Stellar Evolution

I. How are stars born?

- What do they look like before they're born?
- What is the pre-stellar material made of?
- How can stellar nurseries be identified?
- When does a blob of gas officially become a star?
- How long does it take?

II. How do stars evolve?

- How do they change in mass, luminosity, temperature, radius, etc?
- Do all stars evolve in the same manner?
- Do all stars evolve at the same timescale?
- If stars evolve differently, what determines how a star will evolve?
- Do stars run out of power?

III. How do stars die?

- What does it mean for a star to “die”?
- Do all stars die the same way?
- How does a star's death influence its surroundings?

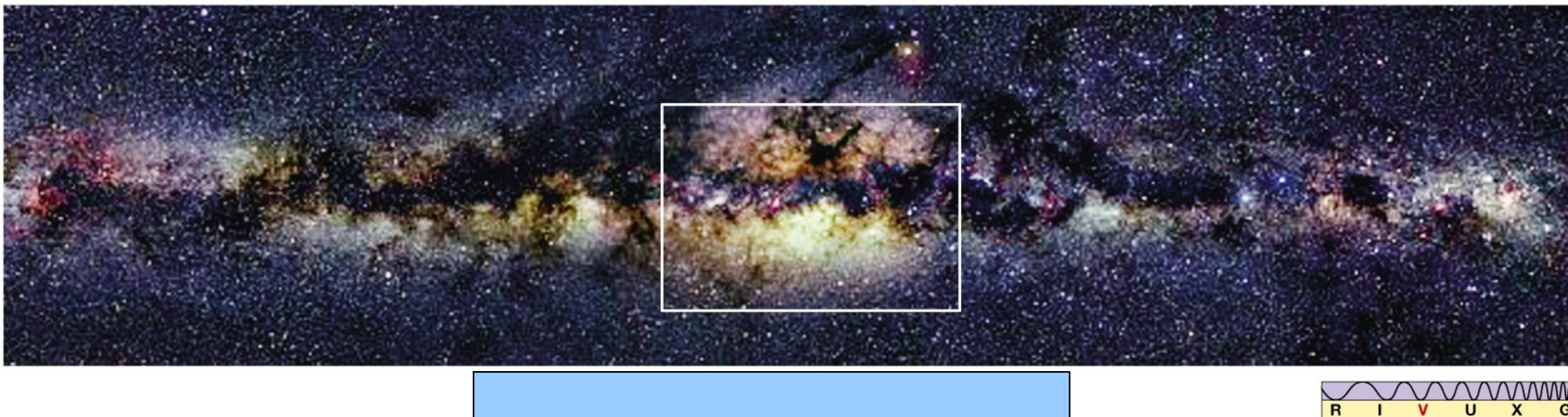
I. How are stars born?

Short answer: they form out of collapsing clouds of gas and dust within a galaxy.

The gas and dust between the stars is called the *Inter-Stellar Medium*, or ***ISM.***

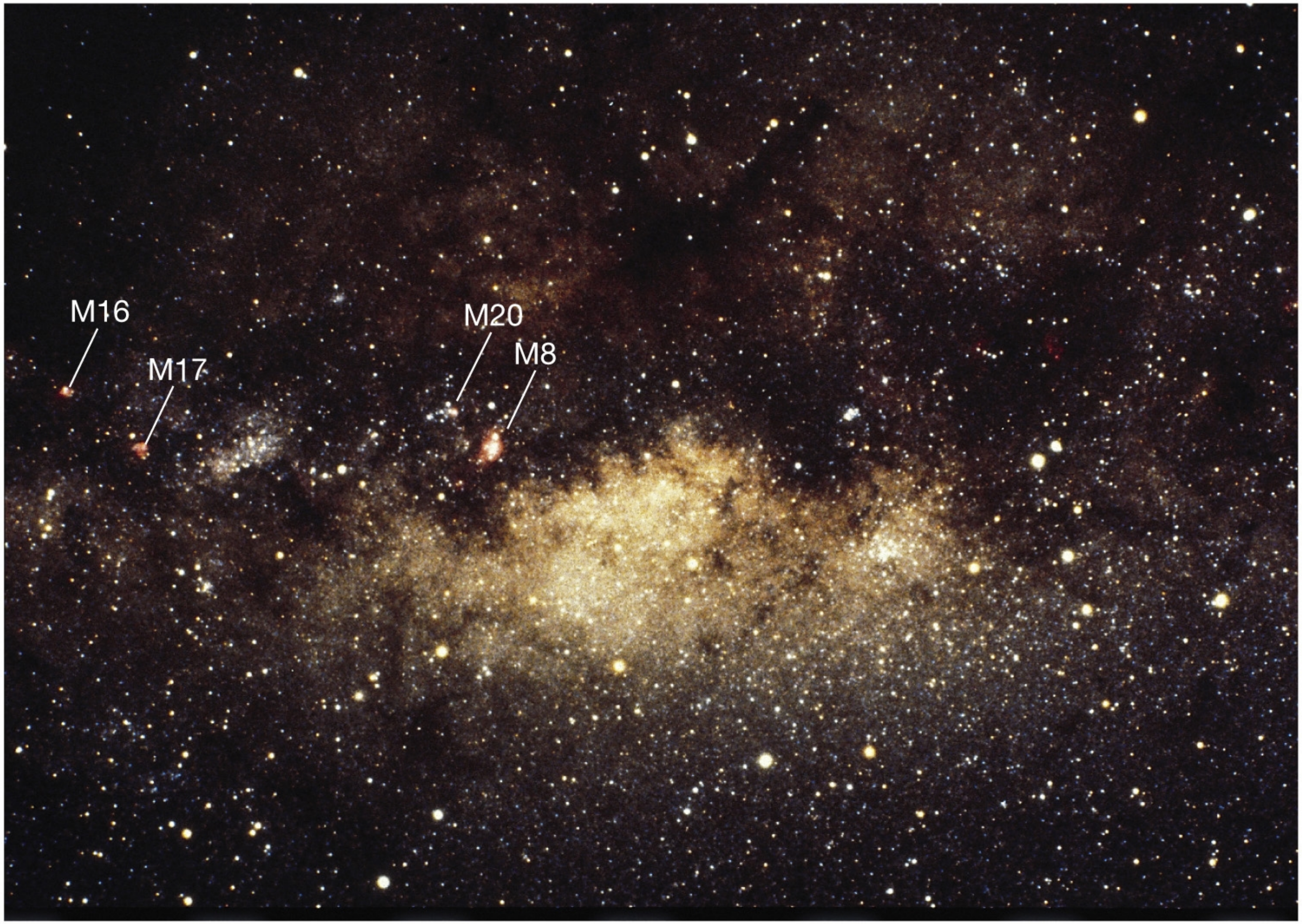
Let's take a look at the ***ISM*** *...*

Figure 18-5
Milky Way Mosaic

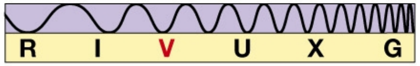


180 degrees of the sky!!

Figure 18-1
The Milky Way (zoomed a little) in visible light.



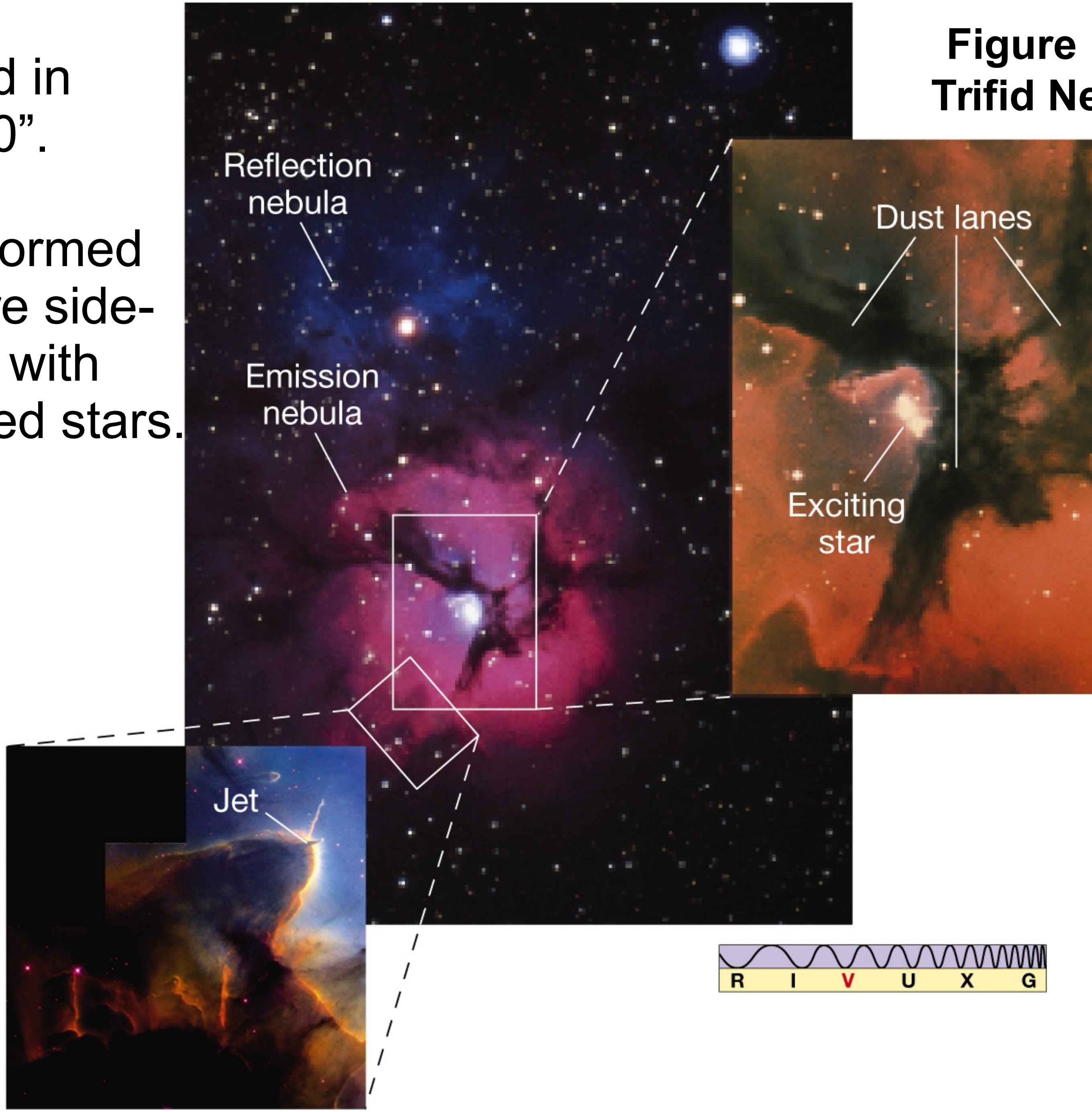
Glowing nebulosities indicate recently formed stars. The dark clouds may hide protostars!



Zoomed in on “M20”.

Newly formed stars are side-by-side with unformed stars.

Figure 18-8 Trifid Nebula



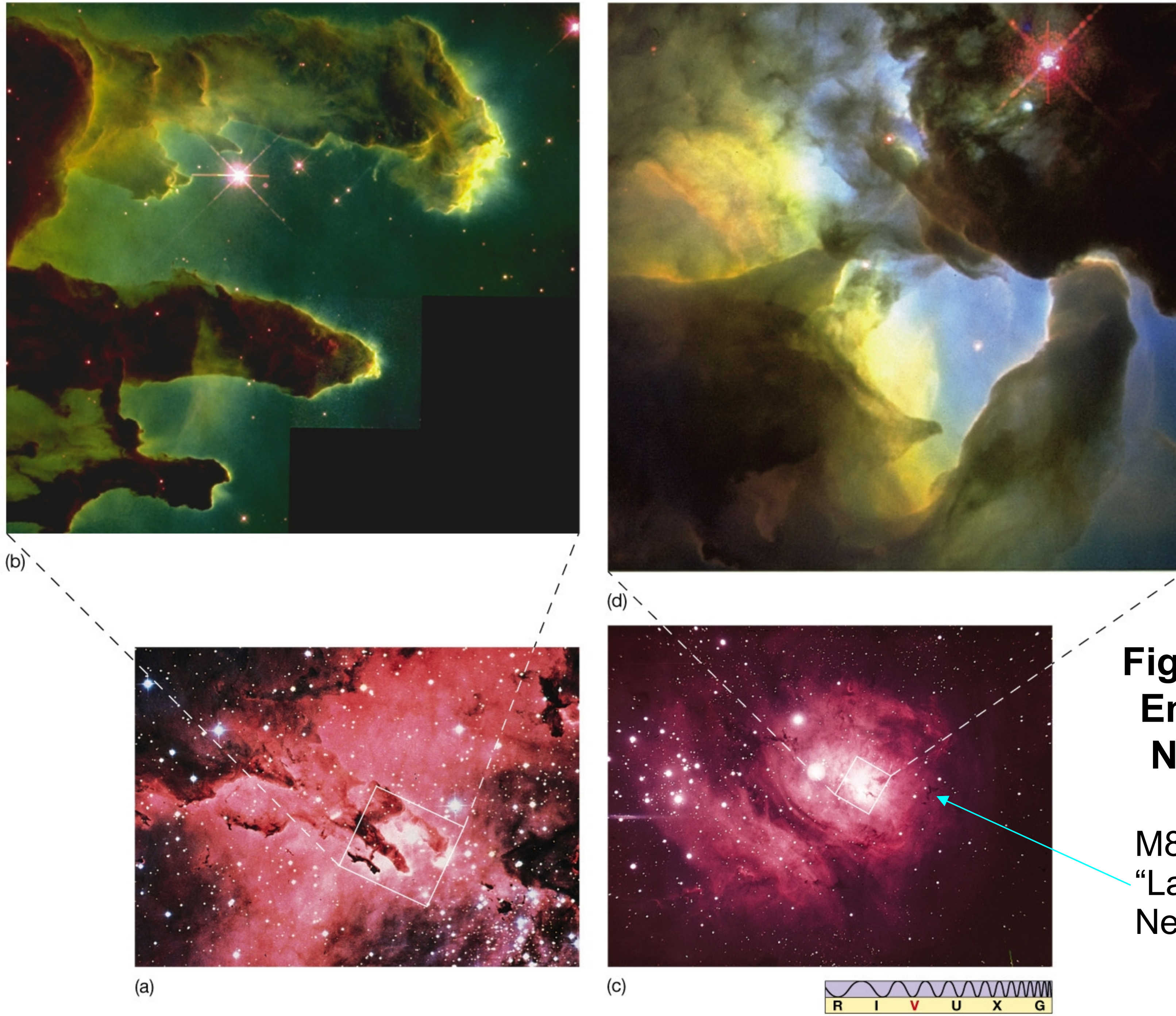
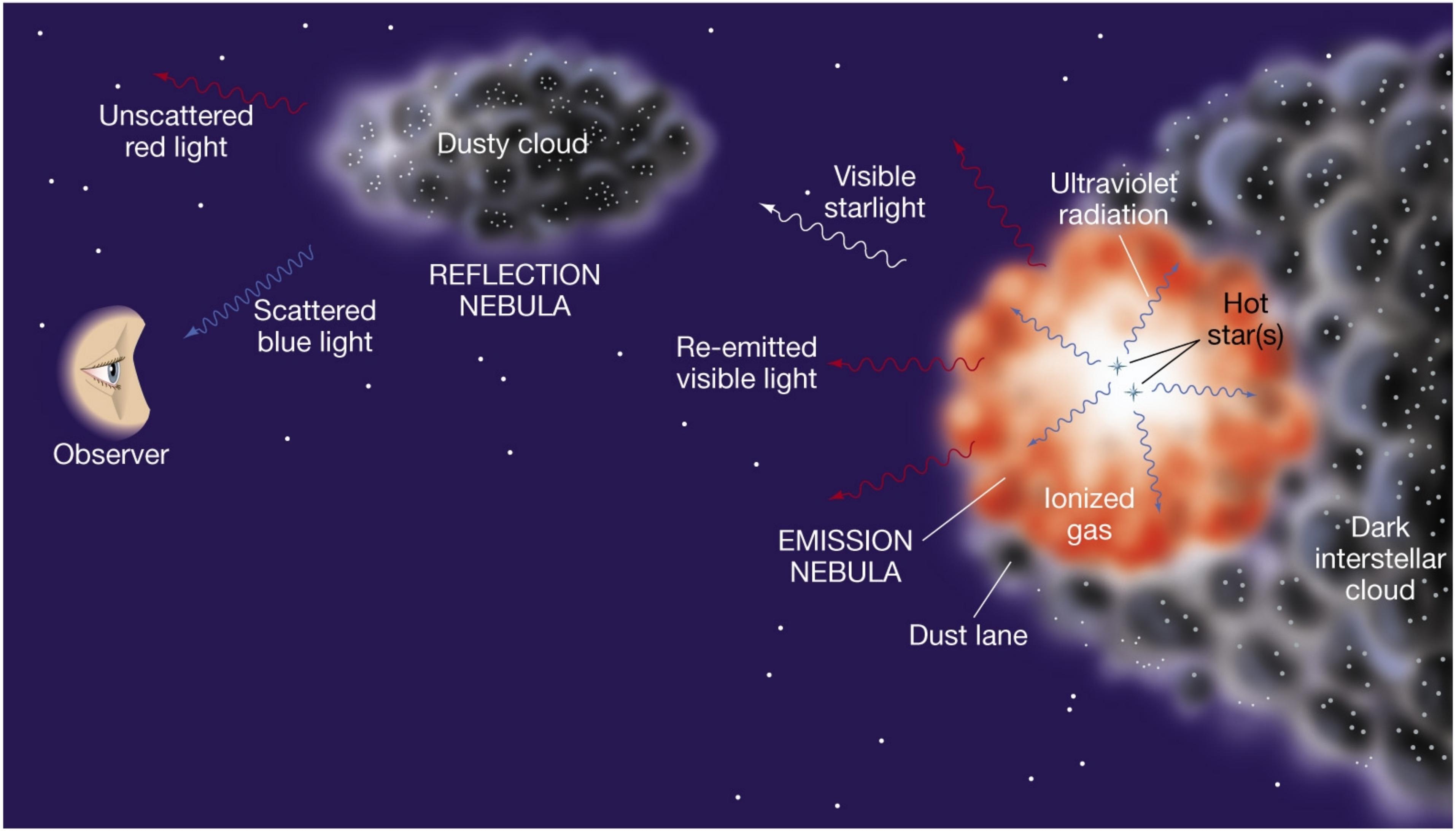


Figure 18-9 Emission Nebulae

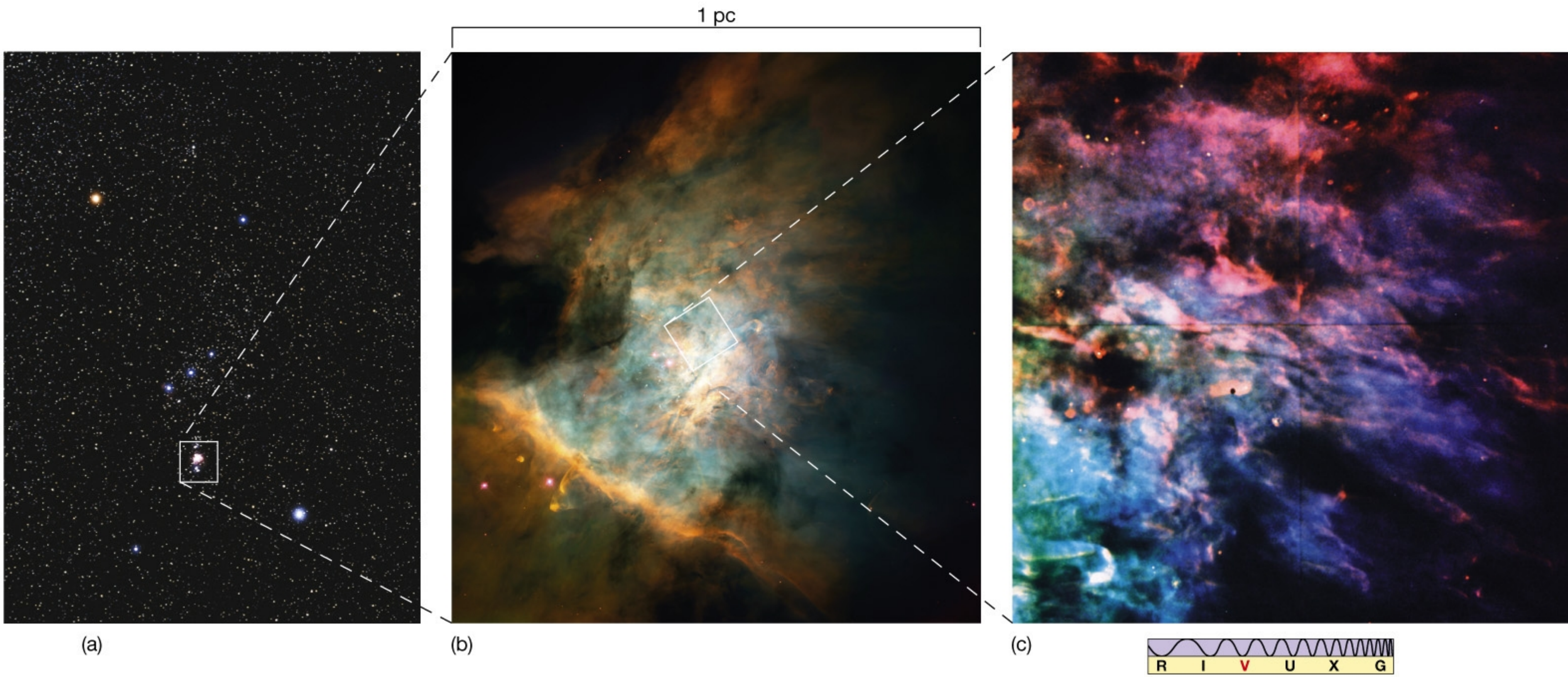
M8, the "Lagoon Nebula"

Figure 18-10
Nebular Structure



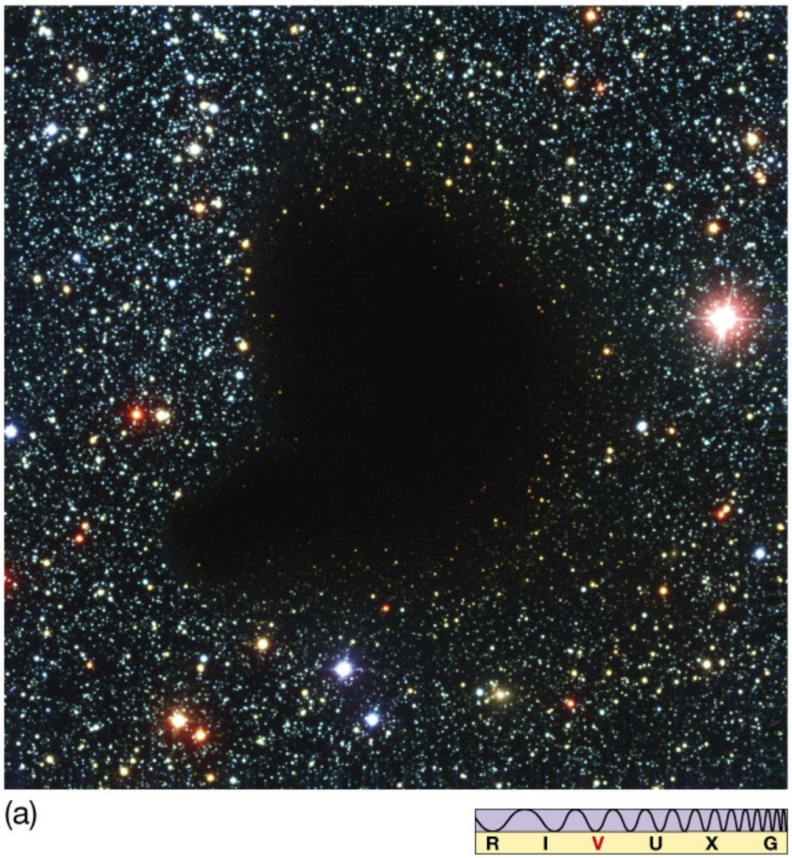
Reflection Nebula- the Pleiades

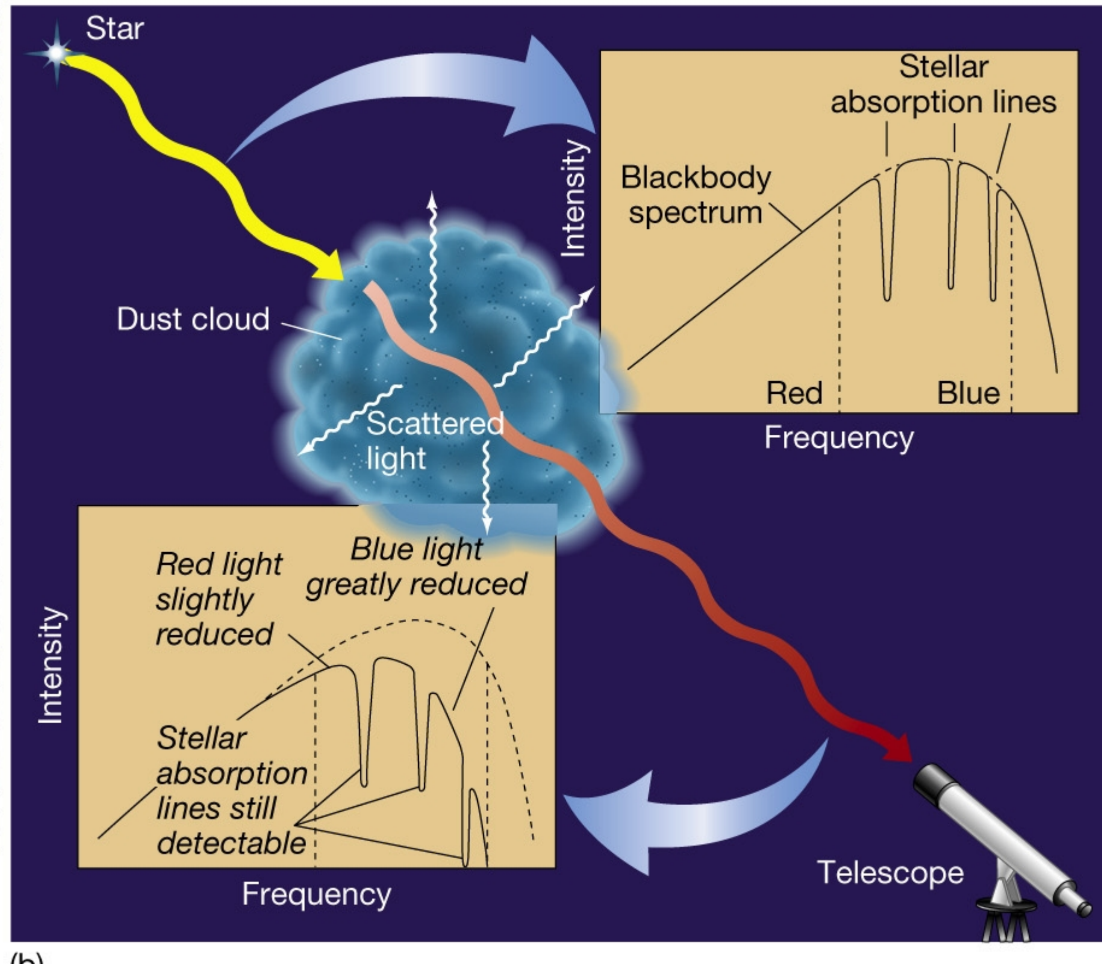
Figure 18-12
Orion Nebula



(See “Star Formation” presentation for observatory.)

Figure 18-2
Reddening

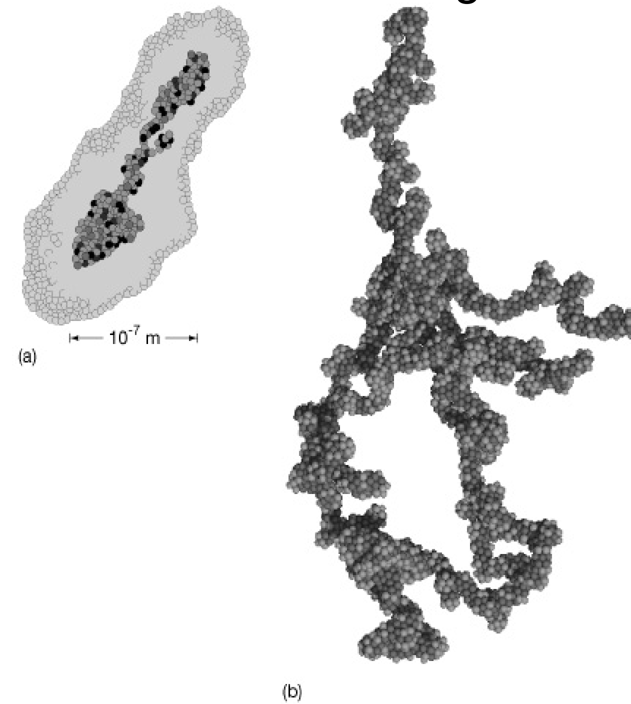


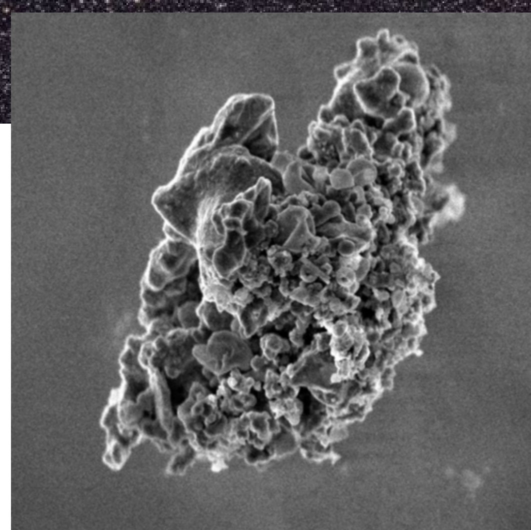


Bok Globule (B68)
An isolated dark cloud of dust and gas.
A few LY across. <10 Msol.

Dust Clouds

Polarization → elongation





Sizes ~0.1-1 micron.
I.S. grains found
in Earth's atmosphere!

Hot dust: Al,Fe,Mg

Cold dust: H_2O,CH_4 ices

Figure 18-15
Horsehead Nebula -
dust *in front* of an emission nebula

Phases of the ISM

ISM = interstellar medium (gas and dust between stars).

Temperature and density vary widely in the ISM.

Composition: mostly H in these *phases*:

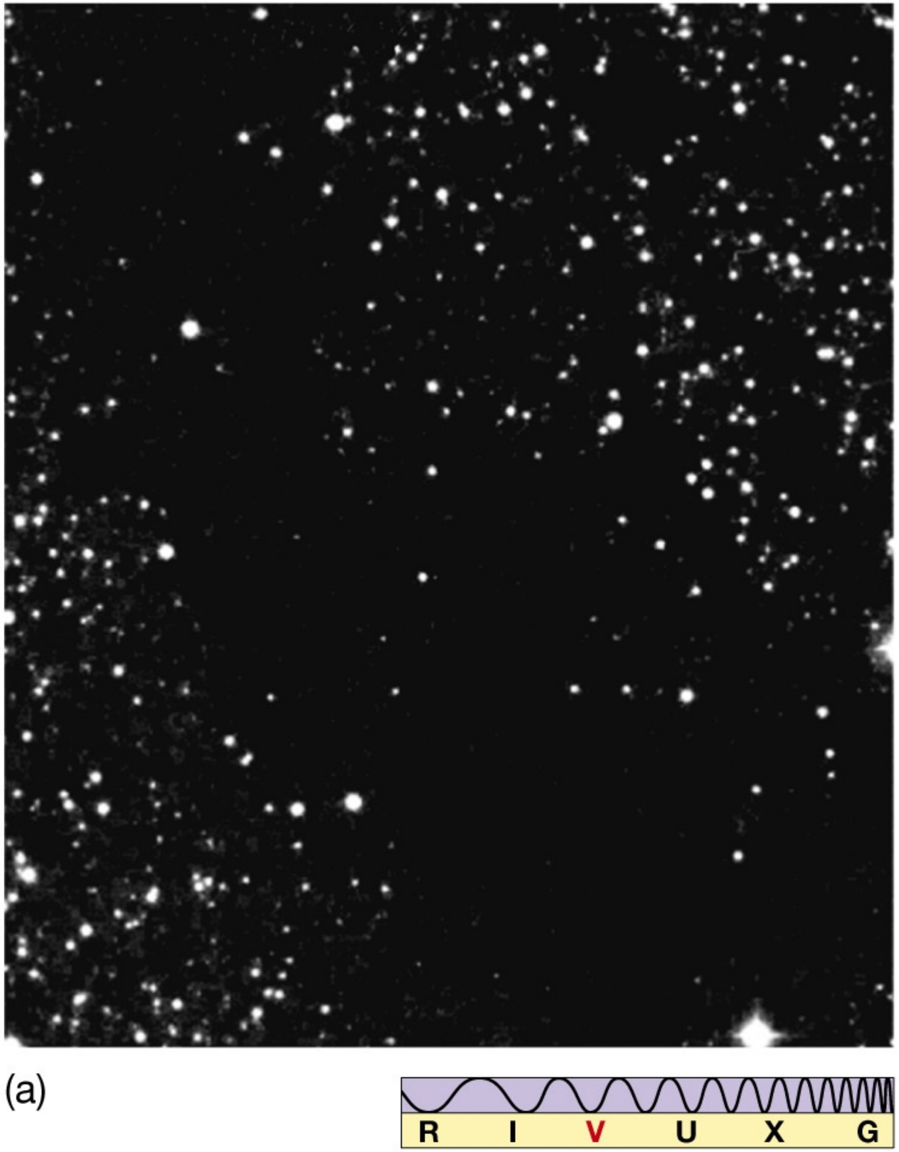
H_2 – cold, molecular hydrogen. Invisible, detected in UV.

HI – cool to warm atomic hydrogen. Invisible, except absorption & emission in UV and radio (21cm).

HII – hot, singly ionized hydrogen gas. Emits Balmer lines, pretty and pink!

Cold regions also contain complex molecules (organic!) and dust. Most molecules are detectable in radio.

Figure 18-11 Dusty molecular cloud
Obscuration (in visible) and Emission (in radio, from CO molecules)



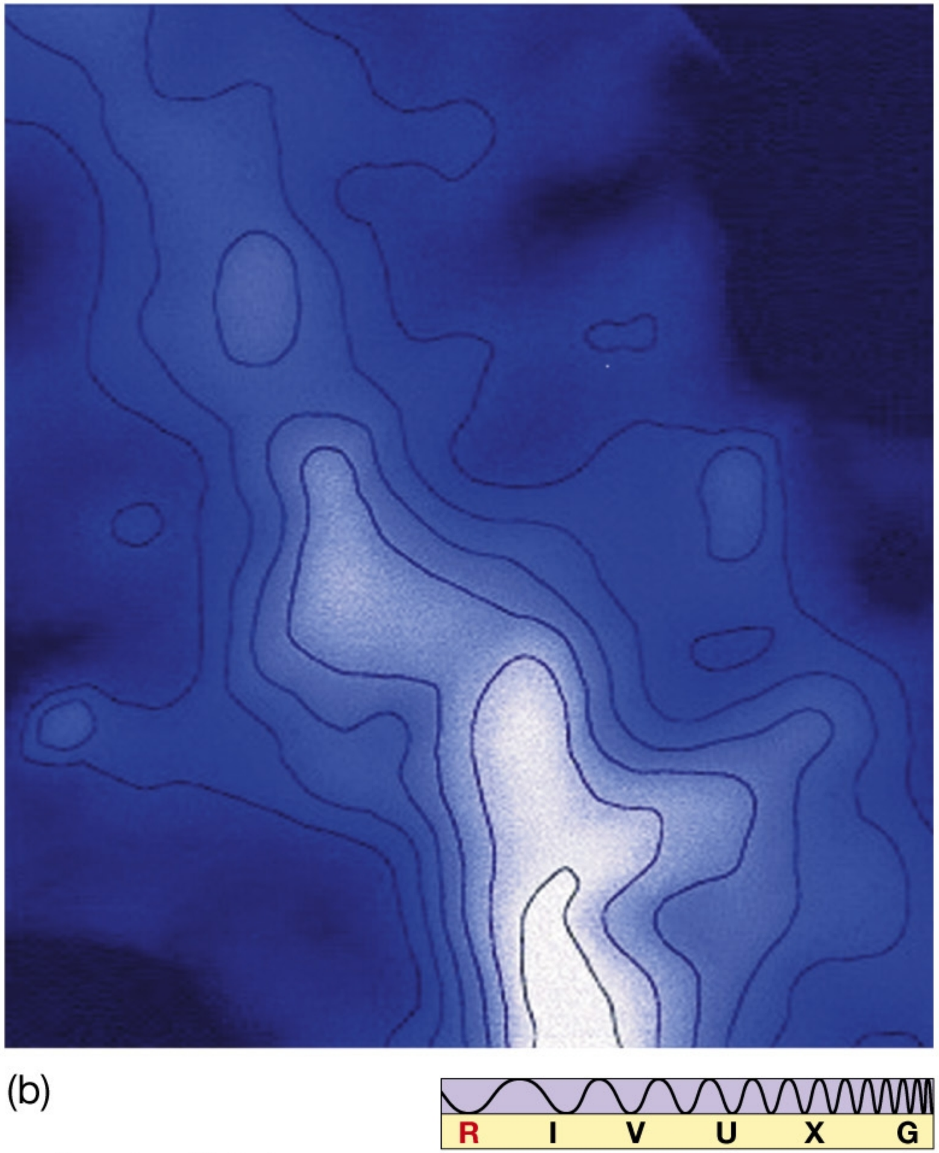


Figure 18-18
Molecular Absorption Near M20

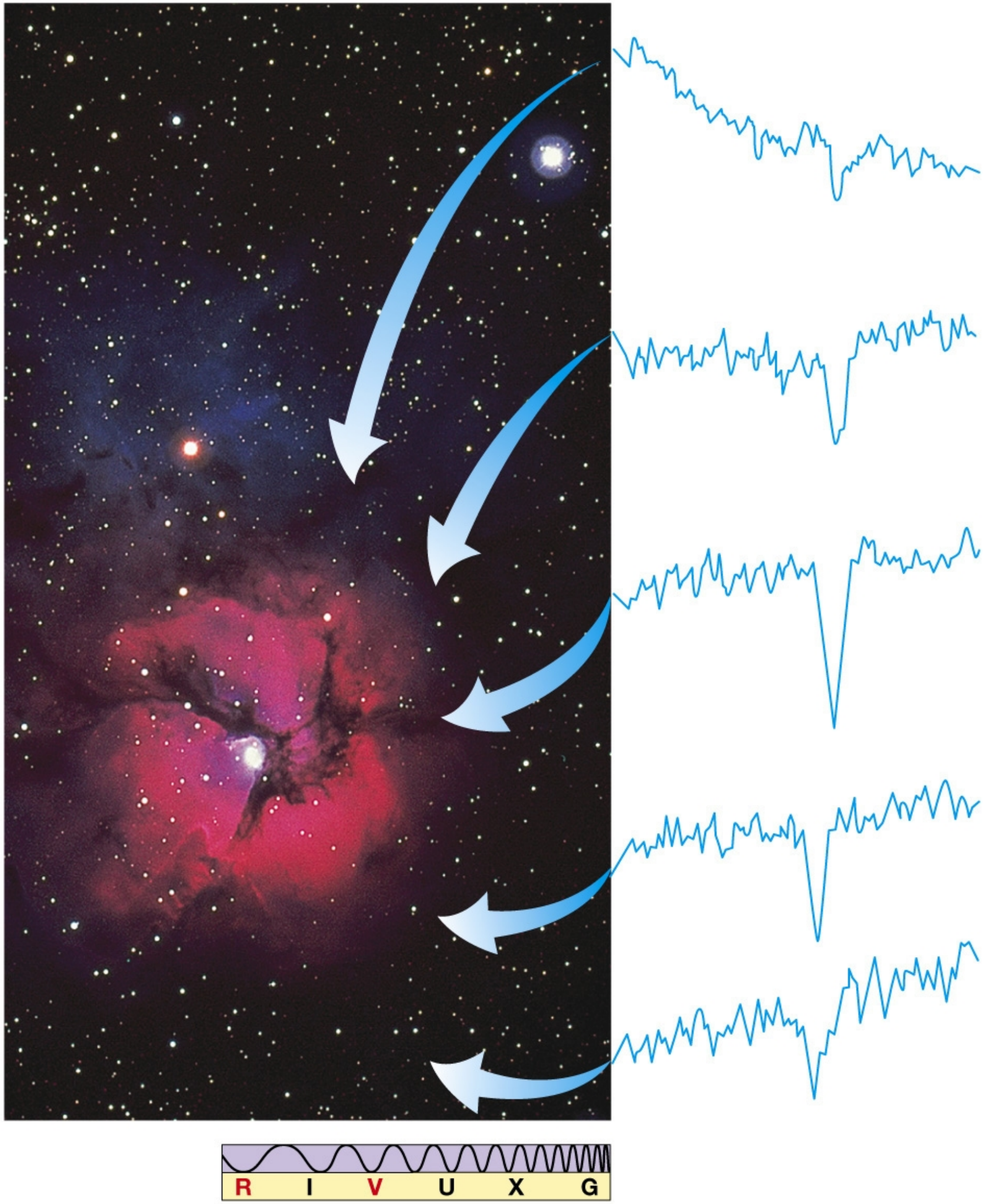
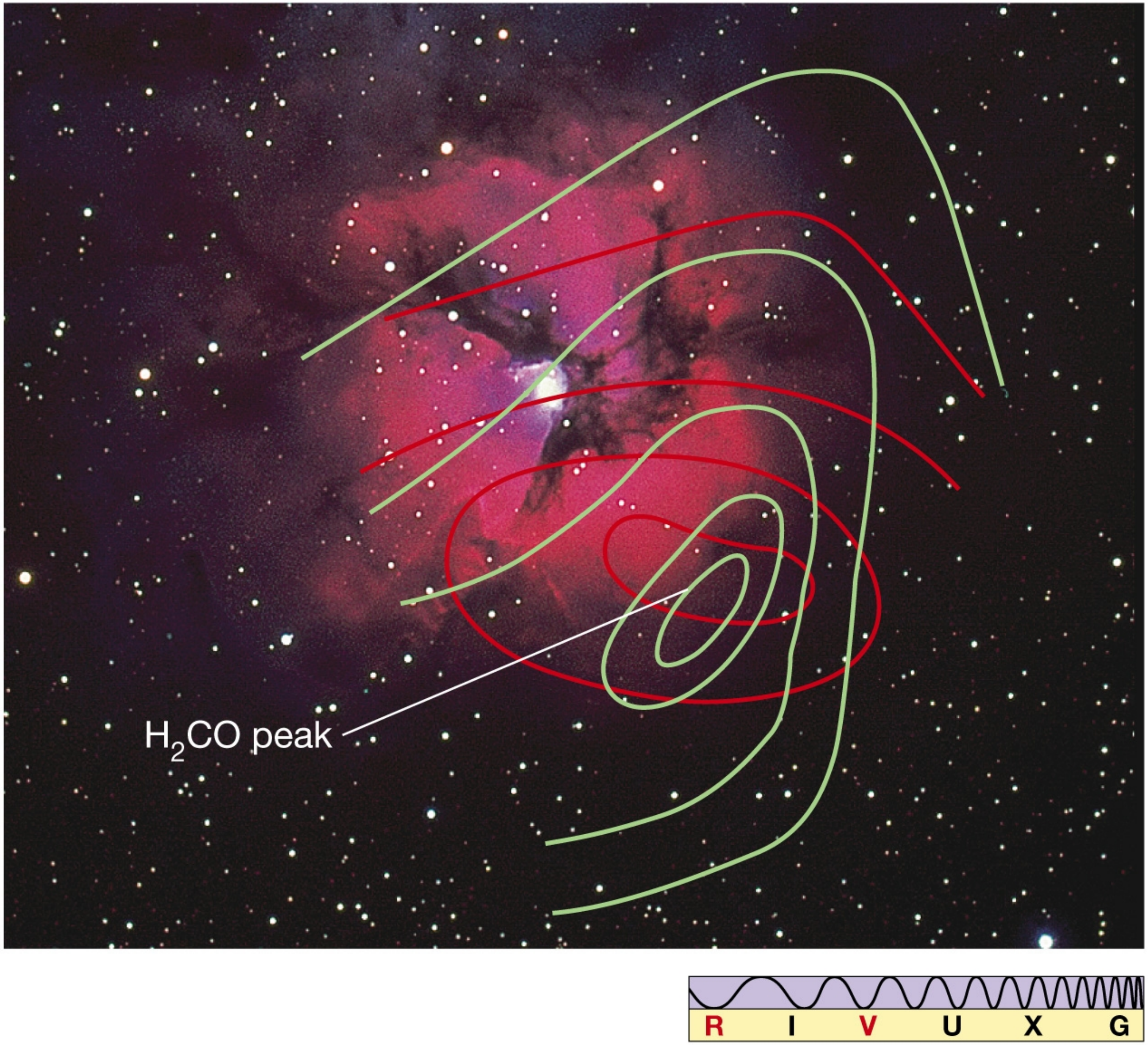


Figure 18-19
M20 Radio Map ... in formaldehyde



Summary of Molecular clouds (MCs and GMCs):

Stars form in big molecular clouds made of mostly H_2.

We study these clouds with radio and infrared emission because H_2 “tracer” molecules emit radio.

Tracer molecules like CO and H_2CO coexist with H_2 and are more detectable in radio emission and absorption.

Infrared can “see into” the dust and reveal hot protostars.

One molecular cloud can form hundreds to thousands of stars.

(Star clusters!)

The first stars to form will “light up” the cloud and begin blowing away the cloud.

Starting questions - checkpoint

I. How are stars born?

a) What do they look like before they're born?

Dark clouds of dust and gas molecules called molecular clouds. We can “see” into these cold clouds in radio and IR wavelengths revealing warmer clumps of collapsing gas. Parts of these clouds will light up with emission and reflection nebula as new stars emerge.

b) What is the pre-stellar material made of?

Mostly H_2 (molecular hydrogen), but a large variety of molecules (e.g., chloroform) have been identified.

c) How can stellar nurseries be identified?

In optical: as bright emission line nebulae, also called HII regions. In IR: as bright (hot) spots inside of molecular clouds.

d) When does a blob of gas officially become a star?

It is a “protostar” as it's cocoon of gas is being shed (stages 3-5, next page), and it is a “star” when H fusion begins.

e) How long does it take (to reach fusion)?

About $5x10^7$ for a 1 solar mass star, but faster for more massive stars.

I. How are stars born?

Table 19-1
Prestellar Evolution of a Solar-Type Star

TABLE 19.1 Prestellar Evolution of a Solar-Type Star

Stage	Approximate Time to Next Stage (yr)	Central Temperature (K)	Surface Temperature (K)	Central Density (particles/m^3)	Diameter* (km)	Object
1	2×10^6	10	10	10^9	10^{14}	Interstellar cloud
2	3×10^4	100	10	10^{12}	10^{12}	Cloud fragment
3	10^5	10,000	100	10^{18}	10^{10}	Cloud fragment/protostar
4	10^6	1,000,000	3000	10^{24}	10^8	Protostar
5	10^7	5,000,000	4000	10^{28}	10^7	Protostar
6	3×10^7	10,000,000	4500	10^{31}	2×10^6	Star
7	10^{10}	15,000,000	6000	10^{32}	1.5×10^6	Main-sequence star

Round numbers; for comparison, recall that the diameter of the Sun is 1.4×10^6 km, while that of the solar system is roughly 1.5×10^{10} km.

Figure 19-6
Interstellar Cloud Evolution

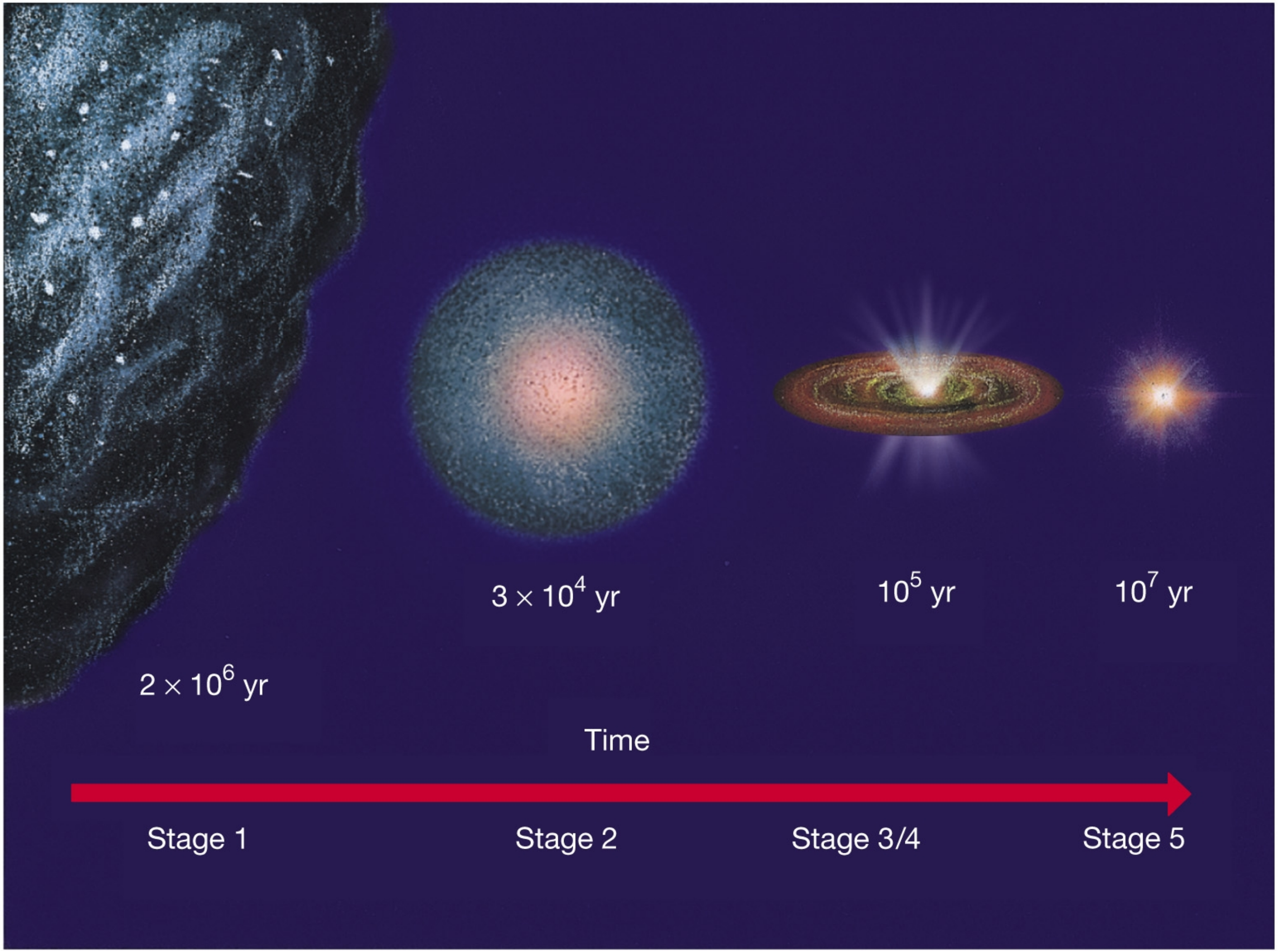
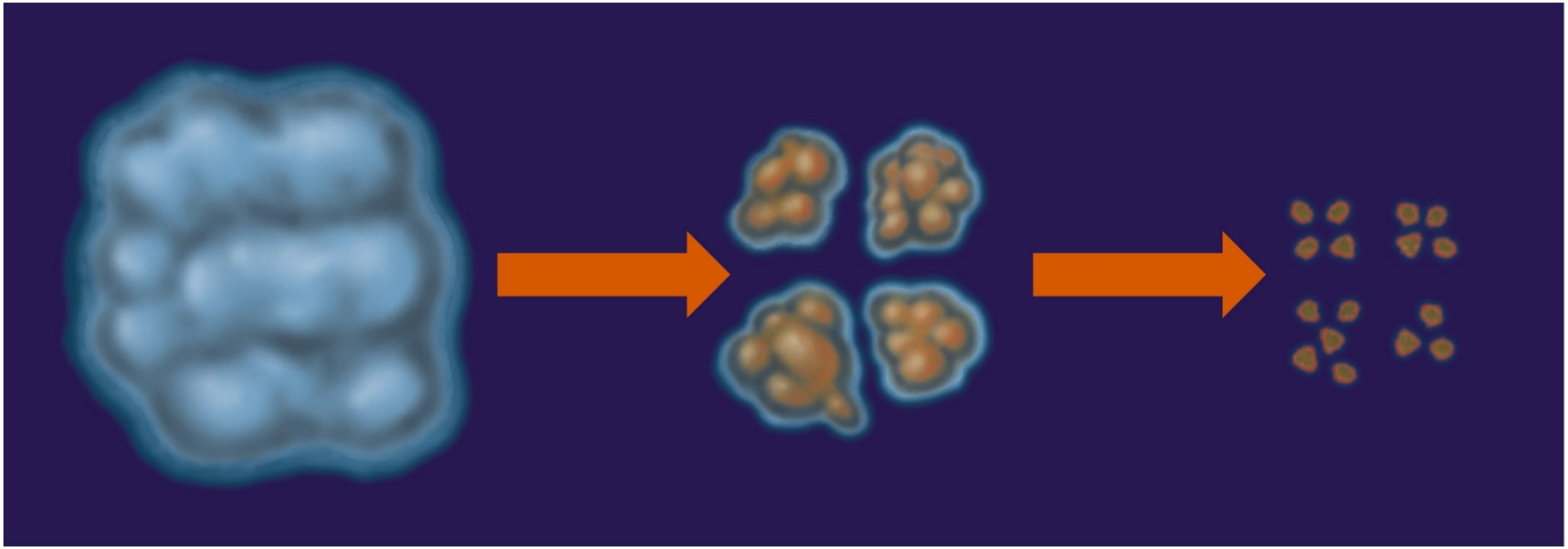
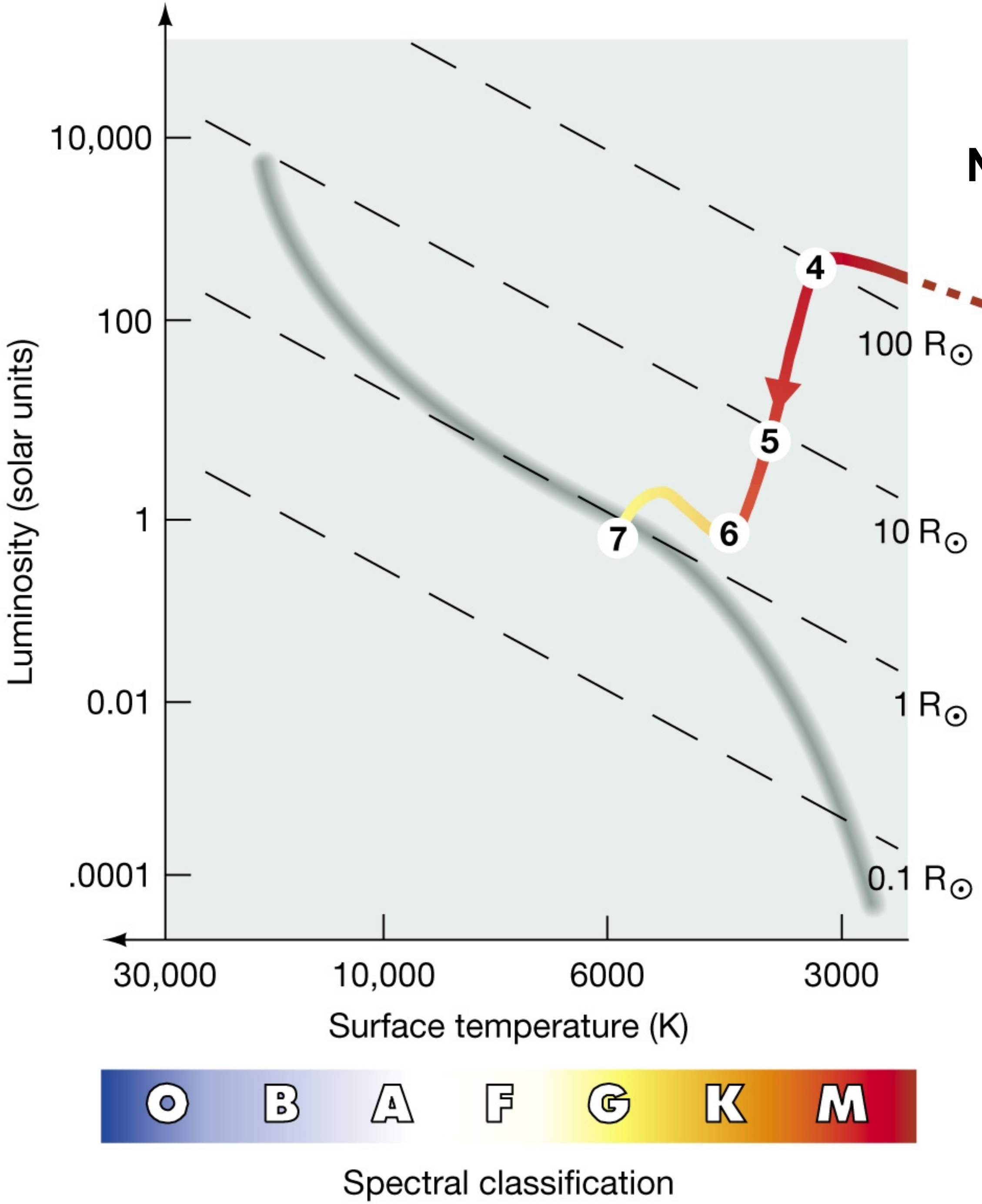


Figure 19-4
Cloud Fragmentation



(Stages 2 and 3)

Figure 19-7
Newborn Star on the H–R Diagram

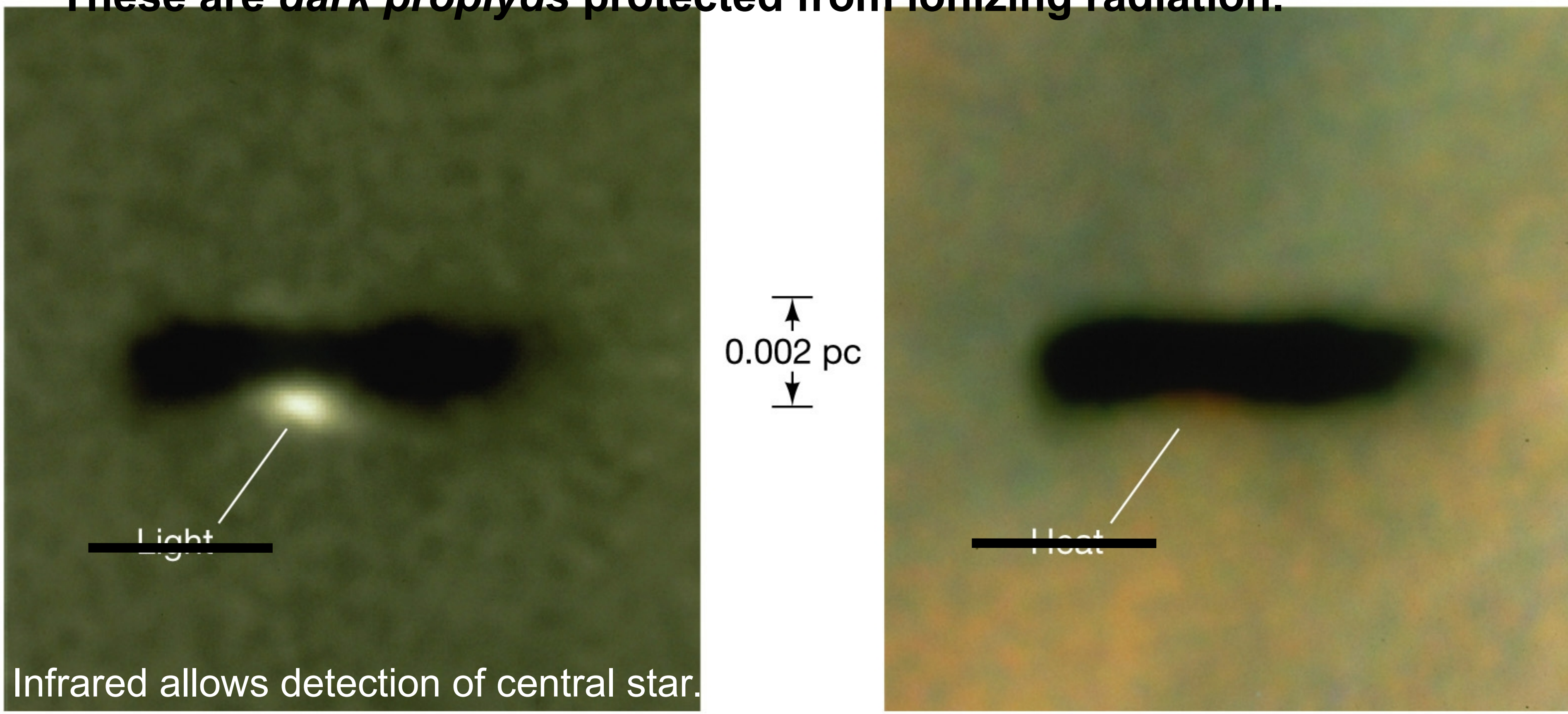


The “Hayashi Track”

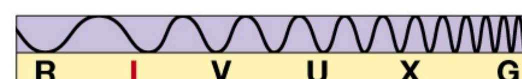
= track on HR Diagram showing pre- main sequence evolution.

Figure 19-11
Protostars in *Proplyds*

Proplyds **stands for Protoplanetary disks. The scale bar shows .002pc = 400 AU, so these are about 5 solar systems across. These are** ***dark proplyds*** **protected from ionizing radiation.**

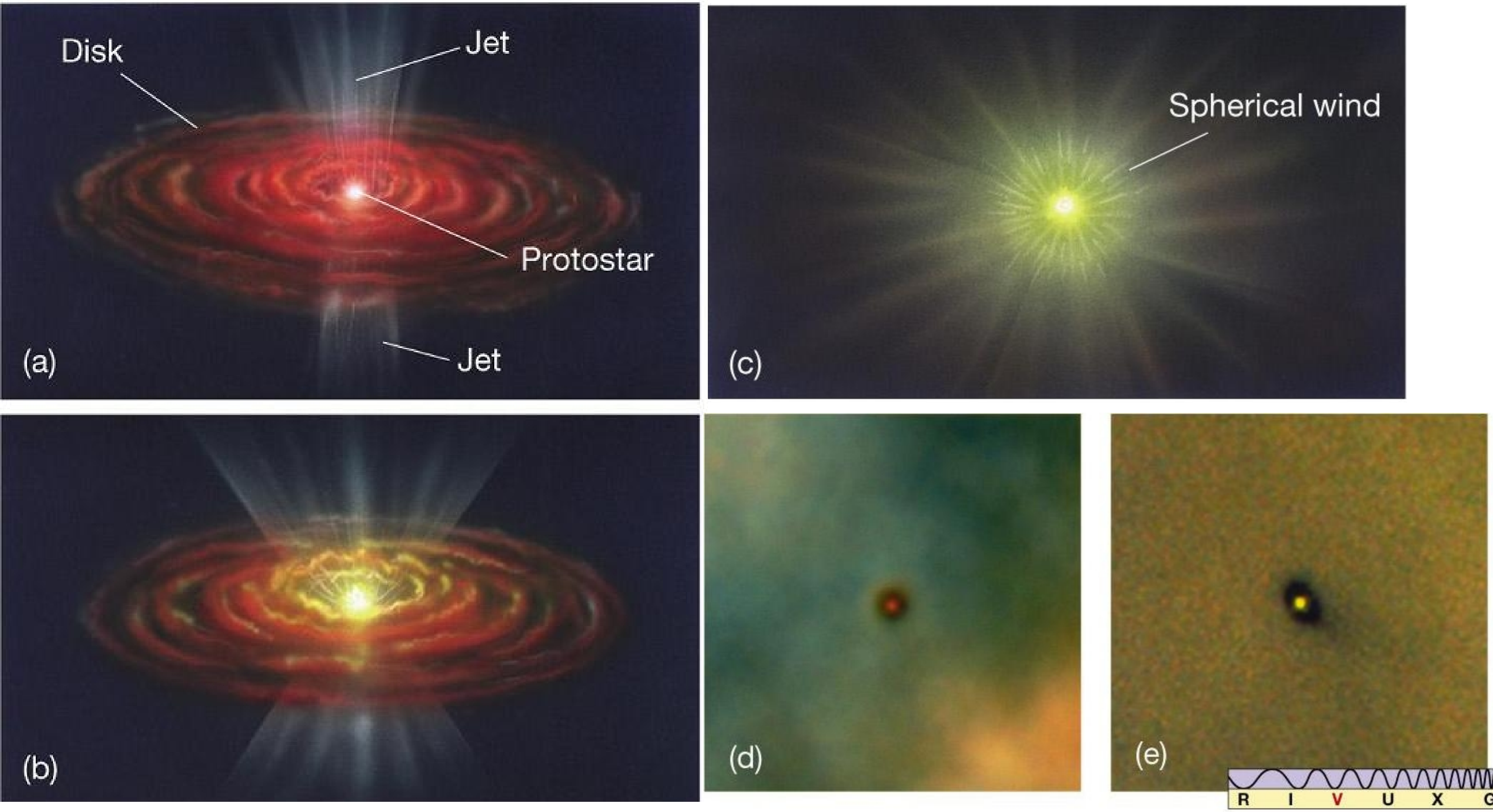


(Stages 3-5)



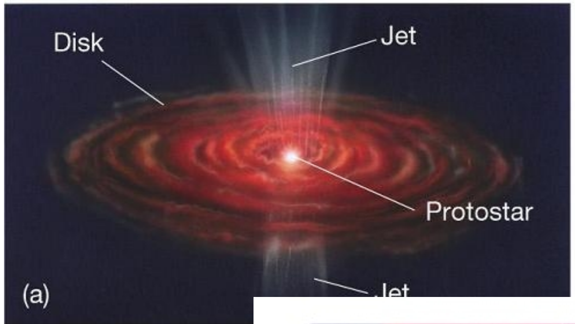
A multitude of *Proplyds* in Orion.

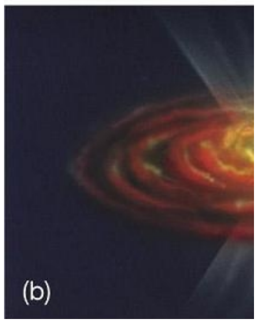
Figure 19-12
Protostellar Wind



Young Stellar Objects (YSOs) in the IR

These are basically proplyds, but in these IR HST images, the disks and outflows are more obvious, and bow shocks and photo-ionization fronts are not seen.





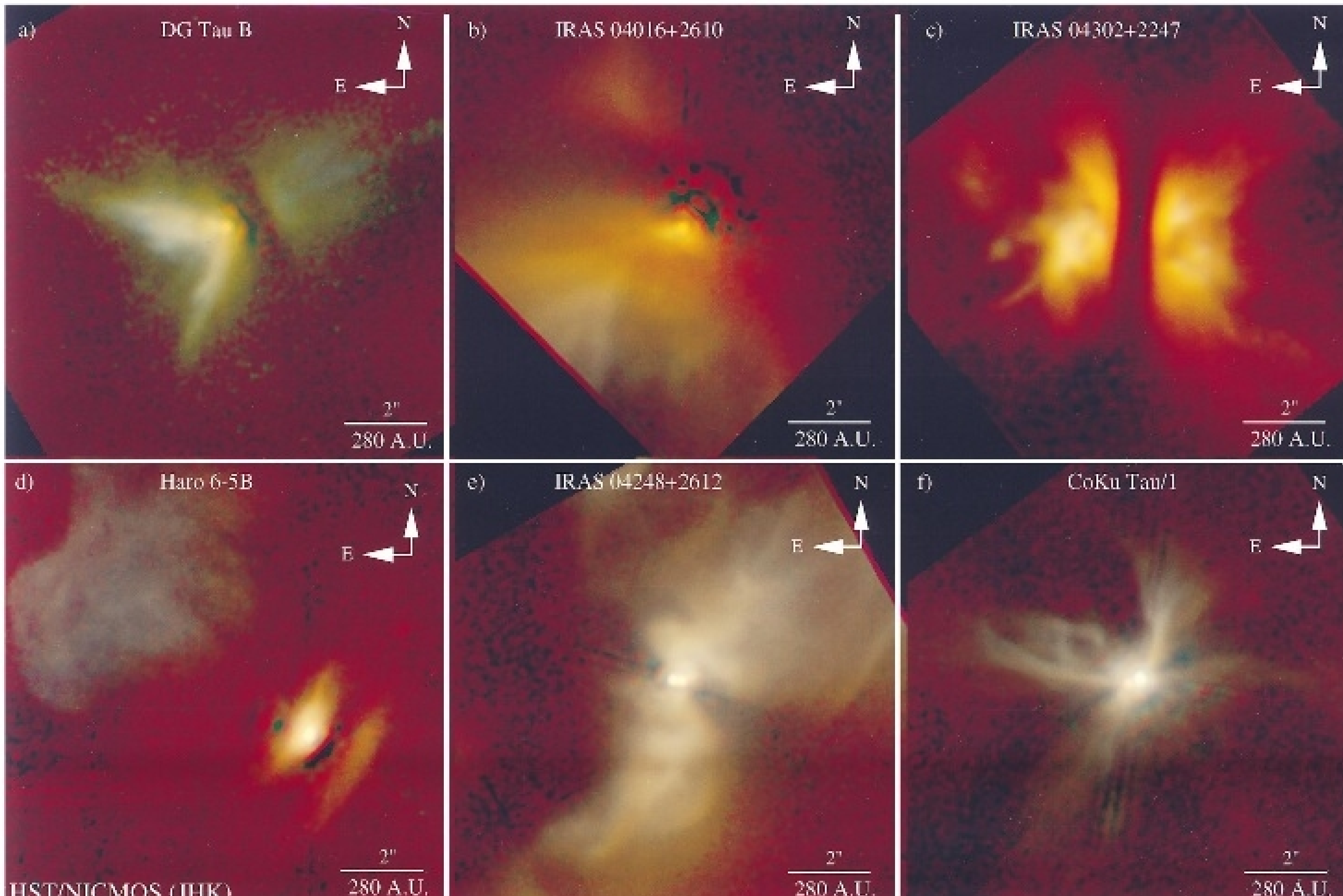


FIG. 1.—*HST*/NICMOS images of Taurus young stellar objects, arranged in order of decreasing circumstellar mass. These are pseudo–true color composites of NICMOS F110W (1.1 μm), F160W (1.6 μm), and F205W (2.05 μm) broadband observations. Each image was deconvolved using theoretical point-spread functions, resulting in a factor of 3 reduction in extended PSF features. Note that objects (*e*) and (*f*) are subarcsecond binaries. North is up in all images.

Evaporating Gaseous Globules (EGGs) and Herbig-Haro objects in the Carina Nebula

Where have you seen this picture before?
(Try Zoomit!)

Star formation terms

Interstellar cloud: denser than average region of ISM that includes other types of clouds (GMCs, MCs, diffuse clouds). Typically 10-500 LY across.

Molecular Cloud: an interstellar cloud or part of an interstellar cloud with at least some regions cold enough to have molecules, especially H_2.

Giant Molecular Cloud (GMC): large complex of molecular clouds (diam > 100 LY) usually containing over 100,000 $M_\odot$ of gas. Temps 10-50 K. Mostly H2 with ~1% dust, 5% He. Ripe for star formation.

Emission nebula: a region within an interstellar cloud which is glowing because its H gas is excited by UV from hot, young stars.

EGGs = Evaporating Gaseous Globules – blobs of gas along the edge or making up the edge of dust "pillars" and clouds undergoing photo-evaporation. These are generally larger than proplyds and may contain many proplyds and hidden, young stars.

Proplyds = protoplanetary disks. 100-1000 AU across (tiny compared to molecular cloud. Traditionally identified in visible wavelength HST images.

YSOs = Young Stellar Objects – young stars still embedded in gas and dust disks but exhibiting strong, polar winds and jets. Traditionally identified in infrared data, but basically these are proplyds that show outflows. These objects are also called *T Tauri stars* if they are < 2 $M_\odot$.

Herbig-Haro Objects = blobs making up the jets shooting out of YSOs. Also identified in the IR.

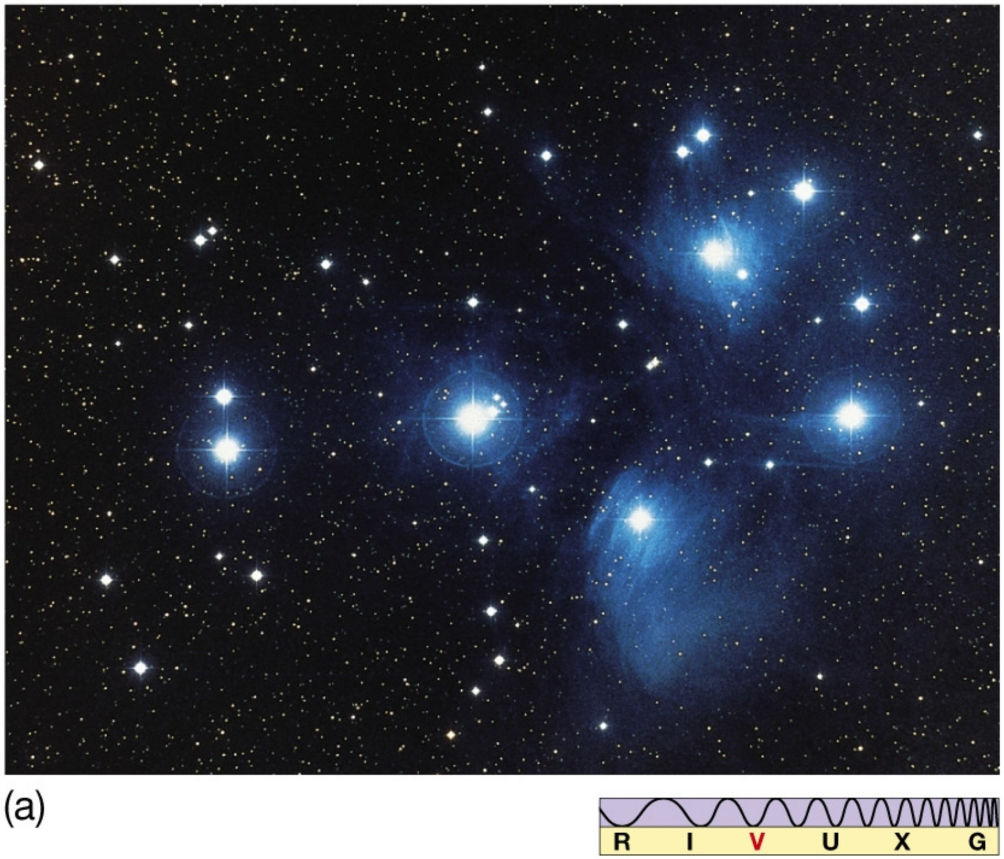
Star formation terms

Protostar = object destined to become a star. It may or may not still have a dust disk or envelope around it. It is not yet hot and dense enough for fusion to occur. It is powered by gravitational collapse (Kelvin-Helmholtz contraction.) Stages 3-5 of star formation; before fusion.

Photoevaporation = the dissipation or blowing away of dusty clouds caused by light (especially UV) and winds from hot, massive young stars.

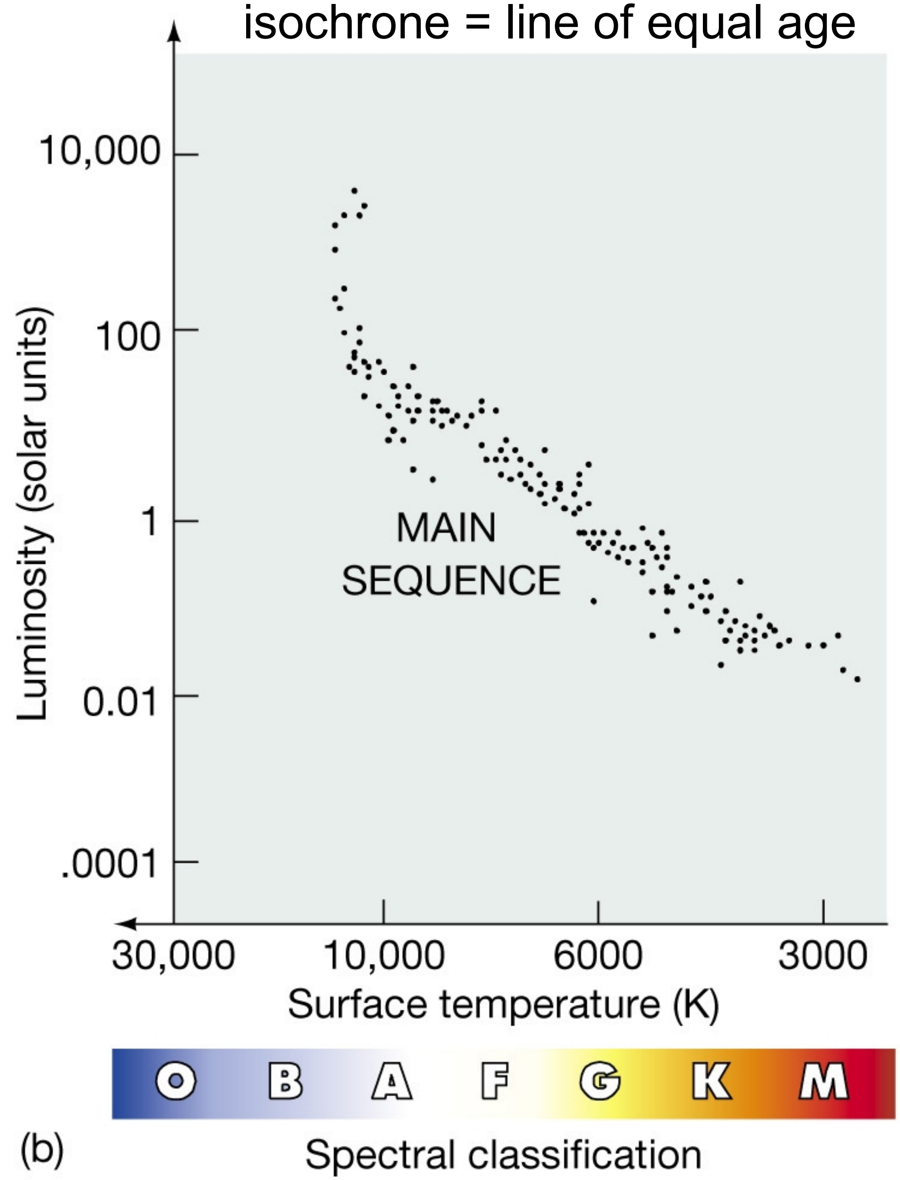
Figure 19-18
Star Clusters

The Pleiades = an open cluster



(a)

isochrone = line of equal age



(b)

Types of star clusters:

1. **O-B associations**
2. **Open Clusters or Galactic Clusters**
3. **Globular clusters**

Figure 19-17
Newborn Cluster

NGC 3603 ~2million yrs old. 20 LY field of view.

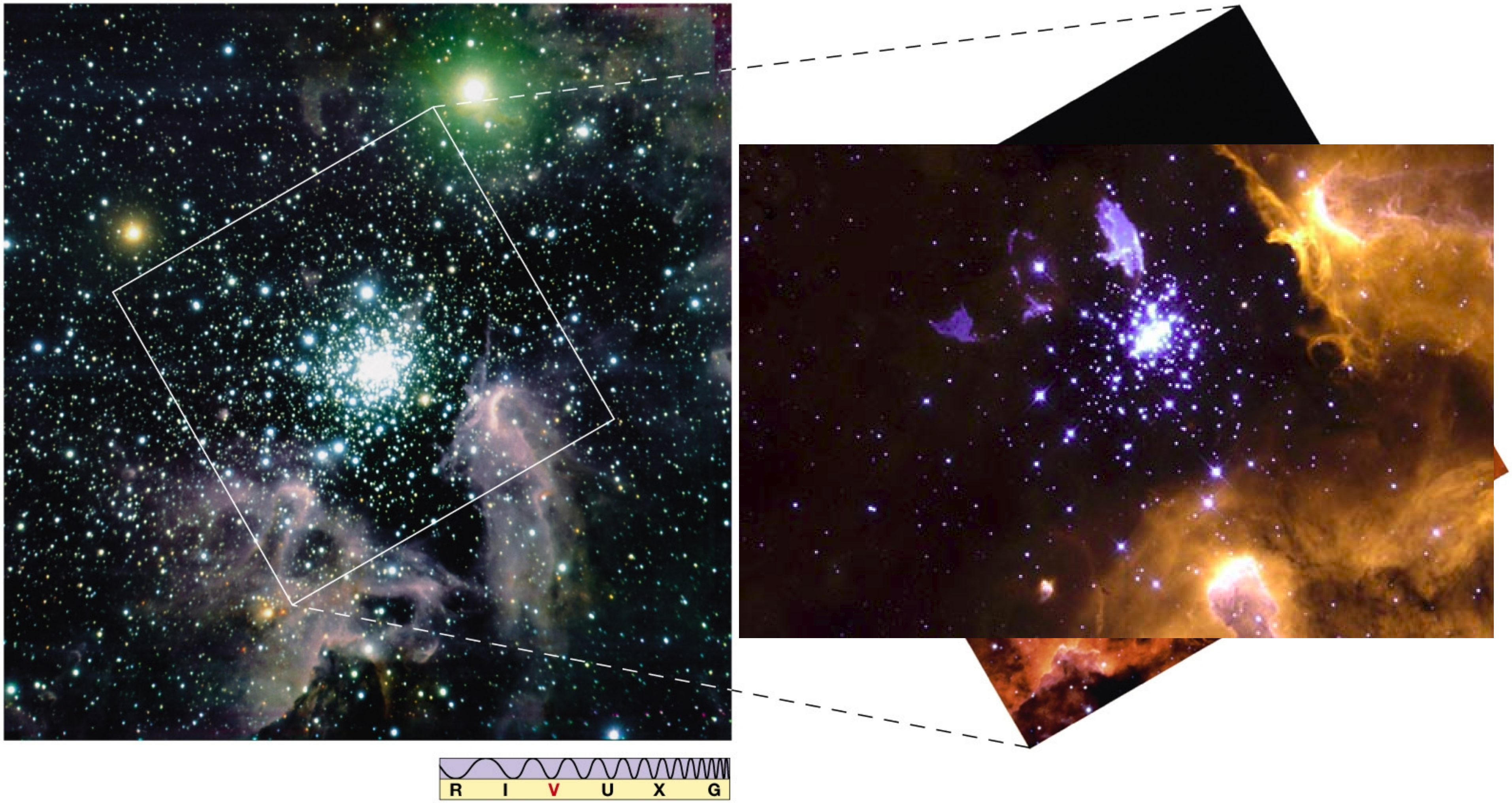
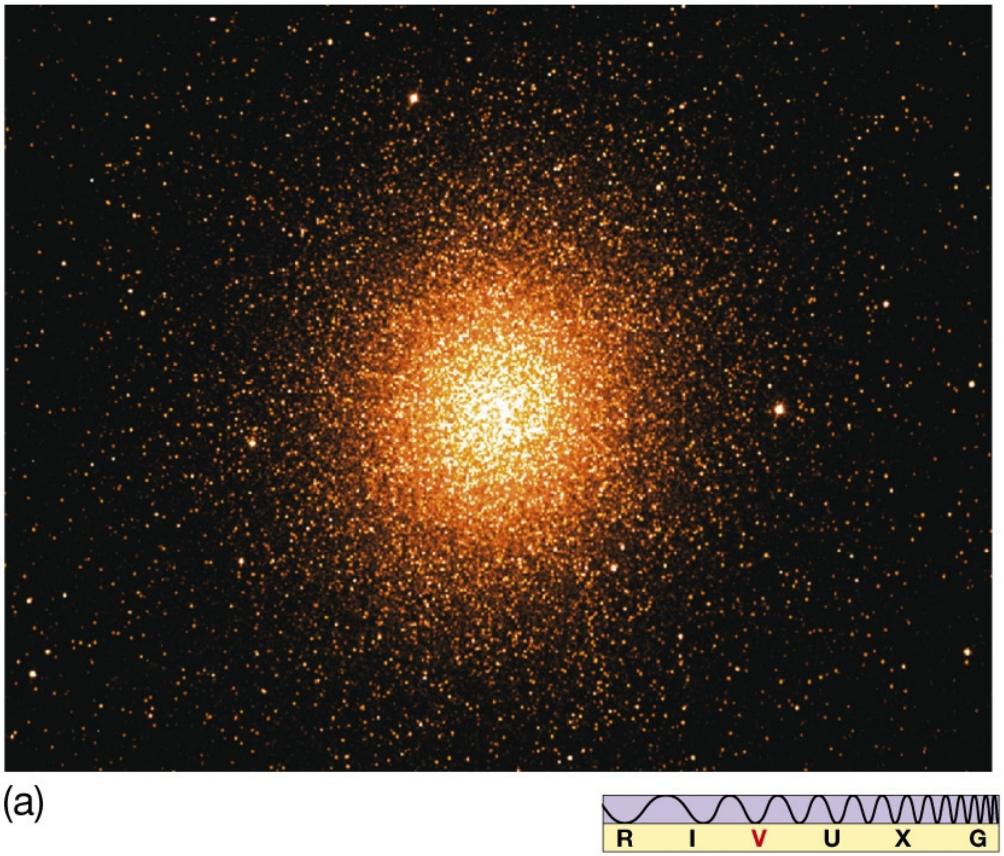
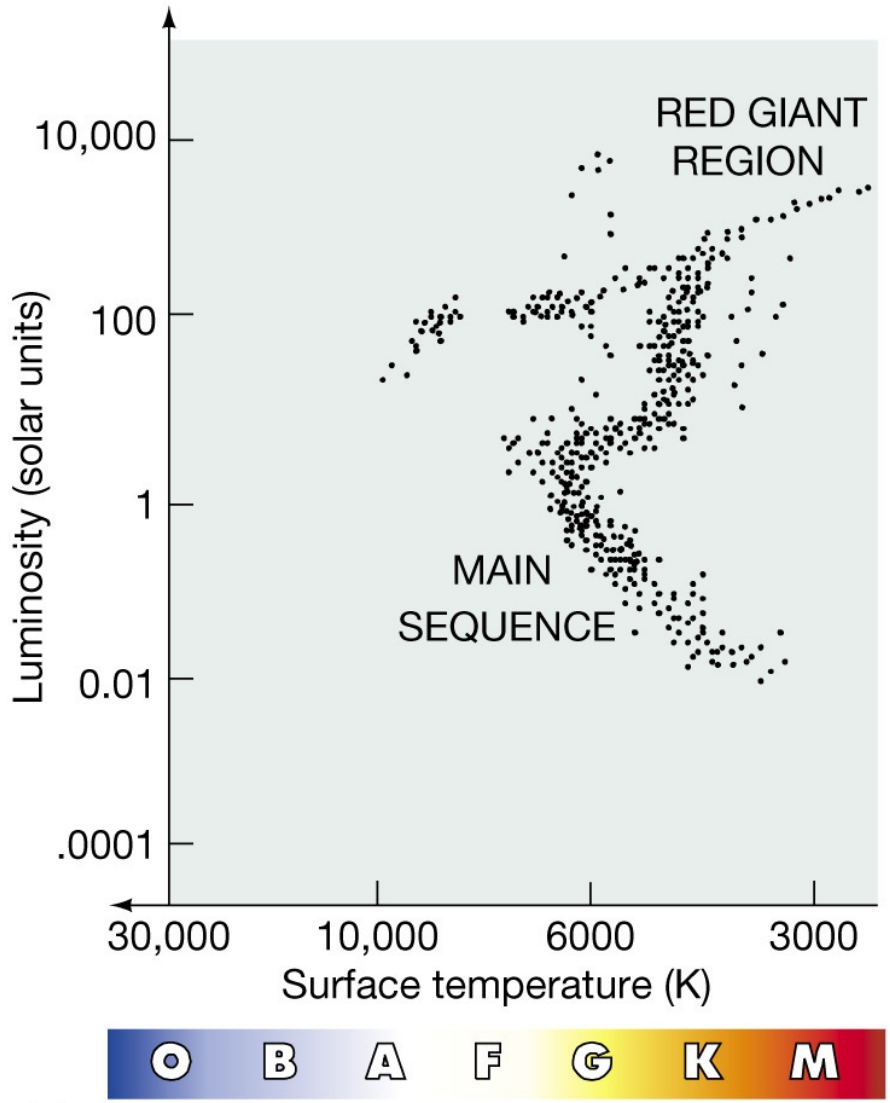


Figure 19-18
Globular Cluster

Omega Centauri, 5 kpc away, 120 LY FOV.



(a)



(b)

II. Stellar Evolution: The Life and Death of a Star

The Helix Nebula

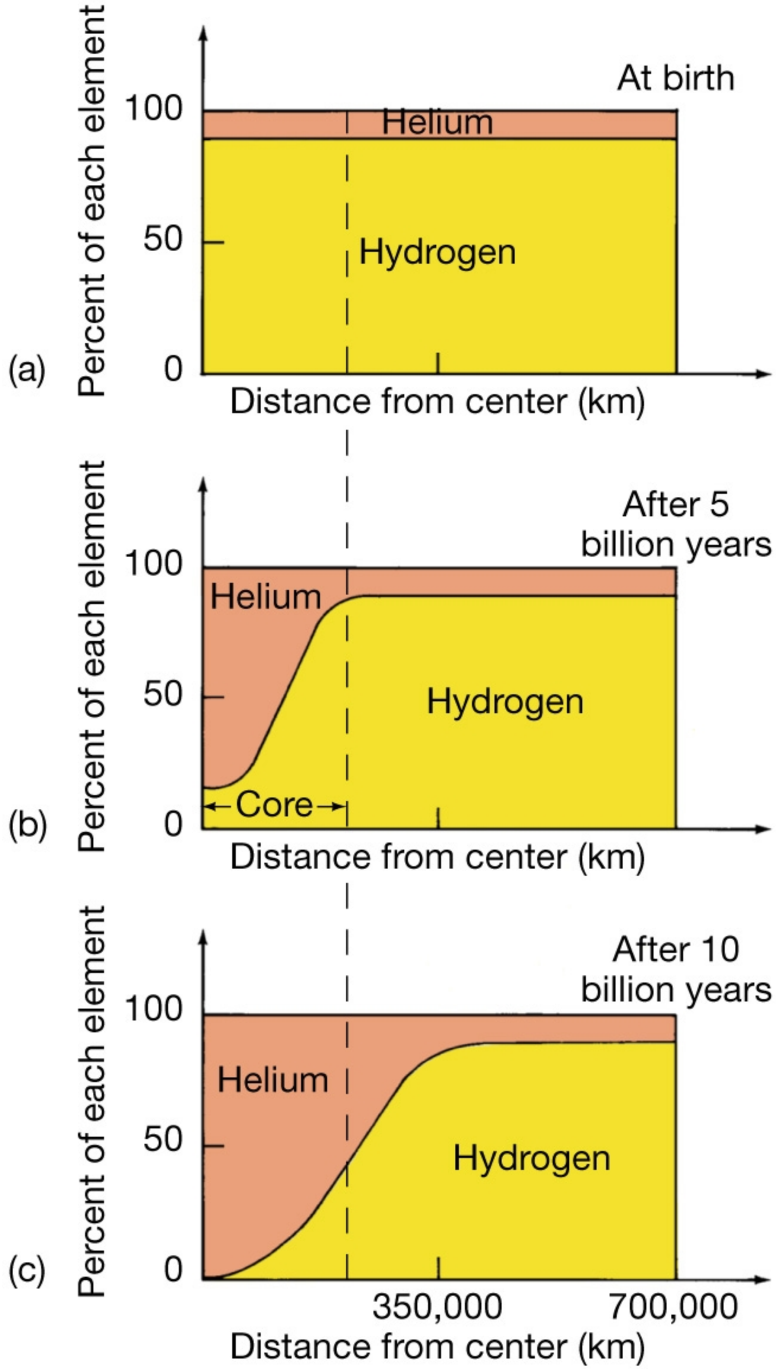
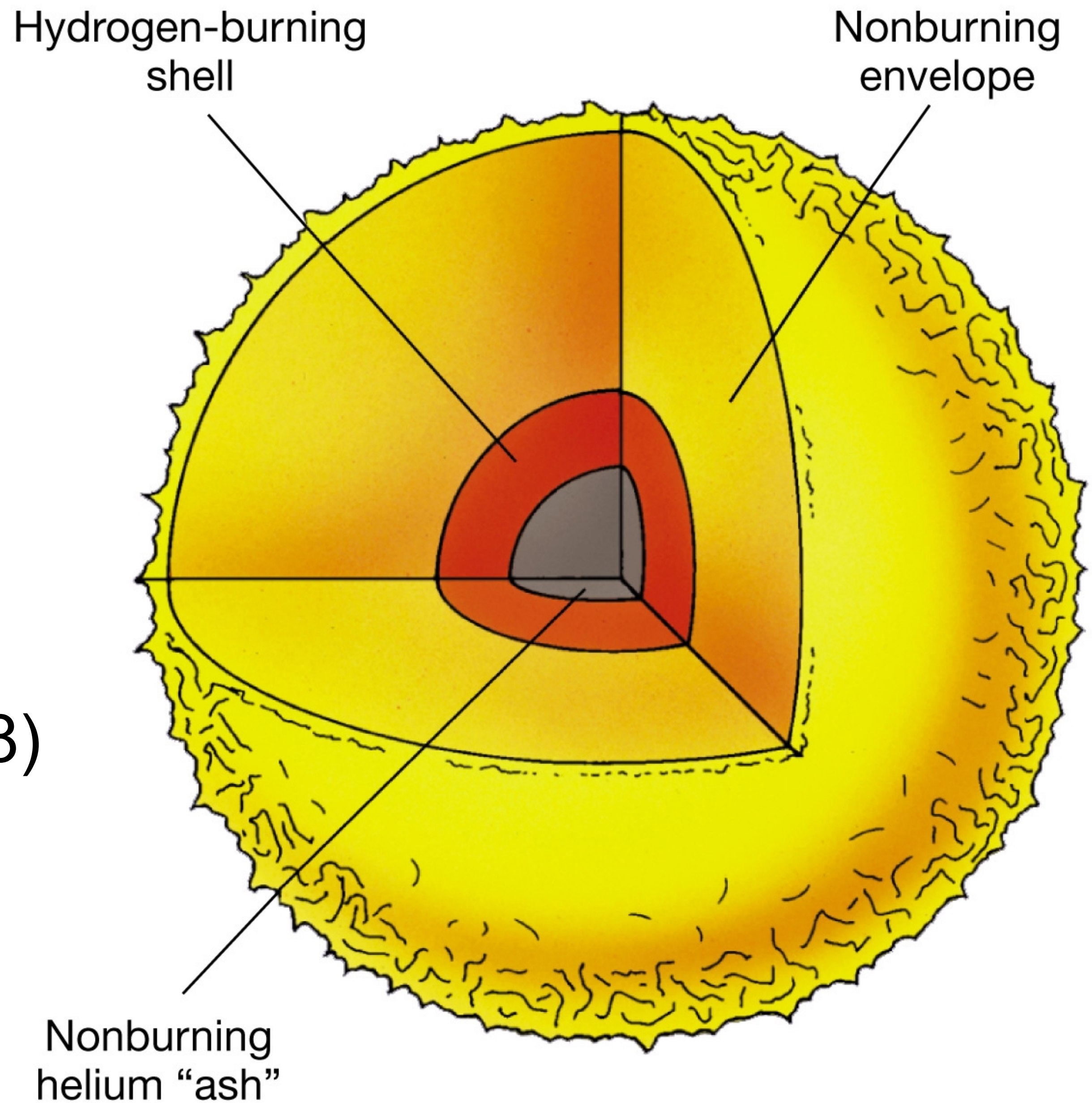


Figure 20-2
Change in Solar Composition on the Main Sequence

Figure 20-3
Hydrogen-Shell Burning



(Stage 8)

Figure 20-1
Hydrostatic Equilibrium

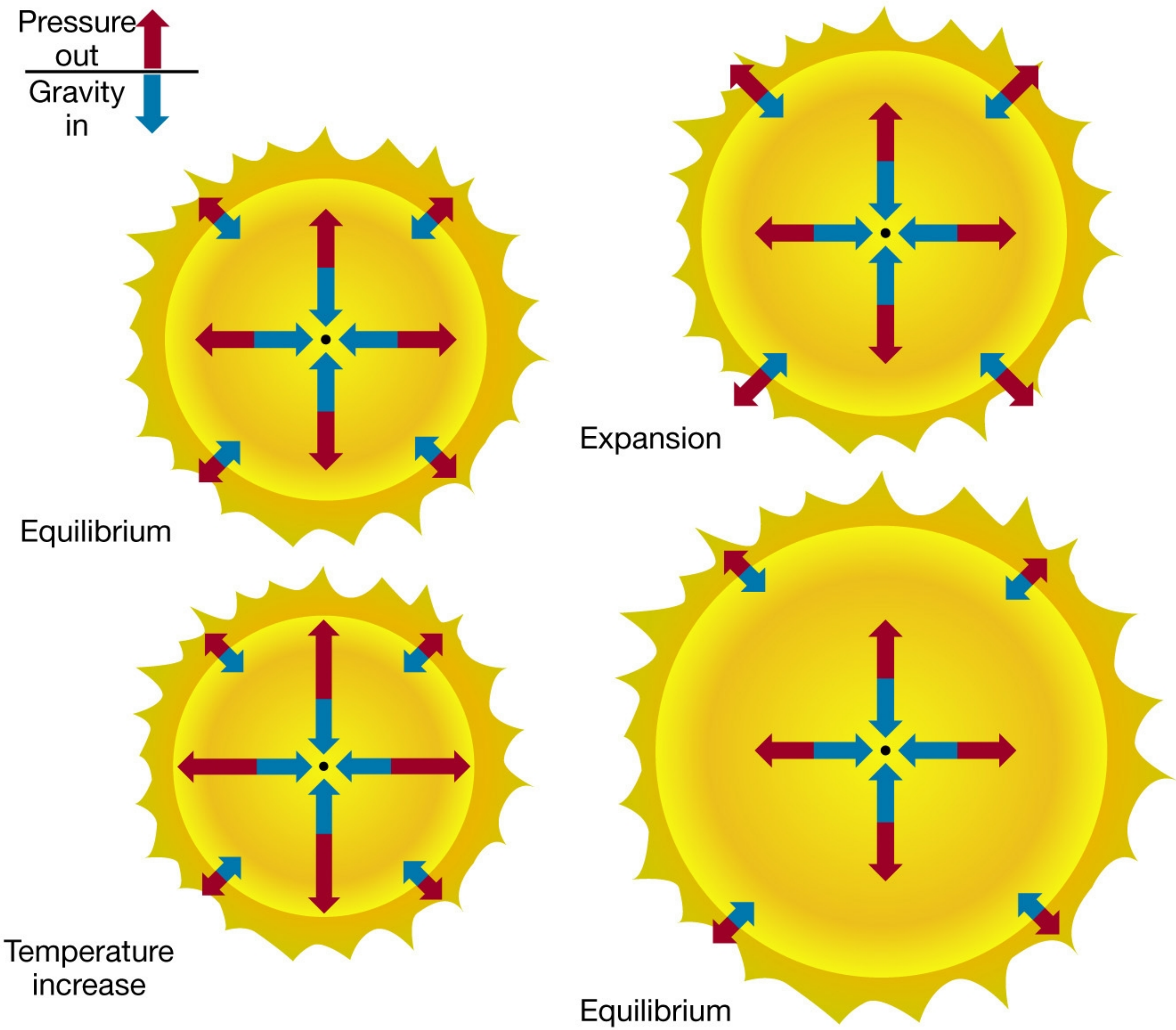
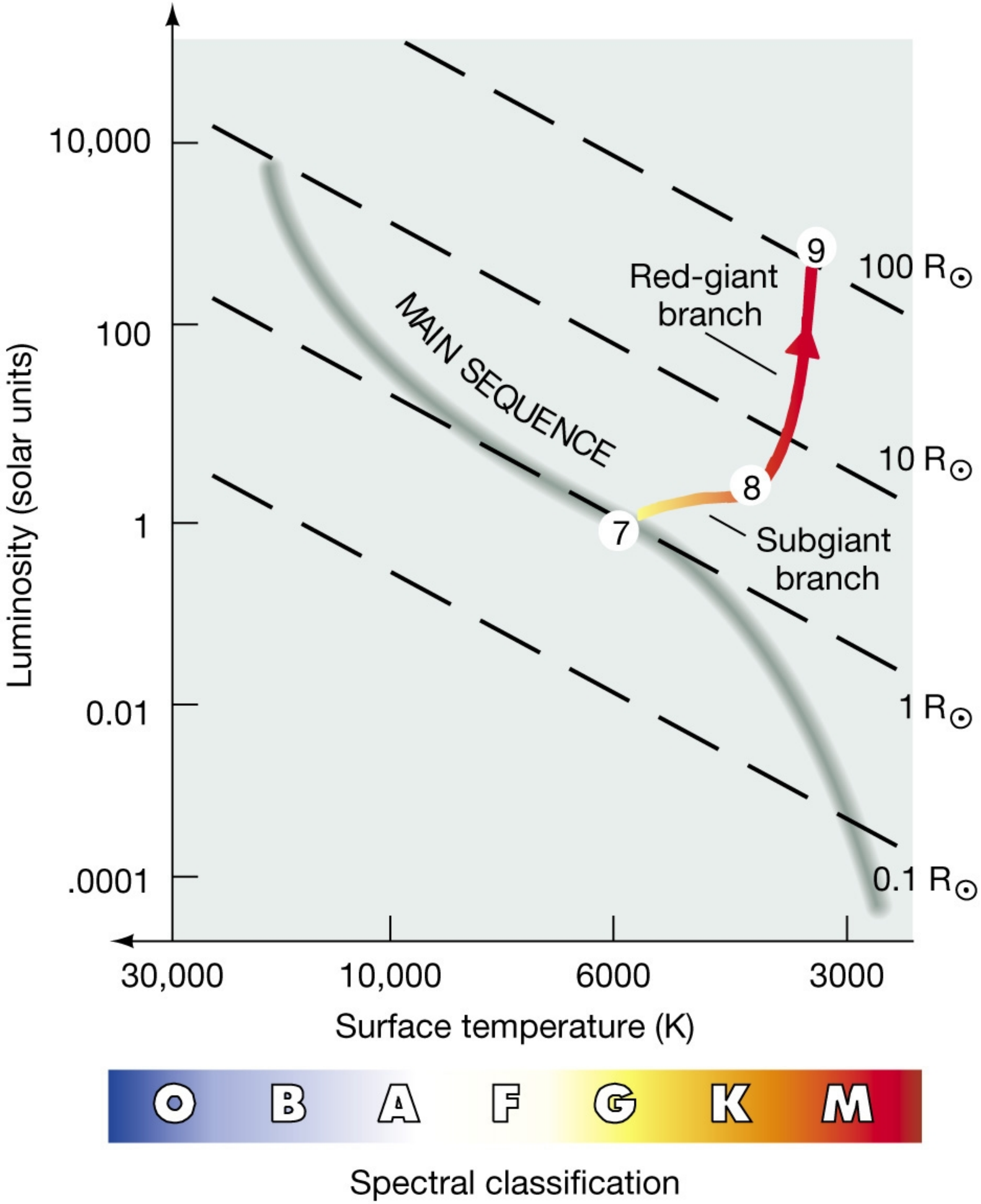


Figure 20-4
Red Giant on the H–R Diagram



Example of low-mass star on red giant branch: Arcturus (KIII).

As core collapses, the outer shells expand.

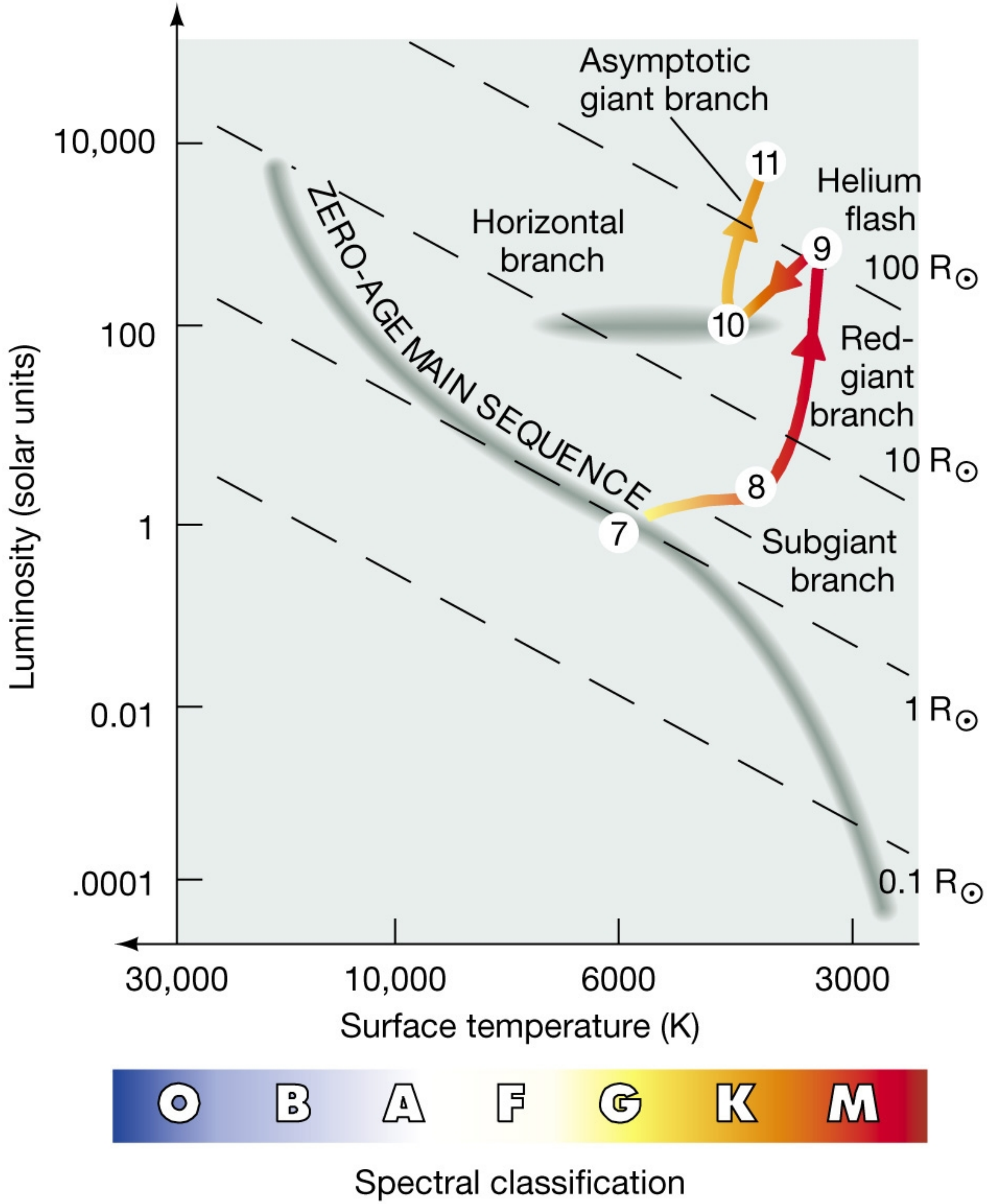


Figure 20-6
Red-Giant Branch Revisited

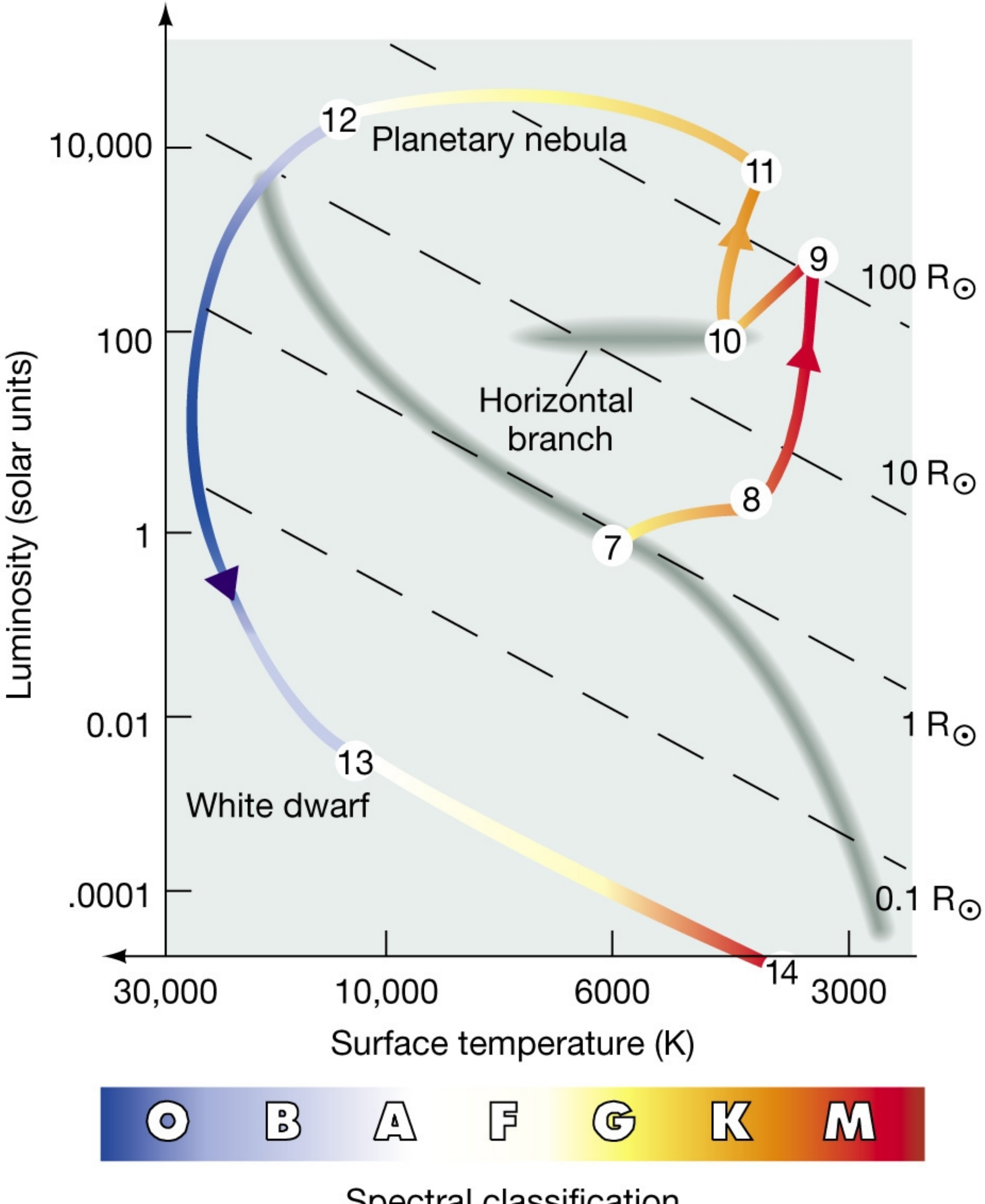
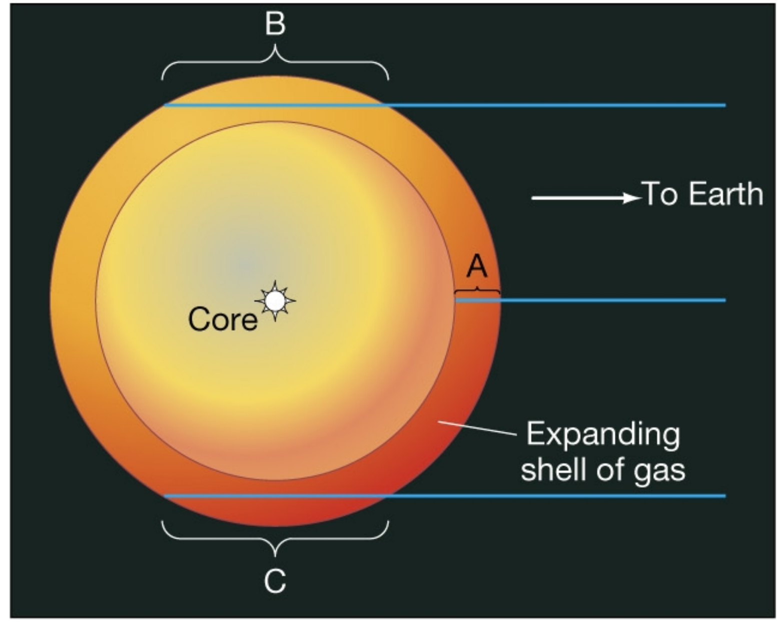


Figure 20-12
White Dwarf on the H–R Diagram

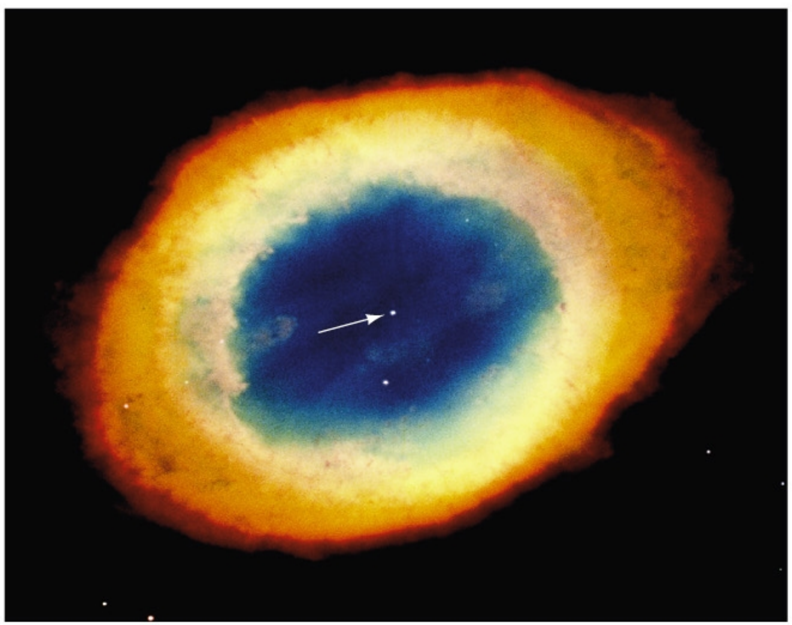
10: triple alpha process (He-> C)
Lasts 10's of millions Of years.

11-12: He shell burning is unstable → Planetary nebula & C+O white Dwarf is created.

(a)



(b)



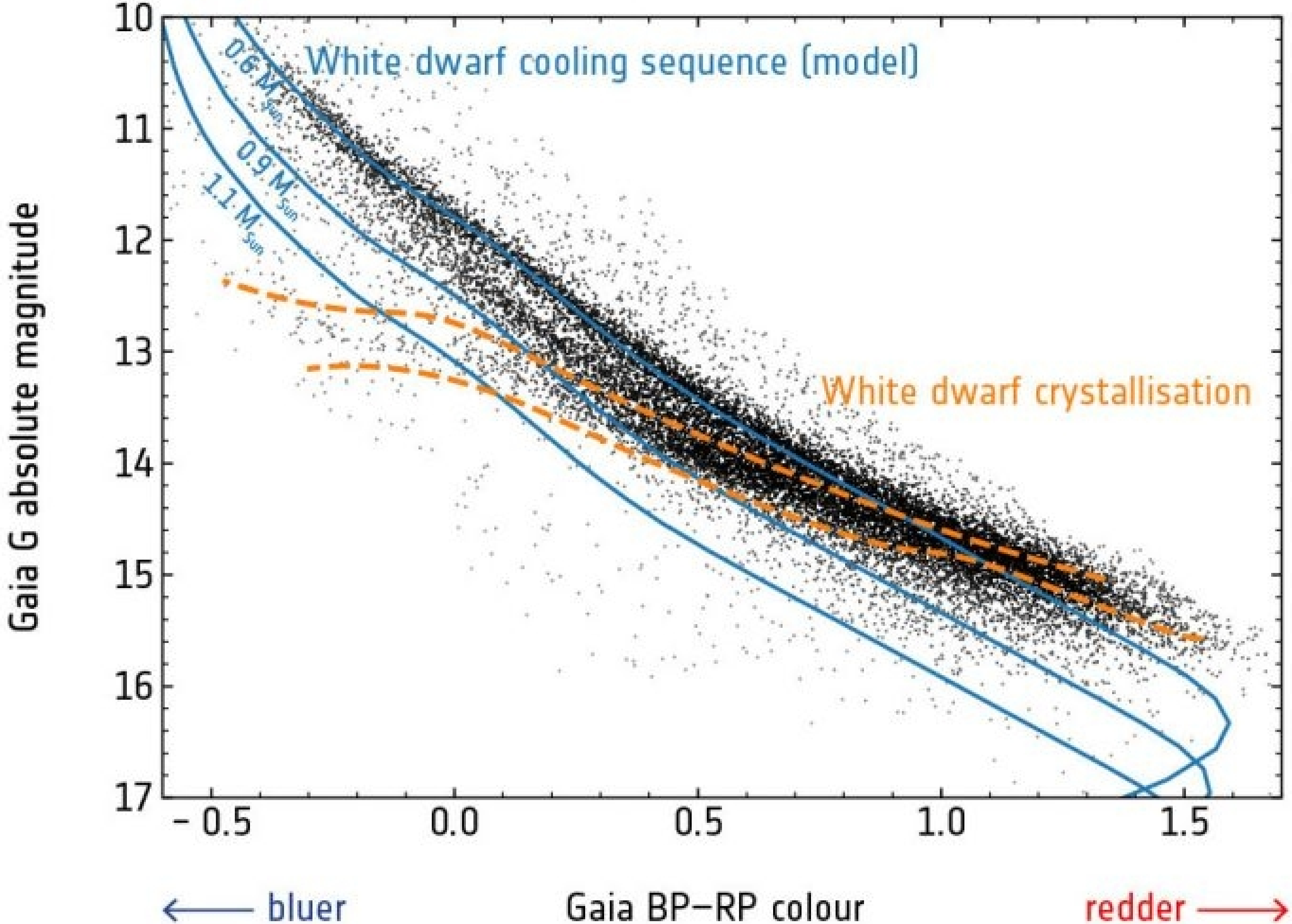
(c)

Figure 20-10
Ejected Envelope

Table 20-2
Sirius B, a Nearby White Dwarf

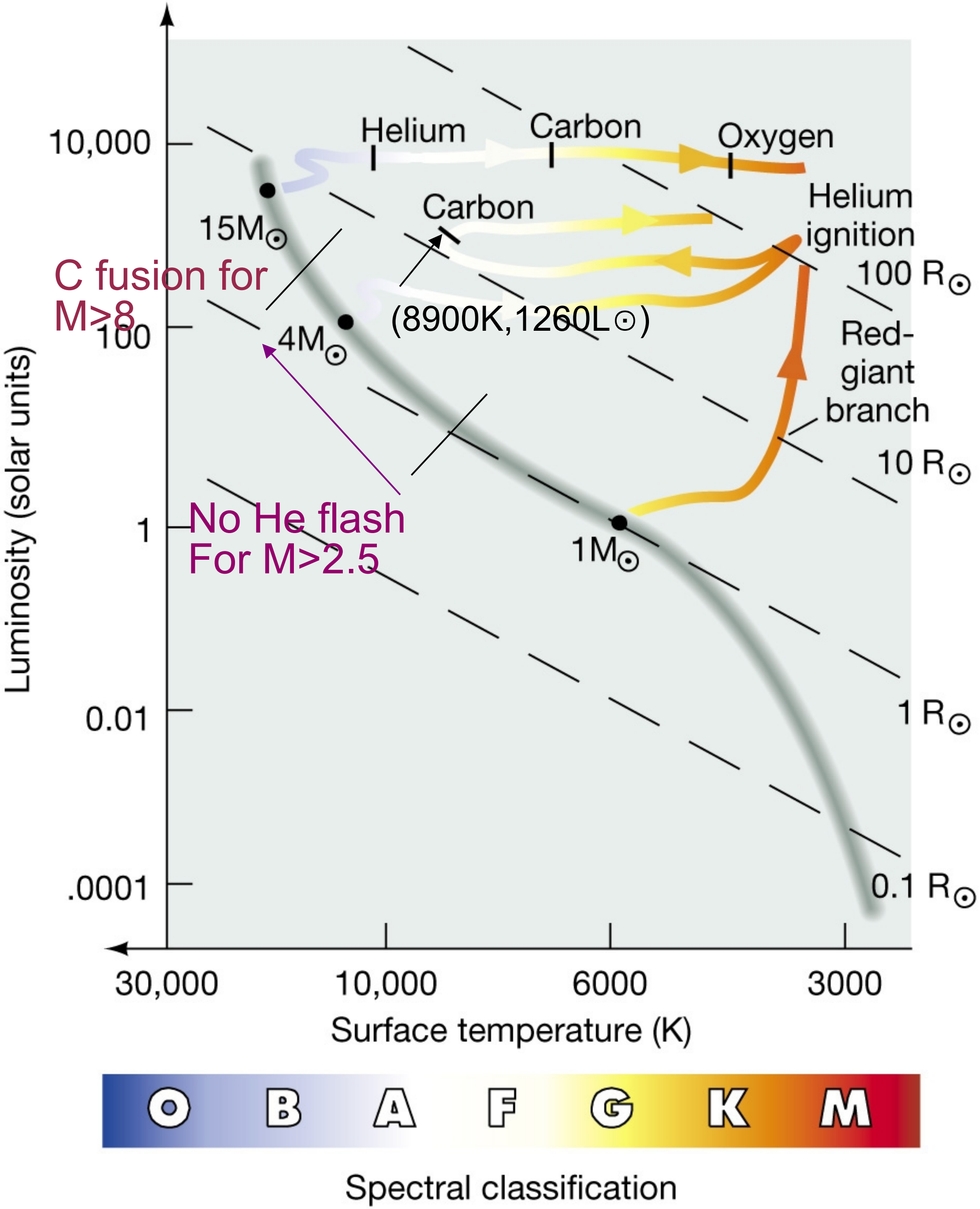
TABLE 20.2	Sirius B, a Nearby White Dwarf
Mass	1.1 solar masses
Radius	0.0073 solar radius (5100 km)
Luminosity (total)	0.025 solar luminosity (9.8×10^{24} W)
Surface temperature	27,000 K
Average density	3.9×10^{9} kg/m^3

In 2019, GAIA provided evidence for the crystallization of white dwarfs.

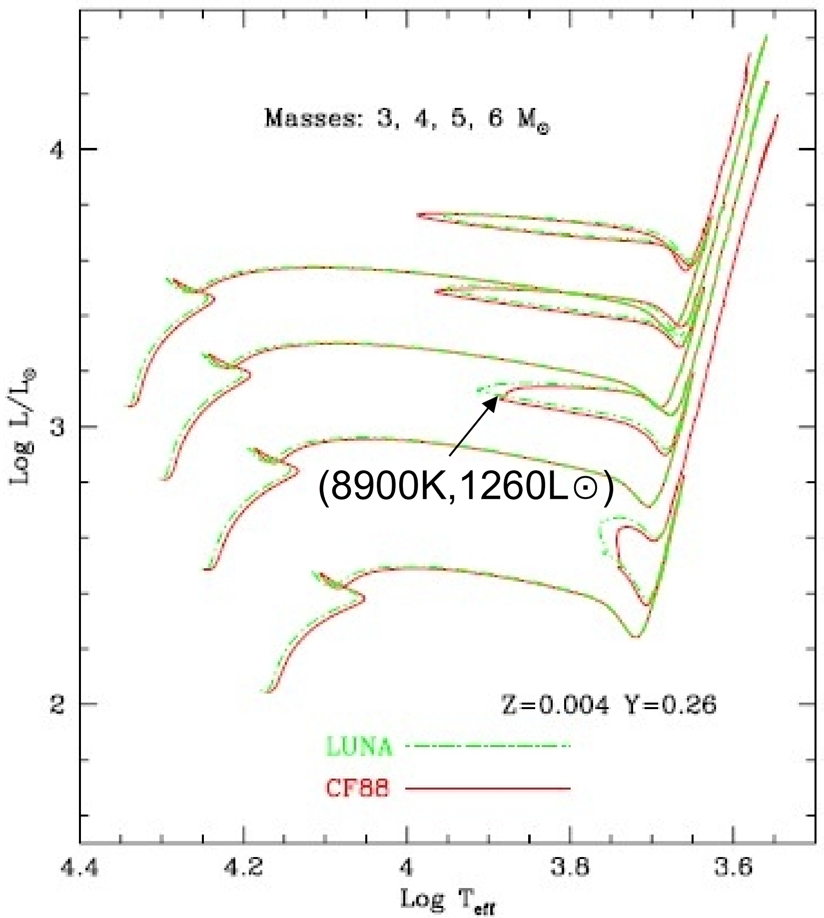


Cooling wd.s move down & right, but cooling slows during phase change, so points bunch up between orange dashed lines.

Figure 20-16 High-Mass Evolutionary Tracks



High mass evolution



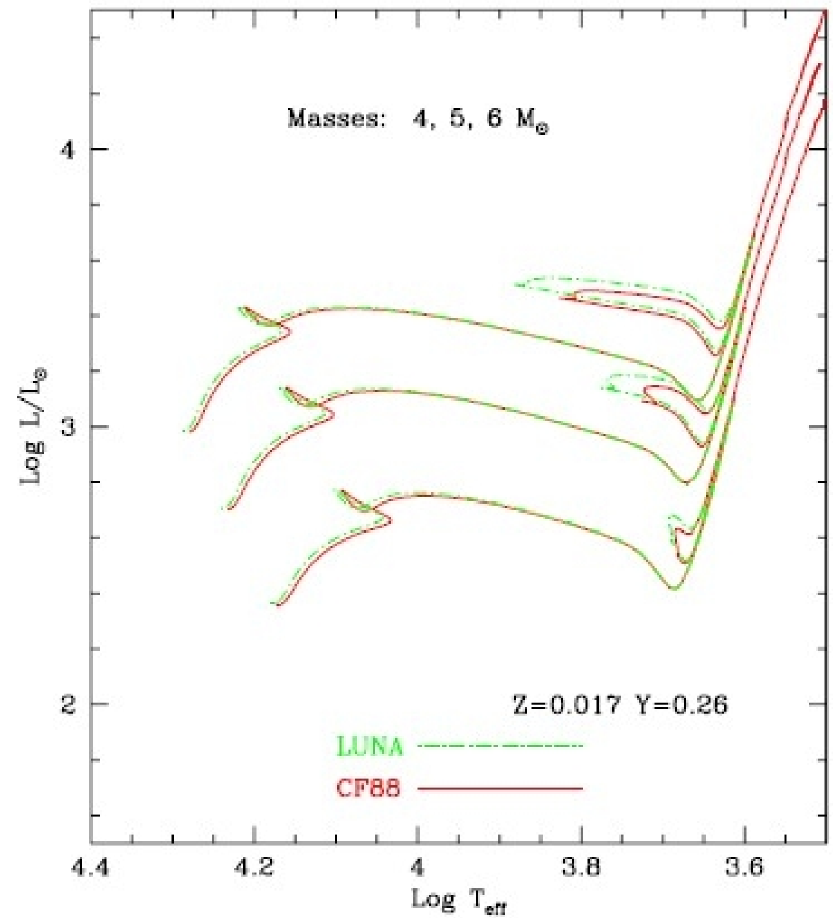


Fig. 3. Evolutionary tracks in the HR diagram for the composition $Z = 0.004$, $Y = 0.26$ computed with the new LUNA rate for the $^{14}N(p,\gamma)^{15}O$ nuclear reaction (dot-dashed line) and with the rate according to Caughlan & Fowler (1988)(solid line).

Fig. 4. Evolutionary tracks in the HR diagram for the composition $Z = 0.017$, $Y = 0.26$ computed with the new LUNA rate for the $^{14}N(p,\gamma)^{15}O$ nuclear reaction (dot-dashed line) and with the rate according to Caughlan & Fowler (1988)(solid line).

From A&A Nov 2009

High mass evolution

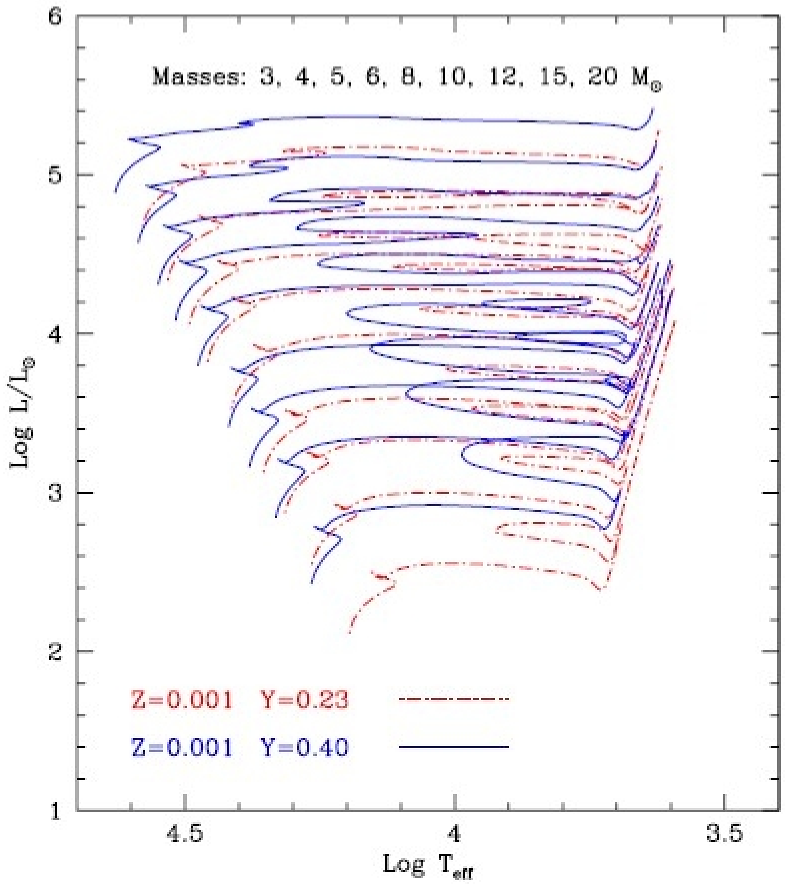


Fig. 1. Evolutionary tracks in the HR diagram for the compos tion $Z = 0.001$, $Y = 0.23$ (dot-dashed line) and $Z = 0.001$, Y = 0.40 (solid line).

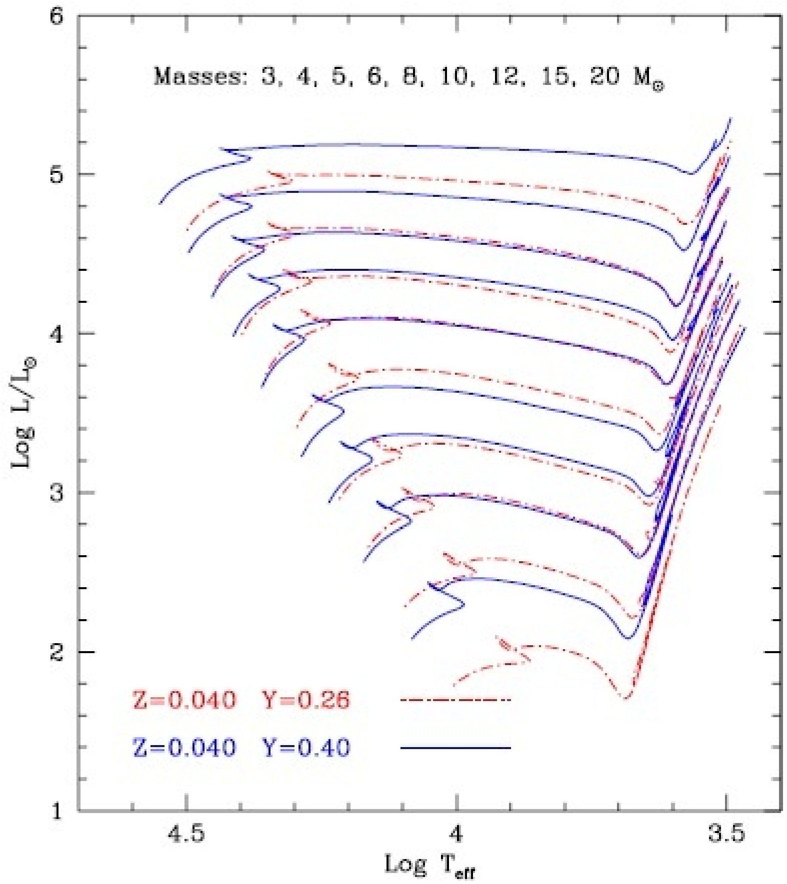
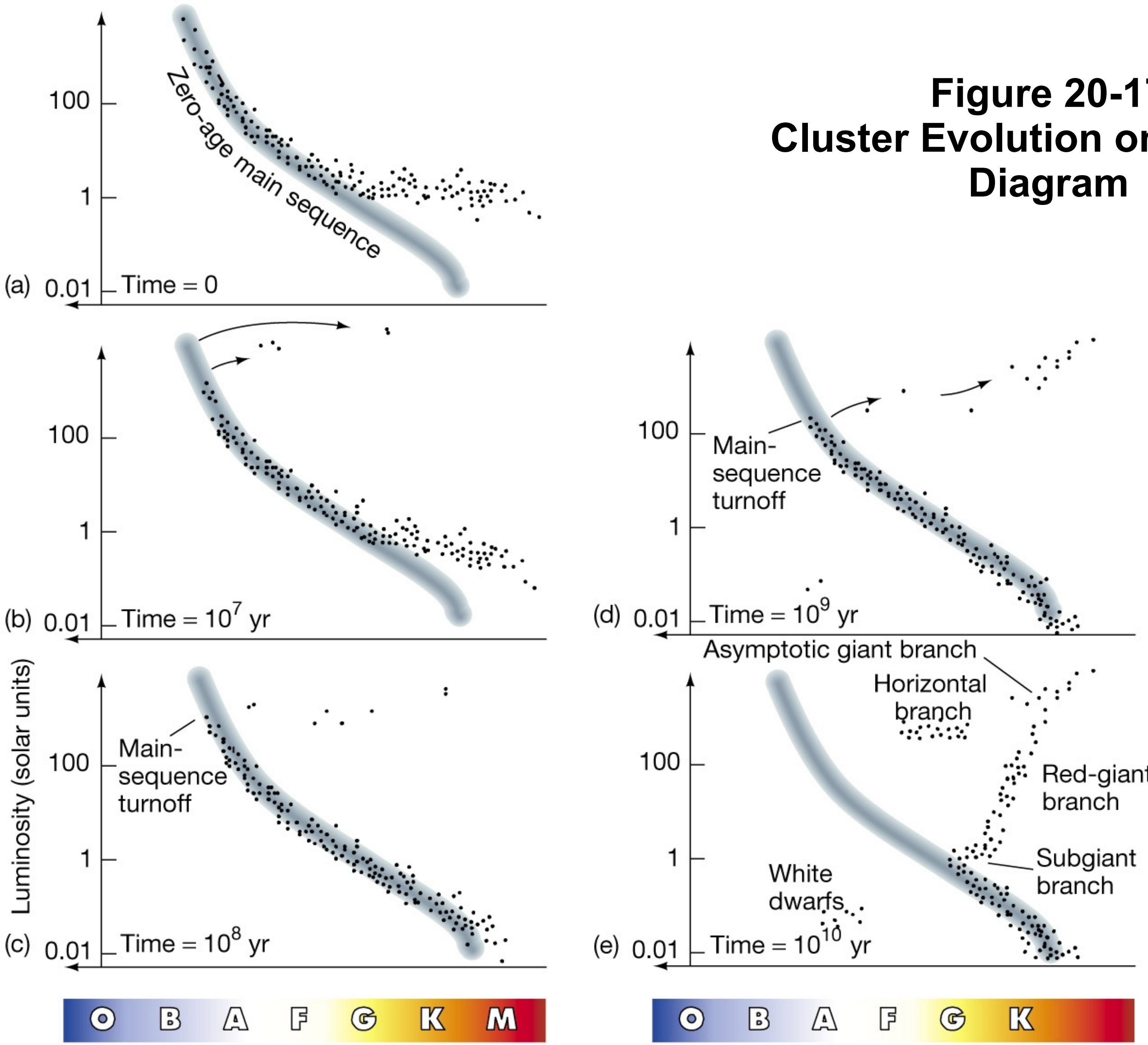


Fig. 2. Evolutionary tracks in the HR diagram for the composition $Z = 0.040$, $Y = 0.26$ (dot-dashed line) and $Z = 0.040$, $Y =$ 0.40 (solid line).

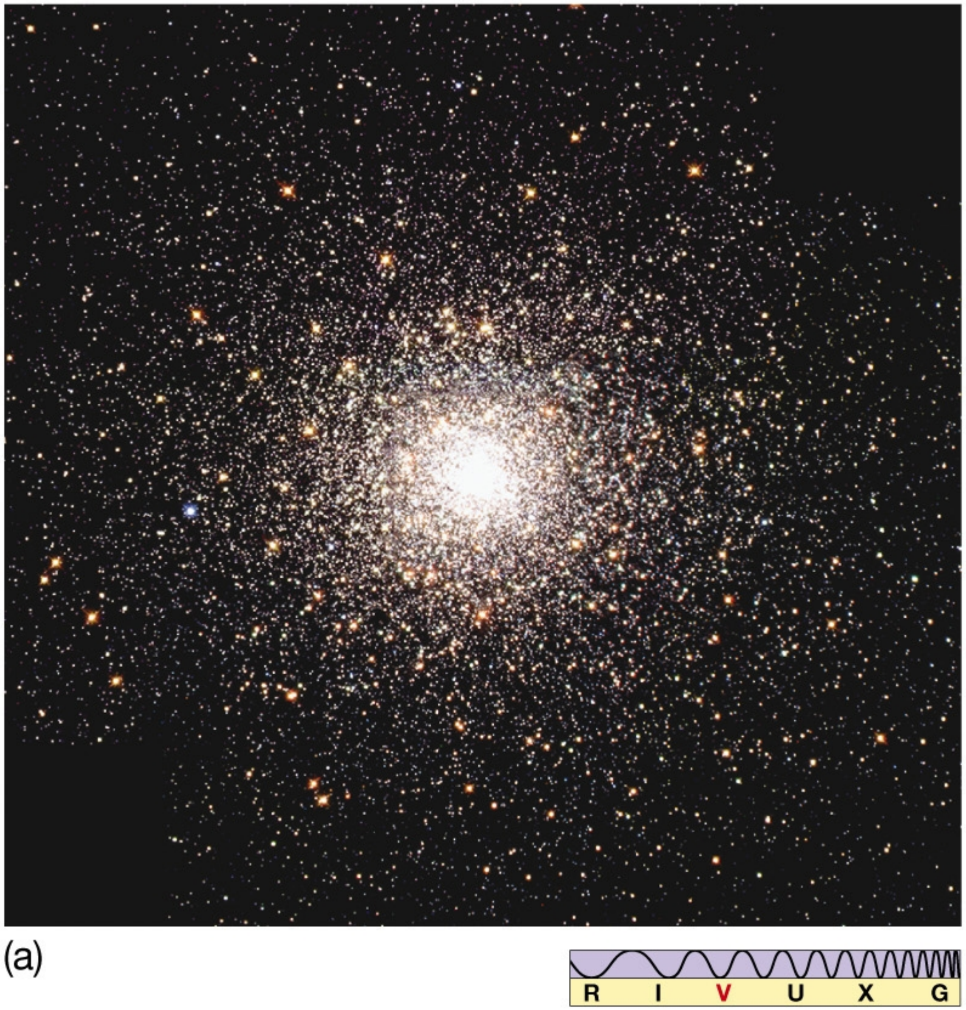
From A&A Nov 2009

Figure 20-17
Cluster Evolution on the H–R Diagram



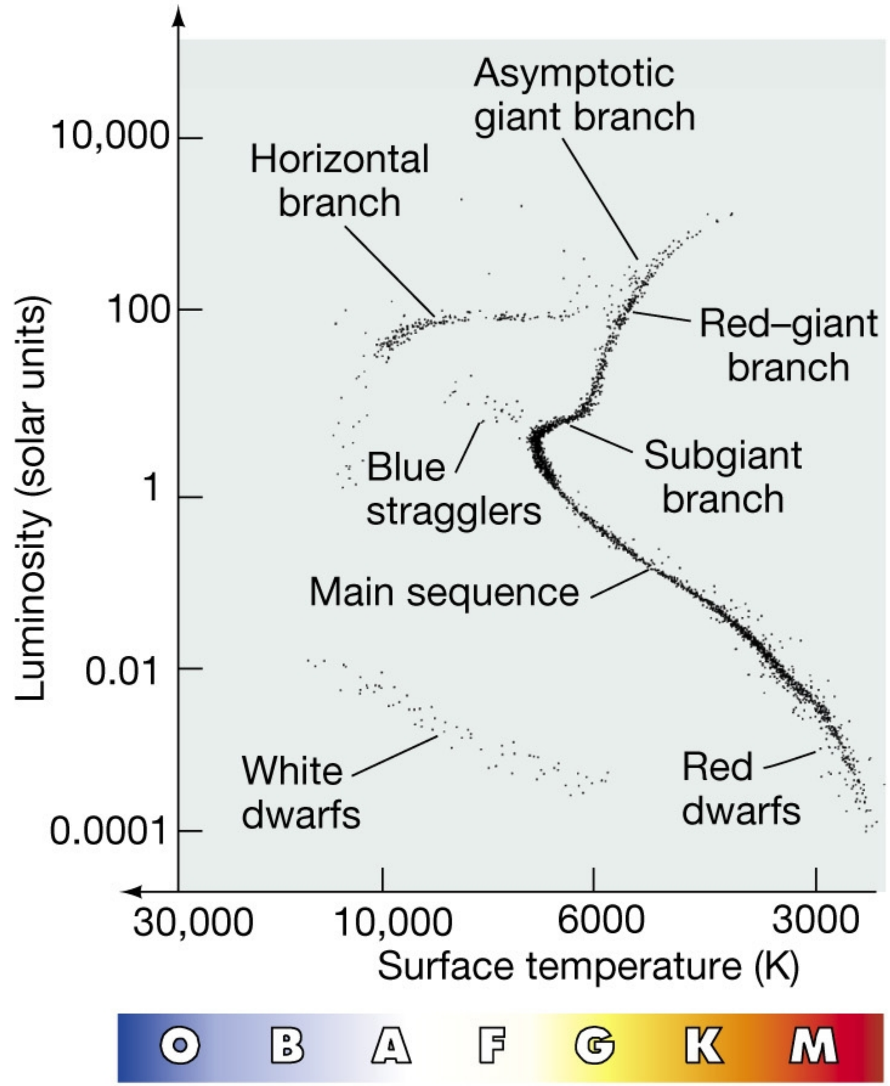
Isochrones - lines of equal age.

Figure 20-15
Globular Cluster H–R Diagram



(a)

Messier 80



(b)

Stellar Evolution

I. How are stars born?

II. How do stars evolve?

- How do they change in mass, luminosity, temperature, radius, etc?
  Ans: they follow “evolution tracks” on HR diagram.
- Do all stars evolve in the same manner?
  Ans: no. The shape of the track depends on mass and composition.
- Do all stars evolve at the same timescale?
  Ans: no. the speed of evolution is greater for higher masses.
- If stars evolve differently, what determines how a star will evolve?
  Ans: mostly mass, but also composition. Low metal stars are shifted left and up on HRD.
- Do stars run out of power?
  Ans: yes, there is a time limit for each type of core fusion process since the “fuel” becomes “ash”.

III. How do stars die?

- What does it mean for a star to “die”?
- Do all stars die the same way?
- How does a star's death influence its surroundings?

III How do stars die?

Low mass; blow off atmosphere and cool as white dwarf

High mass: explode leaving neutron star, pulsar, or BH, (or nothing) at the center of a supernova remnant.

Table 20-3
End Points of Evolution for Stars of Different Masses

TABLE 20.3 End Points of Evolution for Stars of Different Masses

Initial Mass (Solar Masses)	Final State
less than 0.08	(hydrogen) brown dwarf
0.08–~~0.25~~ 0.5	helium white dwarf
0.25–8	carbon–oxygen white dwarf
8–12 (approx.)*	neon–oxygen white dwarf
greater than 12*	supernova (Chapter 21)

**Precise numbers depend on the (poorly known) amount of mass lost while the star is on, and after it leaves, the main sequence.*

Figure 21-5
Heavy-Element Fusion

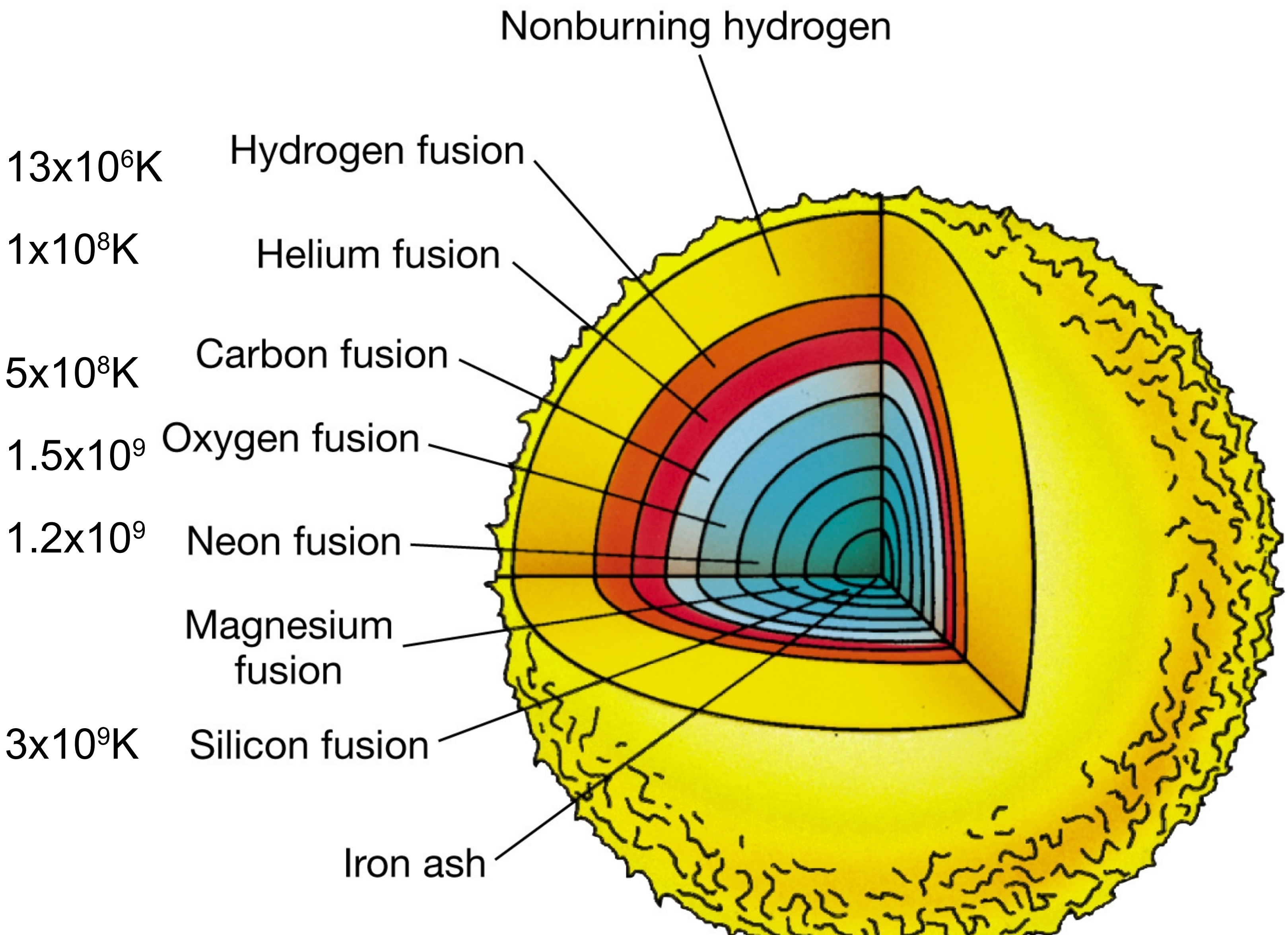


Figure 21-2
Close Binary System

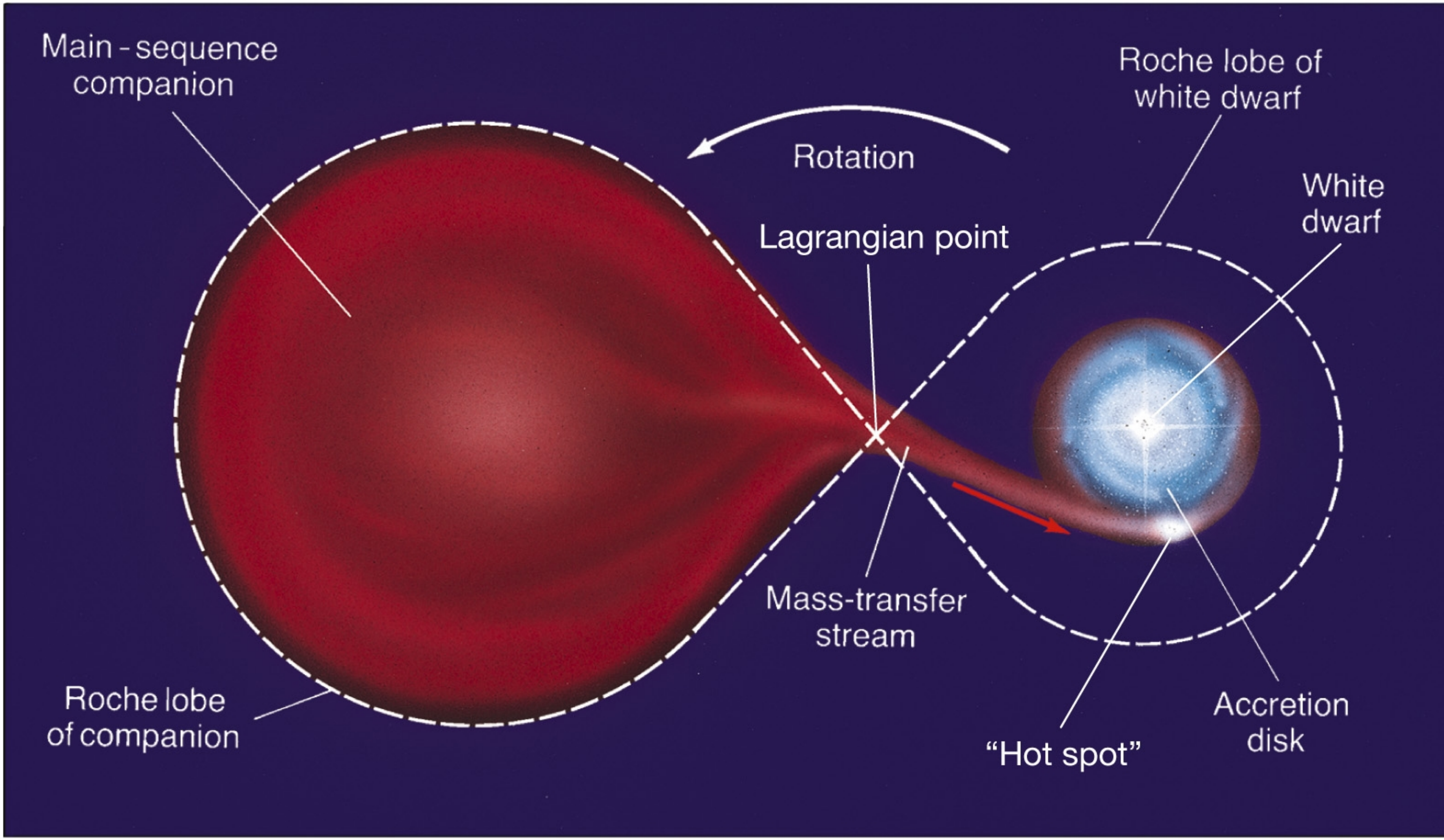
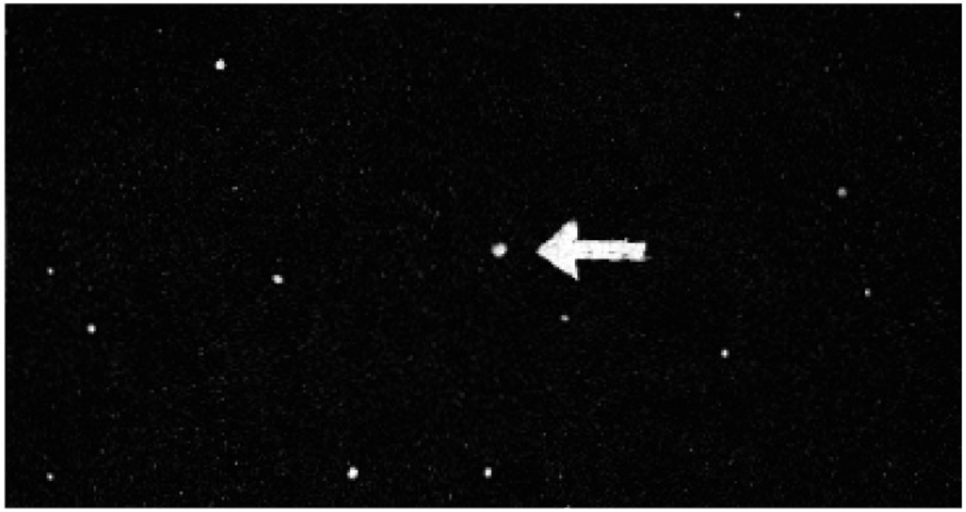
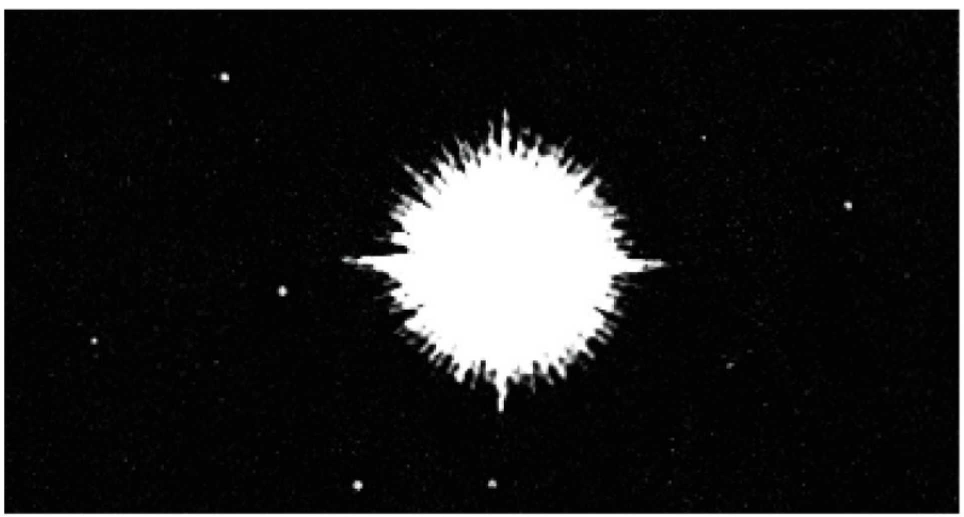


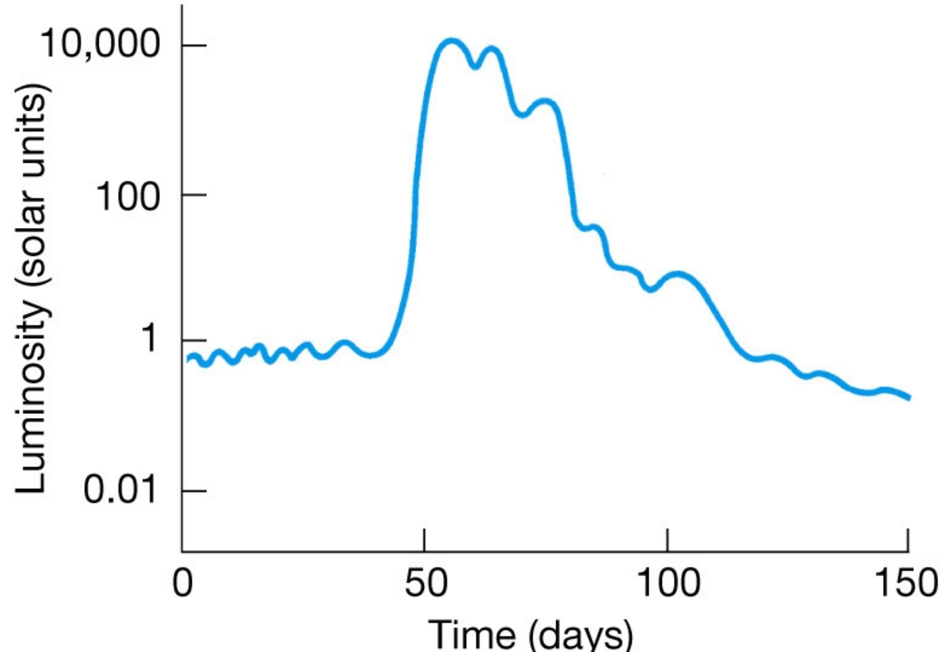
Figure 21-1
Nova



(a)



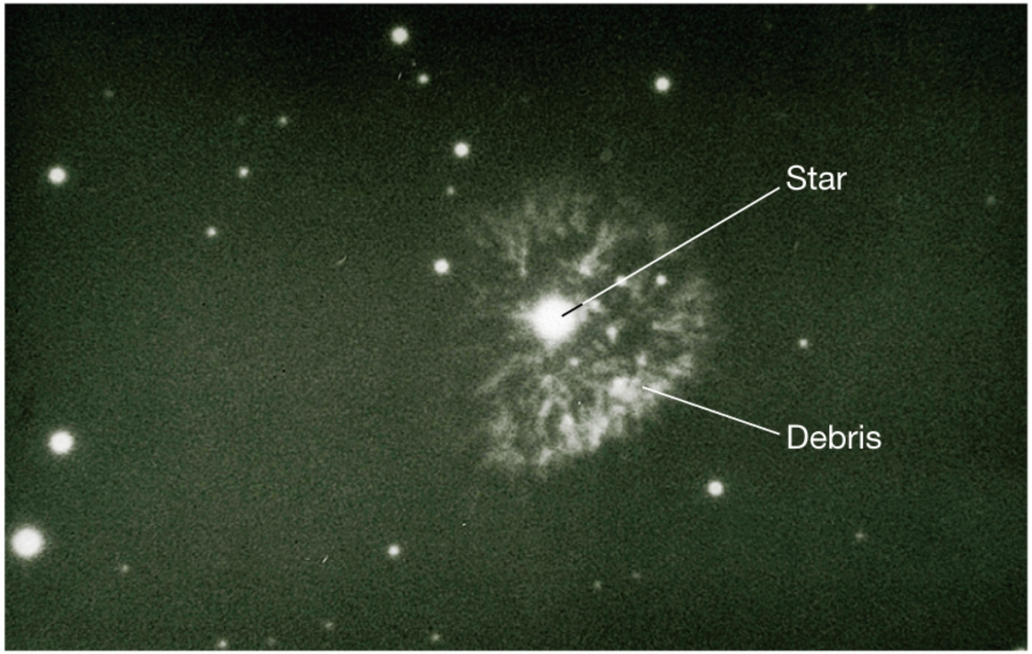
(b)



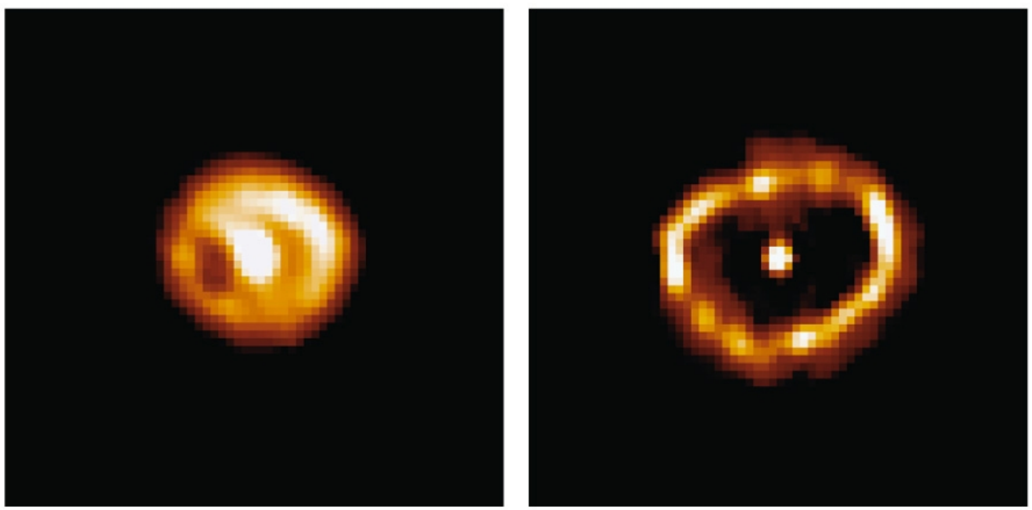
(c)

Nova Herculis, 1934.
60,000 X brightness increase

Figure 21-4
Nova Matter Ejection



(a)



(b)

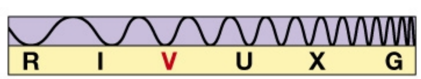
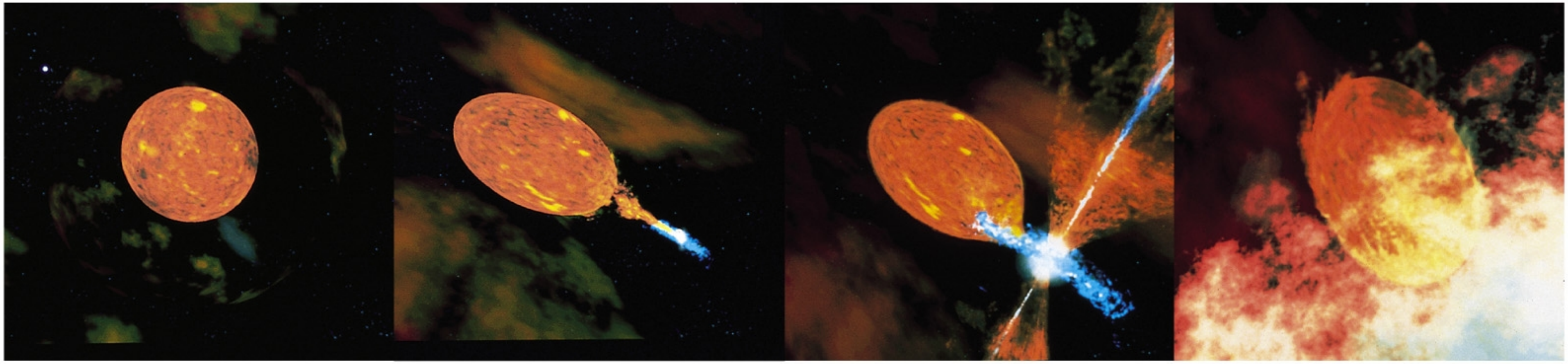


Figure 21-3
Nova Explosion



(a) (b) (c) (d)

Figure 21-7
Supernova 1987A

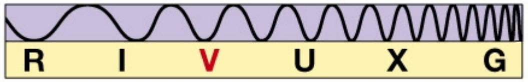
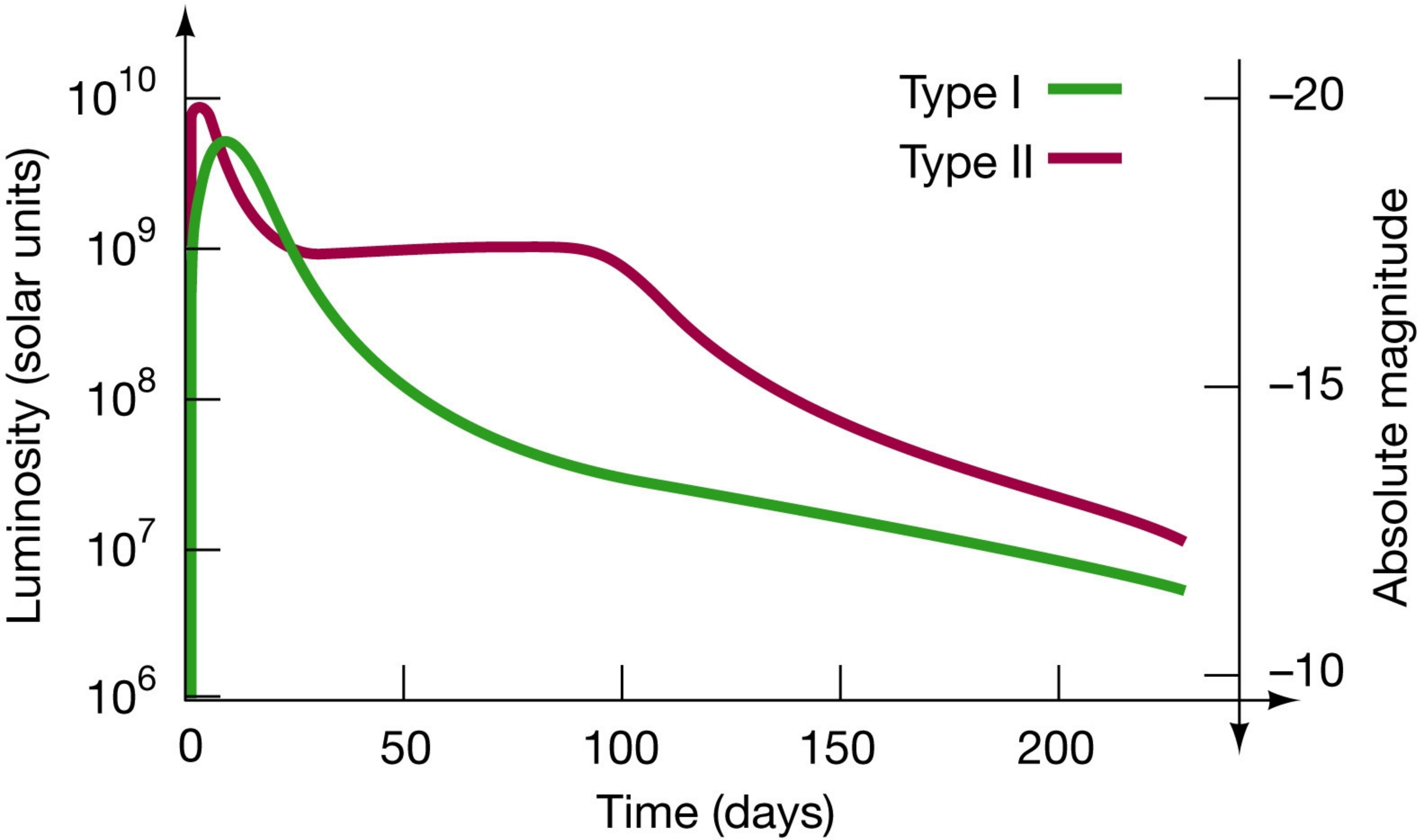
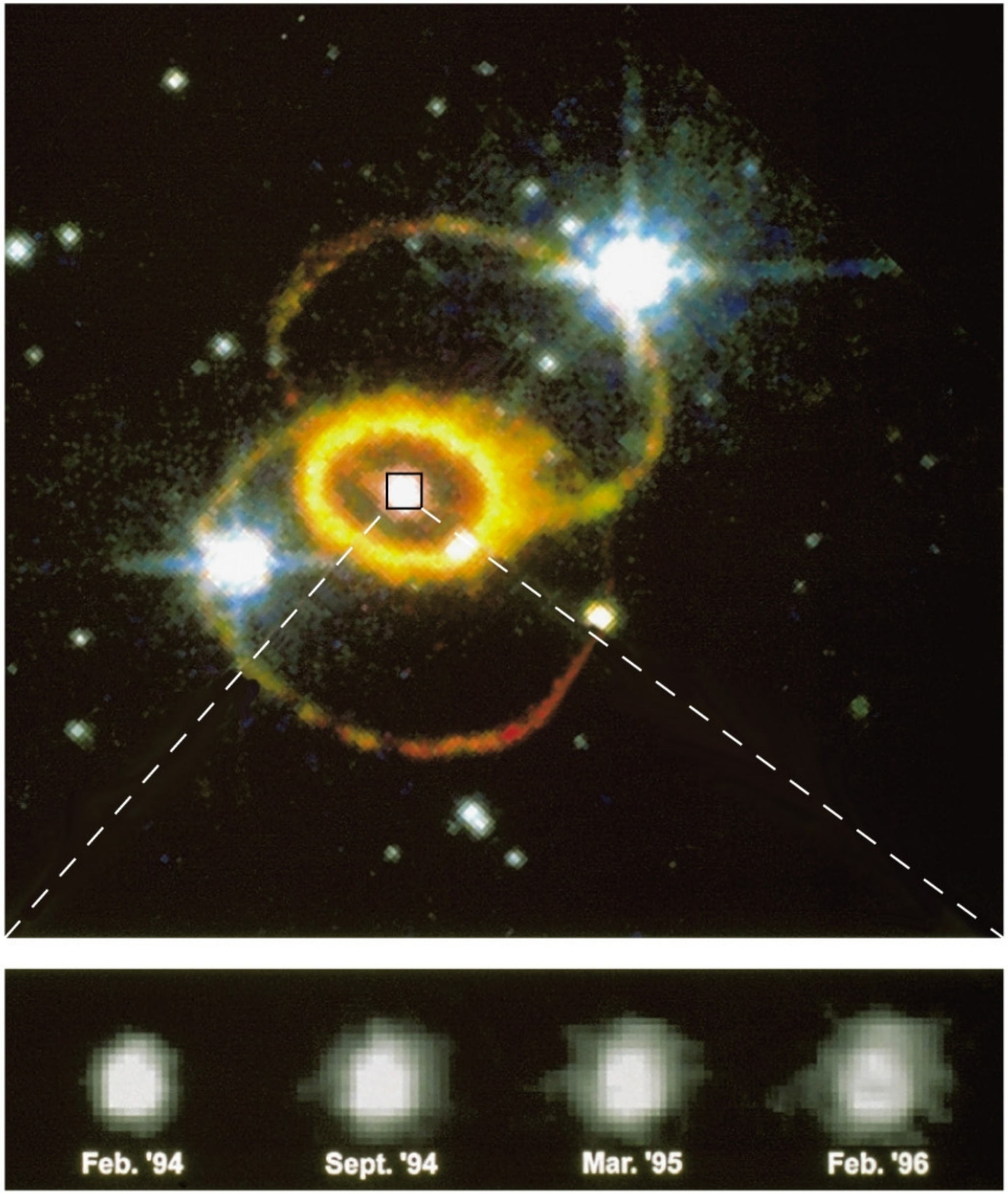
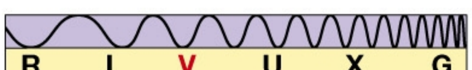
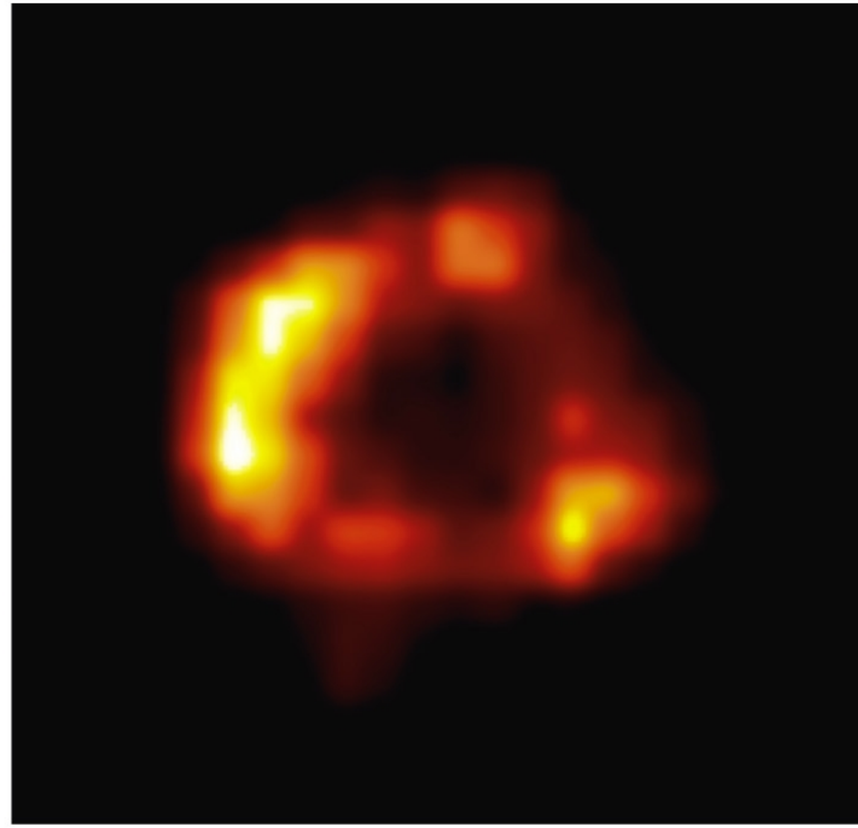


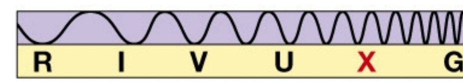
Figure 21-8
Supernova Light Curves











Discovery 21-1b
Supernova 1987A

Figure 21-9
Two Types of Supernova

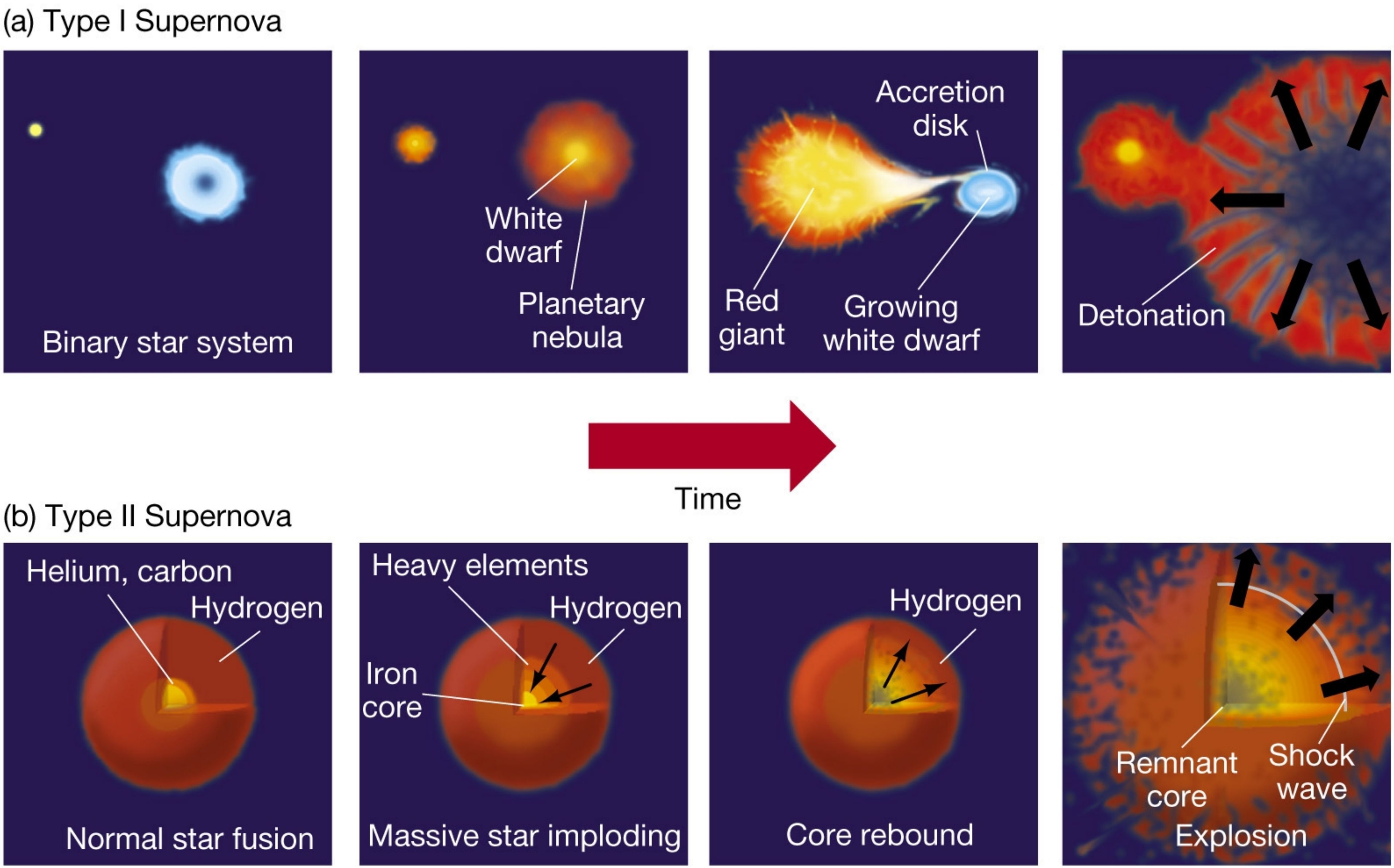
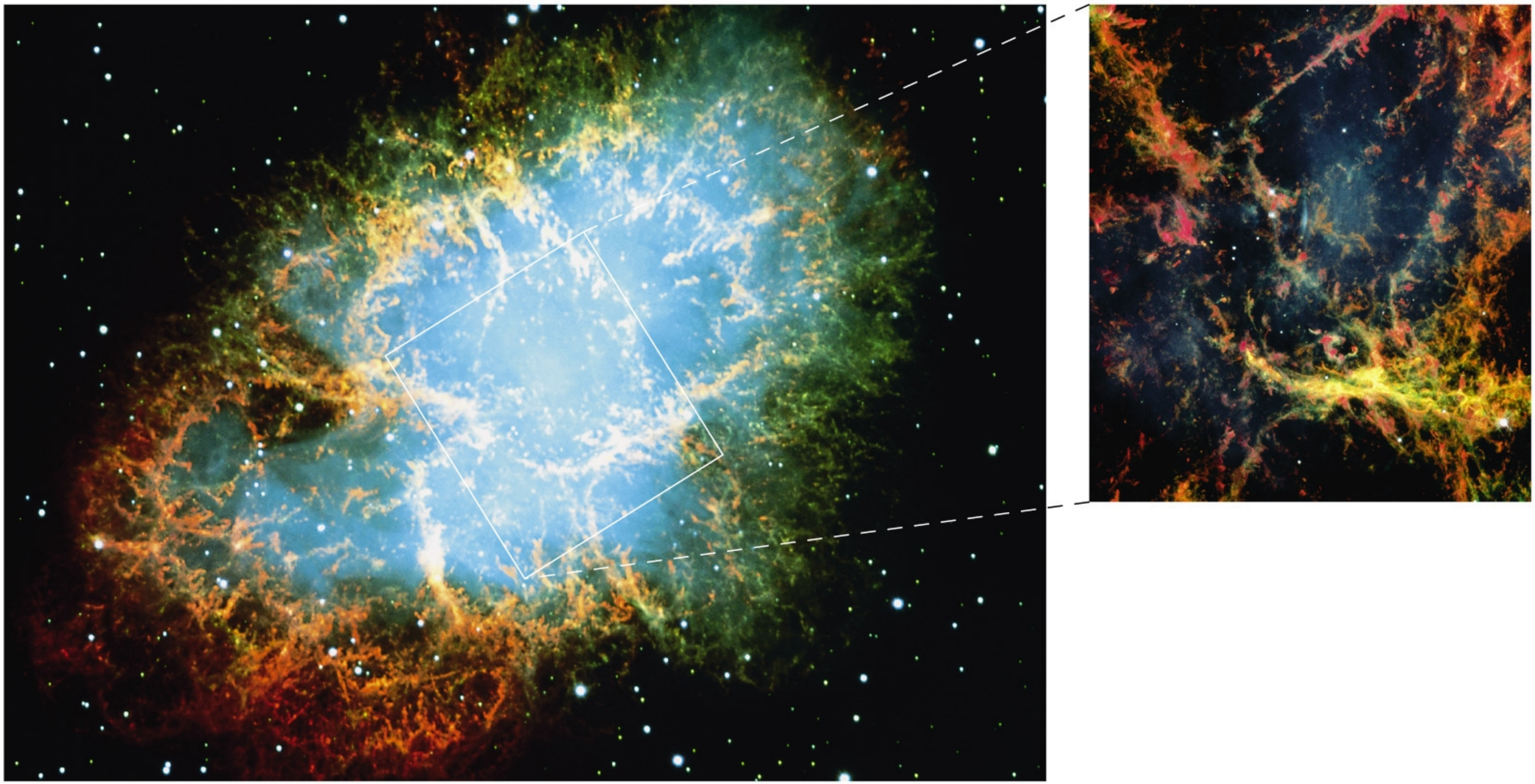


Figure 21-10
Crab Supernova Remnant



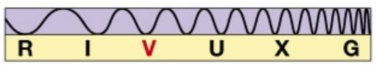
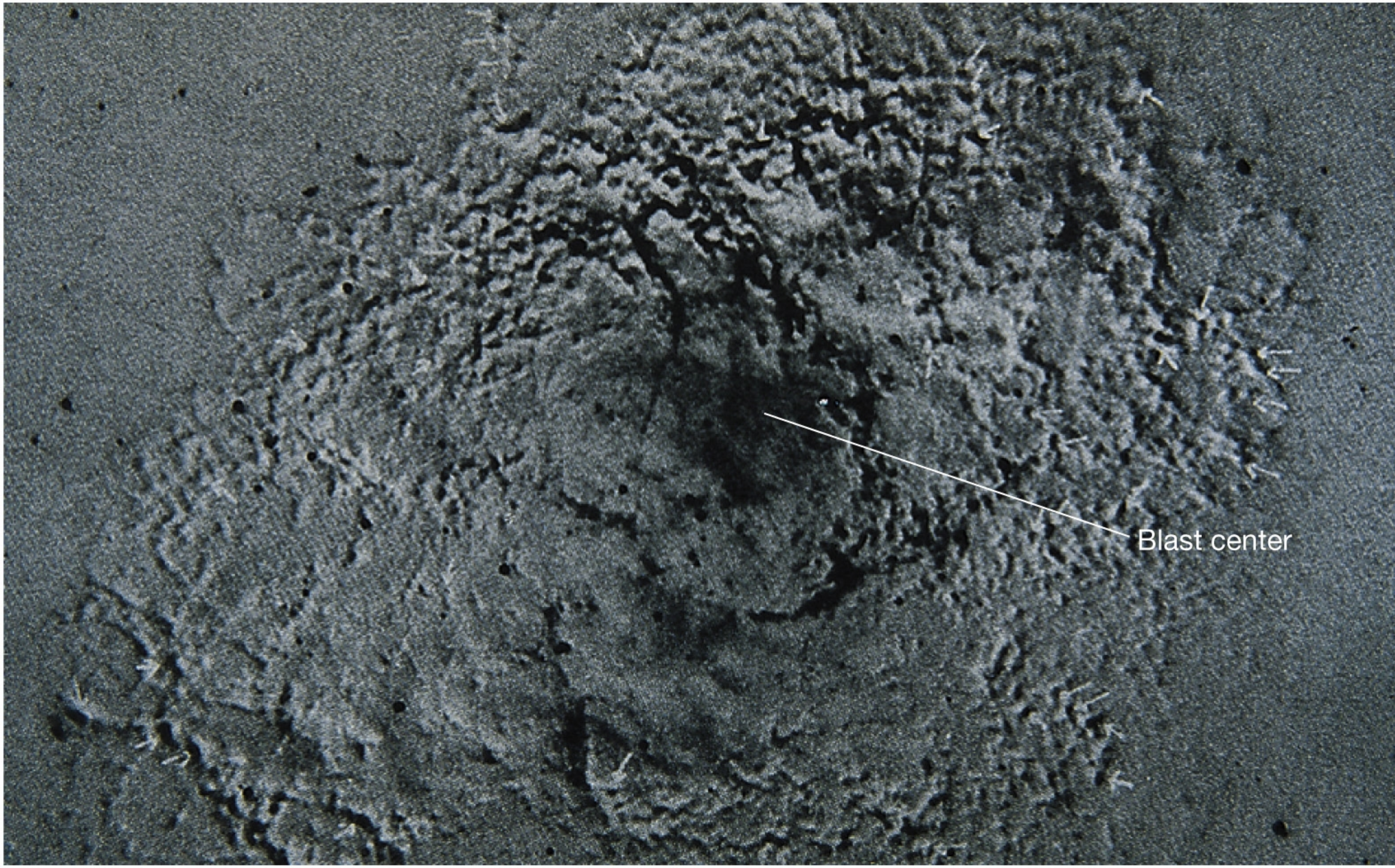


Figure 21-11
The Crab in Motion



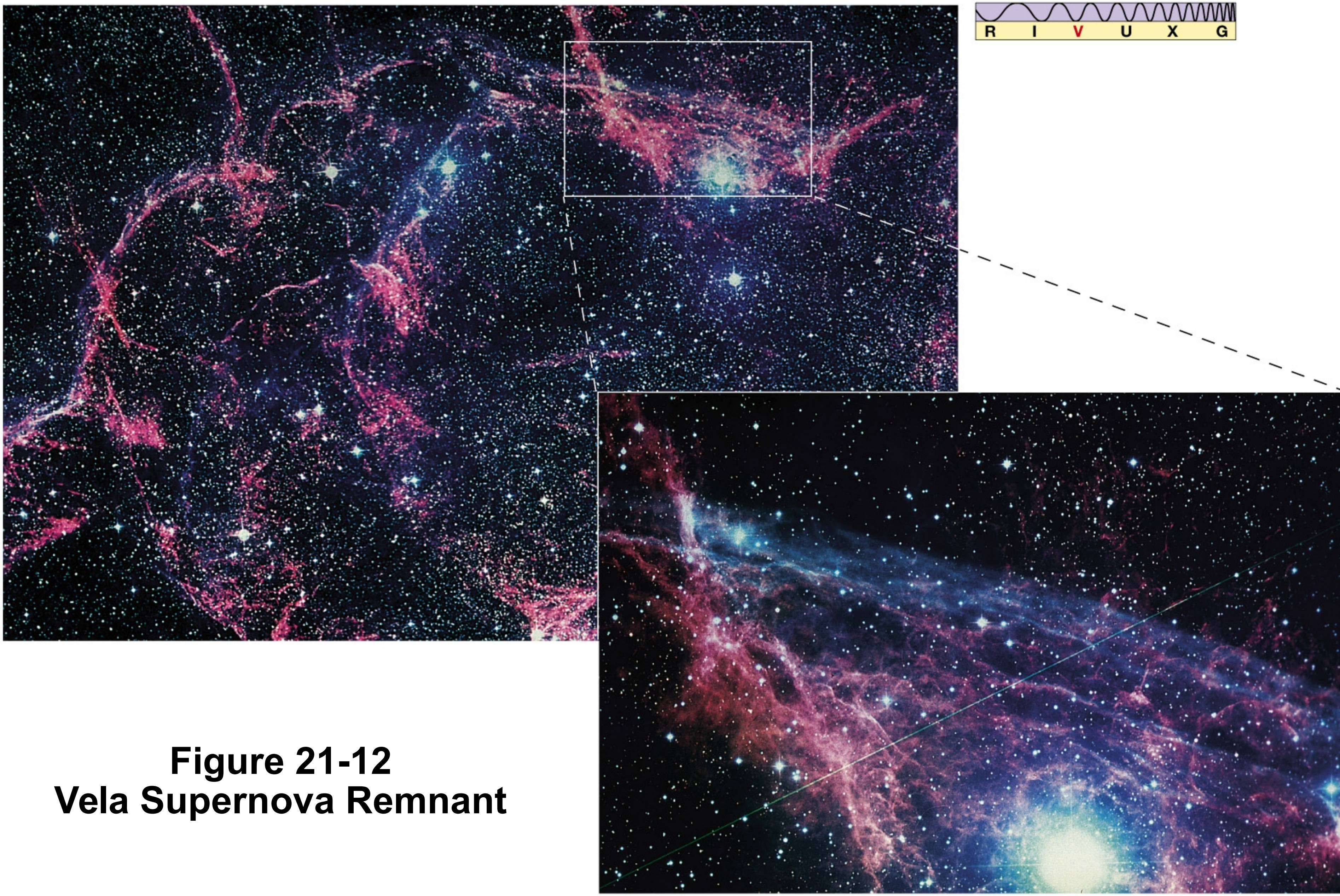


Figure 21-12
Vela Supernova Remnant

Figure 21-13
Elemental Abundance

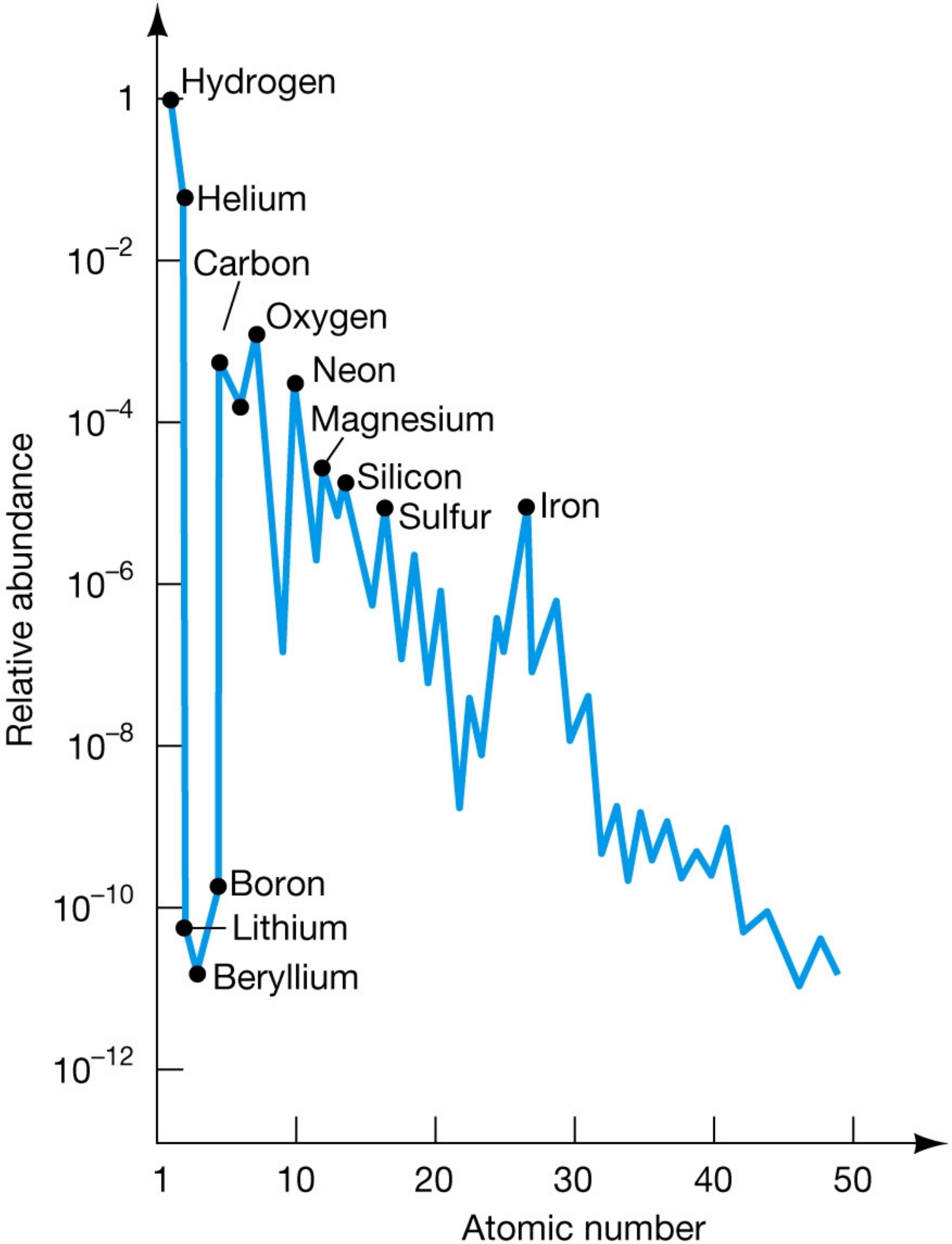


Figure 21-19
Stellar Recycling