ASTR-1020: Astronomy II
Course Lecture Notes
Section VII

Dr. Donald G. Luttermoser
East Tennessee State University

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Abstract

These class notes are designed for use of the instructor and students of the course ASTR-1020: Astronomy II at East Tennessee State University.

VII. Stellar Evolution: Death

A. Post-Red Giant Evolution.

1. In this subsection we will concentrate on the late stages of stellar evolution for isolated (*i.e.*, single) stars. The evolution of binary stars will be presented in §VII.B.

2. The path a star takes on its road to stellar death depends upon its initial mass. Note that the following masses correspond to the mass of the star while on the main sequence.

a) Note that some of the masses listed below are approximate since there is some uncertainty in these values. Also note that these notes list an additional mass range (4 - 8 $M_\odot$) evolution that is not included in the textbook.

b) The amount of mass-loss that a star experiences in the post-red giant stage can vary from star to star. It is this uncertainty in mass-loss that leads to the uncertainty in these mass listings.

c) Metalicity plays a big role in the mass-loss of a star near the end of its thermonuclear life. The higher the metalicity, the more dust than can form in a stellar atmosphere, the easier it is for the stellar radiation field to drive the mass loss.

3. $M < 0.08 M_\odot$: These objects never ignite hydrogen and hence never become main sequence stars. These objects are called **brown dwarfs** as described in the last section of these notes. They are bright at infrared wavelengths from energy liberated from contraction.

4. $0.08M_\odot < M < 0.4M_\odot$: These stars are totally convective, and as such, helium ash gets uniformly mixed throughout the star. No inert He core develops, hence no H-shell burning and no expansion into a red giant. After hydrogen is exhausted, the entire star contracts until the helium becomes degenerate (see the white dwarf section [§VIII.A]) and the star becomes a **helium-rich white dwarf**.

5. $0.4M_\odot < M < 4M_\odot$: These stars ignite He in a degenerate core (He-flash, see §VI.C.3). During the core He-fusion stage, the star sits in the **red giant clump** (Population I stars — see §IX.B) or the **horizontal branch** (Population II stars) on the H-R diagram. He-fusion creates ^{12}C and ^{16}O ash and once the He-fusion stops, the carbon-oxygen core continues to collapse.

  a) This causes energy to be dumped into the He-rich layer just above the core which ignites $\Longrightarrow$ star now has a He-burning shell and H-burning shell. This extra energy source expands the outer layers of the star further — the star becomes a bit more red and a lot more luminous.

  b) Burning in the He-burning shell is quite unstable.

    i) The He-burning shell is subject to a series of explosive *helium-shell flashes* (also called **thermal pulses**), caused by the enormous pressure in the He-burning shell and the extreme sensitivity of the triple-alpha burning rate to small changes in temperature..

    ii) During a thermal pulse, the luminosity of the star increases for a short time (approximately 100 years). Also, the surface pulsations (see §VII.C) can change their periods during this time as well.

R Hya is a long-period variable that has just gone through such a thermal pulse.

iii) While this is going on, the interior of the star also experiences *dredge-ups*. A "dredge-up" simply means that nuclear processed material is being brought from the interior of the star up into the stellar atmosphere where it can be detected in the emergent spectrum of the star.

c) During this time, the star moves up the **asymptotic giant branch** (AGB) on the H-R diagram.

d) For stars $2M_\odot$ and above while on the AGB, carbon produced in the He-burning shell finds its way to the surface through deep convection cells $\Longrightarrow$ the star becomes either an S star (with C/O ~ 1.0) or a carbon (R or N) star (with C/O > 1.0). *TX Psc* is an example of a carbon star that has already gone through a series of thermal pulses.

e) The outer layers of the star can become unstable during this phase (see §VII.C) and it can begin to pulsate $\Longrightarrow$ **Mira-type variables**.

f) Strong stellar winds begin at this phase which produce **planetary nebula**. The mass loss continues until only the core of the star remains.

g) The contracting carbon-oxygen core becomes degenerate before carbon fusion can begin — the star is now dead as a **carbon-oxygen rich white dwarf**.

6. $4M_\odot < M < 8M_\odot$: These stars ignite He in a non-degenerate core following the triple-alpha process which produces carbon (C) and oxygen (O) ash.

   a) Once He-burning stops, the C-O core goes out of equilibrium and collapses.

   b) The C-O core becomes degenerate before C fusion can begin.

   c) A runaway occurs until ^{12}C ignites in a degenerate core. Unlike the He-flash, this **carbon detonation** completely destroys the star in a **supernova** explosion leaving <u>no</u> remnant core.

   d) Such supernovae are sometimes called **Type I$\frac{1}{2}$ supernovae**.

7. $M > 8M_\odot$: These stars burn elements up to iron (Fe) in their cores.

   a) While this is going on, strong stellar winds are pushing much of the star's outer envelope into the ISM. As a result of these strong stellar winds, the mass of the star can decrease by a significant amount.

   b) Mixing can occur between the C-O core and the He-rich shell above it, especially during the thermal pulses.

   c) For those stars with sufficient mass left in the star, the following reactions will occur when the collapsing C-O core gets hot enough:

$$
\begin{aligned}
{}^{14}\mathrm{O} + {}^{4}\mathrm{He} &\longrightarrow {}^{20}\mathrm{Ne} + \gamma \\
{}^{20}\mathrm{Ne} + {}^{4}\mathrm{He} &\longrightarrow {}^{24}\mathrm{Mg} + \gamma \\
{}^{24}\mathrm{Mg} + {}^{4}\mathrm{He} &\longrightarrow {}^{28}\mathrm{Si} + \gamma \\
{}^{28}\mathrm{Si} + {}^{4}\mathrm{He} &\longrightarrow {}^{32}\mathrm{S} + \gamma \\
{}^{32}\mathrm{S} + {}^{4}\mathrm{He} &\longrightarrow {}^{36}\mathrm{Ar} + \gamma \\
{}^{12}\mathrm{C} + {}^{12}\mathrm{C} &\longrightarrow {}^{24}\mathrm{Mg} + \gamma \\
{}^{16}\mathrm{O} + {}^{16}\mathrm{O} &\longrightarrow {}^{32}\mathrm{S} + \gamma
\end{aligned}
$$

note that Ne = neon, Mg = magnesium, Si = silicon, S = sulfer, and Ar = argon in the table above.

d) Various silicon burning reactions can occur at temperatures exceeding 3×10^9 K in the core. Silicon burning produces the iron (Fe) group elements.

e) Once Fe is formed, reactions that produce heavier elements are all endothemic (*i.e.*, requiring an energy input) and have a tough time forming via standard thermonuclear burning. Such elements, and the elements not built upon α-particles, are created via the **r-** (for rapid neutron capture) and **s-** (for slow neutron capture) **processes**. These processes will be discussed in the supernovae subsection below.

f) As a result of this characteristic of Fe, the collapse of the core cannot be halted by the onset of further thermonuclear reactions. The core can do one of 2 things during its final collapse:

i) Achieve nuclear densities ($e^- + p \longrightarrow n + \nu$) and *bounce* when neutron degeneracy sets in $\Longrightarrow$ a **neutron star** forms during a **Type II supernova explosion** (see below).

ii) The core collapses past the neutron degeneracy state (if $M_{\rm core} > 3M_\odot$) down to a **black hole** (see §VIII.D).

B. Stellar Evolution in Binary Star Systems.

1. Stars in binary or multiple star systems will evolve like isolated stars (described in the previous subsection) if the component stars are well separated from each other.

2. Here we will concentrate on stellar evolution in *close* binary star systems where *mass transfer* has a large impact of the evolution of these systems.

a) By "close," we mean that the separation 'a' of the two stars are at most the diameter of the larger star (*i.e.*, $a \leq 2R_1$, where '1' is the larger of the two stars).

b) Such stars will be tidally (*i.e.*, rotationally) "locked" to each other due to the conservation angular momentum.

c) For such systems, 5 points exist where the gravitational force on a small mass near the two larger masses equals zero. These points are called **Lagrangian points**:

i) $\boldsymbol{L_1}$: The zero-force point that lies between the two masses $\Longrightarrow$ the *inner Lagrangian point.*

ii) $\boldsymbol{L_2}$: The zero-force point that lies on the far side of M_2 (the smaller mass).

iii) $\boldsymbol{L_3}$: The zero-force point that lies on the far side of M_1 (the larger mass).

iv) $\boldsymbol{L_4}$: The zero-force point that lies in the orbit of M_2 (the smaller mass), 60° forward from M_2 at a distance r_2 from the center of mass.

v) ***L_5***: The zero-force point that lies in the orbit of M_2 (the smaller mass), 60° behind M_2 at a distance r_2 from the center of mass.

vi) The first 3 Langrangian points (*i.e.*, L_1, L_2, & L_3) are *unstable* (*i.e.*, if moved away from one of these points, the test mass would continue to move away from that point).

vii) The last 2 Langrangian points (*i.e.*, L_4 & L_5) are *stable* (*i.e.*, if moved away from one of these points, the test mass would move back to that point). In the case of Jupiter's orbit about the Sun, the *Trojan asteroids* are found at Jupiter's L_4 and L_5 Lagrangian points.

d) The equipotential gravitational (*i.e.*, the gravitational force remains constant) surface of these two stars that just connects with L_1 (it has a teardrop shape as shown in Fig. 17.3) is called the **Roche lobe** (see Fig. 20.21 of your textbook).

i) If the 2 stars in the binary are too small to fill their Roche lobe, they are said to be in a **detached binary** system.

ii) If one star fills it Roche lobe (and the other has not), the system is said the be a **semidetached binary**. In such a system, the star that has filled it's Roche lobe is called the *secondary* of the binary star independent of what its mass might be with respect to the *primary* star.

iii) If both stars fill their Roche lobe, the system is called a **contact binary**.

3. The semidetached and contact system have mass that transfers from one star to the other star. An important quantity in the evolution of such systems depends upon the **mass transfer rate**.

a) As material flows through L_1, M_1 loses mass and M_2 gains mass through the process of **accretion**.

b) This mass transfer can slow the speed of the evolutionary "steps" of the M_1 star (if it is fast enough) and increase the speed of the evolutionary "steps" of the M_2 star.

c) Nuclear processed material can then be transferred to the companion (this is how dwarf S stars and dwarf carbon stars are made).

d) Sooner or later, one of the stars will reach the final stage of its thermonuclear lifetime.

e) If such a star is massive enough, it will supernovae as described in this section of the notes. Depending upon the distance of the two stars, three possible outcomes will take place of the "secondary" star:

i) It will be ejected from the system.

ii) It will be completely disrupted by the shock wave of the supernova.

  iii) It will experience mass loss (perhaps a substantial amount) by the shock and radiation pressure of the blast.

f) If the star in it final thermonuclear stages has too small a mass to supernova, it will lose its envelope through the creation of a planetary nebula (which will have little impact on the secondary) forming a white dwarf star in orbit about the secondary star of the system.

  i) As this secondary star starts to fill its Roche lobe through stellar evolution, it will begin to dump material onto the white dwarf.

  ii) Since the two stars are in orbit about each other, the material misses the white dwarf on *first pass* and goes into orbit about the white dwarf forming an **accretion disk**.

  iii) Viscosity (*i.e.*, internal fluid friction) causes the material in the disk to slowly spiral in towards the white dwarf. As the gas falls into the potential well, its orbital speed increases, which increases the viscosity, which increases the thermal energy of the gas in the disk $\Longrightarrow$ the inner portion of the disk is much hotter than the outer portion.

  iv) The bulk of the light that is emitted in such a system comes from the inner region of the accretion disk and not from the "normal" star nor the white dwarf.

g) Instabilities can arise in the disk which can result in a rapid increase of the mass flow down through the disk, which in turn, causes a rapid increase in the light output of the system. Such a binary is called a **cataclysmic variable** and can go through numerous (though not necessarily periodic) episodes of rapid brightenings. The most energetic of the cataclysmic variables are called **dwarf novae**. Such systems usually have a mass-transfer rate of $10^{-11} - 10^{-10} M_\odot$/yr during the long quiescent intervals.

4. When the mass-transfer rate from the normal star exceeds 10^{-8} $M_\odot$/yr, material accumulates fast enough on the inner edge of the accretion disk and the surface of the white dwarf for a thermonuclear runaway to occur.

- **a)** When about 10^{-5} to $10^{-4} M_\odot$ of hydrogen has accumulated, the temperature of this gas reaches a few million Kelvins.
- **b)** A shell of burning hydrogen develops using the CNO cycle (from carbon left over from the stellar evolution of the primary).
- **c)** Due to the high pressures caused by the intense gravitational field on the surface of the white dwarf, the gas is degenerate.
- **d)** This results in a thermonuclear runaway to occur. The result is a runaway thermonuclear reaction, with temperatures reaching 10^8 K before the electrons lose their degeneracy.
- **e)** When the luminosity gets high enough (*i.e.*, exceeds 10^{31} Joule/s), the radiation pressure can lift the accreted material and expel it into space.

f) Such an outburst is called a **classical nova** or just **nova**. They all reach the approximate same maximum brightness of $M_V \approx -4.5$.

i) A *fast nova* takes a few weeks to dim by 2 magnitudes after reaching maximum brightness.

ii) A *slow nova* may take nearly 100 days to decline by the same amount from maximum.

iii) The fast and the slow speed classes of novae are probably due to variations in the mass of the white dwarf and in the degree of CNO enrichment of the hydrogen surface layer.

iv) It takes about 10^4 to 10^5 years to accumulate enough material for another runaway to occur. Since this is short in comparison to stellar evolutionary time scales, such systems can go through numerous nova episodes.

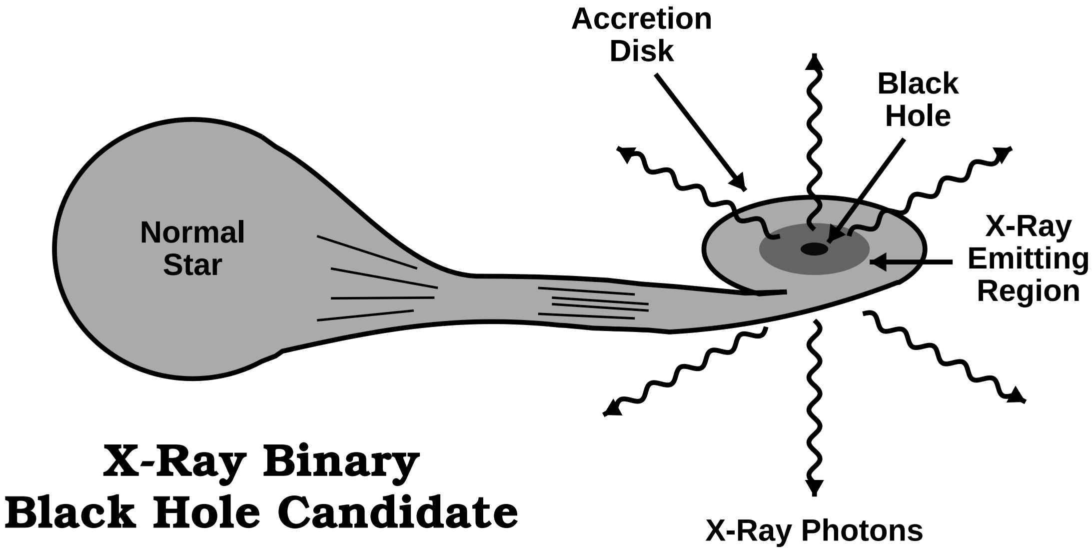
5. If the mass-transfer rate can get as high as $10^{-6} M_\odot$/yr or greater, the white dwarfs mass may build fast enough for its mass to exceed the **Chandrasekhar limit** of 1.4 $M_\odot$ (see §VIII.A of these notes).

a) The white dwarf collapses since the degenerate electron pressure is insufficient to support that weight of this burnt-out core.

b) This sets up a runaway thermonuclear event in the core of the white dwarf which completely destroys the white dwarf as was the case in the carbon detonation of the 4-8 $M_\odot$ main sequence stars (see page VII-4 of these course notes).

c) Such supernova (see §VII.A.6) are called **Type Ia Supernovae**.

6. Besides white dwarfs in a close binary system, the primary also can be a neutron star or black hole (see next section). Indeed, **X-ray binary systems** are suspected to contain one of these two objects $\Longrightarrow$ the X-rays are emitted from the extremely hot (perhaps a high as a billion Kelvins!) inner portion of the accretion disk as shown below.



C. Stellar Pulsations and Mass Loss.

1. The first variable star discovered was *o* Cet in 1596. Astronomers were so surprised by this finding that they renamed the star *Mira* (the wonderful).

a) This was the discovery of the first **long period variable** (LPV) star.

i) Most LPV stars change in brightness on a somewhat periodic time frame anywhere from 150 to

500 days and change by a factor of over 1000 in their brightness. These LPV stars are called **Mira-type (M) variables** after their prototype o Cet.

ii) Some LPVs are less periodic in their variability and are called **semiregular (SR) variables**. These stars typically change in brightness by factors less than 100 of their average brightness.

iii) The remaining stars classified as LPV stars have no periodicity and typically change in brightness by less than 10 from maximum to minimum light. These LPVs are called **irregular (L) variables**.

b) All of these types of variable stars are red giant stars on the asymptotic giant branch of their evolution.

c) The brightness variability is causes by an actual pulsation of the star!

2. Another type a variable star was discovered in 1784, the **Cepheid variables**, with δ Cephei as the prototype.

a) These stars are more luminous and are hotter than the long period variables.

b) Their variability period can range anywhere from 1 to 60 days, depending on their overall luminosity.

c) These are pulsating stars too.

d) Cepheids follow a **period-luminosity relationship**. The luminosity of the star scales with the pulsational period of these stars (see Figure 23.7 in the text) $\Longrightarrow$ by measuring a Cepheid's period, we can deduce its absolute magnitude M_V, then by comparing M_V to its apparent magnitude V, we can deduce its distance via the distance modulus formula (*i.e.*, Eq. III-7).

e) Population I star Cepheids (called **Type I** or **classical Cepheids**) have a slightly different period-luminosity relationship than the Population II star cepheids (called **Type II Cepheids** or **W Virginis stars**).

3. Lower mass versions of Cepheids exist called **RR Lyrae** type variables, which change in brightness with period shorter than 1 day. These stars are horizontal branch stars, and as such, all have the approximate same luminosity (*e.g.*, $100 L_\odot$), hence can also be used as distance indicators.

4. All of these different types of variables pulsate due to their internal structure — they all lie on an **instability strip** on the H-R diagram.

a) The pulsations are due to the **kappa effect**, kappa (κ) for opacity, which results from an ionization zone that lies just beneath the photospheres of these stars.

b) Miras pulsate from a hydrogen ionization zone just beneath the surface of the star.

c) Cepheids and RR Lyr's pulsate from a helium ionization zone just beneath the surface.

D. The Explosive Death of Stars.

1. Supernovae are classified based primarily upon their spectra and their light curves (*i.e.*, how brightness changes with time). We have already discussed a few different types. We now present the complete supernova classification scheme. The primary classification is based upon the appearance of hydrogen Balmer lines.

   a) **Type I** supernovae do <u>not</u> show hydrogen Balmer lines and reach a maximum brightness of $M_V \approx -19$. They are classified into 3 subclasses:

      i) **Type Ia** supernovae display a strong Si II line at 6150 Å. These are white dwarfs in close binary star systems that exceed the Chandrasekhar limit and explode from a runaway thermonuclear reaction in the carbon-oxygen core of the white dwarf. These types of supernovae are seen in both elliptical galaxies and throughout spiral galaxies.

      ii) **Type Ib** supernovae display strong helium lines. These tyeps of supernovae are only seen in the arms of spiral galaxies near star forming regions. Hence, this implied that short-lived massive stars in binary systems are probably involved. These explosions are similar to that of a Type II supernova, only in a binary star system where the outer H envelope has been transferred to the secondary star in the system before the Fe-core bounce.

      iii) **Type Ic** supernovae display weak helium lines and no Si II is seen. Other than this, they are observed in the same location in galaxies as Type Ib. These types of supernovae are likely the same as Type Ib, except the helium-shell has been transferred to the companion in addition to the hydrogen envelope.

b) **Type I$\frac{1}{2}$** supernovae display weak hydrogen lines. These are isolated stars of main sequence mass of the range 4-8 $M_\odot$ where carbon detonates in a degenerate core and completely disrupts the star. Hydrogen lines are weak due to earlier mass loss on the AGB which results in a lower mass hydrogen envelope in comparisons to the Type II supernovae.

c) **Type II** supernovae display strong hydrogen lines and reach a maximum brightness of $M_V \approx -17$. These supernovae result from the explosion of an isolated star due to an Fe-core bounce.

2. During the explosion, material is ejected off of the core at very high velocities. Fast moving free neutrons given off by all of the nucleosynthesis occurring in the outward moving shock interact with nuclei in the envelope to make different chemical elements $\Longrightarrow$ such nuclear reactions are called **rapid neutron capture** or the **r-process**.

a) Most of the heavy elements on the periodic table are made from this r-processed material during supernovae (the iron in your car was made in a supernova, whereas the carbon in your DNA was made via the triple-α process in a now extinct AGB star!).

b) Additional nuclear reactions can occur too from slow moving neutrons, the so-called **slow neutron capture** or **s-process**. This process also occurs during normal thermonuclear burning while a star is a red giant or on the AGB.

3. Supernovae send the envelope of the star, with its nuclear-processed material, out into the ISM at supersonic speed. As this material collides with the ISM material, shocks form which ionizes the gas which induces the gas to “light up” as the electrons recombine with the ions $\Longrightarrow$ a **supernova remnant** is seen.