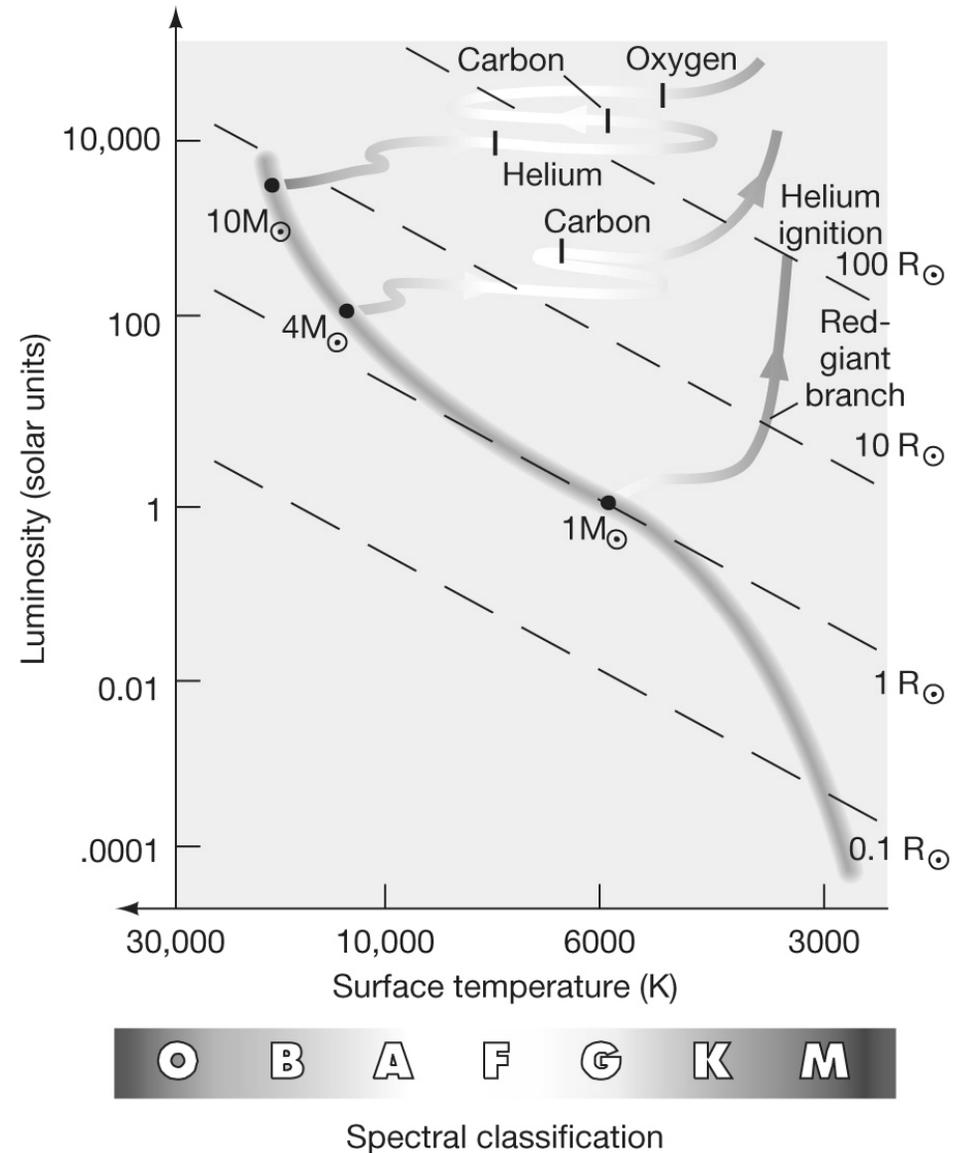


12.4 Evolution of Stars More Massive than the Sun

It can be seen from this H-R diagram that stars more massive than the Sun follow very different paths when leaving the Main Sequence:



12.4 Evolution of Stars More Massive than the Sun

High-mass stars, like all stars, leave the Main Sequence when there is no more hydrogen fuel in their cores.

The first few events are similar to those in lower-mass stars – first a hydrogen shell, then a core burning helium to carbon, surrounded by helium- and hydrogen-burning shells.

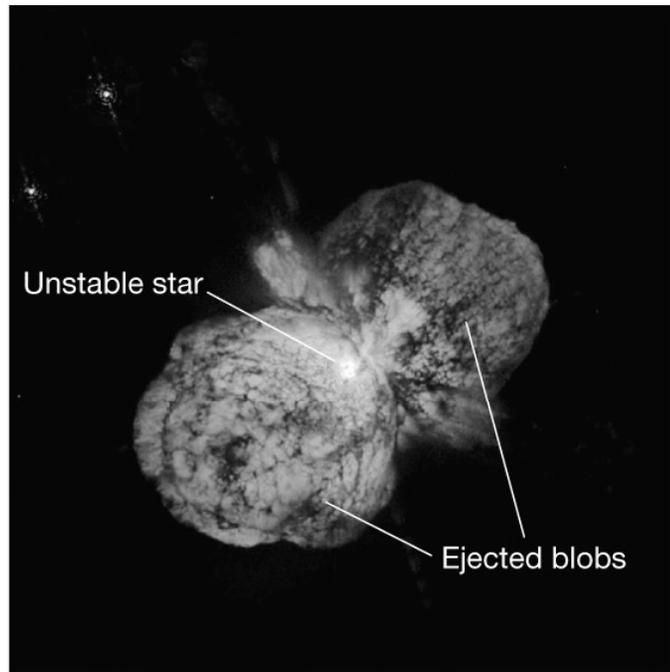
12.4 Evolution of Stars More Massive than the Sun

Stars with masses more than 2.5 solar masses do not experience a helium flash – helium burning starts gradually.

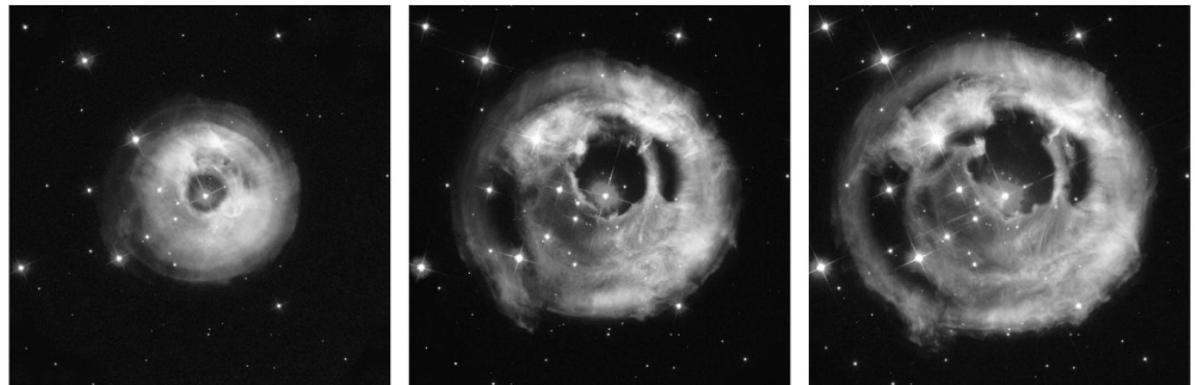
A 4-solar-mass star makes no sharp moves on the H-R diagram – it moves smoothly back and forth.

12.4 Evolution of Stars More Massive than the Sun

The sequence below, of actual Hubble images, shows first a very massive star, then a very unstable red giant star as it emits a burst of light, illuminating the dust around it:



(a)



12.4 Evolution of Stars More Massive than the Sun

A star of more than 8 solar masses can fuse elements far beyond carbon in its core, leading to a very different fate.

Its path across the H-R diagram is essentially a straight line – it stays at just about the same luminosity as it cools off.

Eventually the star dies in a violent explosion called a supernova.

12.4 Evolution of Stars More Massive than the Sun

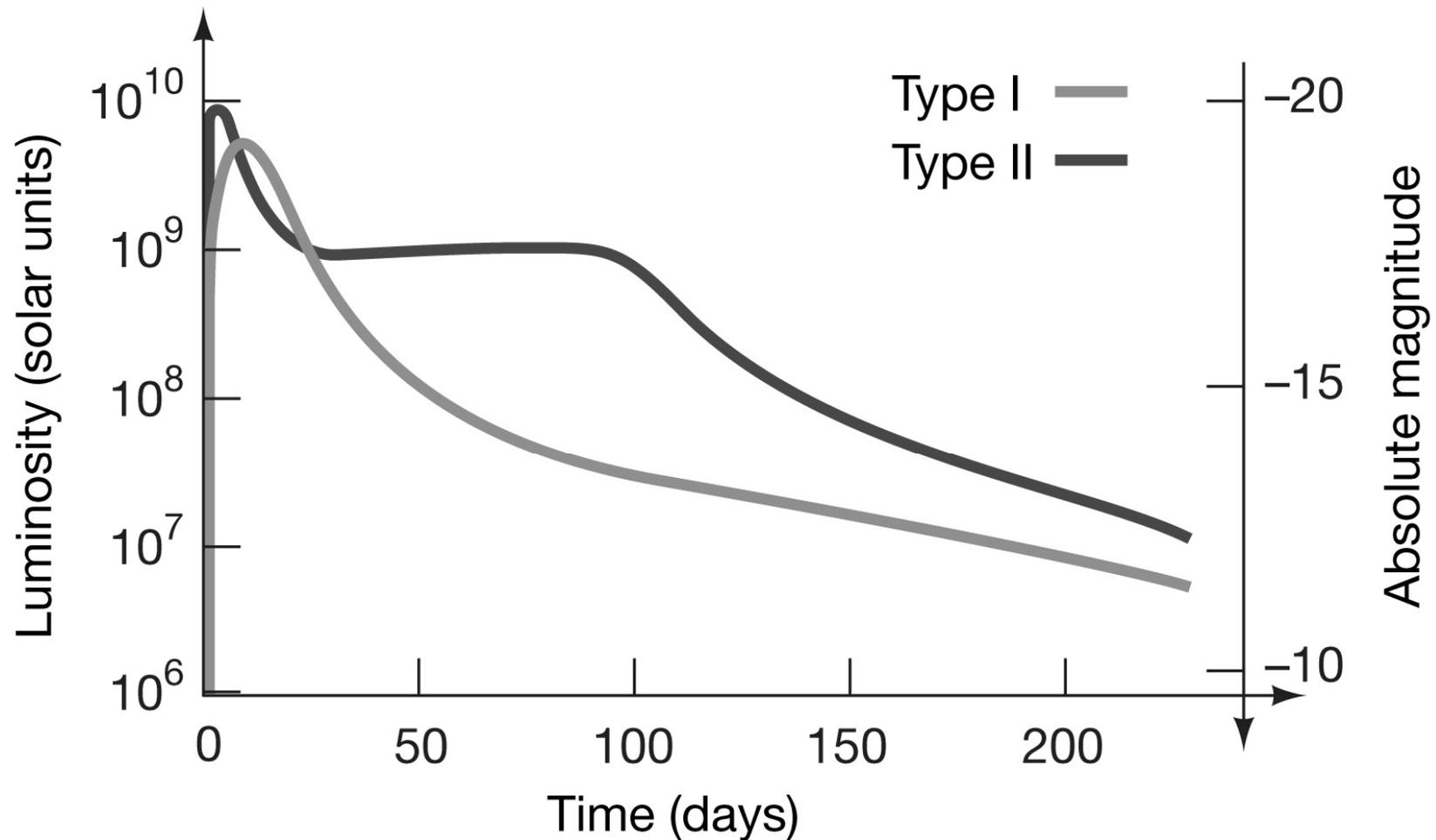
TABLE 12.3 End Points of Evolution for Stars of Different Masses

INITIAL MASS (SOLAR MASSES)	FINAL STATE
Less than 0.08	(Hydrogen) brown dwarf
0.08–0.25	Helium white dwarf
0.25–8	Carbon–oxygen white dwarf
8–12 (approx.)*	Neon–oxygen white dwarf
Greater than 12*	Supernova

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

12.5 Supernova Explosions

A supernova is incredibly luminous, as can be seen from these curves – more than a million times as bright as a nova.



12.5 Supernova Explosions

A supernova is a one-time event – once it happens, there is little or nothing left of the progenitor star.

There are two different types of supernovae, both equally common:

Type I, which is a carbon-detonation supernova;

Type II, which is the death of a high-mass star.

12.5 Supernova Explosions

Carbon-detonation supernova: white dwarf that has accumulated too much mass from binary companion

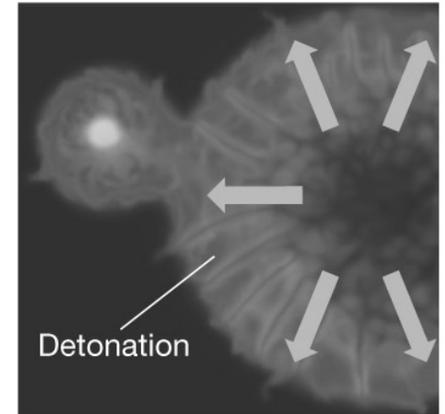
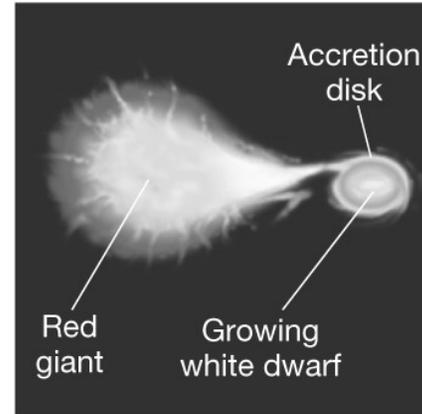
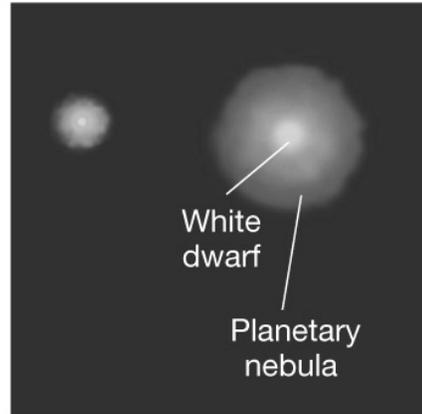
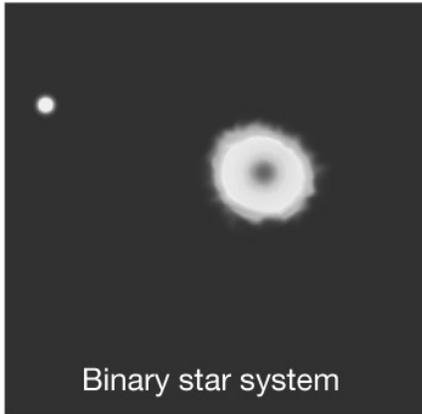
If the white dwarf's mass exceeds 1.4 solar masses, electron degeneracy can no longer keep the core from collapsing.

Carbon fusion begins throughout the star almost simultaneously, resulting in a carbon explosion.

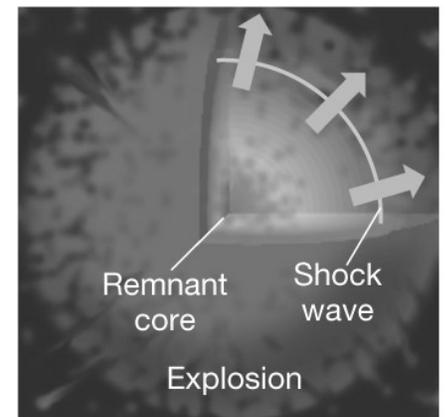
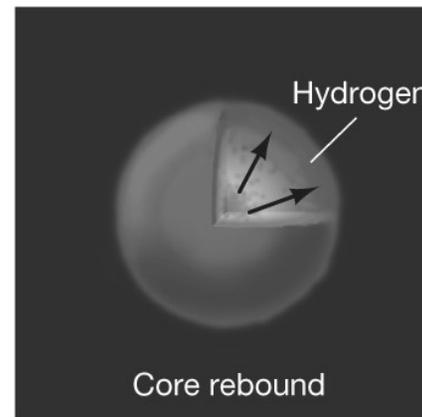
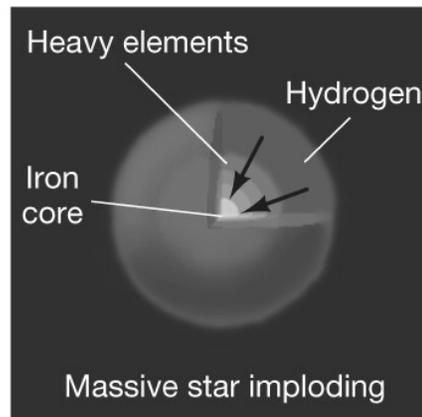
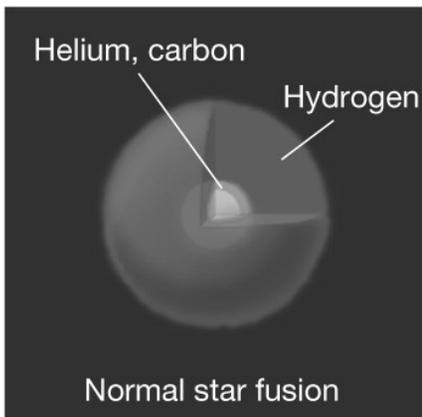
12.5 Supernova Explosions

This graphic illustrates the two different types of supernovae:

(a) Type I Supernova

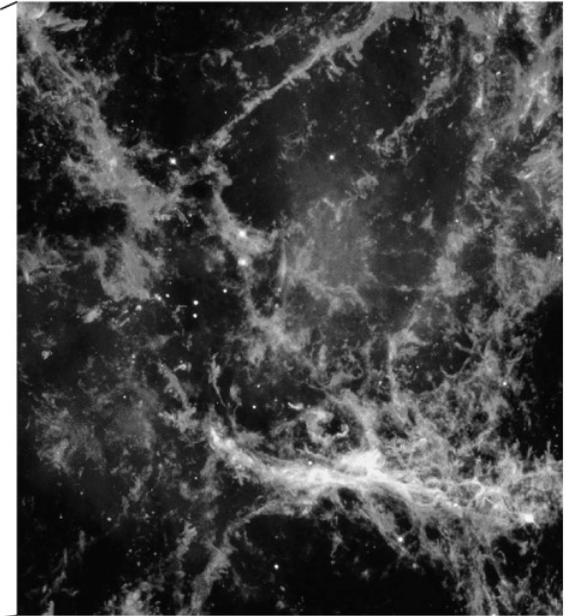
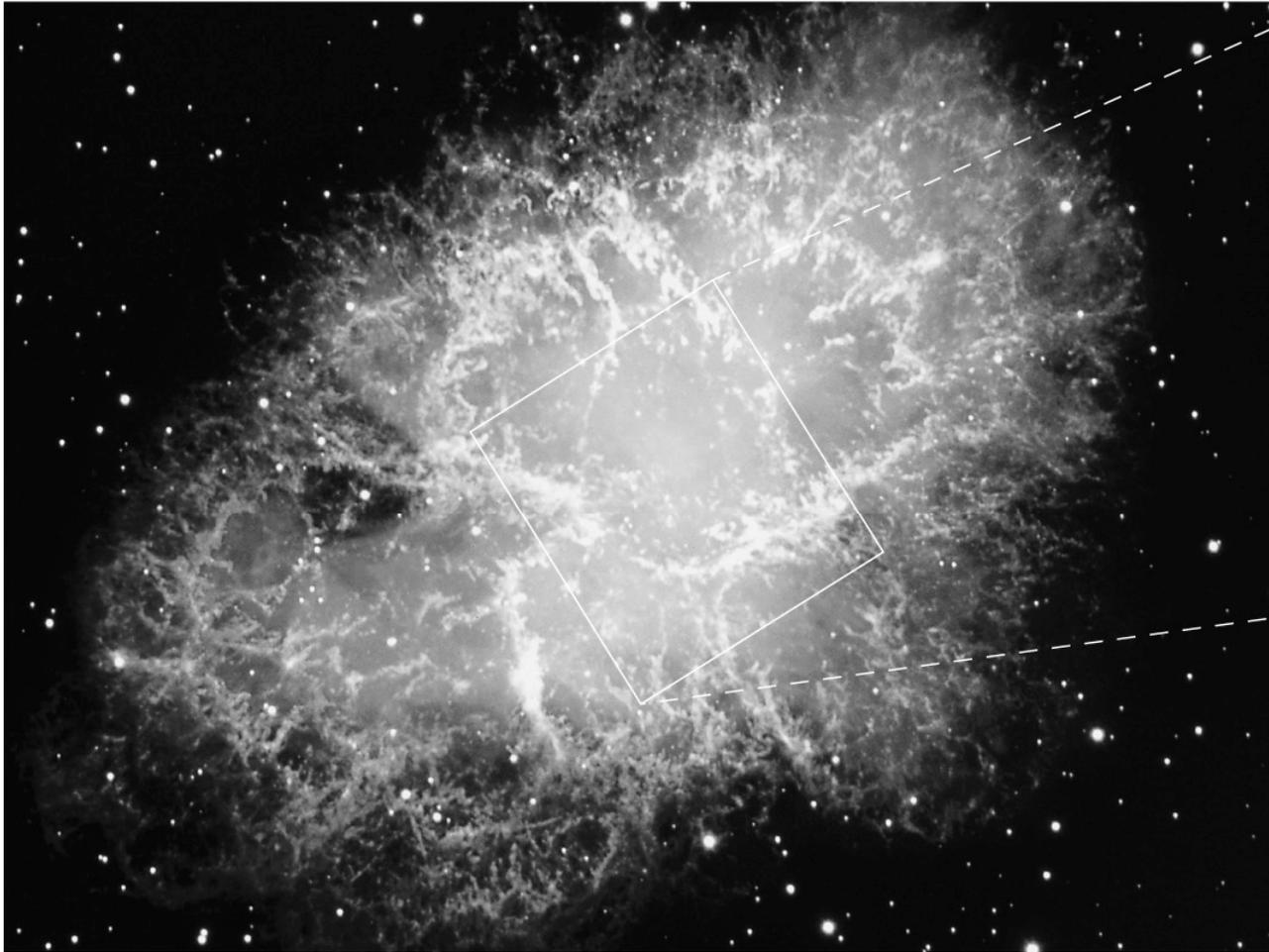


(b) Type II Supernova



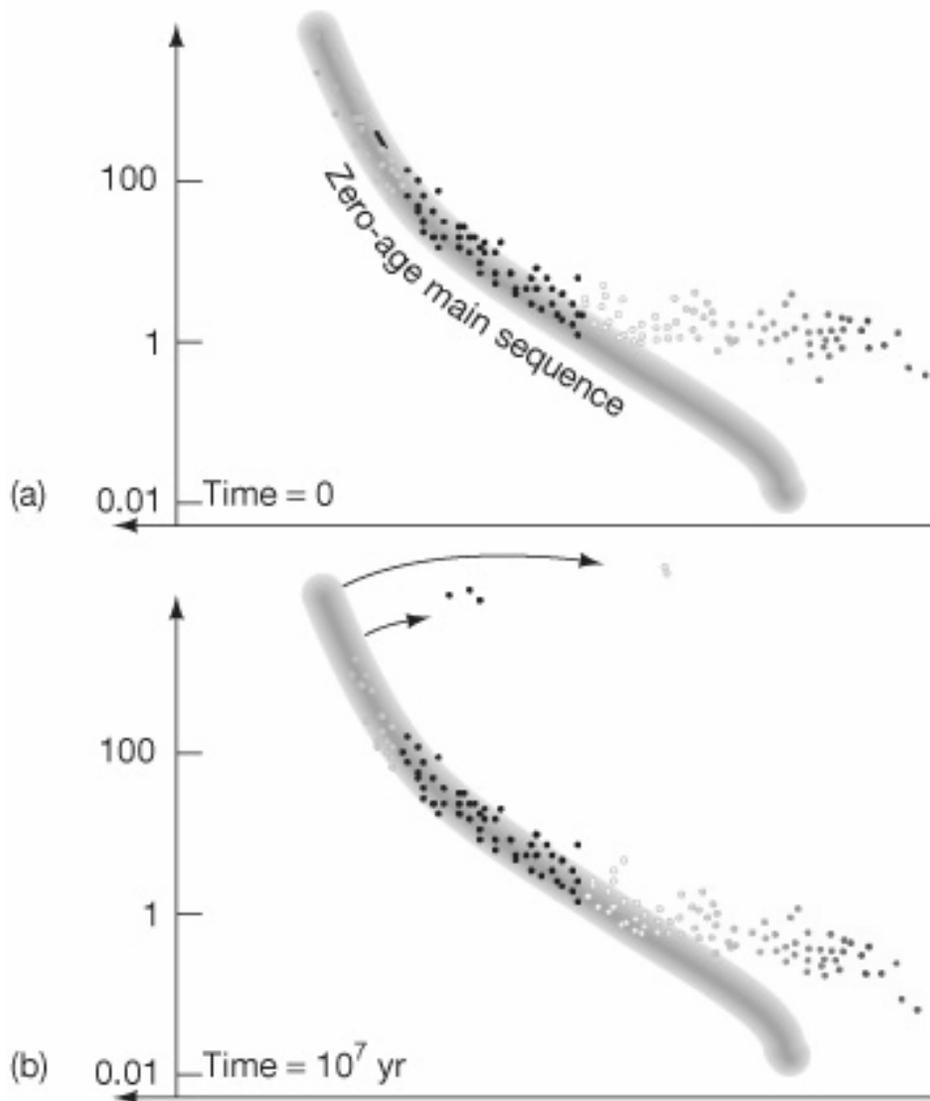
12.5 Supernova Explosions

Supernovae leave remnants – the expanding clouds of material from the explosion.



The Crab nebula is a remnant from a supernova explosion that occurred in the year 1054.

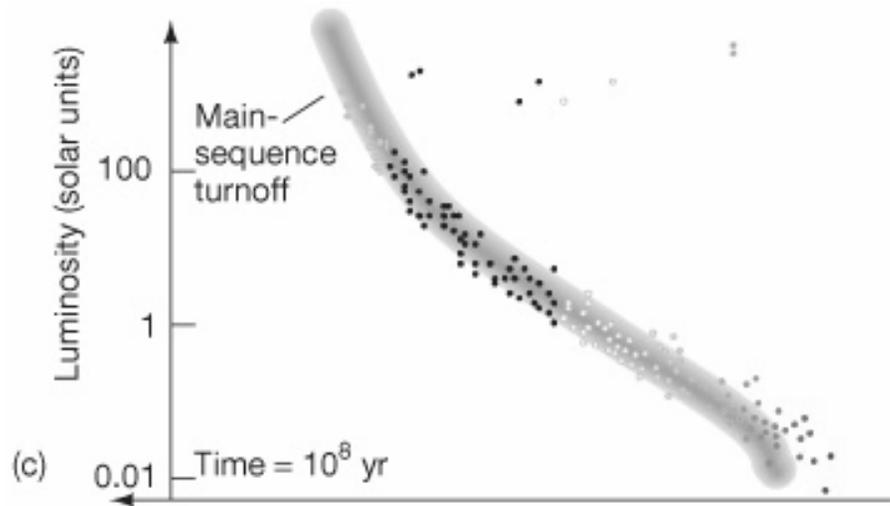
12.6 Observing Stellar Evolution in Star Clusters



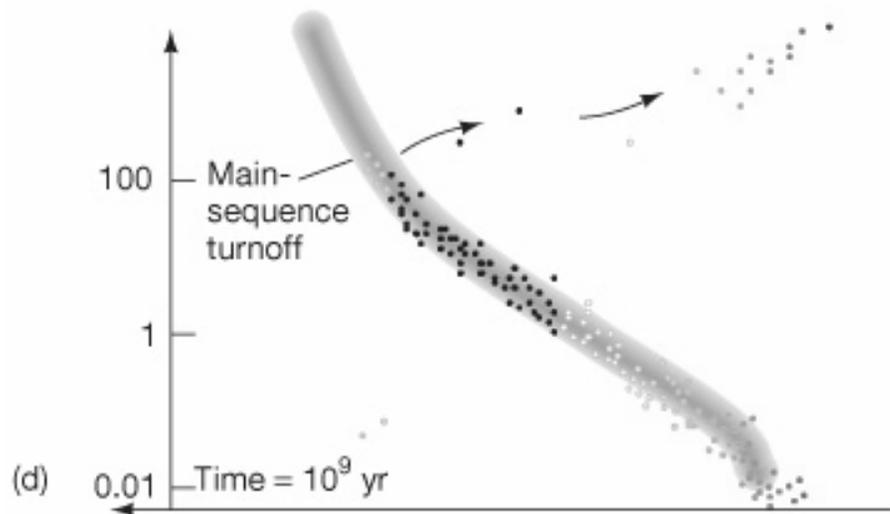
The following series of H-R diagrams shows how stars of the same age, but different masses, appear as the cluster as a whole ages.

After 10 million years, the most massive stars have already left the Main Sequence, while many of the least massive have not even reached it yet.

12.6 Observing Stellar Evolution in Star Clusters

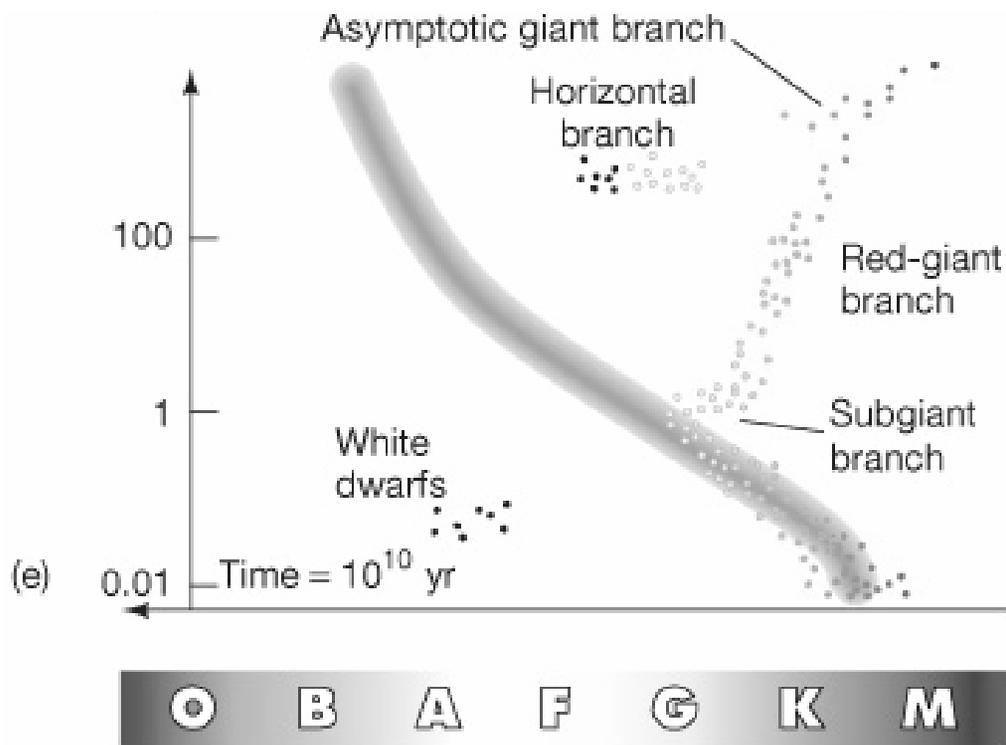


After 100 million years, a distinct main-sequence turnoff begins to develop. This shows the highest-mass stars that are still on the Main Sequence.



After 1 billion years, the main-sequence turnoff is much clearer.

12.6 Observing Stellar Evolution in Star Clusters

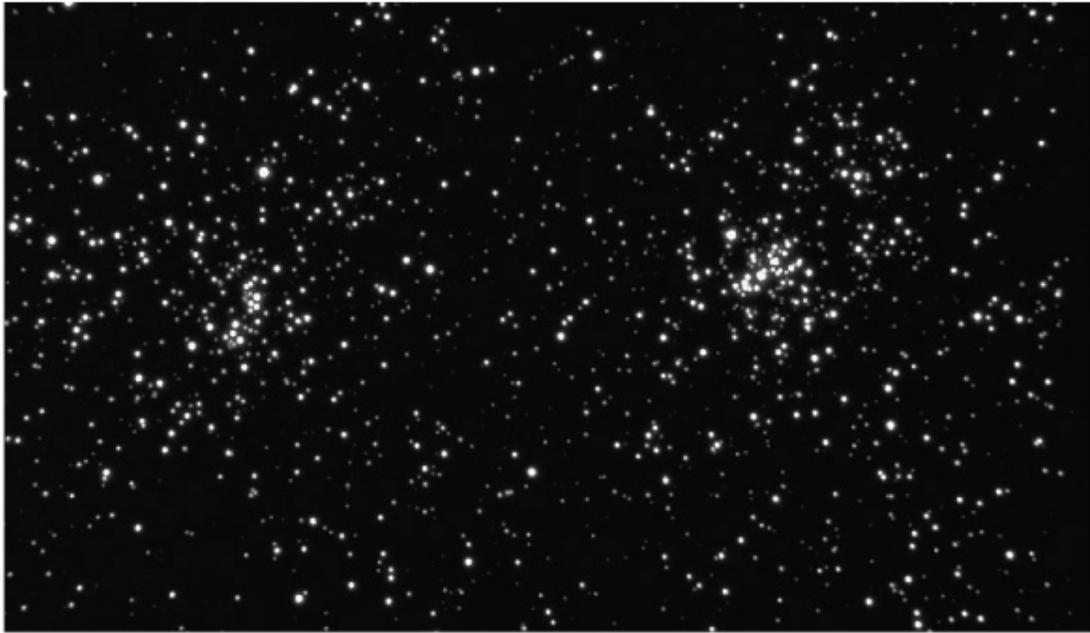


After 10 billion years, a number of features are evident:

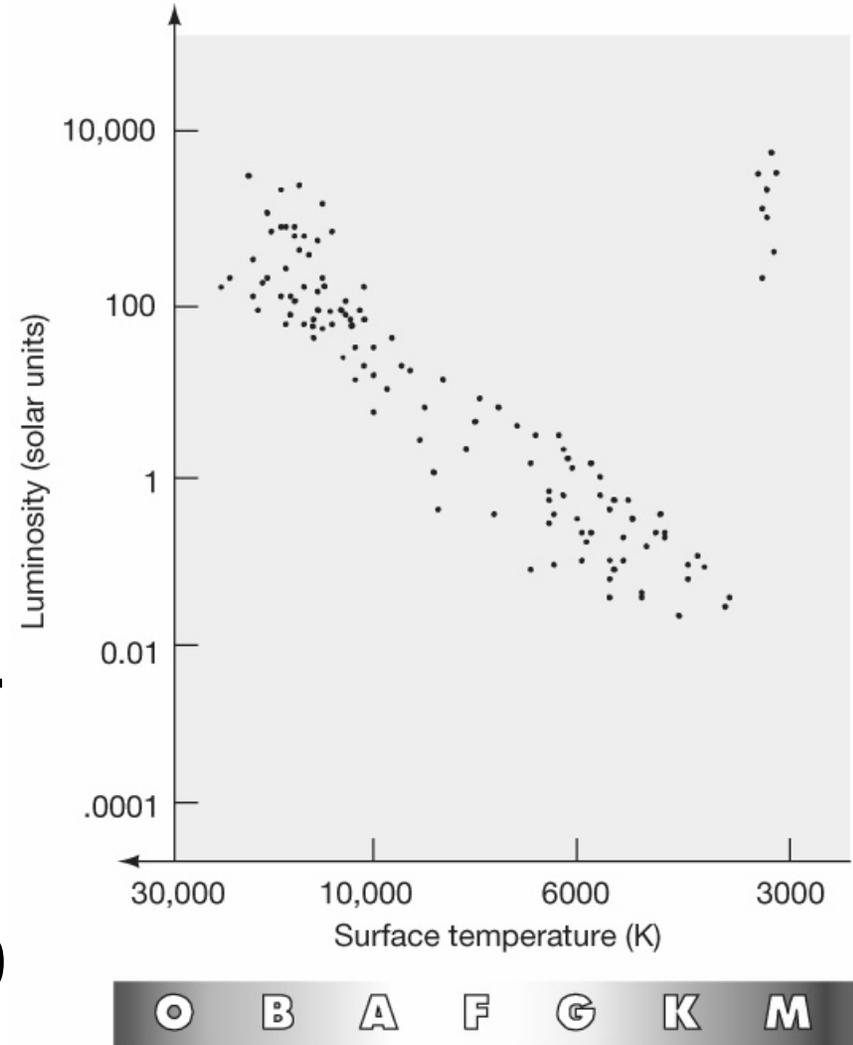
The red-giant, subgiant, asymptotic giant, and horizontal branches are all clearly populated.

White dwarfs, indicating that solar-mass stars are in their last phases, also appear.

12.6 Observing Stellar Evolution in Star Clusters

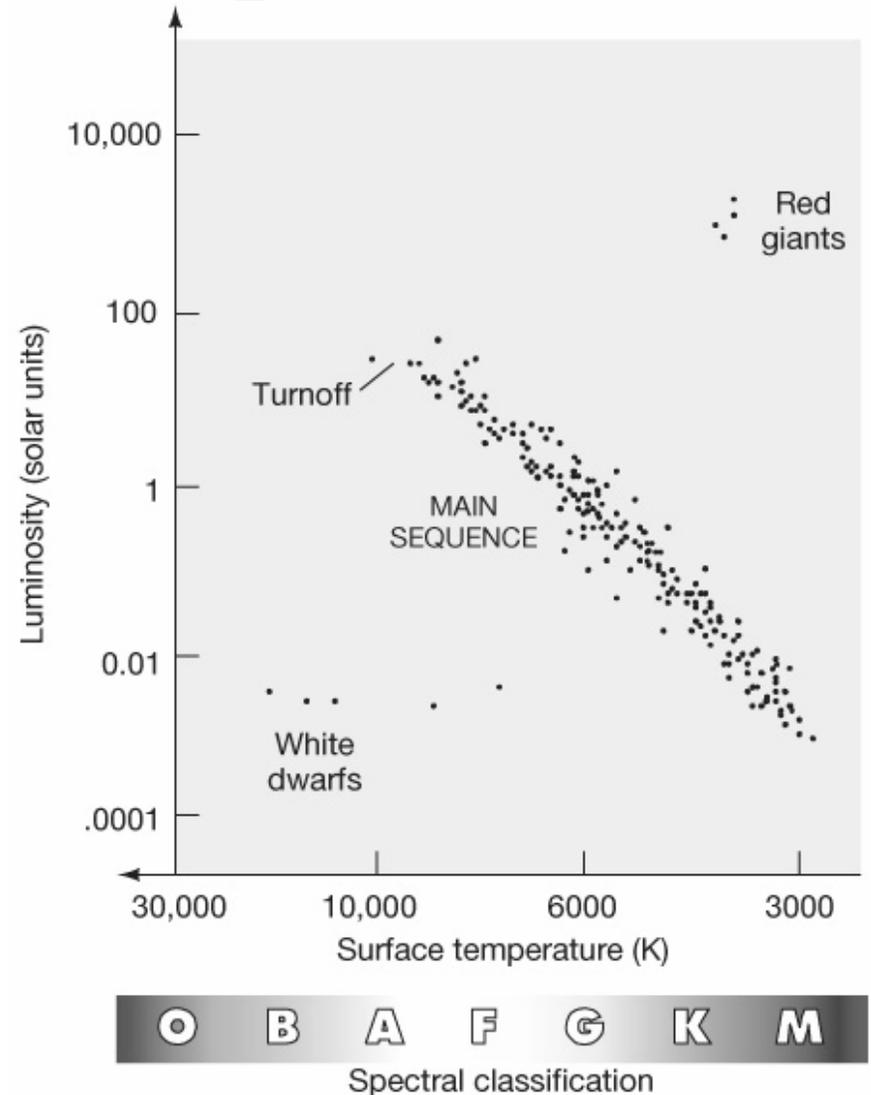
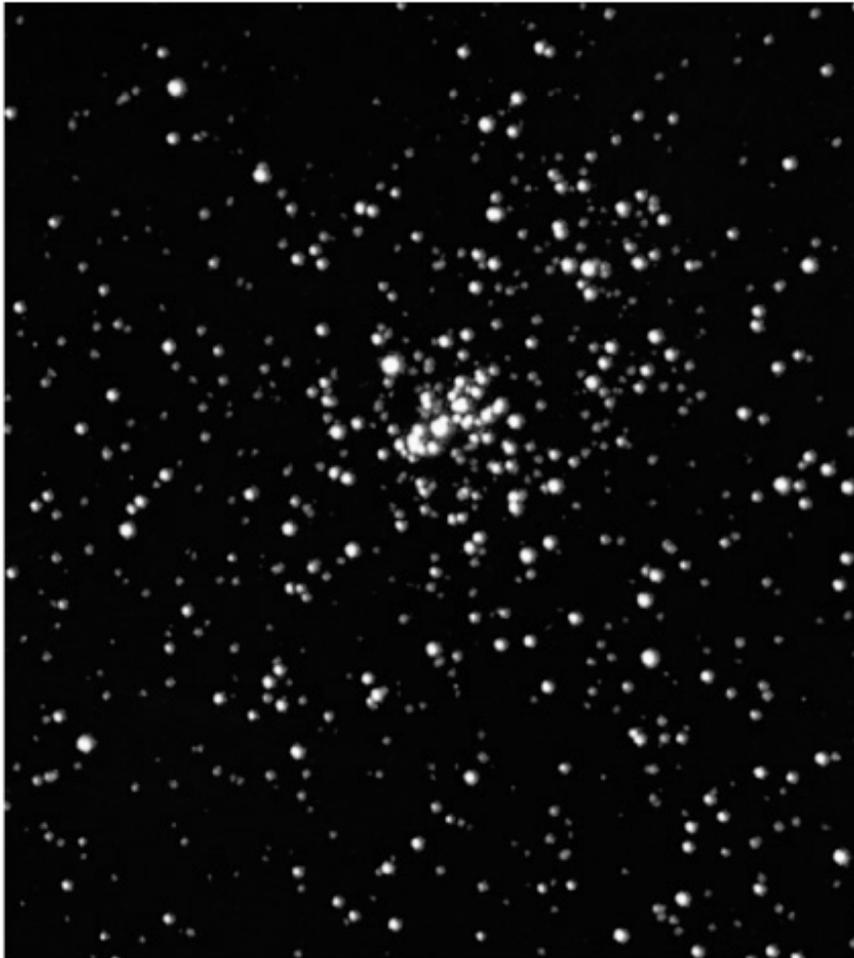


This double cluster, η and χ Persei, must be quite young – its H-R diagram is that of a newborn cluster. Its age cannot be more than about 10 million years.



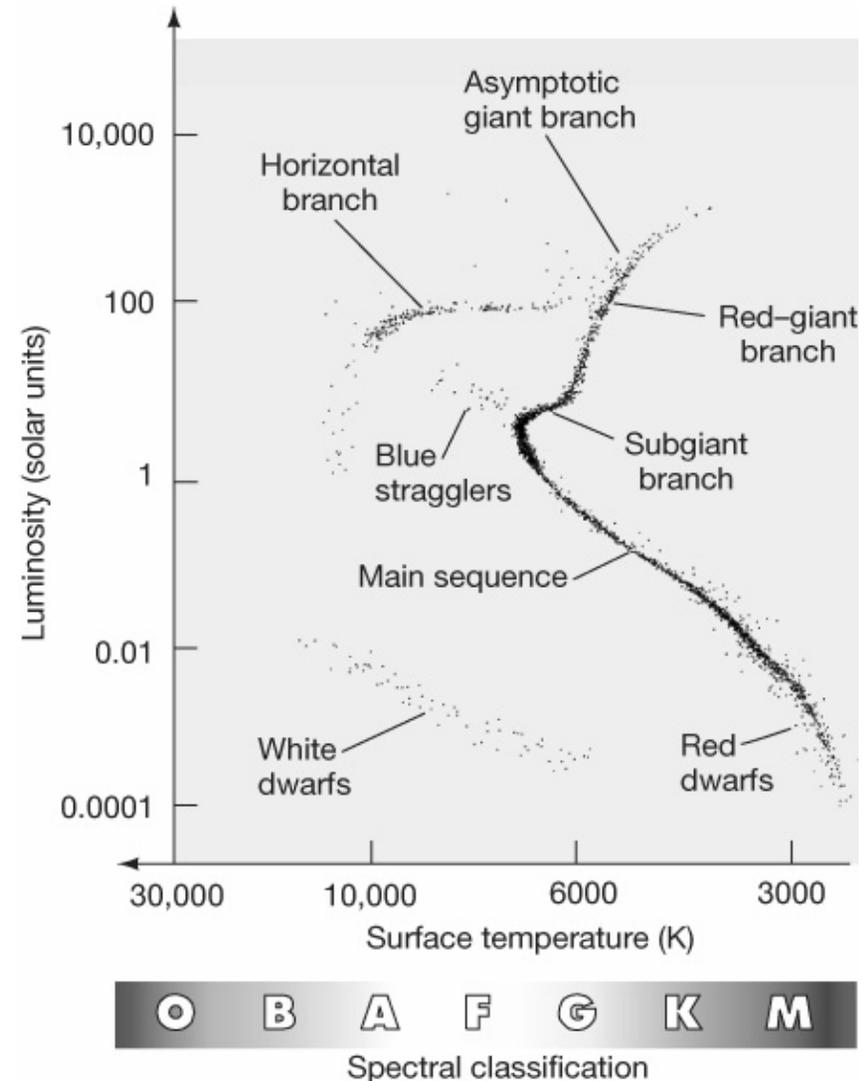
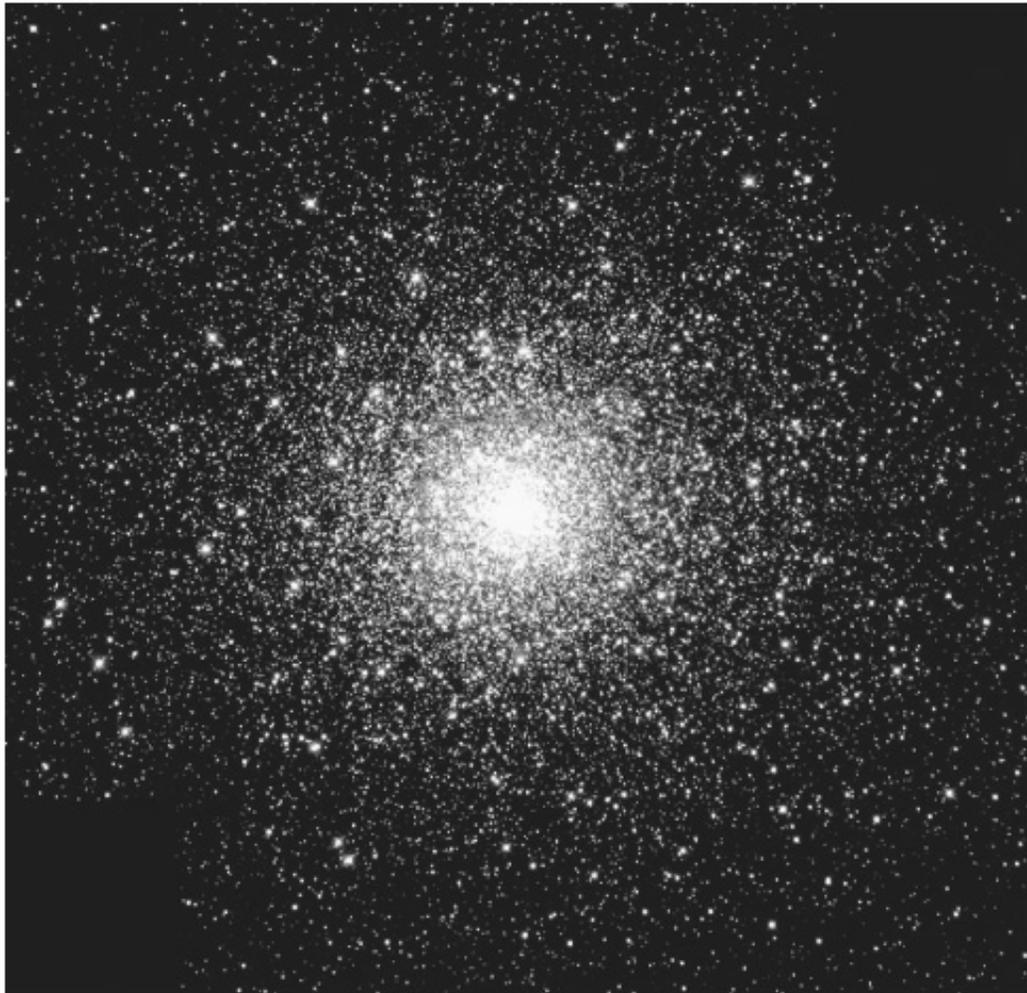
12.6 Observing Stellar Evolution in Star Clusters

The Hyades cluster, shown here, is also rather young; its main-sequence turnoff indicates an age of about 600 million years.



12.6 Observing Stellar Evolution in Star Clusters

This globular cluster, M80, is about 10-12 billion years old, much older than the previous examples.



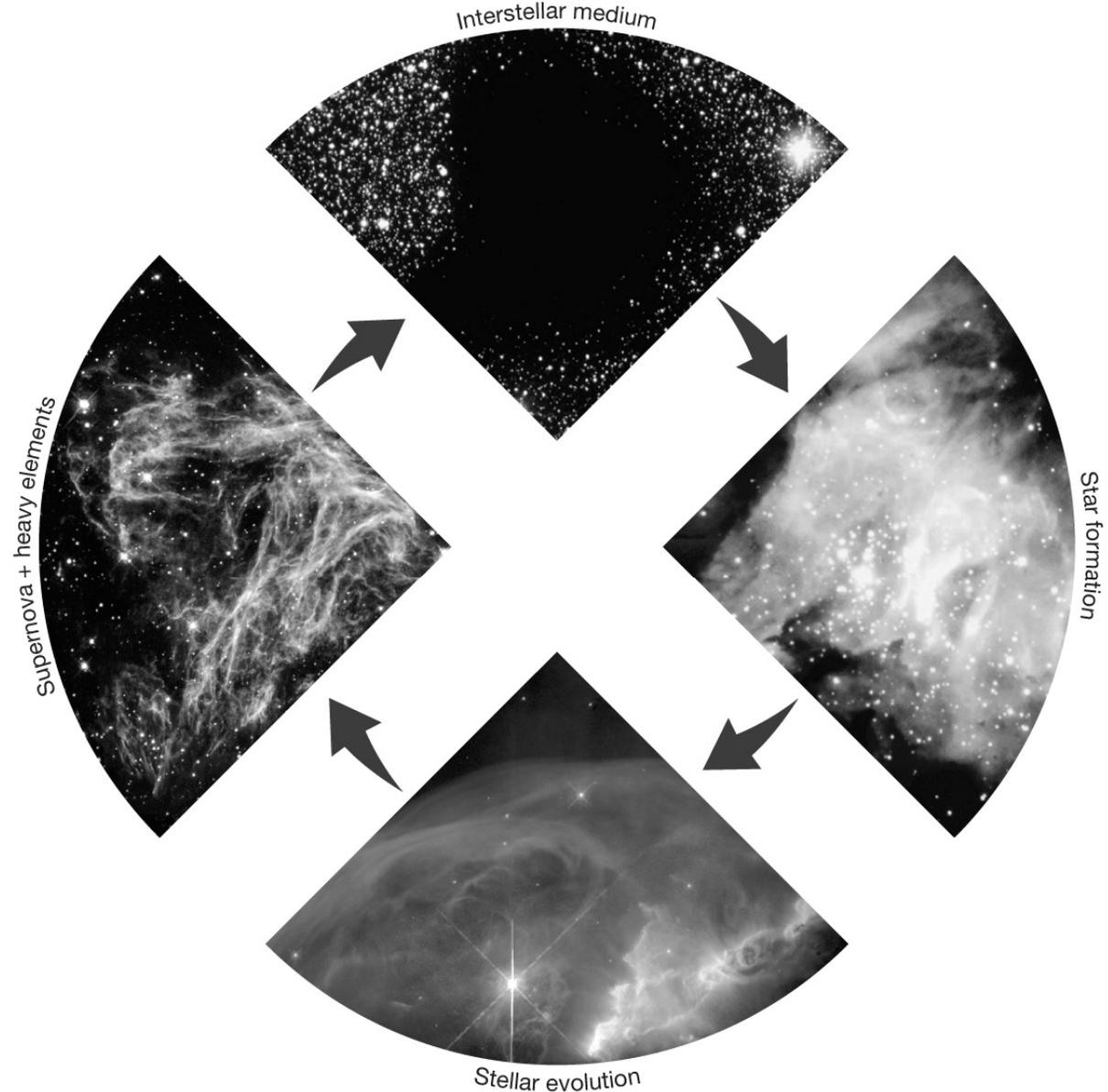
12.7 The Cycle of Stellar Evolution

Star formation is cyclical: stars form, evolve, and die.

In dying, they send heavy elements into the interstellar medium.

These elements then become parts of new stars.

And so it goes.



Summary of Chapter 12

- **Once hydrogen is gone in the core, a star burns hydrogen in the surrounding shell. The core contracts and heats; the outer atmosphere expands and cools.**
- **Helium begins to fuse in the core, as a helium flash. The star expands into a red giant as the core continues to collapse. The envelope blows off, leaving a white dwarf to gradually cool.**
- **Nova results from material accreting onto a white dwarf from a companion star**

Summary of Chapter 12

- **Massive stars become hot enough to fuse carbon, then heavier elements all the way to iron. At the end, the core collapses and rebounds as a Type II supernova.**
- **Type I supernova is a carbon explosion, occurring when too much mass falls onto a white dwarf.**
- **All heavy elements are formed in stellar cores or in supernovae.**
- **Stellar evolution can be understood by observing star clusters.**