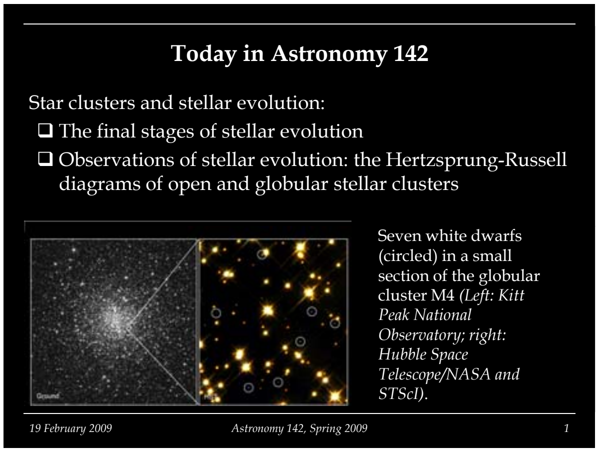


Today in Astronomy 142

Star clusters and stellar evolution:

- ❑ The final stages of stellar evolution
- ❑ Observations of stellar evolution: the Hertzsprung-Russell diagrams of open and globular stellar clusters

Seven white dwarfs (circled) in a small section of the globular cluster M4 *(Left: Kitt Peak National Observatory; right: Hubble Space Telescope/NASA and STScI).*

Late stages of stellar evolution

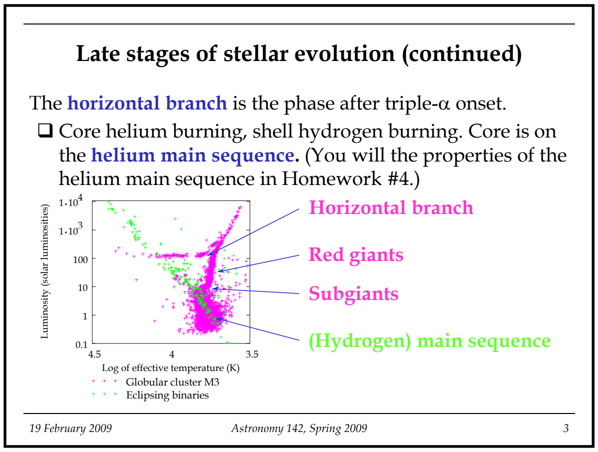
After the main sequence and the subgiant phase:

Red giant phase (moving up in H-R diagram)

- ❑ Core collapse and heating
- ❑ Convection zone extends inward (**dredge-up**)
- ❑ Extreme expansion of envelope of star, from sharp increase in radiation pressure from interior. Radiation pressure now dominates support against the star's weight.
- ❑ Core temperature reaches 10^8 K, and the **triple-α process**,

$$3\,{}^4_2\mathrm{He} \rightarrow {}^8_4\mathrm{Be}^* + {}^0_0\gamma + {}^4_2\mathrm{He} \rightarrow {}^{12}_{6}\mathrm{C} + 2\,{}^0_0\gamma \quad ,$$

begins burning helium. The onset of this process is very rapid in stars with $M \geq 2M_{\odot}$, leading to a phenomenon called the **helium flash**.



Late stages of stellar evolution (continued)

The **horizontal branch** is the phase after triple-α onset.

- ❑ Core helium burning, shell hydrogen burning. Core is on the **helium main sequence**. (You will the properties of the helium main sequence in Homework #4.)

Quick note on nomenclature: spectral type

The "Harvard" spectral type of a star is a classification based upon the strength of absorption lines of several molecules, atoms and ions in its spectrum (Annie J. Cannon, 1901).

- Generally the types A-M correspond to steady decreases in the strength of hydrogen lines; type O "weaker" still (emission lines instead of absorption), P for planetary nebulae, Q for miscellany. N was not used.
- Years later Cecilia Payne (1925) showed that the sequence OBAFGKM is a sequence of decreasing temperature, roughly 35000 – 3500 K. More recently types L, T and Y have been added for brown dwarfs.

Examples: Vega is an A0 star, the Sun a G2 star, Pollux a K2 star, and Betelgeuse an M2 star.

Quick note on nomenclature: luminosity class

At Yerkes Observatory in the 1940s, Morgan, Keenan and Kellman (MKK) added another dimension to classification by introduction of luminosity classes.

- V: main sequence, or dwarf, stars.
- IV: subgiants, brighter than V by a magnitude or two for the same spectral type.
- III: normal giants, another few magnitudes brighter
- II,I: bright giants and supergiants, yet another few magnitudes brighter.
- VI, VIII: subdwarfs and white dwarfs.

Examples: Vega is an A0V star, the Sun is G2V, Pollux is K2III, and Betelgeuse is M2I.

After the horizontal branch

Low mass stars (those with $M < 2M_\odot$):

- Slowly an "isothermal carbon-oxygen core" forms in the center as the helium fuel is exhausted.
- In these stars, however, there is not enough weight to overpower degeneracy pressure, so the core doesn't collapse and reheat to ignite carbon-oxygen fusion.
- Result:
  - H/He burning of outer layers of star, ejection of most of the outer layers and formation of a **planetary nebula**. This lasts a few thousand years; after it drifts away. We'll discuss planetary nebulae two lectures hence.
  - and a carbon-oxygen white dwarf with mass $M \approx 0.6M_\odot$ and initial temperature ~10^8 K is left (lasts ~forever).

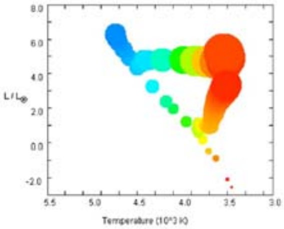
After the horizontal branch (continued)

Massive stars (those with $M > 2M_\odot$):
Asymptotic giant branch (AGB, or supergiant) evolution

- ☐ Repeated core collapse - fusion reignition - nuclear fuel exhaustion occurs, including silicon burning to produce iron-peak elements.
- ☐ Each of the successive fuel exhaustions is faster than the last. For a $20M_\odot$ star,
  - hydrogen burning (main sequence) lasts 10^7 years
  - helium burning (horizontal branch) lasts 10^6 years
  - carbon burning lasts 300 years
  - oxygen burning lasts 200 days
  - silicon burning lasts 2 days !

Simulation of stellar evolution from main sequence to AGB

Terry Herter's (Cornell) AST 101/103 site, the source of the nice binary-star simulations we've used, also has a stellar-evolution simulator. Have a look here.



Results from Terry's simulator, for stars with $M = 1.5$ and $15M_\odot$. The tracks take 5.6 Gyr for the lighter star and only 14 Myr for the heavier one.

What happens when all the nuclear fuel is gone?

Most $M > 2M_\odot$ stars

- ☐ During the burning of heavier elements, and radiative support of the stellar envelope, stars tend to be hydrodynamically unstable, leading to the loss large fractions of stars' mass.
  - Oscillations: note that evolution takes stars across the instability strip (lecture, 5 February), which is nearly vertical at effective temperature ~ 10,000K.
  - Stellar winds (see this week's Recitation, and HW#4).
- ☐ This can keep a star's core mass below the Chandrasekhar limit, and the final states of the star are just like that of less massive ones: planetary nebula phase and white dwarf remnant.

What happens when all the nuclear fuel is gone? (continued)

The most massive stars $\left(M \gtrsim 8M_\odot\right)$

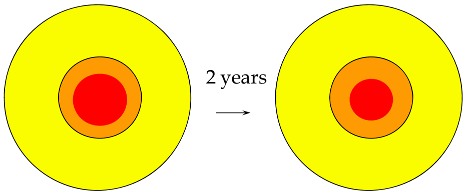
- ❑ Mass loss insufficient to keep core in white dwarf range: further collapse and neutronization.
- ❑ When the collapsing core reaches tens-of-km dimensions, neutron degeneracy pressure sets in, and this can stop or slow the collapse.
- ❑ However, since the collapse has been from white-dwarf dimensions to neutron-star dimensions, infalling material from the star's envelope is going *very* fast. It bounces off the stiffened neutron-degenerate material and blows up the rest of the star.

Core collapse and Type II supernovae

- ❑ This event is called a **core collapse**, or **type II**, **supernova.**
  - How did we get to type II before type I? We'll get to that later in the course, when we talk about the extragalactic distance scale.
- ❑ Remnant: a neutron star or more rarely a black hole, depending upon core mass.

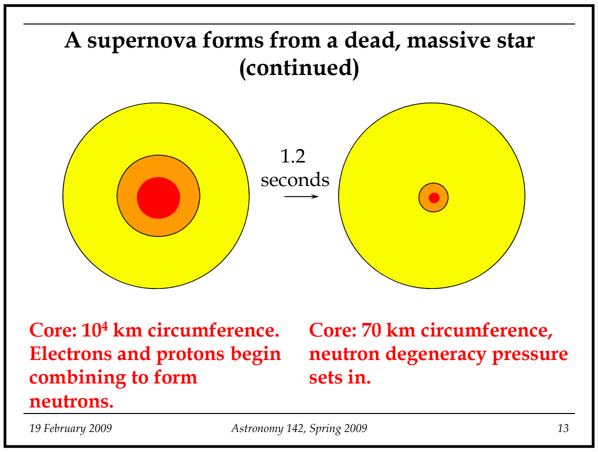
Artist's conception of a SNII and the formation of a supernova remnant (*Chandra/CfA/NASA*).

A supernova forms from a dead, massive star (not drawn to scale)



Star: 6 $M_\odot$, 10^7 km circumference
Core: 1.4 $M_\odot$, 10^5 km circumference

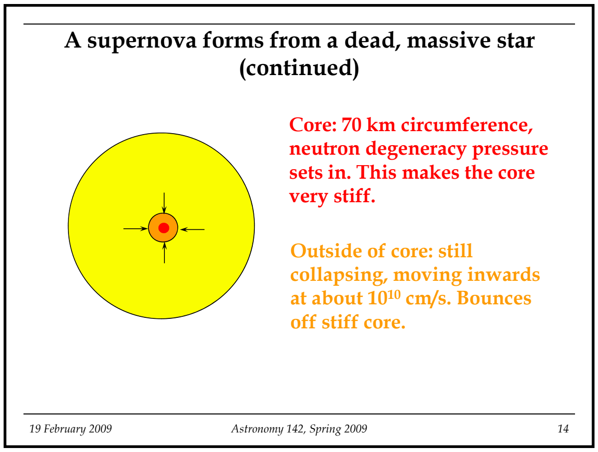
Core: 10^4 km circumference. Electrons and protons begin combining to form neutrons.



A supernova forms from a dead, massive star (continued)

Core: 10^4 km circumference. Electrons and protons begin combining to form neutrons.

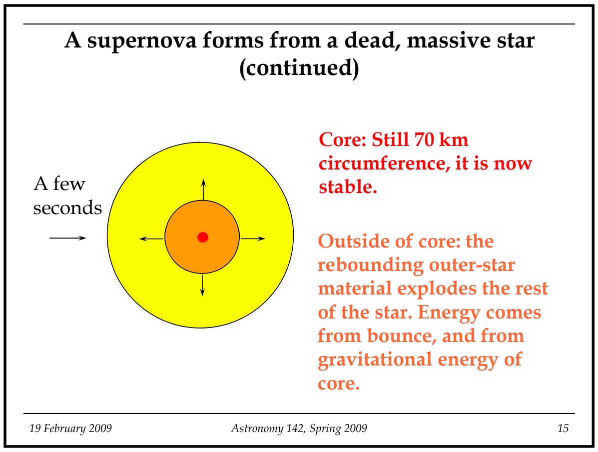
Core: 70 km circumference, neutron degeneracy pressure sets in.



A supernova forms from a dead, massive star (continued)

Core: 70 km circumference, neutron degeneracy pressure sets in. This makes the core very stiff.

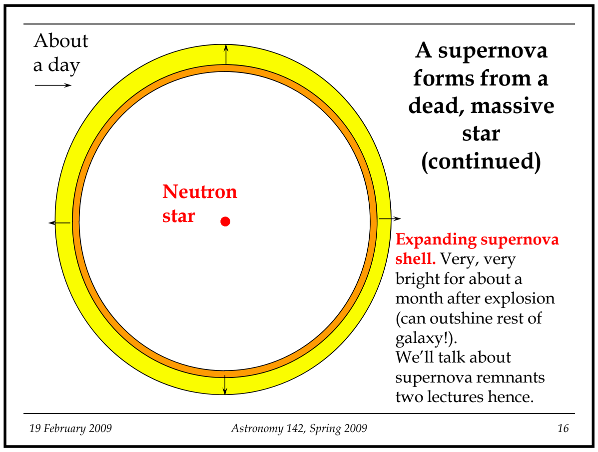
Outside of core: still collapsing, moving inwards at about 10^{10} cm/s. Bounces off stiff core.



A supernova forms from a dead, massive star (continued)

Core: Still 70 km circumference, it is now stable.

Outside of core: the rebounding outer-star material explodes the rest of the star. Energy comes from bounce, and from gravitational energy of core.

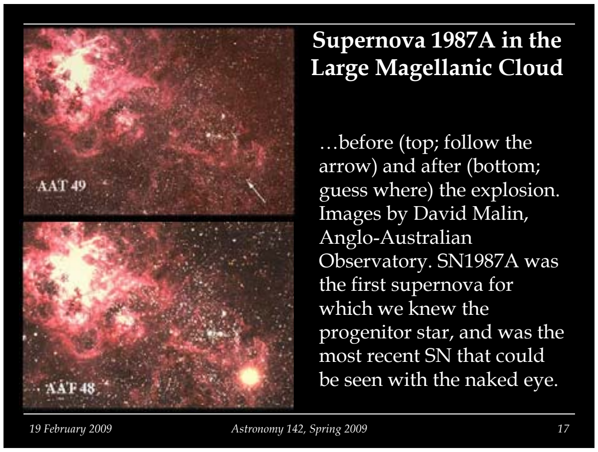


A supernova forms from a dead, massive star (continued)

About a day

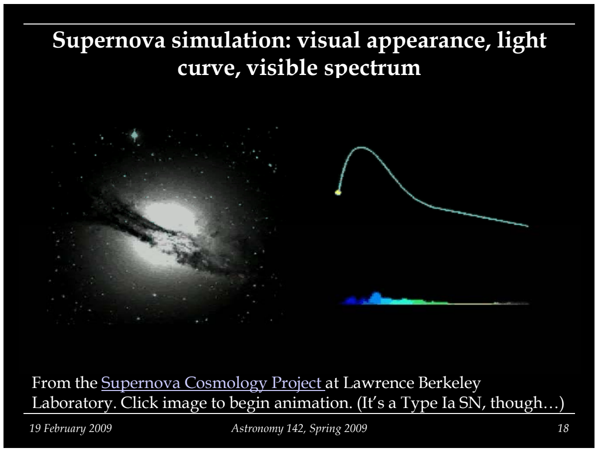
Neutron star

Expanding supernova shell. Very, very bright for about a month after explosion (can outshine rest of galaxy!).
We'll talk about supernova remnants two lectures hence.



Supernova 1987A in the Large Magellanic Cloud

…before (top; follow the arrow) and after (bottom; guess where) the explosion. Images by David Malin, Anglo-Australian Observatory. SN1987A was the first supernova for which we knew the progenitor star, and was the most recent SN that could be seen with the naked eye.



Supernova simulation: visual appearance, light curve, visible spectrum

From the Supernova Cosmology Project at Lawrence Berkeley Laboratory. Click image to begin animation. (It's a Type Ia SN, though…)

Observation of stellar evolution: star clusters

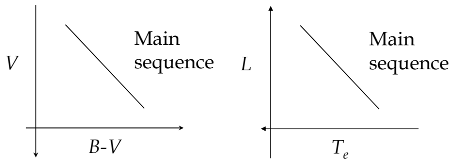
Stars tend to form in clusters, with all members nearly the same age.

- **Open clusters** (young): low density, irregular, lots of blue stars, low random velocities (few km/sec), hundreds to thousands of stars, not always gravitationally bound. Archetypes: Pleiades (M45), Hyades.
- **Globular clusters** (old): high density, spherically symmetrical, few blue stars, higher random velocities (tens of km/sec), millions of stars, gravitationally bound. Archetypes: ω Centauri, M3, M13, 47 Tucanae.

Star clusters are very useful for studying stellar evolution and for determination of distance scales in the universe.

The (observer's) H-R diagram for clusters

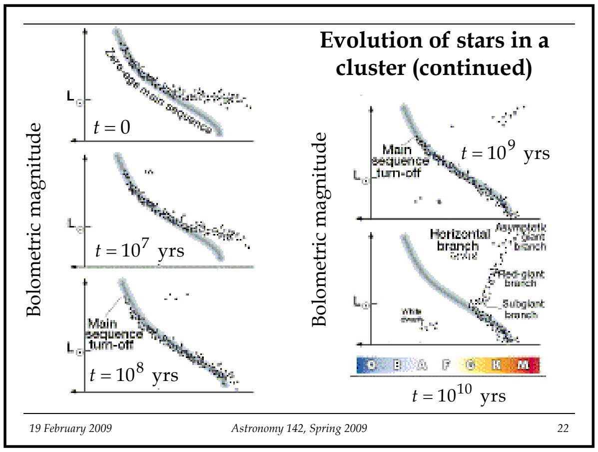
The plot of apparent magnitude in the *V* band (backwards) against the color index *B*-*V* is the classical Hertzsprung-Russell diagram. Plotted in this way such diagrams will resemble our previous logarithmic plots of luminosity vs. effective temperature (backwards).



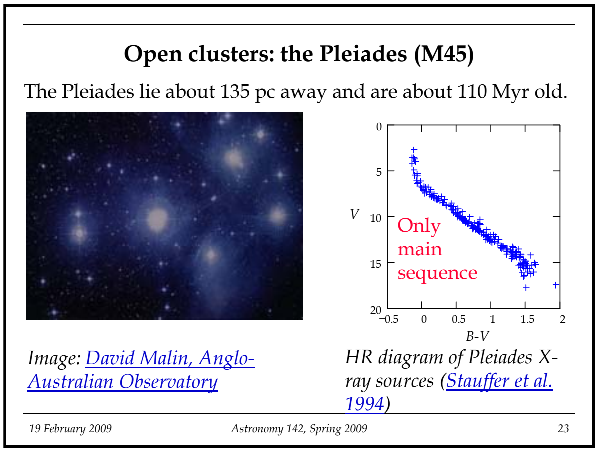
Evolution of stars in a cluster

Because the measurement of an HR diagram is a snapshot in stellar age terms – made in an instant – the HR diagram of a cluster does not resemble the tracks in L-T_e space followed by individual stars as they age.

- Instead there will tend to be a **turnoff** at some point on the main sequence, above which there are no main sequence stars left. All the stars originally on the upper main sequence have moved elsewhere in the HR diagram, with identifiable collections only in the longer-lived stages like the RGB and the horizontal branch.
- Nice animation of cluster evolution by Leslie Tomley (San Jose State): look here. Does white-dwarf cooling too fast but is otherwise accurate.



Evolution of stars in a cluster (continued)

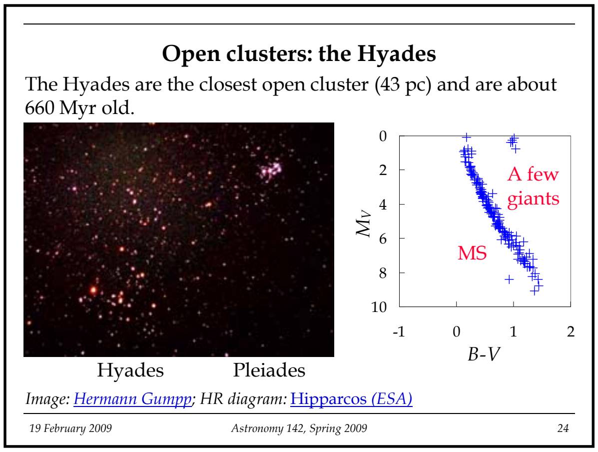


Open clusters: the Pleiades (M45)

The Pleiades lie about 135 pc away and are about 110 Myr old.

Image: David Malin, Anglo-Australian Observatory

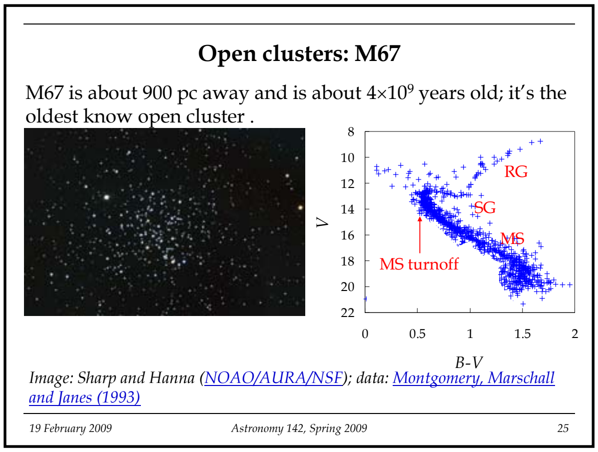
HR diagram of Pleiades X-ray sources (Stauffer et al. 1994)



Open clusters: the Hyades

The Hyades are the closest open cluster (43 pc) and are about 660 Myr old.

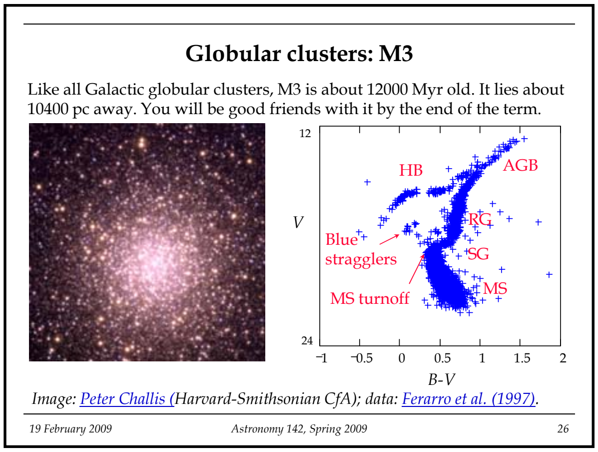
Image: Hermann Gumpp; HR diagram: Hipparcos (ESA)



Open clusters: M67

M67 is about 900 pc away and is about 4×10^9 years old; it's the oldest know open cluster .

Image: Sharp and Hanna (NOAO/AURA/NSF); data: Montgomery, Marschall and Janes (1993)



Globular clusters: M3

Like all Galactic globular clusters, M3 is about 12000 Myr old. It lies about 10400 pc away. You will be good friends with it by the end of the term.

Image: Peter Challis (Harvard-Smithsonian CfA); data: Ferarro et al. (1997).