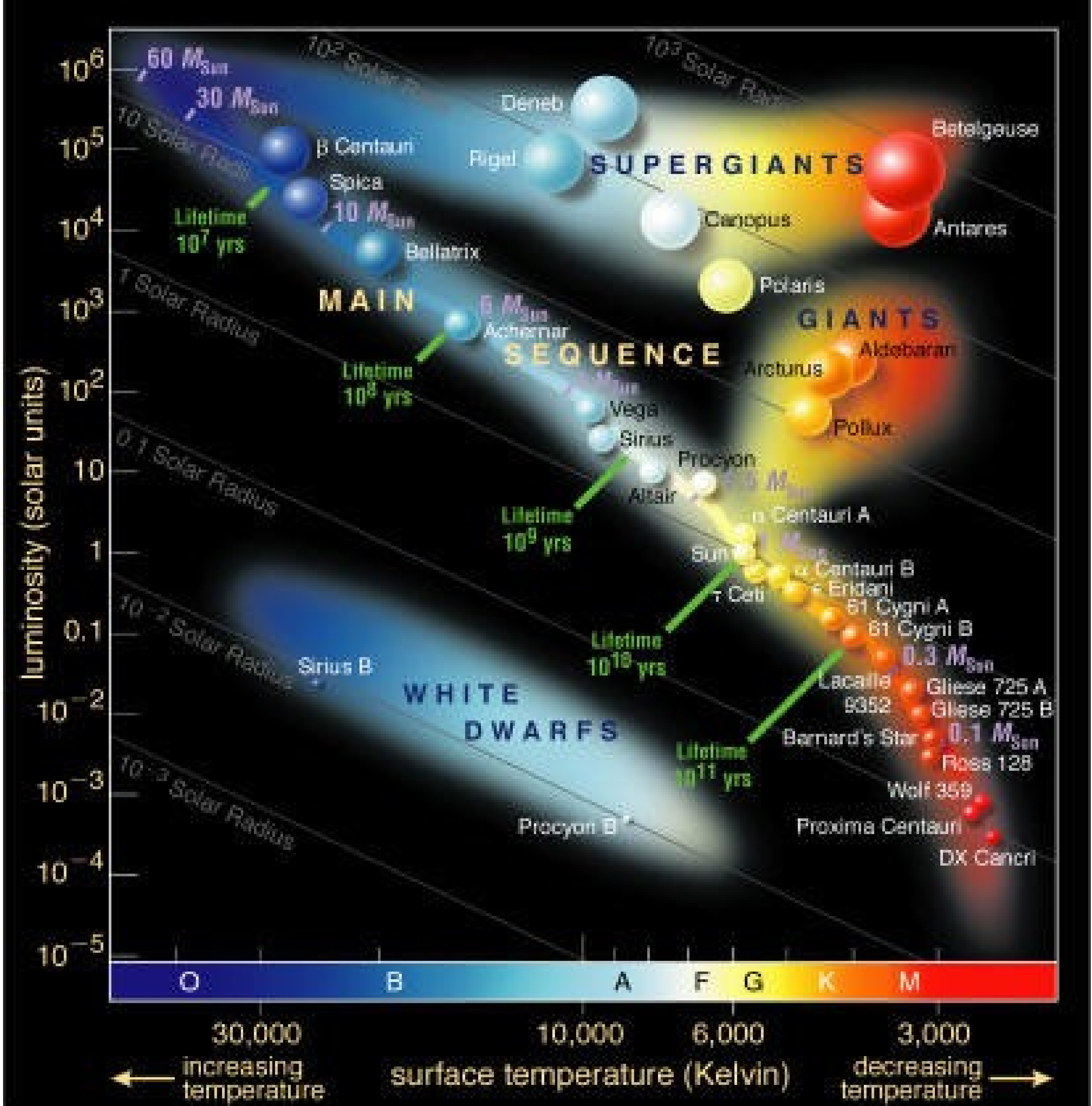
Announcements

- **Quiz 6** due tonight, covers Stars, Chapter 10
  - Problem sets 6A, 6B for practice
- **Quiz 7** on Chapters 10 and 11 due next Monday
- **Today:** finish Chapter 10, start Chapter 11
- **Wednesday and Friday:** Chapters 11 and 12

Astronomy 103

The Stars, continued
Please read chapter 10

The H-R Diagram



H-R Diagram

From the masses of stars, one can understand the main sequence.

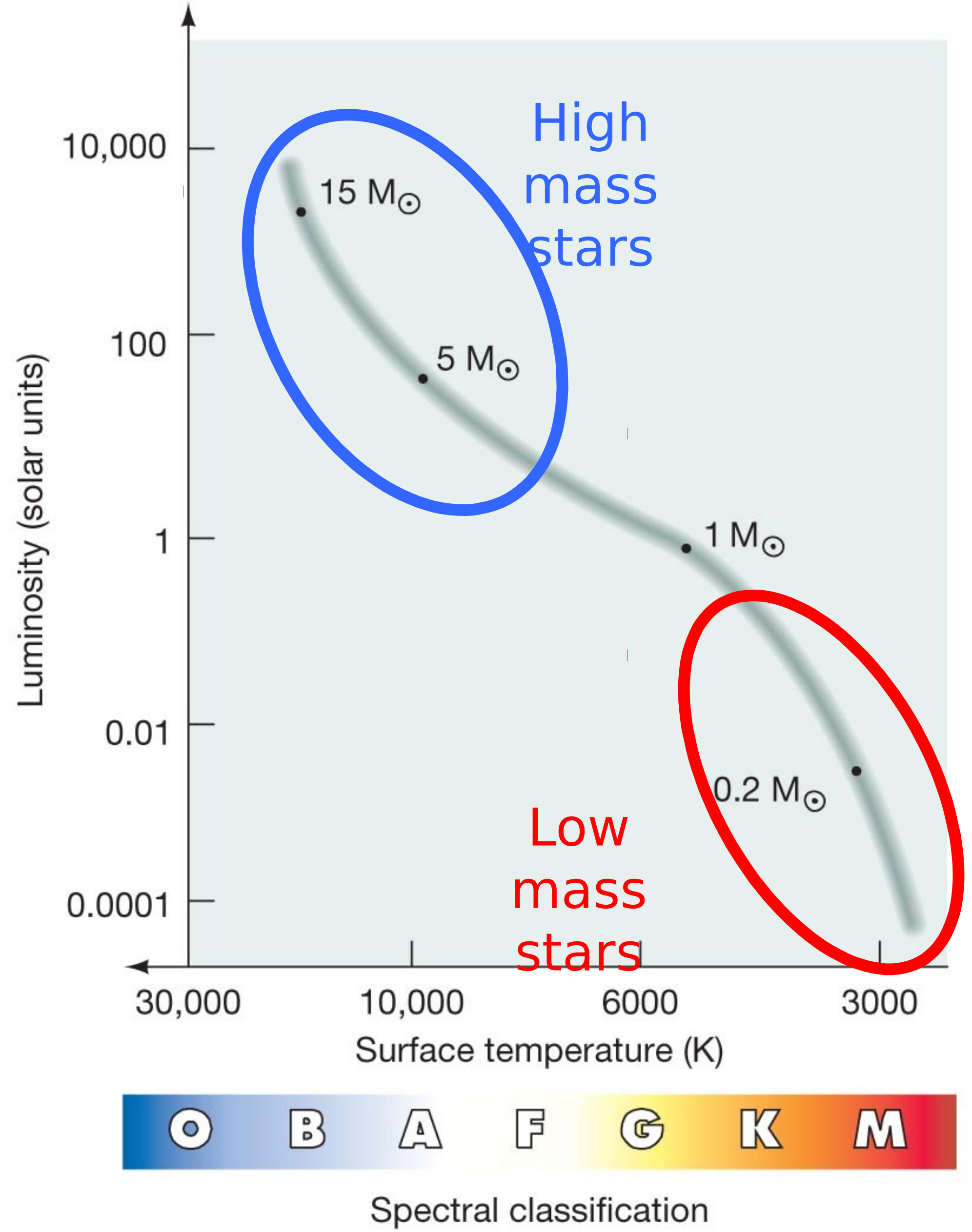
What determines where on the main sequence a star will be when it forms?

Stars on the main sequence are only distinguished by their mass

Position of low- and mass stars in the H-R diagram

Stars with small masses are the stars that are low on the main sequence. They burn much more slowly, so they are much dimmer and their surfaces are cooler.

Stars with larger masses burn much more quickly and have hotter surfaces (and hotter interiors).



Stars on the Main Sequence

Stars don't move along the main sequence – that would require them to change their mass.

Instead they just sit on the main sequence until their time there is up.

The main sequence is a waystation, where stars spend MOST of their lives.

Summary

- The **difference between stars** on the main sequence **is due to the difference in their masses.**
- **Low mass stars** are low on the main sequence, and **are dim and cool** --- a star of 1/10 of a solar mass is only 1/1000 as bright as the Sun.
- Similarly, **high mass stars** are high on the main sequence, and **are hot and bright** --- a star of 10 solar masses is 10,000 times brighter than the Sun

How long does a star live?

A star spends nearly all of its life burning hydrogen to helium in its core. The time it can do that is limited by it supply of hydrogen.

We will figure out how long it takes the star to fuse the hydrogen in its core to helium.

Review: The Energy of Starlight

The mass of a helium atom is slightly less than the mass of 4 hydrogen atoms (by 0.7%=0.007):

$$4m_H - m_{He} = 0.007 m_H$$

Eddington's guess (1920):

Hydrogen can turn into helium, and when it does, 0.7% of its mass changes to energy – and that energy powers the Sun

The lifetime of a star

There are 3 steps in this problem

1) Use the amount of energy the star emits per second to find the mass the star changes into energy each second: $m=E/c^2$

We have already done this for the Sun.

The lifetime of a star

Now we know how much mass the star changes into energy each second. Next:

2) Find the amount of hydrogen consumed per second this represents. Only 0.7% of the total mass of hydrogen burned is actually changed into energy, so the amount of hydrogen used is 1/0.007 = 143 times the mass found in step 1.

The lifetime of a star

Now we can calculate the lifetime of the star.

3) $$\text{Lifetime} = \frac{\text{amount of fuel}}{\text{amount of fuel consumed per sec}}$$

The amount of fuel a star has is equal to the mass of its core, so:

$$\text{Lifetime} = \frac{\text{mass of core}}{\text{amount of fuel consumed per sec}}$$

A similar terrestrial problem

- How long can you stay underwater?
- Until you use up all your air!
- How many hours will this be?

→ **Total amount of air divided by amount of air used per hour**

Lifetime of the Sun – Step 1

How much mass does a star change into energy each second? (you've already done this part)

$$\text{mass changed to energy per second} = \frac{\text{energy produced per second}}{c^2}$$

$$= \frac{\text{luminosity}}{c^2}$$

Example: For the Sun, luminosity = 4×10^{26} watt :

$$\text{mass changed to energy per second} = \frac{4\times10^{26}\,\text{watt}}{(3\times10^{8}\,\text{m/s})^2}$$

$$= 4.4\times10^{9}\ \text{kg per second}$$

Lifetime of the Sun – Step 2

How much hydrogen does the star burn per second?

$$\text{Hydrogen burned per sec} = \frac{\text{Mass changed into energy per sec}}{0.007}$$
$$= \text{Mass changed into energy per sec} \times 143$$

For the sun, which converts 4.4×10^9 kg into energy per second

$$\text{Hydrogen burned per sec} = \frac{\text{Mass changed into energy per sec}}{0.007}$$
$$= \text{Mass changed into energy per sec} \times 143$$
$$= 4.4 \times 10^9 \text{ kg} \times 143$$
$$= 6.3 \times 10^{11} \text{ kg}$$

Lifetime of the Sun – Step 3

$$\text{Lifetime} = \frac{\text{mass of core}}{\text{amount of fuel consumed per sec}}$$

Example:
For the Sun:

$$\begin{aligned} \text{mass of core} &= 10\,\%\ \text{mass of sun} \\ &= 0.1 \times 2 \times 10^{30}\ \text{kg} \\ &= 2 \times 10^{29}\ \text{kg} \end{aligned}$$

Lifetime of the Sun – Step 3

$$\text{Lifetime} = \frac{\text{mass of core}}{\text{amount of fuel consumed per sec}}$$

Example:
For the Sun:

$$\begin{aligned} \text{mass of core} &= 10\,\%\ \text{mass of sun} \\ &= 0.1 \times 2 \times 10^{30}\,\text{kg} \\ &= 2 \times 10^{29}\,\text{kg} \end{aligned}$$

$$\begin{aligned} \text{Lifetime} &= \frac{2 \times 10^{29}}{6.3 \times 10^{11}} \\ &= 3.17 \times 10^{17}\,\text{sec} \\ &= 10\ \text{billion years} \end{aligned}$$

Lifetime of other stars

Once we know the lifetime of the Sun, the lifetime of other stars can be found much more quickly:

$$\text{Lifetime} = \frac{\text{mass of core}}{\text{amount of fuel consumed per sec}}$$

The total mass changed to energy is proportional to the mass of the star. If a star has 5 times the mass of the Sun it will change 5 times as much mass to energy in its lifetime.

The mass changed to energy each second (the amount of fuel consumed) is proportional to the luminosity of the star. If a star has 1000 times the luminosity of the Sun, it will change 1000 times as much mass to energy each second.

Lifetime of other stars

A star with 5 times the mass and 1000 times the luminosity of the Sun then has a lifetime 5/1000 = 0.005 times as long

$$\text{lifetime of a star} =$$

$$= \quad 10^{10}\,\text{years} \times \frac{\text{mass of star in solar masses}}{\text{luminosity of star in solar luminosities}}$$

$$= \quad 10^{10}\,\text{years} \times \frac{5}{1000} = 5 \times 10^{7}\,\text{years}$$

Lifetimes of other stars

The math we just did can be summarized as the following formula:

$$\text{lifetime of star} = 10^{10}\,\text{years} \times \frac{M}{L}$$

Here's the same example:
A main sequence star has mass $5M_\odot$ and luminosity $1000\ L_\odot$ What is the star's lifetime? The calculation is again

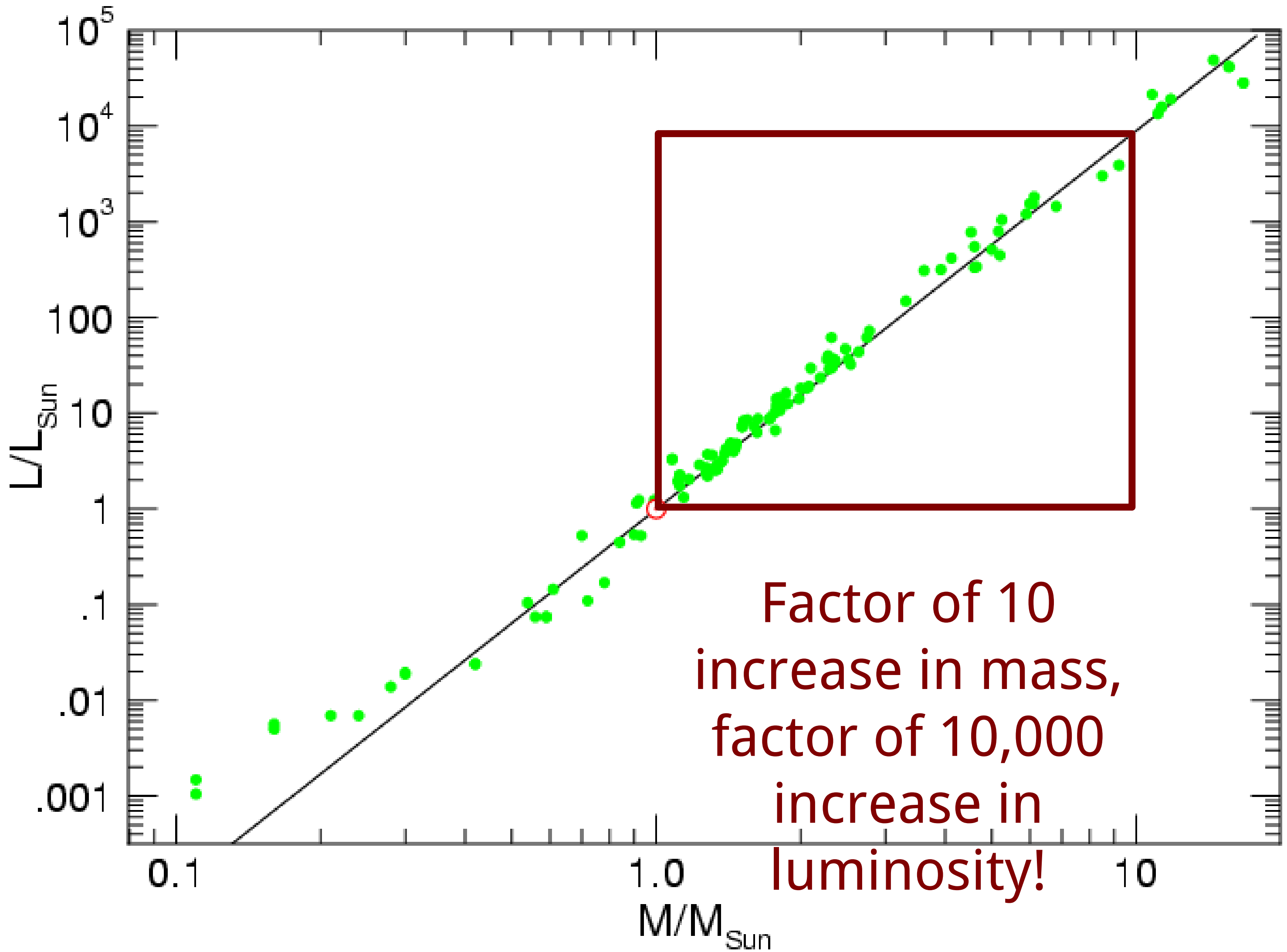
$$\text{lifetime of star} = 10^{10}\,\text{years} \times \frac{5}{1000} = 5 \times 10^{7}\,\text{years}$$

Lifetimes of Stars

To understand what this means for the lifetimes of stars, we need to understand how mass M and luminosity L are related for stars of different masses

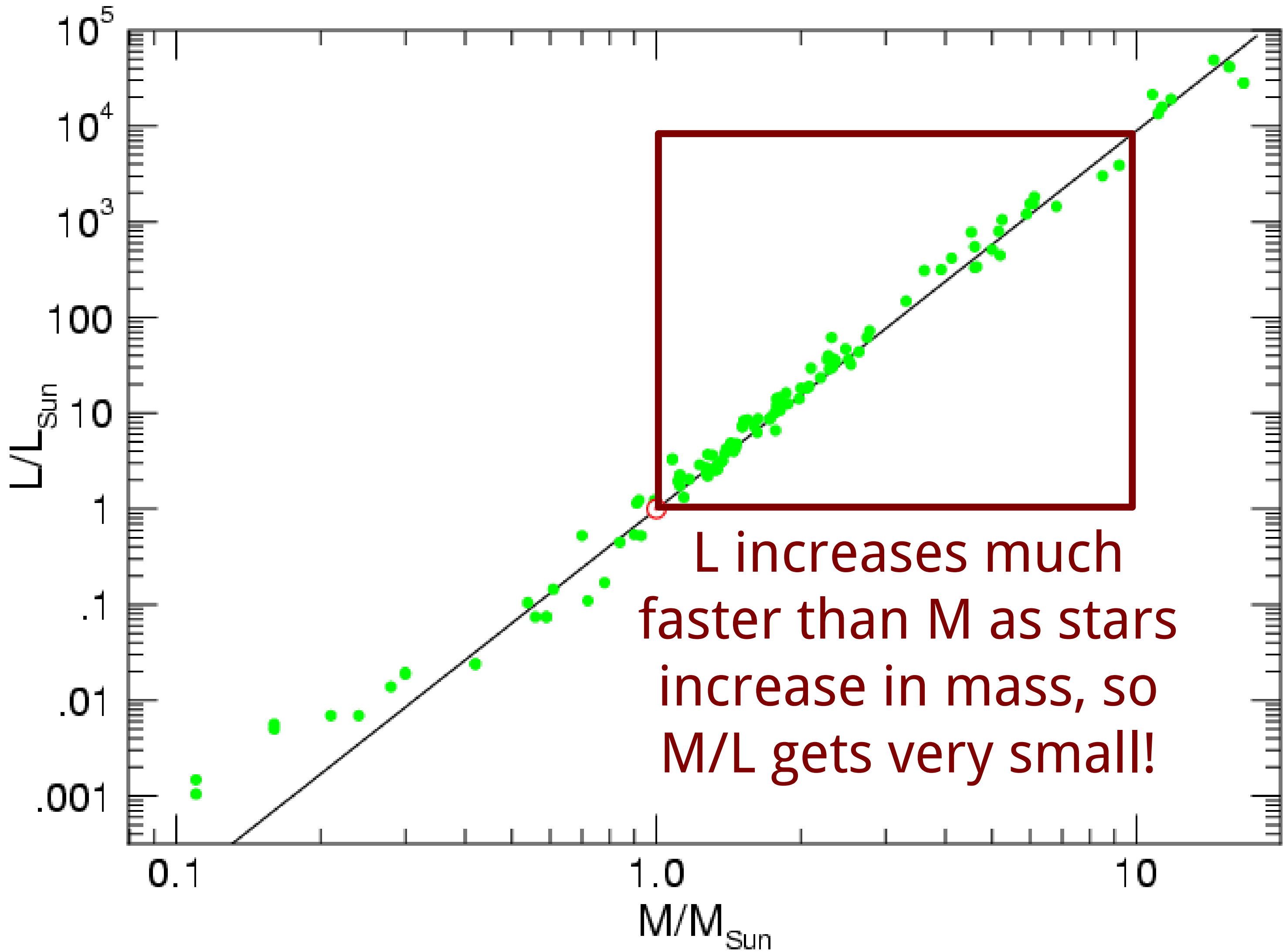
$$\text{lifetime of star} = 10^{10}\ \text{years} \times \frac{M}{L}$$

What is the luminosity of stars of different masses?



Factor of 10 increase in mass, factor of 10,000 increase in luminosity!

What is the luminosity of stars of different masses?



Massive stars burn bright, die young

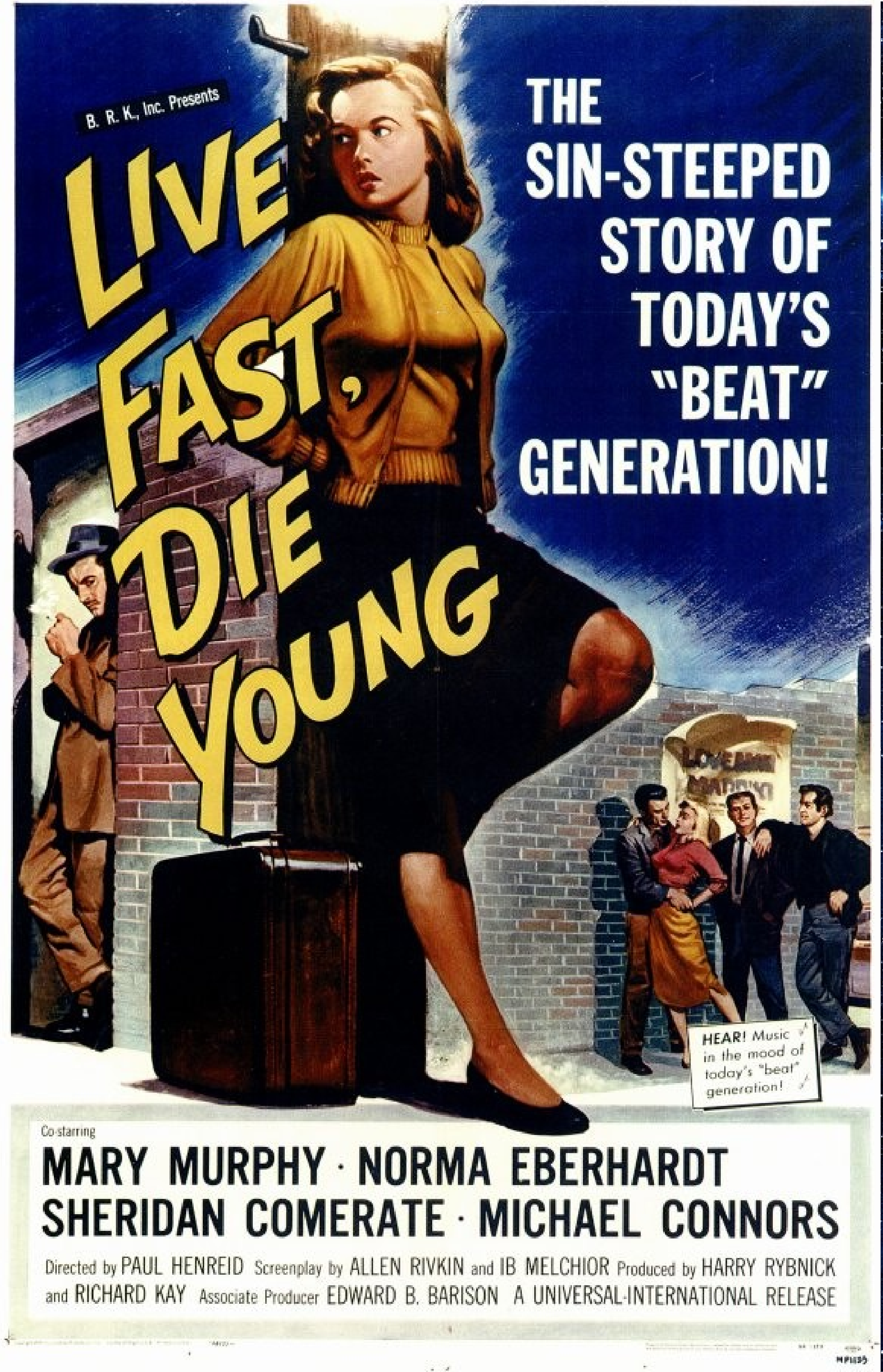
$$\text{lifetime of star} = 10^{10}\,\text{years} \times \frac{M}{L}$$

M/L gets very small for more massive stars!

This tells us that **massive stars have very short lifetimes**

They burn very brightly and use up their fuel very quickly

You will find problems about the lifetimes of stars in Quiz 7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LIVE FAST, DIE YOUNG
THE SIN-STEEPED STORY OF TODAY'S "BEAT" GENERATION!
HEAR! Music in the mood of today's "beat" generation!
Co-starring
MARY MURPHY · NORMA EBERHARDT
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Directed by PAUL HENREID Screenplay by ALLEN RIVKIN and IB MELCHIOR Produced by HARRY RYBNICK and RICHARD KAY Associate Producer EDWARD B. BARISON A UNIVERSAL-INTERNATIONAL RELEASE


Astronomy 103

The Interstellar Medium and Star Formation

Please read Chapter 11

The Interstellar Medium (ISM)

Space is empty.

The Interstellar Medium (ISM)

Space is empty.

Almost....

In interstellar space (the space between the stars), there is around 1 atom/cm^3. By contrast the earth's atmosphere is 10^{20} atoms/cm^3 and the best vacuum on earth is 1000 atoms/cm^3.

There are also dust grains in interstellar space, but only about 1 grain/km^3.

Gas in the ISM

Gas in the ISM is mostly hydrogen.
It is in **three phases:**

- Cold (10-100s K)
- Warm (around 8000 K)
- Hot (10^6 K)

Most of the volume is hot, but hot gas is very diffuse – most of the gas is warm or cold. This cold gas is important because it is found in clouds that form stars. Cold gas clouds are what stars come from.

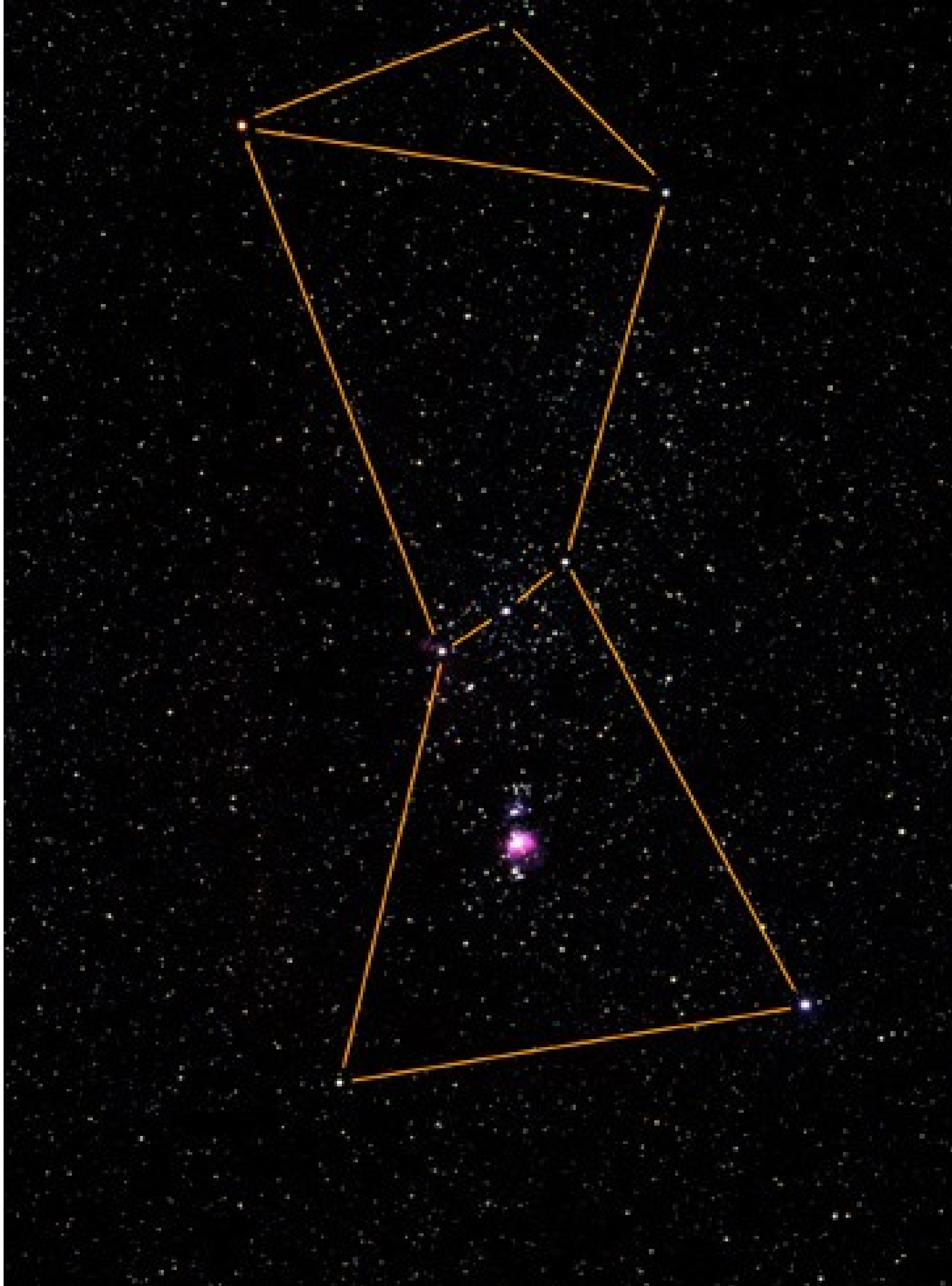
Some of these cold clouds have formed hot, massive stars that have heated up the gas hot enough for the hydrogen to be ionized. These regions of hot gas are called **HII regions**.

HII ("H two") is astronomer-speak for ionized hydrogen.

Gas cool enough that its hydrogen is in the form of atoms is called **HI**.

HI (“H one”) is astronomer-speak for neutral hydrogen.

Neutral hydrogen gas cannot be seen in visible light. This is a **radio** image of HI gas in the constallation of Orion.



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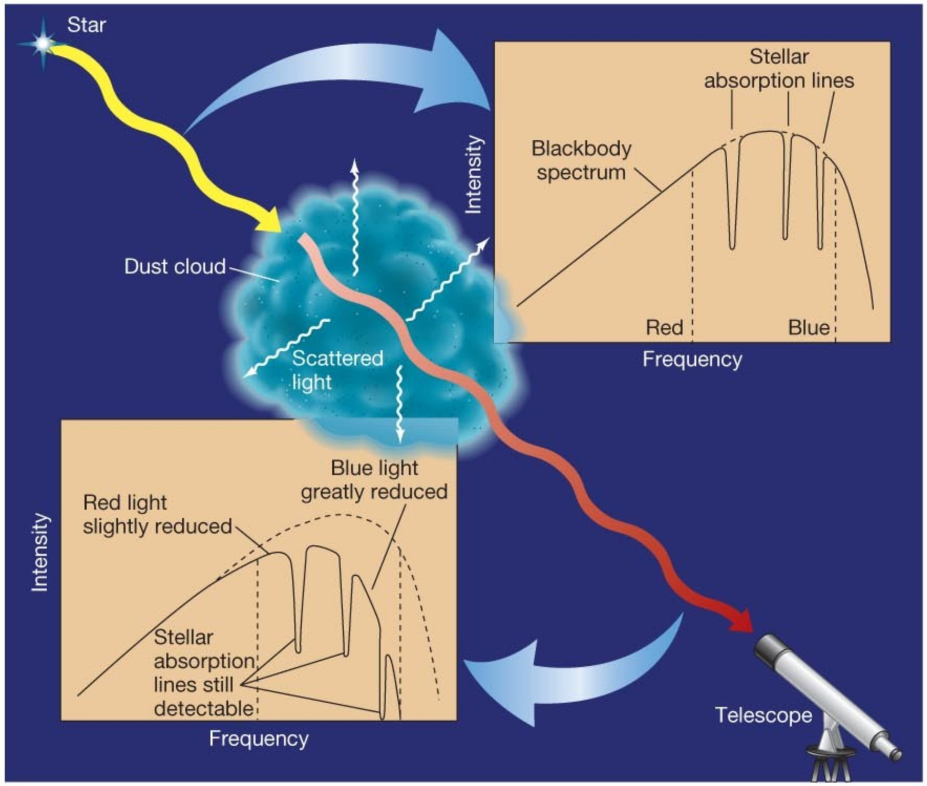
Neutral hydrogen gas cannot be seen in visible light. This is a **radio** image of HI gas in the constallation of Orion.

Hot clouds are bright and the light they emit can be seen.

This picture shows visible light from ionized hydrogen gas.

Cool clouds emit little visible light and are observed as dark nebulae, dark clouds that block the light from the stars behind them. Cool clouds also contain dust, which scatters light of wavelengths shorter than the size of a typical dust grain, reddening the light that goes through it.



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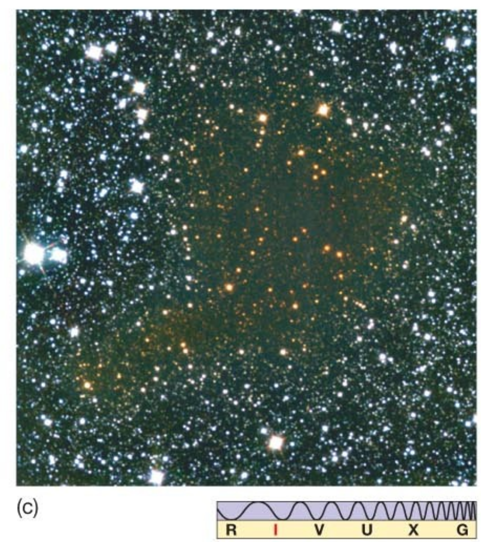


(c)

Dusty clouds become transparent in infrared light.

Dust Clouds

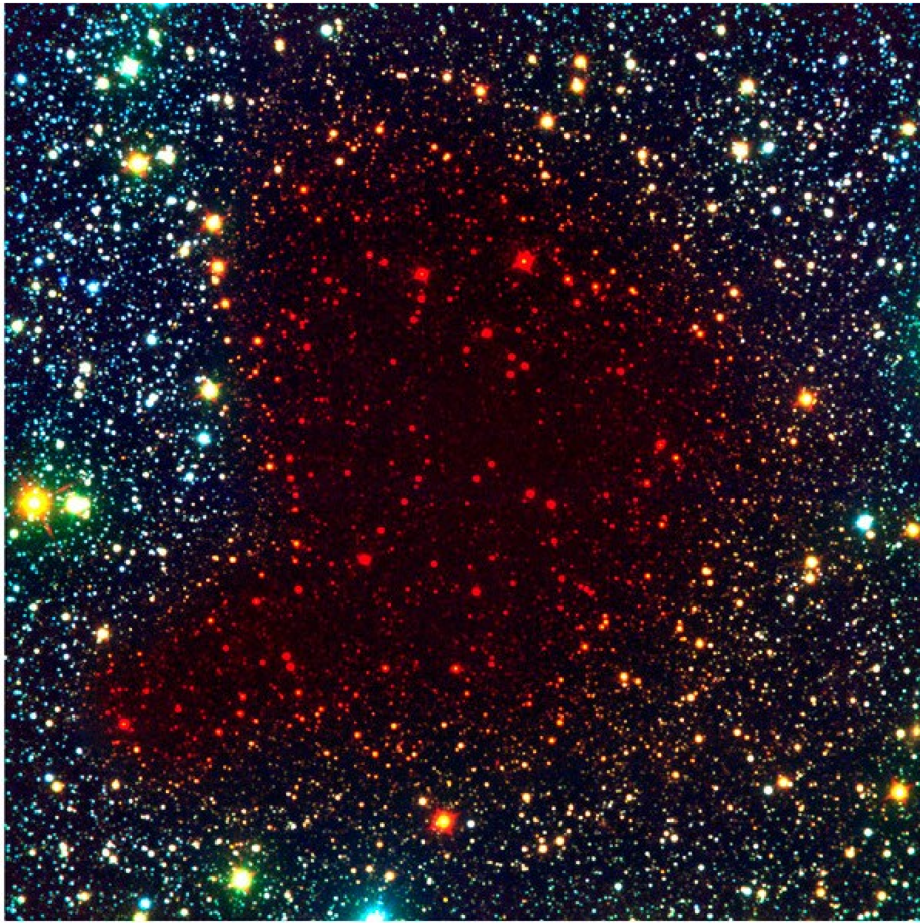
These cold clouds are cold enough to have a lot of dust.

The dust grains are a few hundred nm in size, about the wavelength of visible light. Because they are this size, they affect different colors differently.

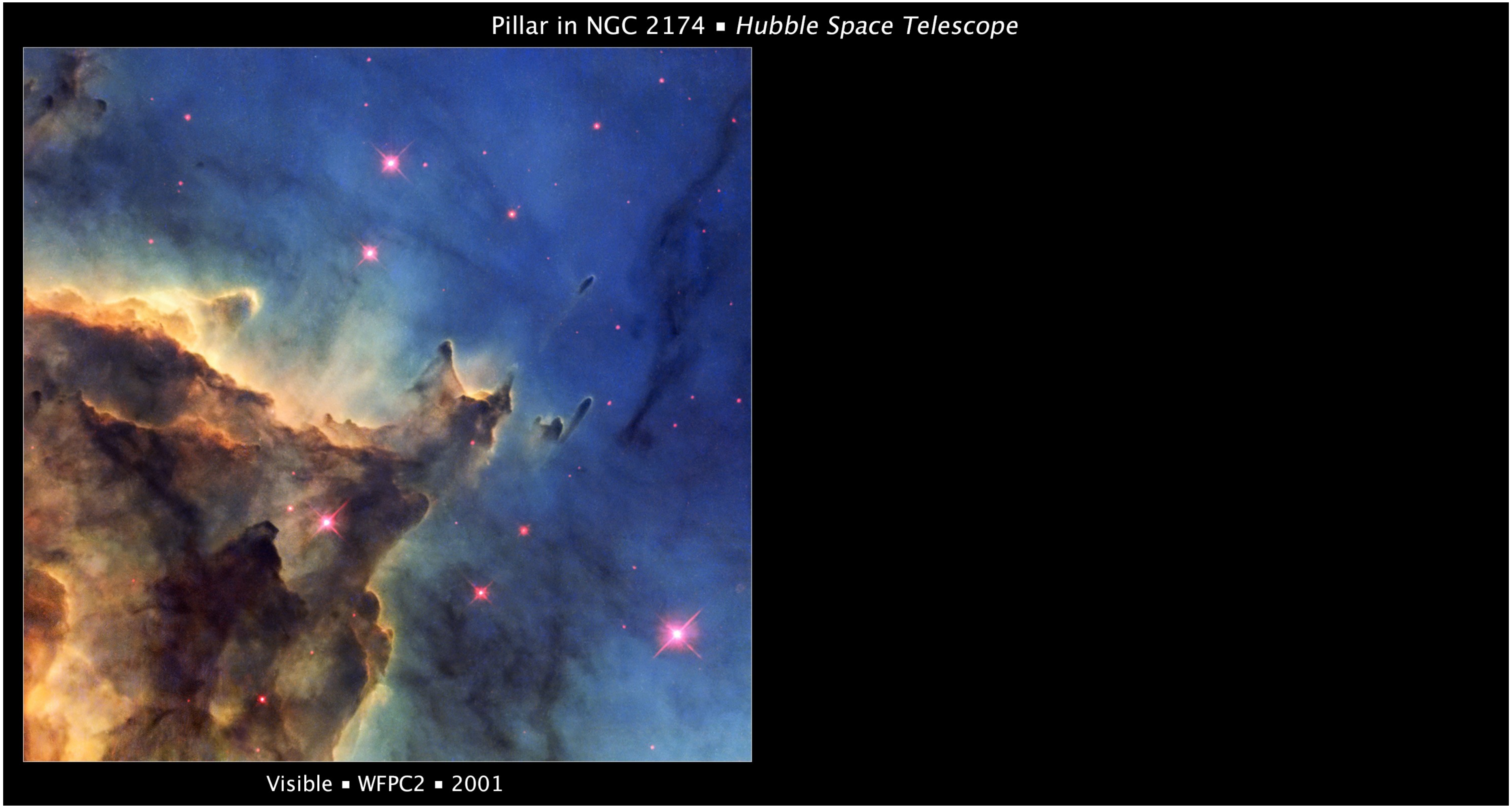
Light is scattered by things about the same size as its wavelength. Blue light is shorter in wavelength than red light, and blue light is scattered more by dust than red light. This makes dusty regions look redder.

Laser beams! The green laser is strongly scattered by the atmosphere, so we see the beam more easily than a red laser

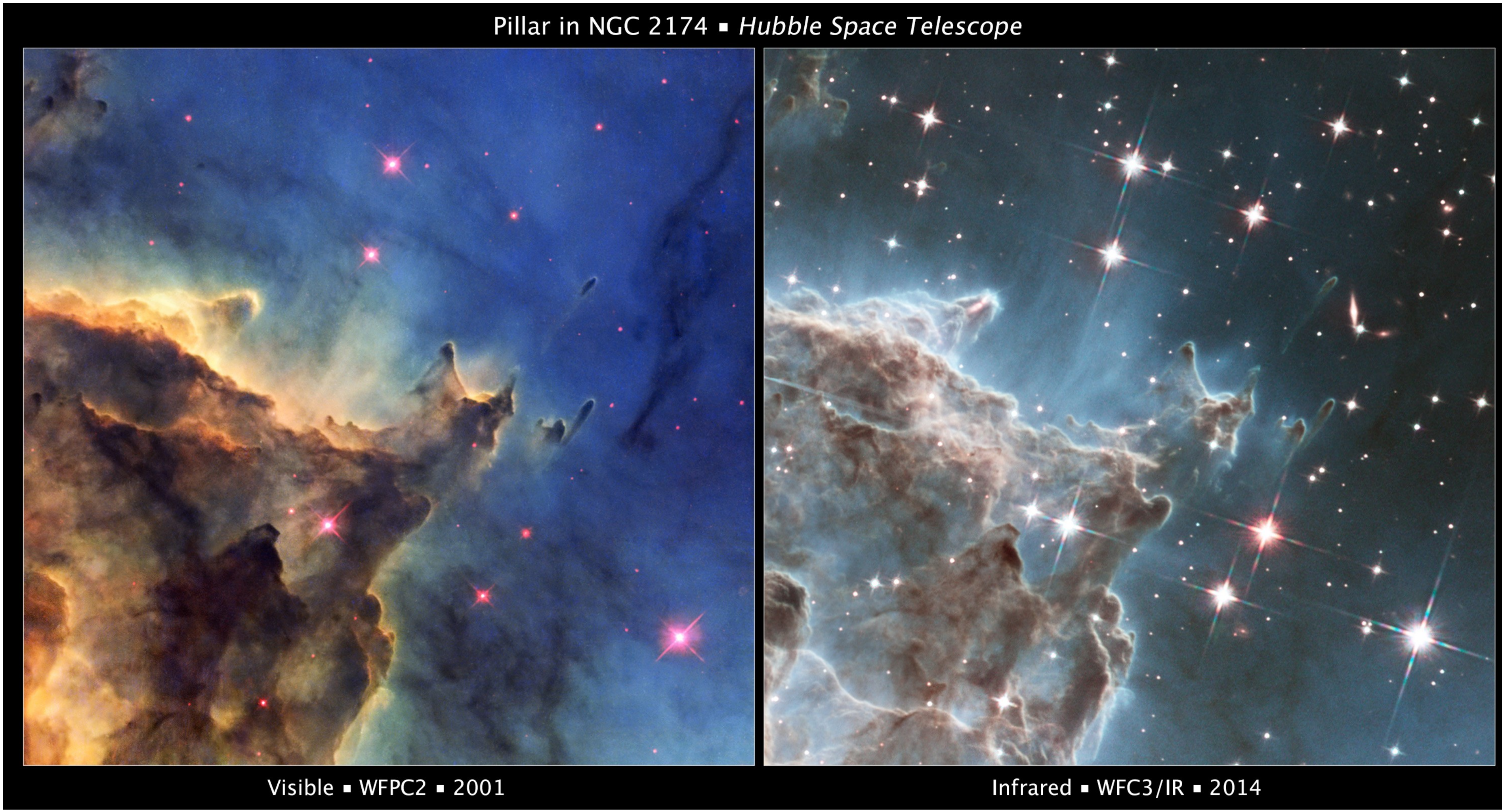
Reddening due to Barnard 68.



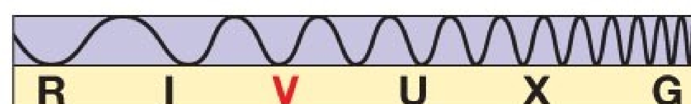
Star formation region NGC 2174 at optical and infrared wavelengths

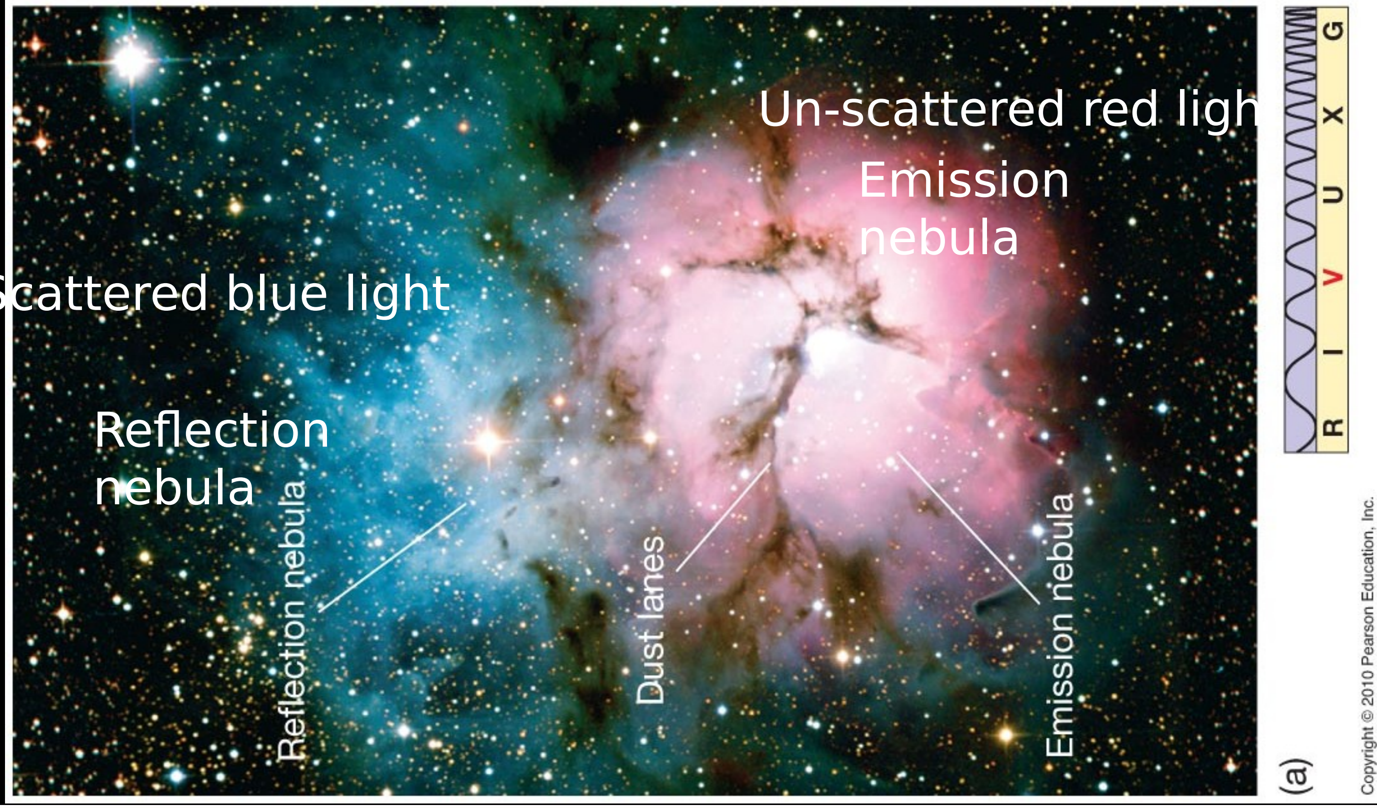


Star formation region NGC 2174 at optical and infrared wavelengths



The same effect is responsible for sunsets




Un-scattered red ligh
Emission
nebula
Scattered blue light
Reflection
nebula
Reflection nebula
Dust lanes
Emission nebula
R I V U X G
(a)
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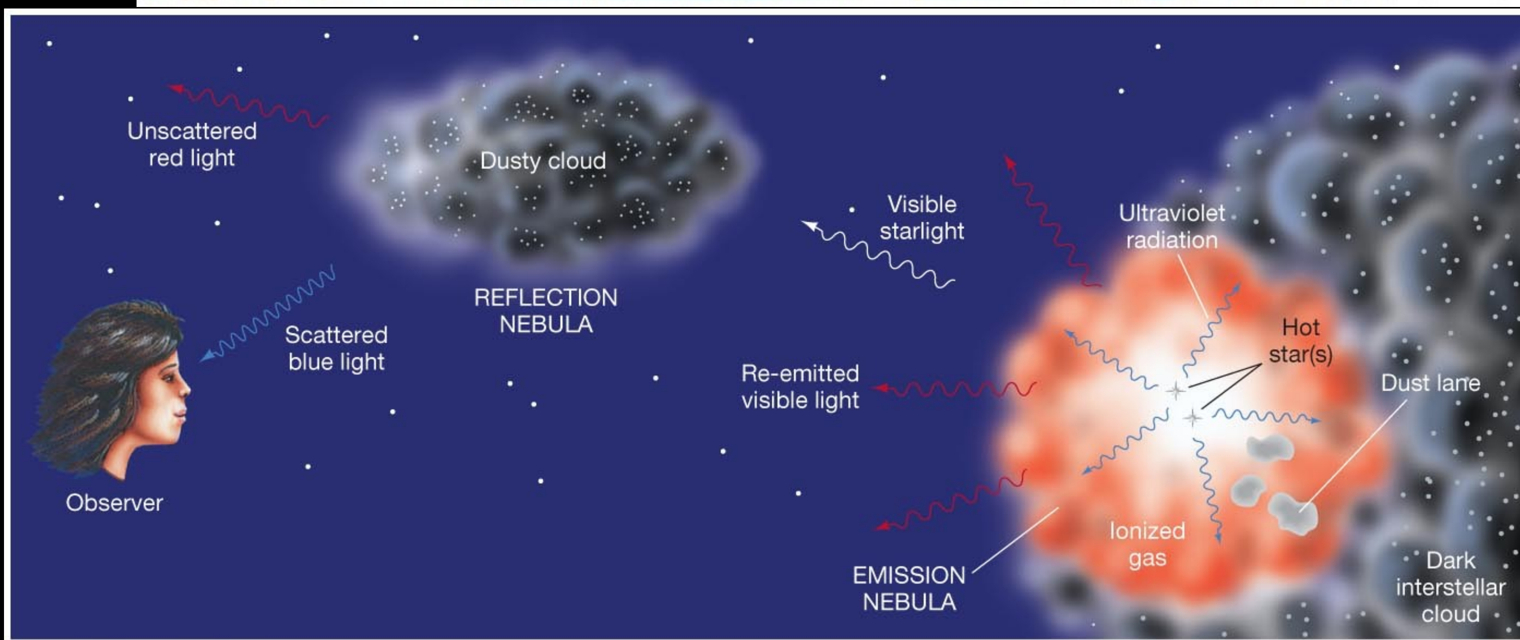
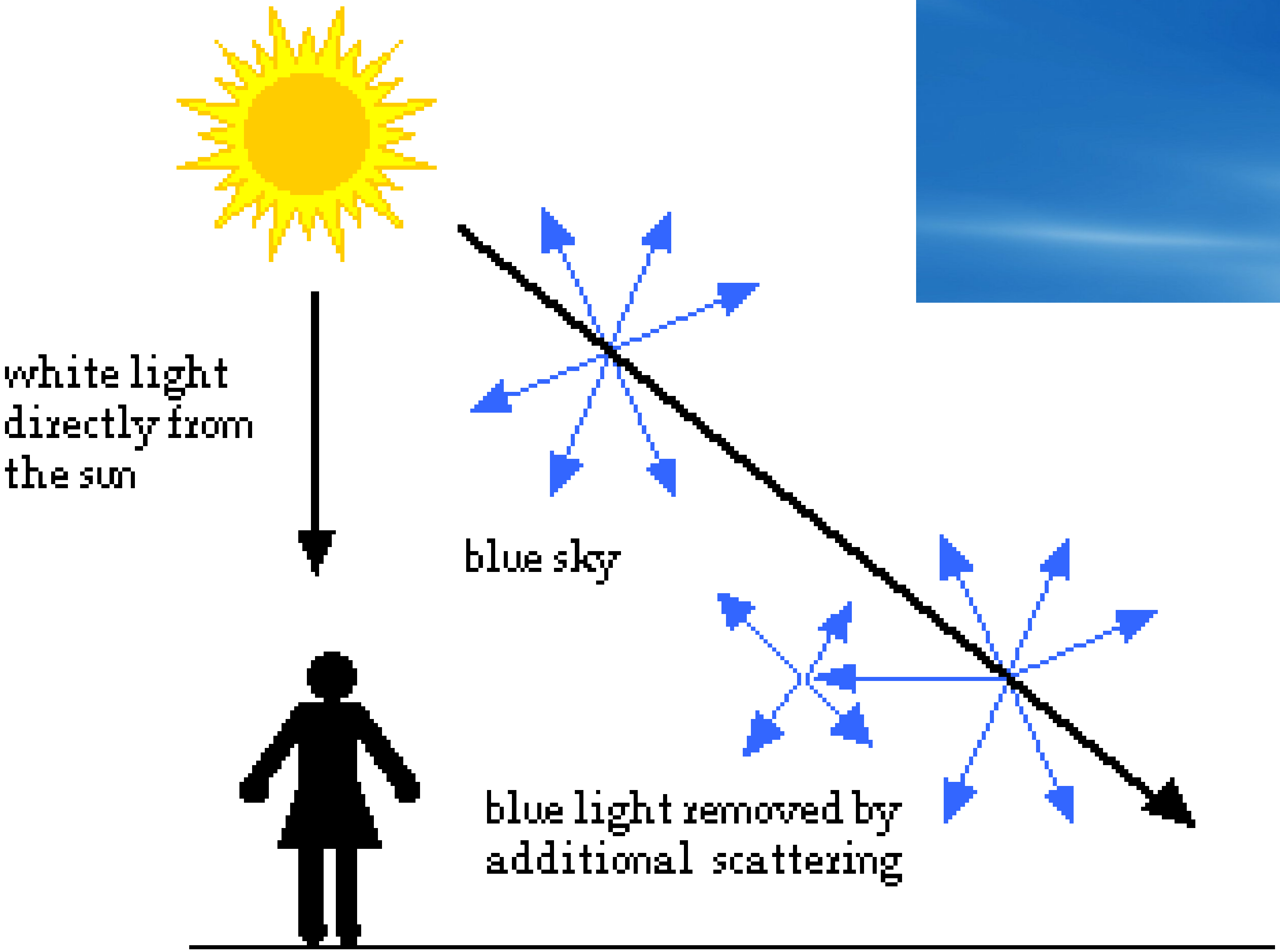
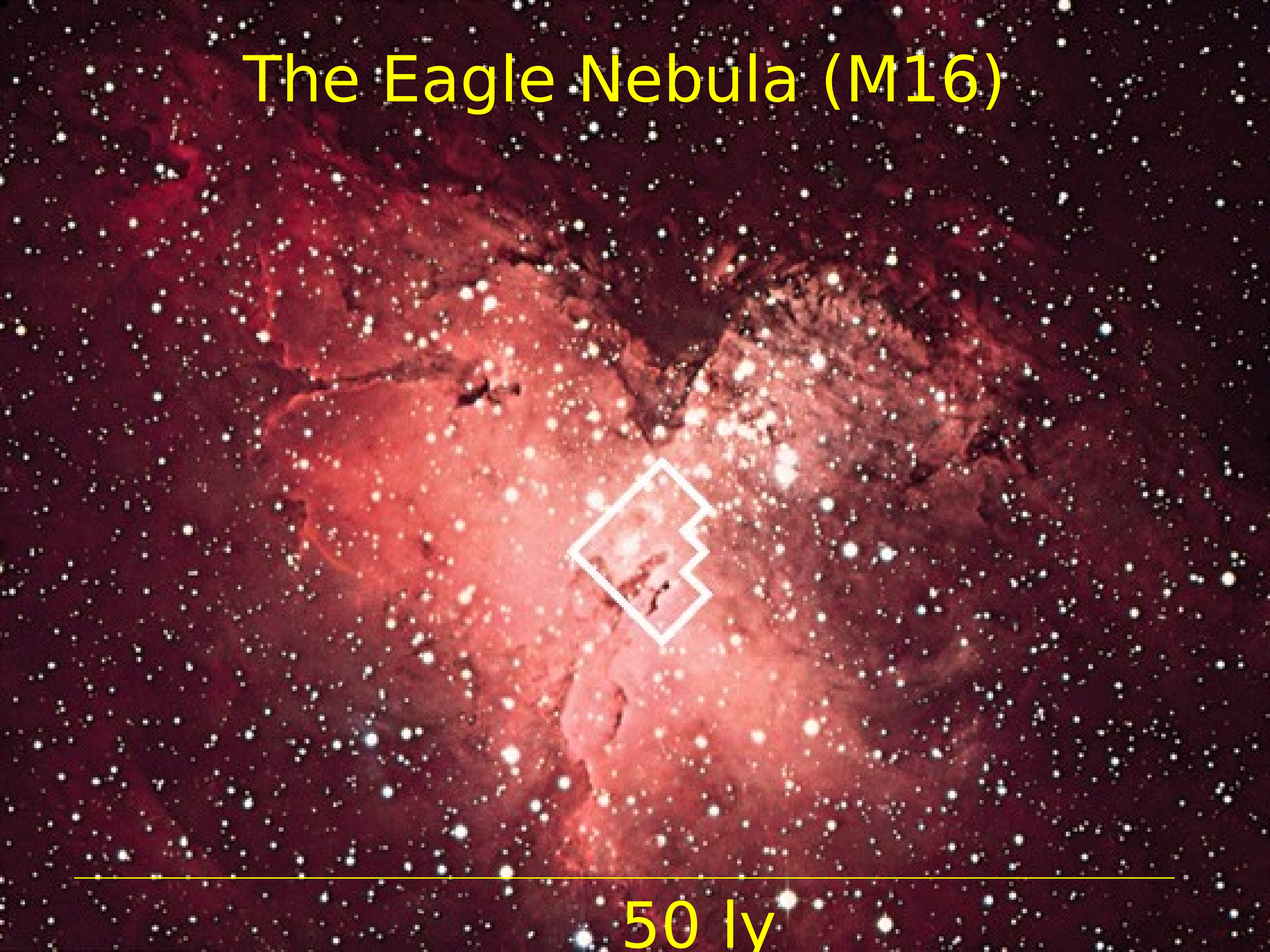
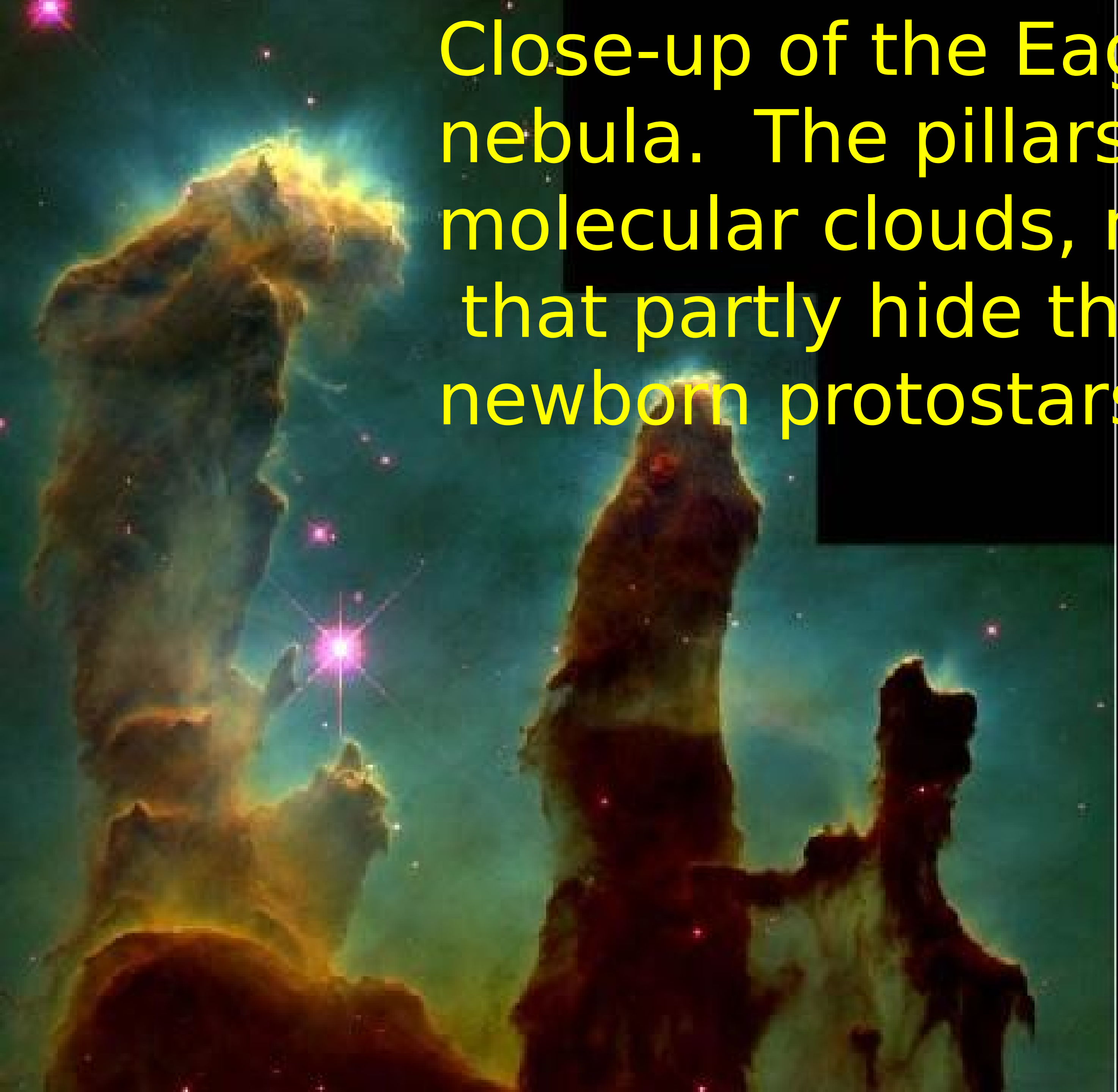

Unscattered
red light
Dusty cloud
REFLECTION
NEBULA
Scattered
blue light
Observer
Visible
starlight
Ultraviolet
radiation
Hot
star(s)
Re-emitted
visible light
Dust lane
Ionized
gas
EMISSION
NEBULA
Dark
interstellar
cloud

The reflection nebula is blue for the same reason the sky is blue.




The Eagle Nebula (M16)
50 ly

Close-up of the Eagle nebula. The pillars are molecular clouds, nurseries that partly hide their newborn protostars



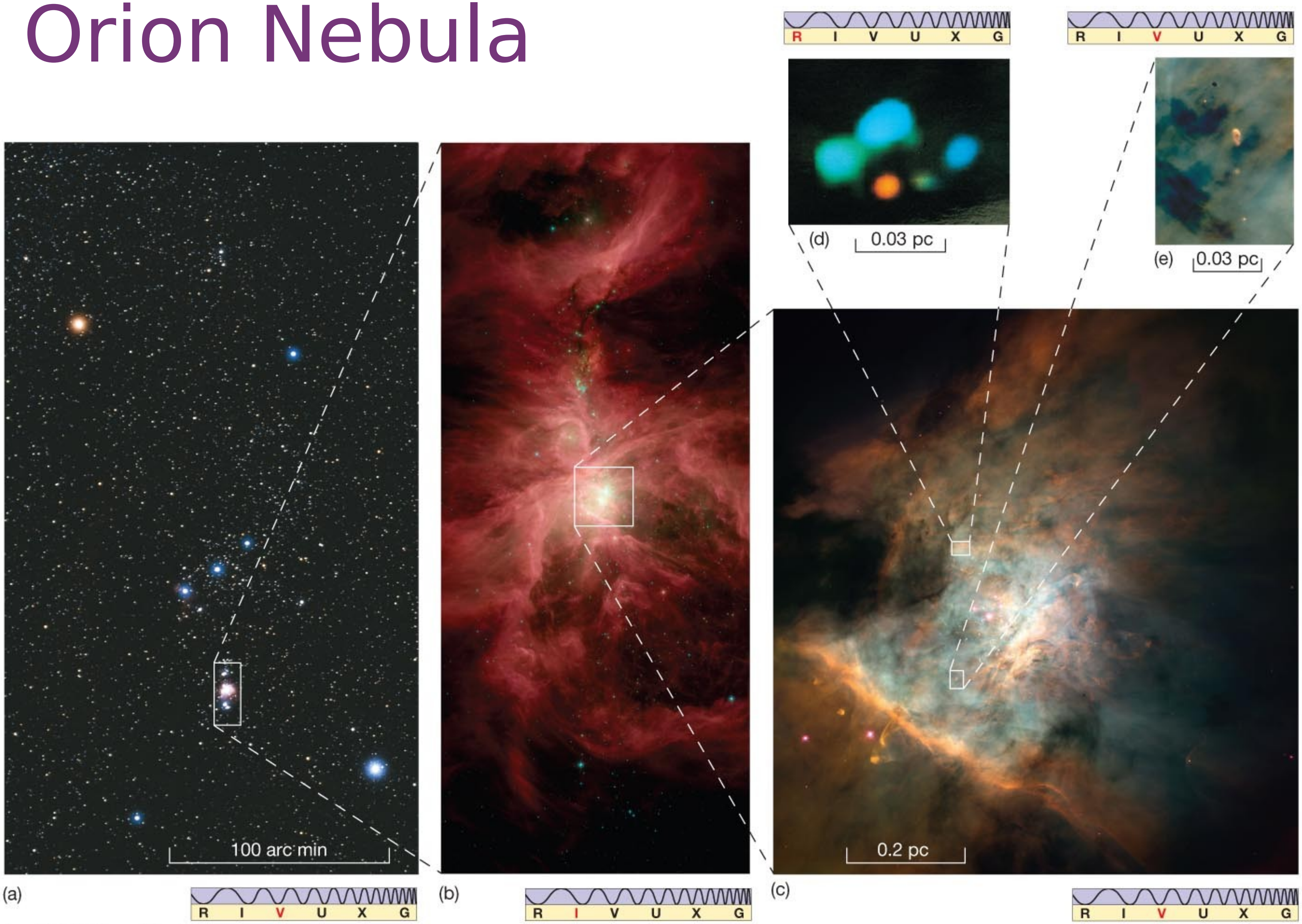
Carina Nebula Details

HST•ACS/WFC

Rosette Nebula

Rosette Closeup: Newly formed O and B stars have heated the center of this cloud, and the pressure of their starlight has blown gas away from the center.

Orion Nebula

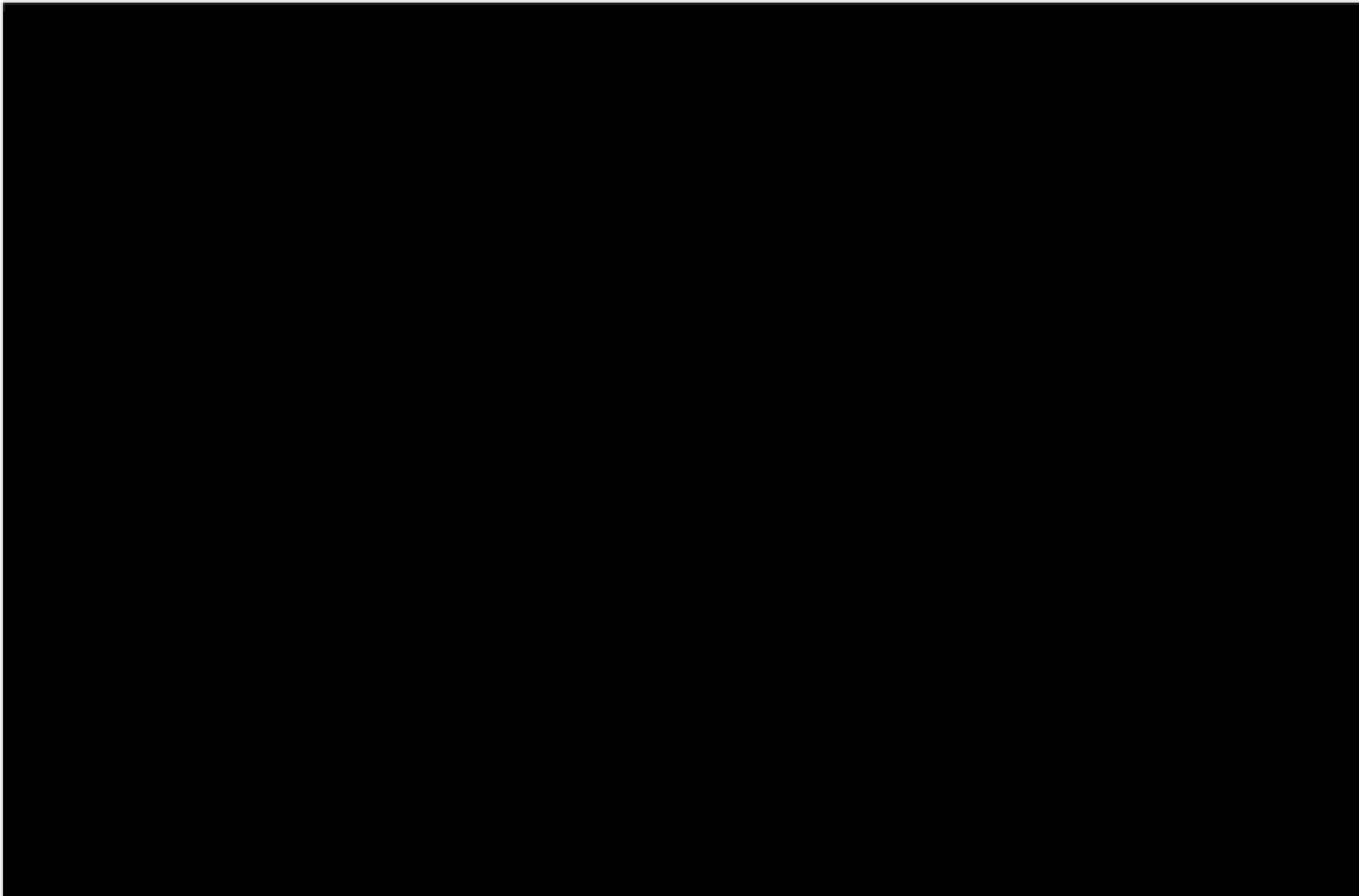


Orion Nebula

Spitzer Space Telescope (IR):
Star formation in the Orion nebula

Radiation and wind from massive stars blows away gas and dust

The Cygnus Wall of Star Formation



Radio Emission from Gas

The clouds also give off radiation at **radio wavelengths**. This happens via two methods:

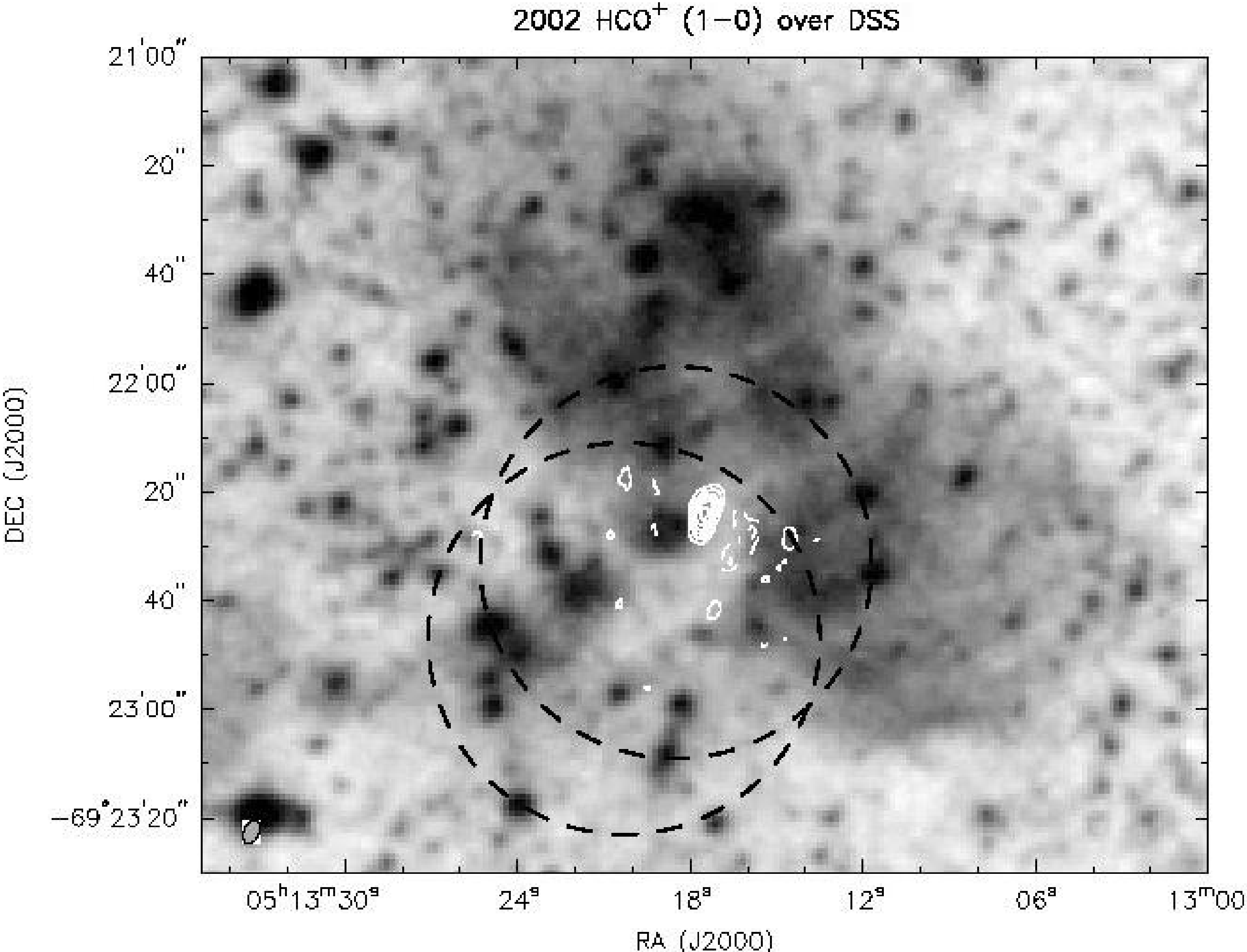
- Molecular radio lines: works best for the densest clouds
- 21 cm radiation from hydrogen

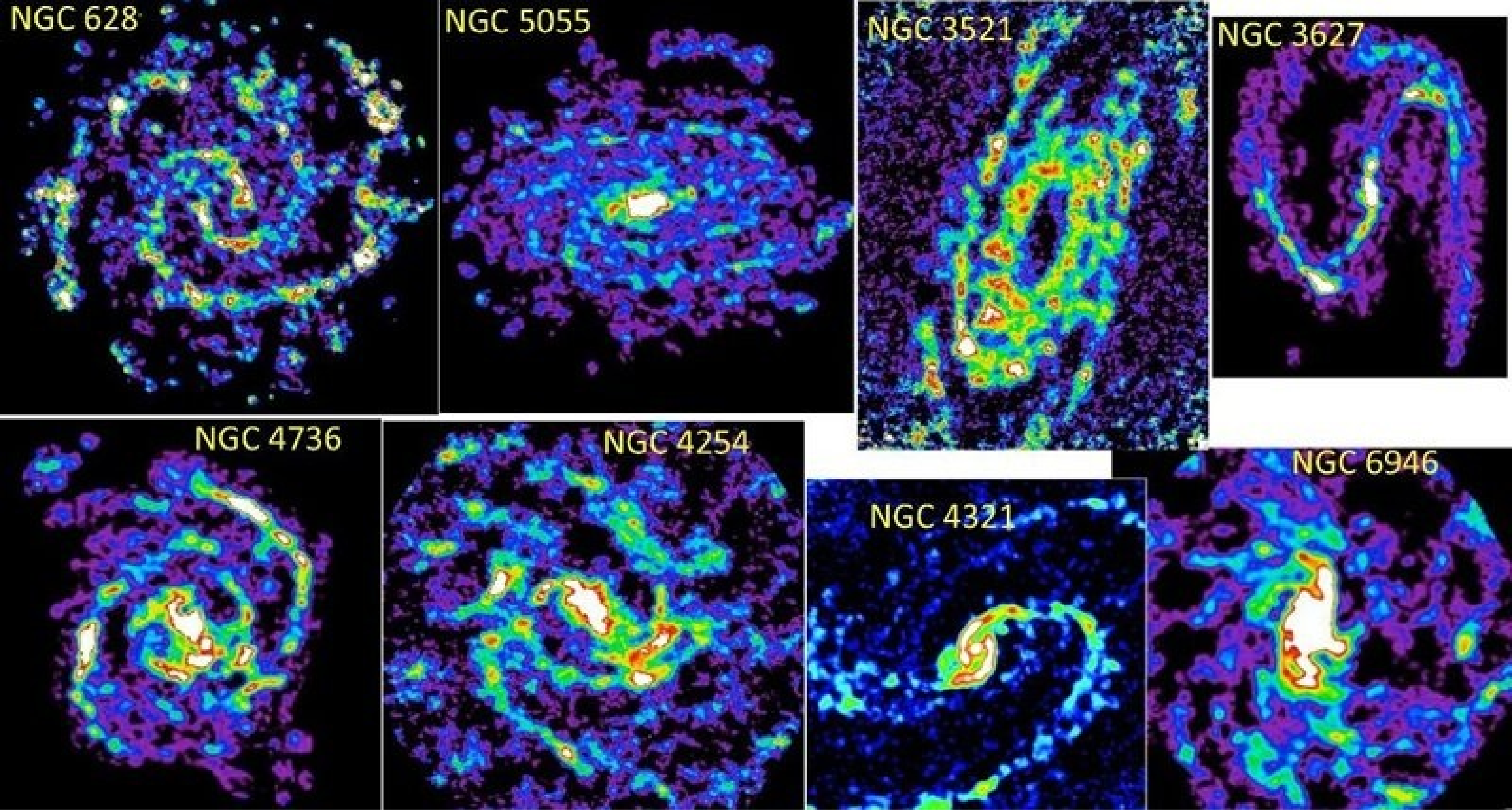
Gas radio emission allows you to map the gas without looking at emission from stars.

Looking for Molecular Gas

- Stars form in regions where the gas is coldest and densest
- Under these conditions, hydrogen forms **molecules**
- Molecular hydrogen gas (two hydrogen atoms bonded together to form a molecule) is hard to see, but it's usually accompanied by more complex molecules like carbon monoxide (CO)
- These more complex molecules have emission lines we can see with radio telescopes

Molecular lines: like carbon monoxide or CO

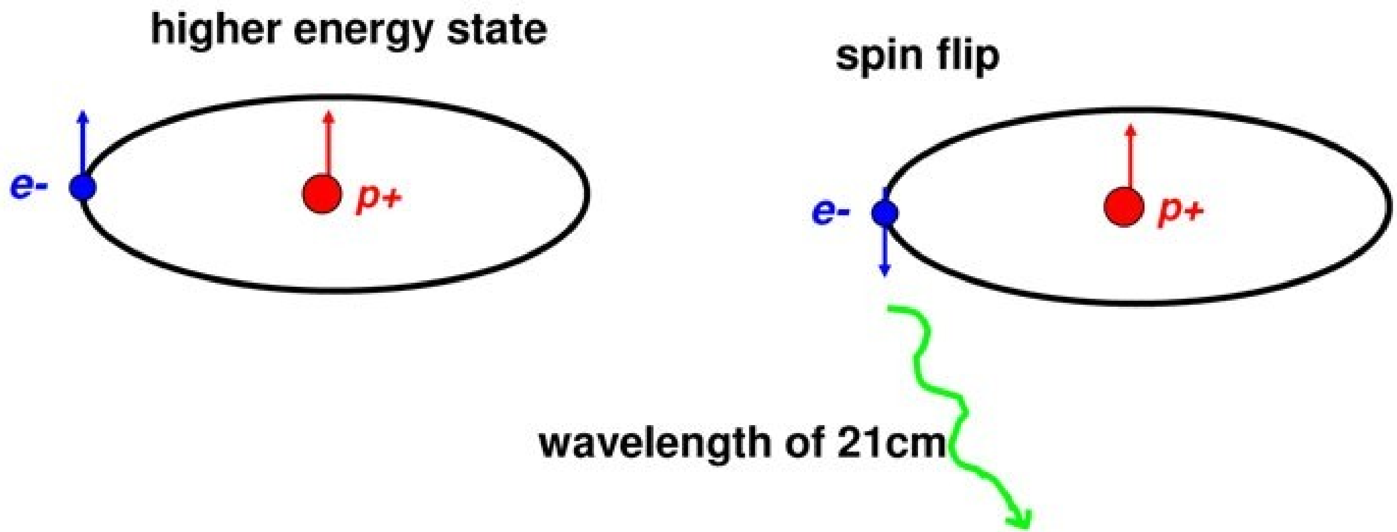




Images of the Carbon Monoxide (CO) emission tracing the molecular cloud distribution in 8 spiral galaxies. The basic spiral pattern seen in the starlight is also clear in the molecular gas. The blue-to-purple represents the lowest level emission and the red-to-white the brightest.
Credit: Jin Koda, Stony Brook University

21cm radio emission

The electron and proton in an atom of neutral hydrogen have **spin**. Their spins can be aligned, or they can point in opposite directions.

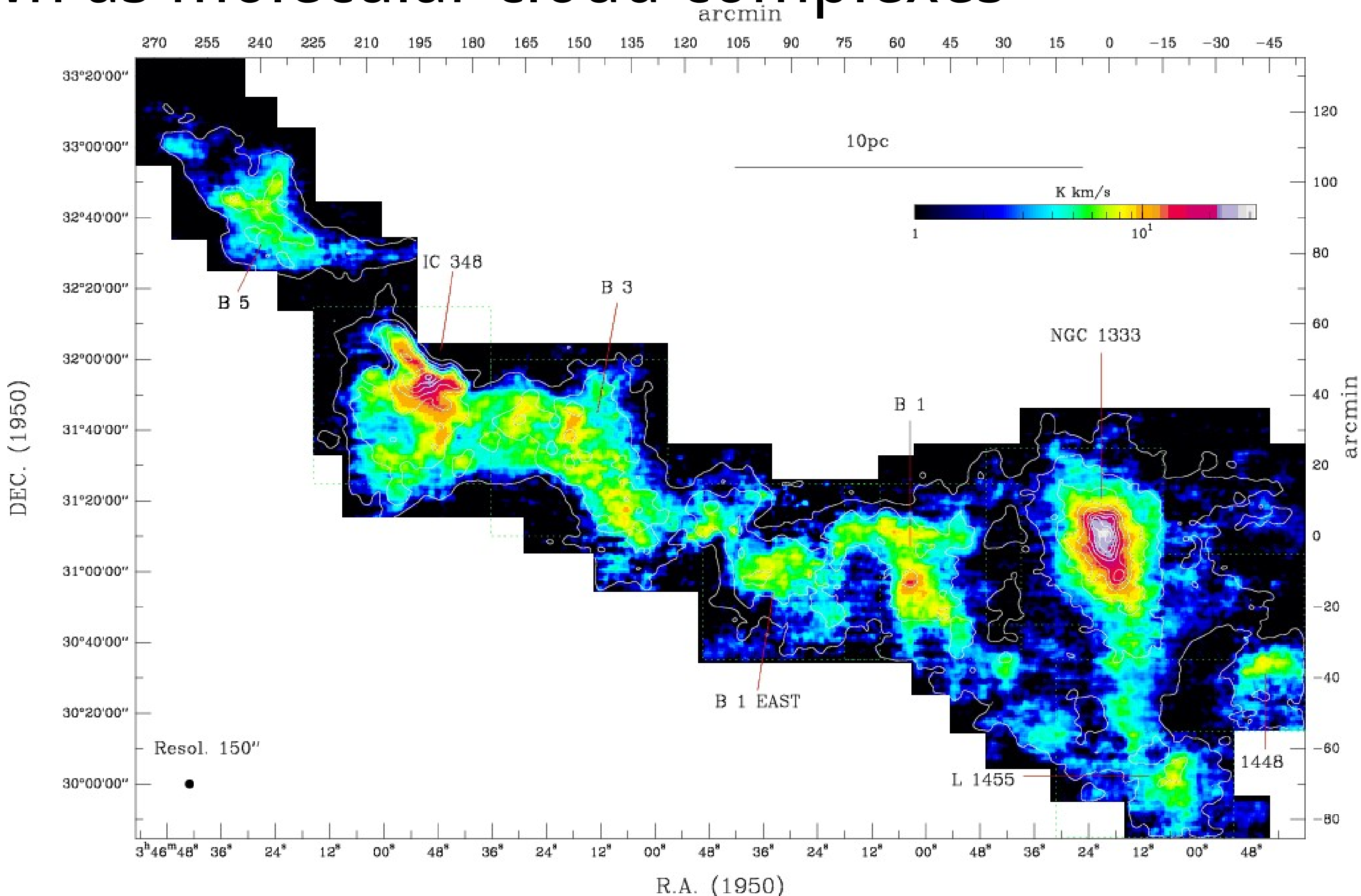


Sometimes the spin of the electron flips, and when this happens a photon is emitted with wavelength 21 cm. This can be observed in the radio, and is used to map neutral hydrogen gas.

Contours of
21 cm emission
overlaid on
an IR image

M51 in 21 cm + IR

By mapping gas in CO (molecules) and HI (atomic hydrogen), we know that molecular clouds contain an enormous amount of gas, > 1 million times the mass of the sun. They are also in enormous collections known as molecular cloud complexes



Preview for next class

- How to turn gas and dust from ISM into stars (and planets)
- How do young stars begin their lifes
- How do grown-up stars evolve
- How do old stars end their lifes

→ Read chapters 11 & 12