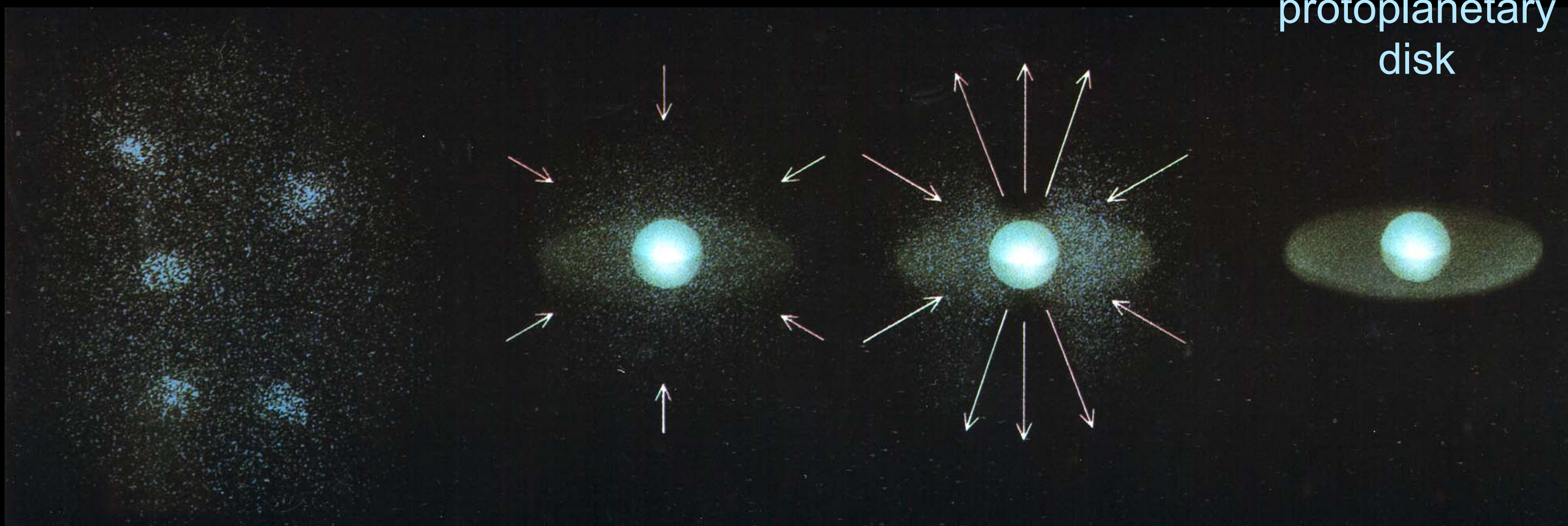
# A Star Is Born

A dense molecular cloud...

…collapses and forms a disk and protostar...

accretion, winds and jets,

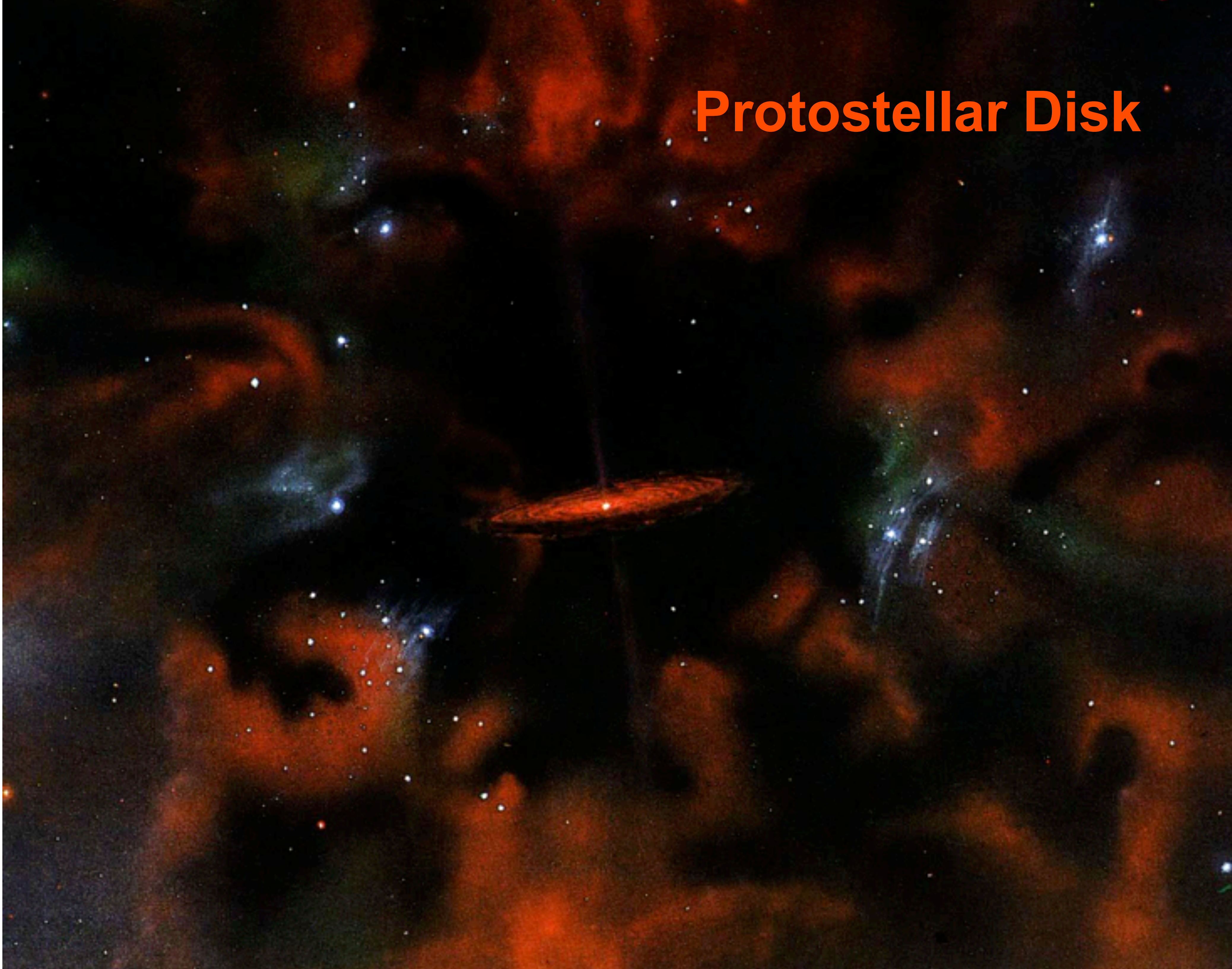
...and eventually a young star and protoplanetary disk



~ 10,000 AU

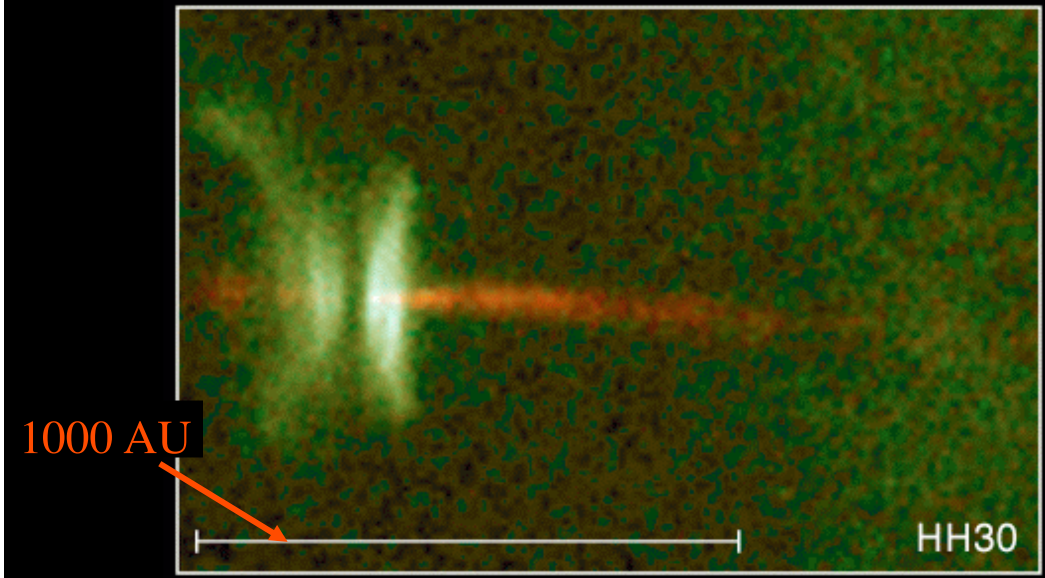
~ 100 AU

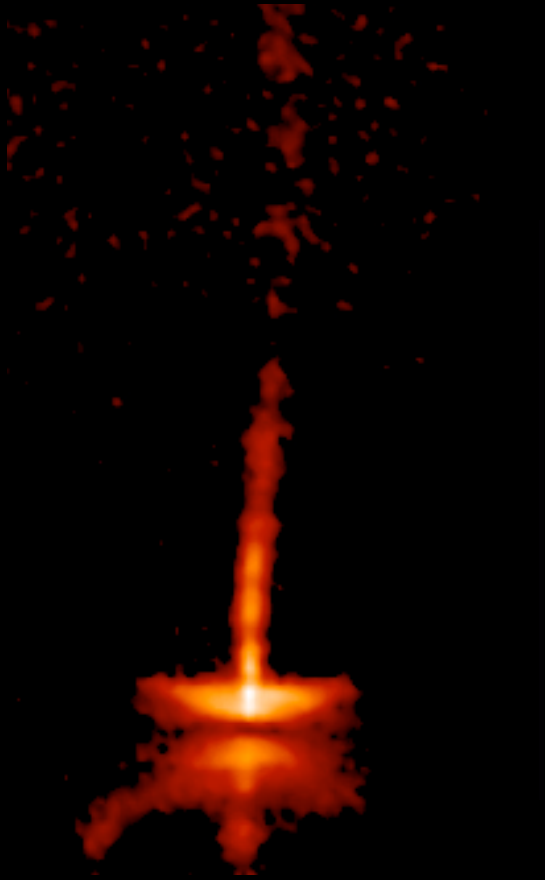
a few AU


Protostellar Disk

Herbig-Haro 24 Jets From Dust-Obscured Protostar

# Young Stellar Jets

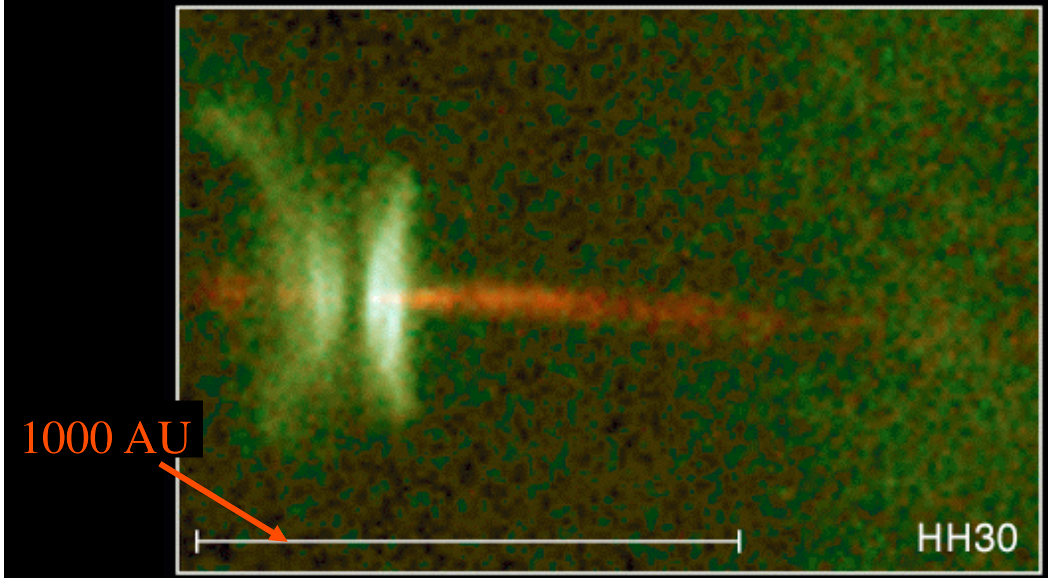


Hubble observations of HH 30 show two jets that stream away from the center of a dusty disk. The disk, which is over 40 billion miles (64 billion kilometers) in diameter, is seen almost edge-on. The dusty disk blocks our direct view of its central star. We see only the top and bottom sides of the dusty disk as they reflect light from the star, like the "silver lining" of a cloud. The jets reveal the hidden star's location. Astronomers are interested in the disk because it is probably similar to the one that formed our Sun and the planets in our Solar System.

HH 30's disk and jet clearly show changes in the six years covered by the time-lapse movie. The jets are easiest to explain: material is ejected along the magnetic poles of the star at speeds between 200,000 and 600,000 miles per hour (320,000 and 960,000 kilometers per hour). Every few months a compact clump of gas is ejected and may eventually merge with other clumps downstream.

# Young Stellar Jets

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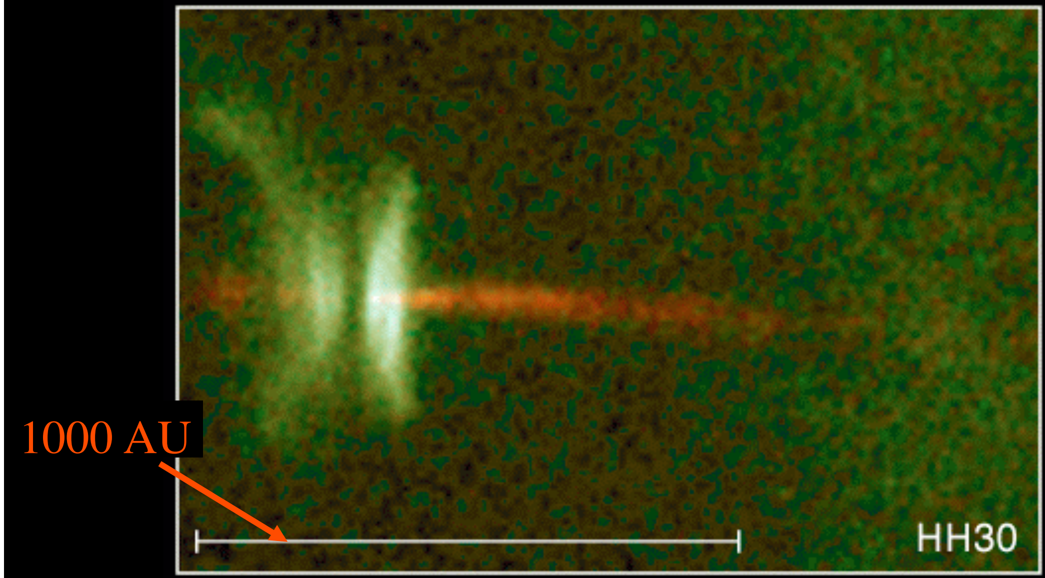
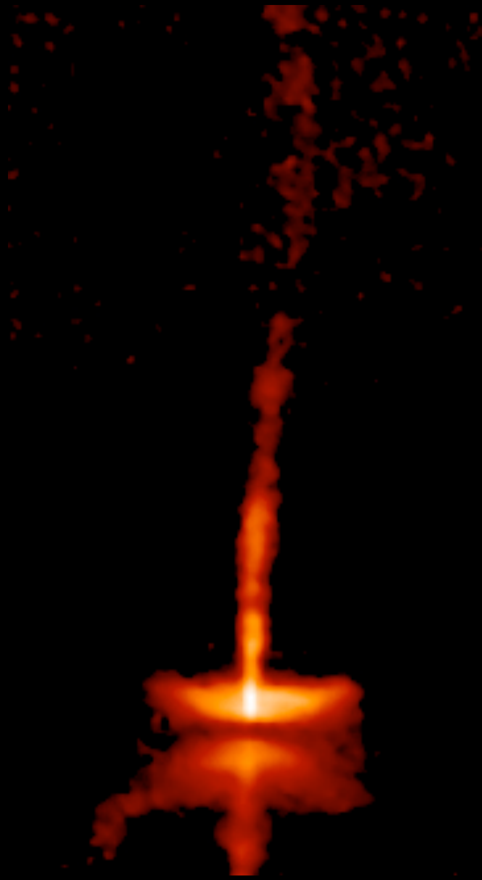


Hubble observations of HH 30 show two jets that stream away from the center of a dusty disk. The disk, which is over 40 billion miles (64 billion kilometers) in diameter, is seen almost edge-on. The dusty disk blocks our direct view of its central star. We see only the top and bottom sides of the dusty disk as they reflect light from the star, like the "silver lining" of a cloud. The jets reveal the hidden star's location. Astronomers are interested in the disk because it is probably similar to the one that formed our Sun and the planets in our Solar System.

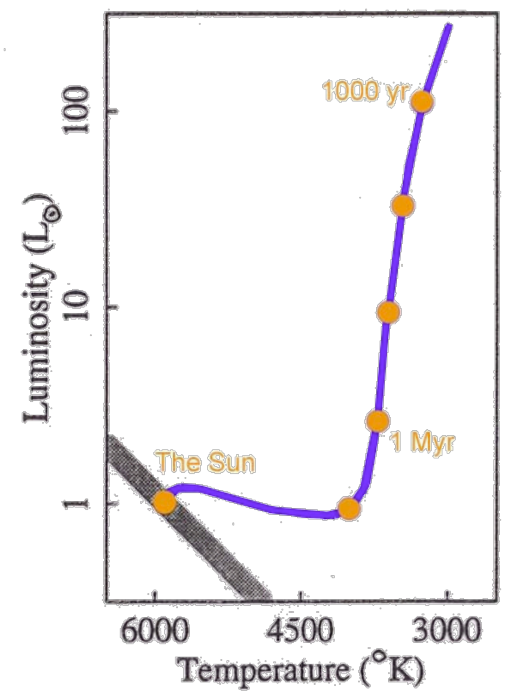
HH 30's disk and jet clearly show changes in the six years covered by the time-lapse movie. The jets are easiest to explain: material is ejected along the magnetic poles of the star at speeds between 200,000 and 600,000 miles per hour (320,000 and 960,000 kilometers per hour). Every few months a compact clump of gas is ejected and may eventually merge with other clumps downstream.

# Pre-Main-Sequence Evolution

Eventually, the collapsing gas cloud gets dense enough and opaque enough so that energy can no longer escape quickly from inside. Gravitational energy that is released by contraction now starts to heat the insides. The gas pressure rises and now determines the cloud structure.

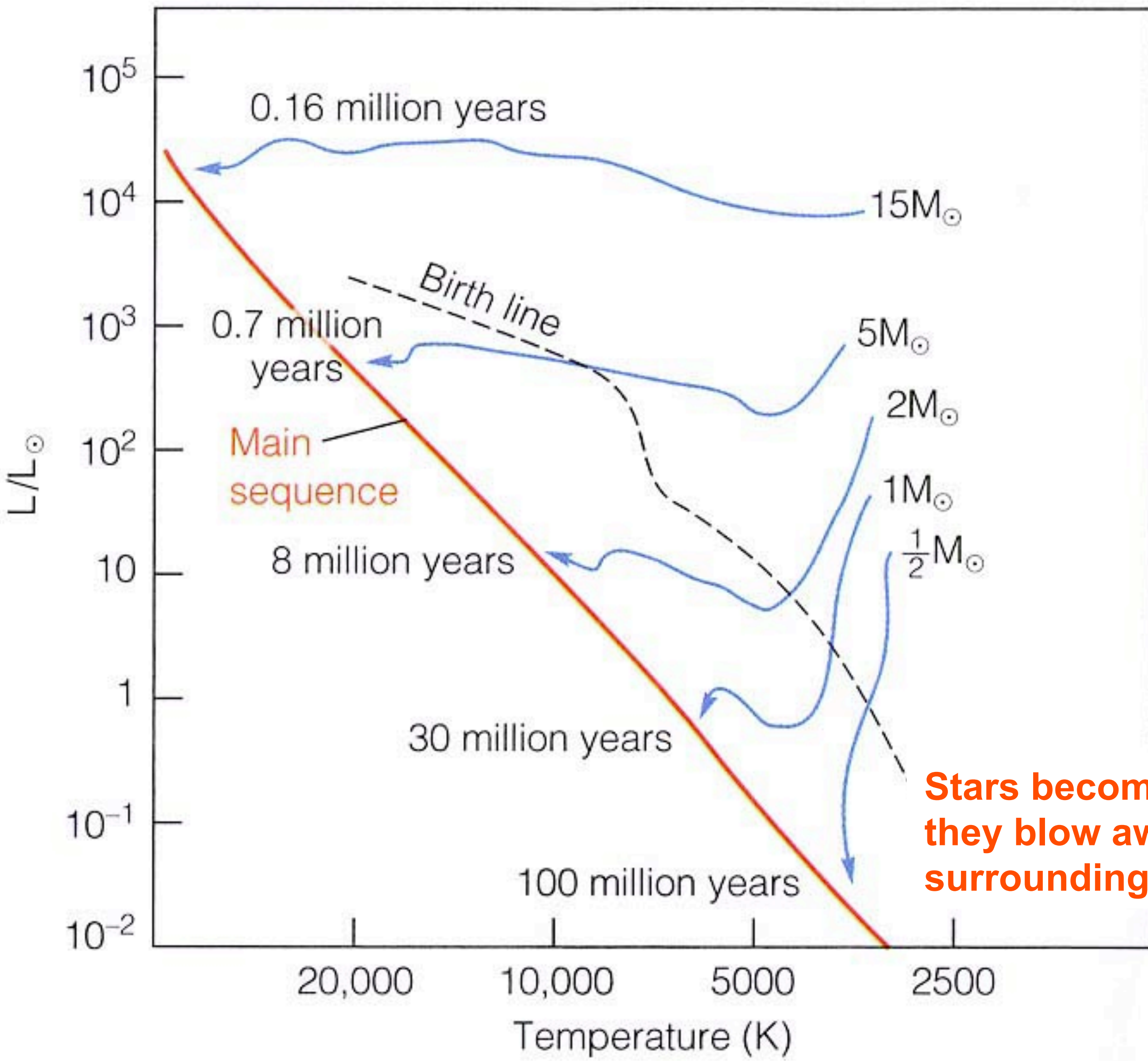
The collapsing cloud has become a protostar.

A protostar starts to emit visible light as it heats up. It is still very large compared to a main sequence star, so it is very luminous. It becomes fainter as it shrinks, because its surface area decreases rapidly whereas its surface temperature increases only slowly. Therefore it moves down and to the left in an HR diagram.

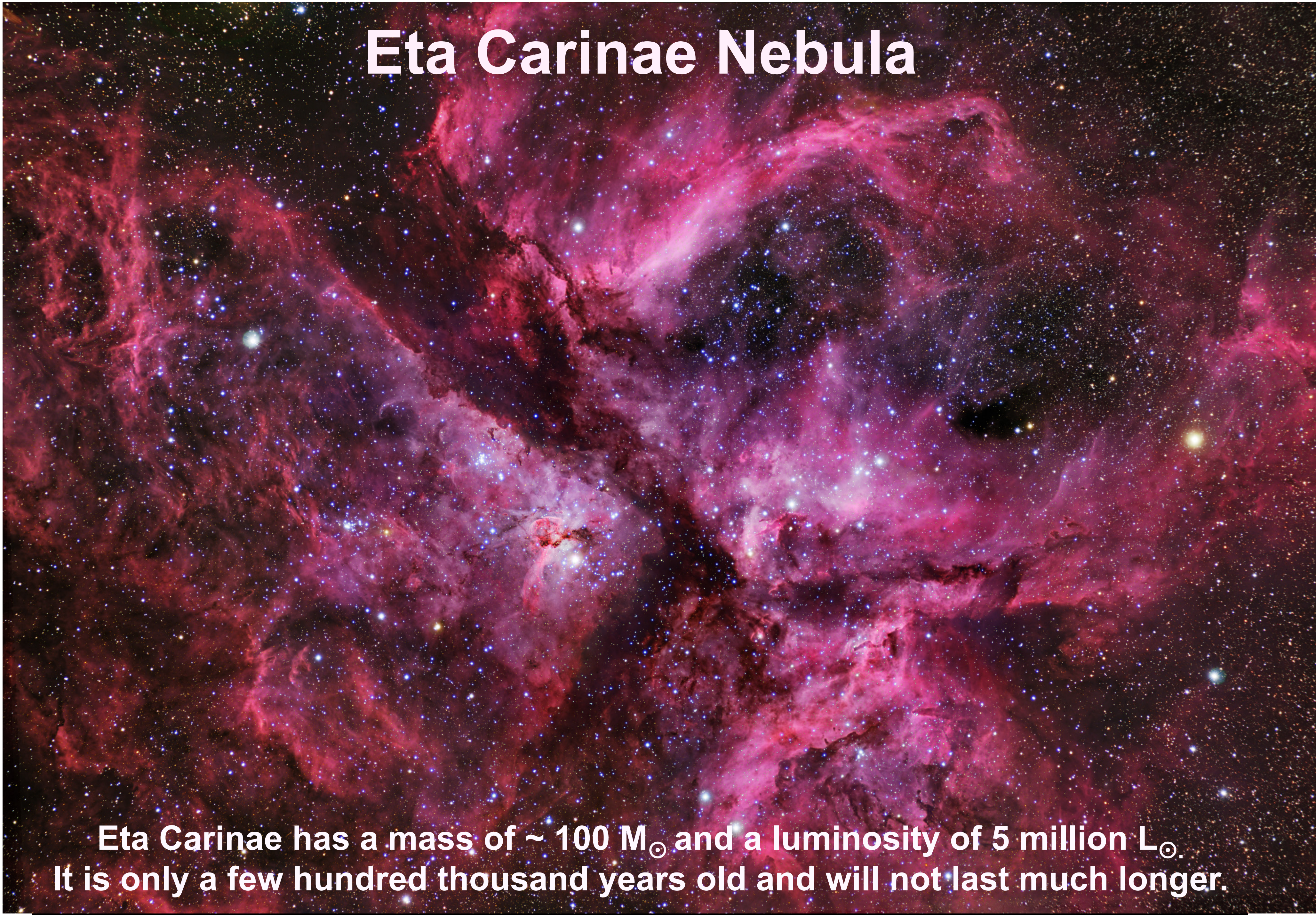



Finally, the temperature at the center of the star gets high enough to 'ignite' hydrogen. The energy released maintains the interior temperature of the star constant with no need for more contraction. The star is on the main sequence.

# Pre-main-sequence evolution is <u>faster</u> for <u>more massive stars</u>.




Stars become visible as they blow away surrounding gas and dust.


Eta Carinae Nebula
Eta Carinae has a mass of ~ 100 $M_{\odot}$ and a luminosity of 5 million $L_{\odot}$.
It is only a few hundred thousand years old and will not last much longer.

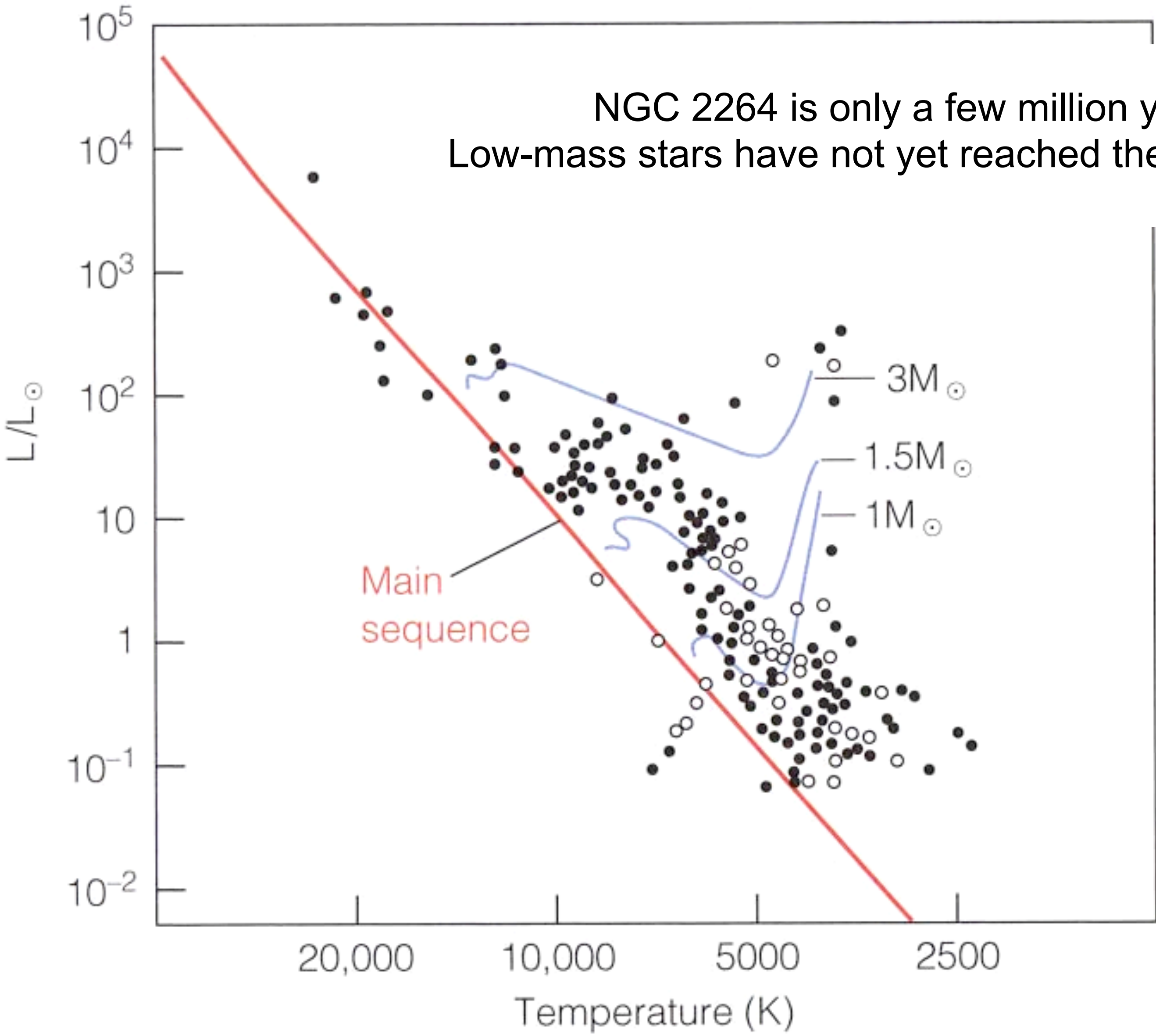
The ferocious light output of Eta Carinae is blowing away its outer parts via radiation pressure.

Eta Carinae has a mass of ~ 100 $M_\odot$ and a luminosity of 5 million $L_\odot$.
It is only a few hundred thousand years old and will not last much longer.

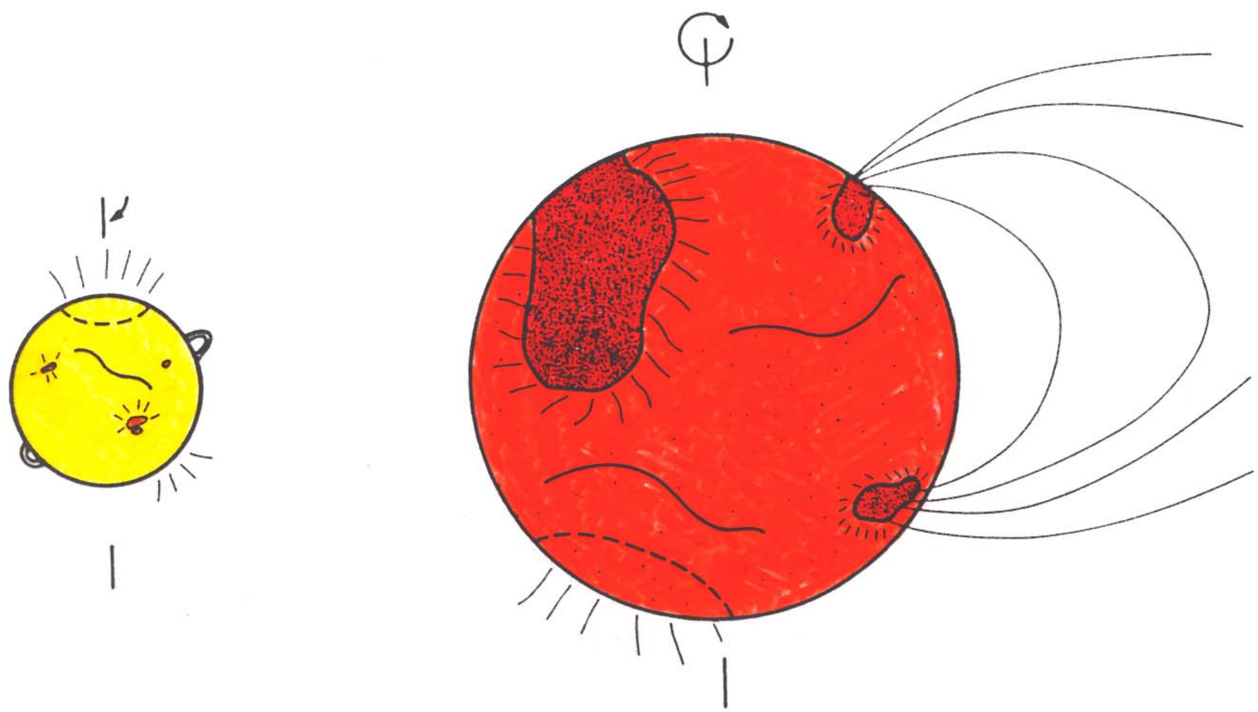
# Eta Carinae is blowing away the rest of its nebula.

# Star Cluster NGC 2264

NGC 2264 is only a few million years old.
Low-mass stars have not yet reached the main sequence.



# Our Sun now and as a pre-main-sequence star.



Our Sun today (left) and as a million-year-old, pre-main-sequence star (right). Back then, the Sun was bigger, cooler, more luminous, more rapidly rotating, and more active than it is now.

# Double Star Cluster in Perseus