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).*
Nomenclature: luminosity class

At Yerkes Observatory in the 1940s, Morgan, Keenan and Kellman (1943; 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, VII: subdwarfs and white dwarfs.

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

Data from Schmidt-Kaler 1982
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-$\alpha$ process**, 
  \[
  3 \frac{4}{2}\text{He} \rightarrow \frac{8}{4}\text{Be}^* + 0^0\gamma + \frac{4}{2}\text{He} \rightarrow \frac{12}{6}\text{C} + 20^0\gamma 
  \]
  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**.
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 $\sim 10^8$ 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!
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
  - Stellar winds

- 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.
The Chaotic Winds of Cool Giants
Peter Woitke
What happens when all the nuclear fuel is gone? (continued)

The most massive stars

- 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. This event is called a type II supernova.
  - How did we get to type II before type I?
- Remnant: a neutron star or more rarely a black hole, depending upon core mass.
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.

2 years
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

A supernova shell. Very, very bright for about a month after explosion (can outshine rest of galaxy!). We’ll talk about supernova remnants soon!
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…)

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Types of Supernovae

Supernovae are divided into two basic physical types:

**Type Ia.** These result in some binary star systems in which a carbon-oxygen white dwarf is accreting matter from a companion. (What kind of companion star is best suited to produce Type Ia supernovae is hotly debated.) In a popular scenario, so much mass piles up on the white dwarf that its core reaches a critical density of $2 \times 10^9 \text{ g/cm}^3$. This is enough to result in an uncontrolled fusion of carbon and oxygen, thus detonating the star.

**Type II.** These supernovae occur at the end of a massive star's lifetime, when its nuclear fuel is exhausted and it is no longer supported by the release of nuclear energy. If the star's iron core is massive enough then it will collapse and become a supernova.
Types of SN

These types of supernovae were originally classified based on the existence of hydrogen spectral lines: Type Ia do not show hydrogen lines, while Type II do. In general this observational classification agrees with the physical classification outlined above, because massive stars have atmospheres (made of mostly hydrogen) while white dwarf stars are bare. However, if the original star was so massive that its strong stellar wind had already blown off the hydrogen from its atmosphere by the time of the explosion, then it too will not show hydrogen spectral lines. These supernovae are often called Type Ib supernovae, despite really being part of the Type II class of supernovae.
Supernova light curves

Type I and II supernovae are distinguished observationally by the shape of their luminosity as a function of time (light curve).

- SNe I decline in brightness by about 0.1 mag/day and reach peak absolute magnitudes in the $V = -18 \rightarrow -19$ range.
- SNe II decline more slowly (> 0.05 mag/day) and have smaller peak absolute magnitudes ($V \sim -17$).
SN Ia

SN type Ia all have the same light curve and the same maximum intensity. They are referred to as a “standard candle” and used to probe the shape of the universe.
Crab nebula and pulsar+ Vela supernova remnant
Cas A SN remnant chandra image
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).
Open clusters: the Pleiades (M45)

The Pleiades lie about 130 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 $4 \times 10^9$ years old; it’s the oldest known open cluster.

Image: Sharp and Hanna (NOAO); 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.

Image: J. Challis (Harvard-Smithsonian CfA); data: Ferarro et al. (1997).
Evolution off the Main Sequence

- Ionizing stars
- H II region
- Young cluster
- Main sequence fully populated
- No Red Giants

1 Billion years old --→ more stars on the giant branch; some white dwarfs now. Upper main sequence gone above 2 solar masses

10 Million years Old --→ Most massive main sequence stars are now Red Giants --→ H II regions are gone

T = 10 billion years old --→ just red stars left; lots of white dwarfs; no stars more massive than one solar mass left on the main sequence
More on the Hyades

The best HR diagram that I could find in the literature from de Bruijne et al. 2001

Careful removal of uncertain stars results in this accurate sequence.
Initial mass function

The initial mass function describes the numbers of stars as a function of mass that are born.
Usually measured in clusters using the luminosity function (numbers of stars as a function of luminosity) and a relation between mass and luminosity

Number of stars in a mass bin $dM$  
$N(M)dM \propto M^{-\alpha} dM$
$\alpha=2.3$ Salpeter IMF
likely to be shallower at lower masses

Cutoffs likely:
at high mass end $\sim 100\text{M}_\odot$
at low mass end: Brown dwarf scale

Because exponent is negative most mass is in smaller bodies.
Most luminosity in larger bodies (at least for main sequence, most luminosity in Giants overall
Mass function in log space

On a log log plot we expect a line with slope related to the exponent of the IMF.

Useful for finding initial mass function from a luminosity function of a cluster.

If we weight by lifetime we can also infer the initial mass function for stars in the field using magnitude bins.

\[ u = \log_{10} M \quad 10^u = M \]
\[ e^{u \ln 10} = M \quad \ln 10 M du = dM \]

\[ \frac{dM}{du} = M \ln 10 \]

\[ N(M)dM = N(u)du \]

\[ N(u) = N(M) \frac{dM}{du} = N(M) M \ln 10 \]
\[ = A M^{-\alpha + 1} \ln 10 \]
\[ = A 10^{u(1-\alpha)} \ln 10 \]

\[ \log_{10}(N(u)) = u(1 - \alpha) + \text{Constant} \] in bins of size \( du \)
Summary

- Supernovae, late stages of evolution, different types of giants
- HR diagrams of clusters
- Initial mass function and how to transform it