Chapter 13: High Mass Star Evolution and their Remnants: NSs and BHs

Chapter 13 Reading Assignment due now!

Are your grades in Canvas correct???

Midterms available up front

Turn in extra credit planetarium and public observing reports up front when complete
Nobel Prize in Physics goes to… Astronomers!

Jim Peebles
various contributions to cosmology

Michel Mayor and Didier Queloz
first exoplanet around a main sequence star
Nobel Prize in Physics goes to… Astronomers!

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Future Evolution of the Sun
How do we know the different stages of a star's life? We obviously have not been observing stars for long enough to see it go through all the stages.
Star Clusters: stars of many masses born at the same time.
Which of these star clusters is the oldest?

A

B

C

Visual luminosity relative to Sun

Surface temperature (K)

60,000 30,000 10,000 6,000 2,000

10^{-3} 10^{-2} 10^{-1} 1 10 10^{2} 10^{3} 10^{4} 10^{5} 10^{6} 10^{7}

60,000 30,000 10,000 6,000 2,000

10^{-3} 10^{-2} 10^{-1} 1 10 10^{2} 10^{3} 10^{4} 10^{5} 10^{6} 10^{7}

60,000 30,000 10,000 6,000 2,000

10^{-3} 10^{-2} 10^{-1} 1 10 10^{2} 10^{3} 10^{4} 10^{5} 10^{6} 10^{7}
Theory (red line) & Observations (white dots)

We can make a model of any star based on its mass and age.
Which stars in this cluster are the most massive?
Because stars in clusters form at the same time, and a star’s evolution is determined primarily by its mass, we can observe many clusters and figure out how stars evolve.
H Burning in High Mass Stars: CNO Cycle

(a) CNO cycle

\[ ^{12}\text{C} \rightarrow ^{13}\text{N} \rightarrow ^{13}\text{C} \rightarrow ^{14}\text{N} \rightarrow ^{15}\text{O} \]

Gamma rays (\(\gamma\))
Positron (\(e^+\))
Neutrino (\(\nu\))

(b) Net reaction

\[ ^{12}\text{C} + 4 \ 1\text{H} + 2 e^- \rightarrow ^{12}\text{C} + ^4\text{He} + 2\nu + 7\gamma \]

Very Temperature Sensitive
(higher temp = more energy)

\( ^{12}\text{C} \) is a catalyst for H burning.
High Mass Stars = High Core Temps = CNO

Llamas live hard and fast. CNO cycling is my bag, baby
Evolution of High Mass Stars

Time spent on the Main Sequence is short: why?

A) CNO is much more efficient
B) Massive stars use up their fuel more quickly
C) Not all the hydrogen in the core gets burned
D) The core is much smaller than a low mass star
Evolution of High Mass Stars

1. High-mass stars leave the main sequence...

2. ...then move horizontally back and forth across the H-R diagram.

3. As stars pass through the instability strip, they become pulsating variable stars.

4. Cepheid variables occupy a region near the top of the instability strip, while RR Lyrae stars are located farther down.

5. The ash of one reaction becomes the fuel for the next as the star evolves a layered structure.

6. Degenerate Fe core
   - S, Si burning to Fe
   - O burning to S, Si
   - Ne burning to O, Mg
   - C burning to Na, Ne, Mg
   - He burning to C
   - H burning to He
   - Nonburning envelope

7. As in a low-mass red giant, burning occurs in a tiny, dense region at the center of the giant bloated star.

8. Highly evolved massive star

- The end: A degenerate iron core sits within "onionlike" shells of progressive nuclear burning.

- A massive main-sequence star burns hydrogen in a convective core...

- ...then immediately begins burning helium in its core as it leaves the main sequence.
Based on this graph, what do you think the heaviest element is that is fused inside of stars?

A) Lithium
B) Iron
C) Lead
D) Uranium
Cepheid Variables

1. The star falls inward. As the star contracts...

2. Thermal energy ionizes helium, lowering the temperature...

3. As helium has all recombined, the star cools and begins to fall back inward...

4. Decreasing the pressure support, allowing it to fall through its equilibrium size...

5. As it expands, helium recombines, releasing energy, driving up the temperature...

6. Stopping the contraction. The star "bounces."

7. Adding to the pressure, which pushes the star past its equilibrium size...

8. ...and move horizontally back and forth across the H-R diagram...

3. As stars pass through the instability strip, they become pulsating variable stars.

4. Cepheid variables occupy a region near the top of the instability strip, while RR Lyrae stars are located farther down.

Visual luminosity relative to Sun

Surface temperature (K)

Spectral type

O5 B0 B5 A0 F0 G0 K5 M5

ASTR/PHYS 1060: The Universe

Fall 2019: Chapter 13
Aside: Standard Candles

- **Cepheid Variables**
  - Period-Luminosity Relationship
  - Type I (Classical) Cepheids
  - Type II (W/V) Cepheids
  - RR Lyrace

- **Type Ia Supernovae**
  - Luminous SN fade slowly
  - Less luminous SN fade fast

- Graphs showing luminosities and time from peak for different types of standard candles.
What happens when close binary stars evolve?

Two low-mass main-sequence stars orbit their center of mass.

Roche lobes

What is this???
What happens when close binary stars evolve?

The more massive star 1 begins to evolve...
What happens when close binary stars evolve?

...until it overfills its Roche lobe and begins transferring mass onto its companion, star 2.

Star 2 gains mass, becoming a hotter, more luminous main-sequence star.
What happens when close binary stars evolve?

Eventually star 1 leaves behind a white dwarf orbiting together with the now more massive main-sequence star 2.
What happens when close binary stars evolve?

When star 2 evolves beyond the main sequence, it too overfills its Roche lobe and begins transferring mass onto its white dwarf companion.
What happens when close binary stars evolve?

Different possible fates may await star 1, including recurrent eruptions of nova explosions and possibly complete disintegration in a Type Ia supernova.
What happens when close binary stars evolve?

If star 1 survives, two white dwarfs are eventually left behind...
What happens when close binary stars evolve?

...but if star 1 explodes as a Type Ia supernova, star 2 remains as an isolated giant evolving to become a lone white dwarf.
Type Ia Supernovae

If the white dwarf mass exceeds the Chandrasekhar limit, it begins to collapse...

...pushing up the temperature until carbon ignites and burns explosively.

The Type Ia supernova consumes the white dwarf completely.
Back to Massive Star Evolution

Eta Carinae
binary star

What causes massive stars to have strong winds?

A) High surface temperatures

B) Light elements in their atmospheres

C) Strong radiation pressure (from photons)

D) Like Llamas, they’re quite gassy
Type II Supernovae

(a) Before

(b) After

SN 1987A
Betelgeuse: Future Supernova

... were a supernova to go off within about 30 light-years of us, that would lead to major effects on the Earth, possibly mass extinctions. X-rays and more energetic gamma-rays from the supernova could destroy the ozone layer that protects us from solar ultraviolet rays. It also could ionize nitrogen and oxygen in the atmosphere, leading to the formation of large amounts of smog-like nitrous oxide in the atmosphere.

- Mark Reid, Harvard-Smithsonian CfA

430 light-years away (safe distance, unless it explodes as a gamma ray burst pointed at us)

May appear as bright as the full moon, visible during the day!
Chapter 13: High Mass Star Evolution and their Remnants: NSs and BHs

Chapter 14 Reading Assignment due next Tuesday
Stellar Lifetimes worksheet due now!

Turn in extra credit planetarium and public observing reports up front when complete
Are your grades in Canvas correct???

Midterms available up front
How lost are you regarding stellar evolution? (Chapters 12 & 13, the most recent ones)

A) Not lost at all - I’m a little bored to be honest

B) It mostly makes sense - I’m following it as well as I followed the material in previous chapters

C) It’s a lot more confusing - I kind of get it, but am really worried about what I need to know for the next midterm exam

D) What’s stellar evolution?
Hertzsprung-Russell (HR) Diagram

- Blackbody Spectra
- Spectral Type, Color, Temperature on the x-axis
- Luminosity (intrinsic brightness) on the y-axis

- Hot stars are blue.
- Cool stars are red.

- All stars with a radius of 1 \( R_\odot \) lie along this line.
- H-R diagrams are sometimes plotted with either spectral type or temperature.

ASTR/PHYS 1060: The Universe

Fall 2019: Chapter 10

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Nuclear Reactions

Hydrogen or higher atomic number element collides with proton

Proton fuses with the element, producing a photon and sometimes a neutrino (if the proton turns into a neutron, the new nucleus has to eject a positron [anti-electron] and a neutrino to conserve charge and angular momentum)

Process continues with new elements until temperature can no longer get high enough or Iron (Fe) is all that’s left in the core

[To fuse Fe, the reaction no longer produces a photon but NEEDS to absorb a photon]
Type II Supernovae

1. Not even electron degeneracy pressure can stop the collapse of an iron ash core.

2. As the core collapses, the core temperature climbs so high that photons photodisintegrate iron...

3. ...and the core becomes so dense that electrons are absorbed by protons in atomic nuclei, forming neutrons and releasing neutrinos.

4. Photocisintegration and electron absorption reduce the pressure in the core. The collapse accelerates...

5. As in a low-mass red giant, burning occurs in a tiny, dense region at the center of the giant bloated star.

4. The end: A degenerate iron core sits within "onionlike" shells of progressive nuclear burning.

HIGHLY EVOLVED MASSIVE STAR

Degenerate Fe core
S, Si burning to Fe
O burning to S, Si
Ne burning to O, Mg
C burning to Na, Ne, Mg
He burning to C
H burning to He
Nonburning envelope

Iron core of evolved massive star
Gamma rays

Iron nucleus

Electron (-)

Proton (+)

Neutrino (ν)

Neutron

H

0.01 R_⊙

1,000 R_⊙
Type II Supernovae

1. Photodisintegration and electron absorption reduce the pressure in the core. The collapse accelerates...

2. ...until nuclear forces suddenly become repulsive. The overcompressed core bounces, driving its outer layers outward through the star.

3. The expanding shock is strengthened by the pressure of a hot bubble of trapped neutrinos from the core.

4. Neutron star

5. ...and leaving behind the collapsed remains of the core, a neutron star.

6. ...blasting forth in a Type II supernova...

7. The shock continues through the outer layers of the star...
Supernova Remnants

Cygnus Loop
Heavy elements are created in massive stars, with the heaviest elements created in and returned to interstellar space by supernovae.
Created in supernovae caused by NS-NS mergers??
The Origin of the Solar System Elements

Graphic created by Jennifer Johnson

Astronomical Image Credits: ESA/NASA/AASNova
A question for Neil DeGrasse Tyson…

http://www.youtube.com/watch?v=9D05ej8u-gU
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Stellar Remnant Activity

**Goal:** Contrast the end-stages of stars’ lives, black holes, neutron stars, and white dwarfs.

**Group Activity:** Groups of 3-4
   Hand in one sheet for the group

**Roles:**
   Secretary (write on the sheet)
   Spokesperson (for class discussion)
   Group Leader (keep on task)
Neutron Stars / Pulsars

Exploded 1054

Filaments of gas ejected by the supernova explosion
Synchrotron emission from pulsar wind

(a) Ground-based image
(b) Visible-light image
(c) X-ray image
Exploded 1572

Exploded ~1680

To view
Download the add-in.
liveslides.com/download
Start the presentation.

https://www.youtube.com/watch?v=_diLnFGRSFQ
Neutron stars have enormously strong magnetic fields.

Electrons and positrons moving in the neutron star’s magnetic field produce radiation that is beamed away from the poles of the neutron star.

As the neutron star rotates, these beams sweep around like the beam of a lighthouse.

Field accelerates electrons and positrons, which causes them to emit radiation across the spectrum.

We see the beam once or twice each time the star rotates.

As the beams sweep past an observer, the neutron star appears to pulse on and off, earning it the name pulser.
Pulsar Computer Simulation

To view

Download the add-in.
liveslides.com/download

Start the presentation.

https://www.youtube.com/watch?v=jwC6_oWwbSE
Low magnetic field neutron stars and black holes are observed through accretion.

1. An evolving star overflows its Roche lobe, pouring matter onto its neutron star companion.
2. Infalling matter heats the accretion disk to X-ray-emitting temperatures...
3. ...and feeds relativistic jets from the rotating neutron star.
Millisecond Pulsar

https://www.youtube.com/watch?v=MPpDTvYL5ik
Official NASA Black Hole Safety Video

https://youtu.be/aMTwtb3TVlk

LiveSlides web content

To view

Download the add-in.
liveslides.com/download

Start the presentation.
How do we know black holes ACTUALLY exist in the Universe?
Highly suggestive results that black holes exist

Stars orbiting SMBH in center of our galaxy

Animation of gas falling into SMBH in M87 galaxy
Cygnus X-1: First X-ray source and confirmed black hole

https://www.youtube.com/watch?v=ZdjCpSCh02g
Cygnus X-1

Andromeda Galaxy (M31)

NuSTAR

GALEX
To understand black holes and extreme gravity, we need help from Einstein and Hawking

But first, what do you know about black holes and/or relativity?
Reference Frames

In everyday experience velocities simply add...

Reference frame of the red car

A ball thrown at 25 mph relative to a car moving at 50 mph...

\[ v_{\text{ball}} = 25 \text{ mph} \]

Reference frame of the green car

\[ v_{\text{ball}} = 125 \text{ mph} \]

Special Relativity (postulates)

1) Physical laws same for all reference frames
2) Speed of light is always measured to be \( c \)
Reference Frames

...but as \( v \) nears \( c \), things are different.

Reference frame of the yellow spaceship

A moving spaceship fires a laser. In the reference frame of the spaceship, the light travels at the speed of light, \( c \).

Reference frame of the blue spaceship

By analogy with the ball in the panel at left, we might expect that in a planetbound observer’s reference frame the light’s velocity would be \( 1.5c \)...

Special Relativity (postulates)

1) Physical laws same for all reference frames
2) Speed of light is always measured to be \( c \)
The passage of time is not the same everywhere!

\[ t' = \frac{t}{\sqrt{1 - \frac{v^2}{c^2}}} \]
Muons created by cosmic rays colliding with the atmosphere exhibit time dilation

\[ t' = \frac{t}{\sqrt{1 - \frac{v^2}{c^2}}} \]

Faster a muon is traveling, the slower time passes for it, so it survives longer before decaying.

Imagine that 1,000 muons are produced at a height of 15 km. The diagram shows the survival time for muons traveling at different speeds:

- \( v = 0.9c \)
- \( v = 0.99c \)
- \( v = 0.999c \)

The number of muons reaching the ground before decaying is shown as follows:

- 1
- 108
- 495
- 800
Implications of Special Relativity

\[ E = mc^2 \]
when moving, have kinetic energy
\( \rightarrow \) increase your mass!

Speed of Light is the universal speed limit
(can only approach it)

Time passes more slowly for moving reference frames

Length of moving objects contract in the direction of motion
General Relativity: analogous case for gravity

A spacecraft that is "stationary" in deep space and a spacecraft that is moving at a constant velocity both represent inertial reference frames. Both are floating freely in space.

A spacecraft falling freely in a gravitational field also represents an inertial reference frame, even though it is accelerating.

The equivalence between "free fall" and "free float" is the basis of general relativity.
General Relativity: analogous case for gravity

Sitting in an accelerating room with no gravity...

...is the same as sitting still in a gravitational field.

Both are accelerated reference frames in which forces are pushing objects away from their natural geodesics.

Inertial and gravitational mass both resist these forces. They are the same thing.

Equivalence Principle

\[ F = m_{\text{inertial}} a \]

\[ F = m_{\text{gravitational}} g \]
Space-time is curved
Gravitational Redshift

Keck/UCLA Galactic Center Group

Supermassive black hole (4 million solar masses)

Orbital period 16 years

Closest approach 19 May 2018

30 billion kilometres = 120 × Earth–Sun

Maximum speed > 25 million km/h
What are Black Holes?

Particular solutions to Einstein’s equations of General Relativity

Inevitable end-state of ultra-dense matter

Inside the event horizon, the escape velocity is larger than the speed of light (c)

Matter inside the event horizon must fall to the center, toward the singularity

Black holes have “no hair” - defined only by their mass, charge, and spin (rotation)

$R_S = \frac{2GM_{BH}}{c^2} \sim 3 \text{ km} \frac{M_{BH}}{M_\odot}$
The black hole in *Interstellar*

called Gargantua, b/c it’s supermassive (like the one in the centers of galaxies)

keeps Matthew McConaughey from “spaghettification” as he crosses the event horizon
—> stellar mass black holes have huuuuuuge tidal forces here that would kill you!
Black holes are not completely black after all

Emit Hawking radiation

Hawking himself popularized the explanation used in the textbook, but that explanation is wrong!

The virtual “particles,” which have large quantum waveforms (uncertainty in their position is as large as the black hole), separate at a distance several times larger than the event horizon.

They result mainly from space-time changing dynamically when the black hole forms, creating thermal radiation.

Temperature is very tiny, but carries away energy, causing the black hole to lose mass ($E=mc^2$), but it takes a loooooong time (~$10^{66}$ years).
Gravitational Waves: LIGO!

Virgo facility near Pisa, Italy
other detectors in Louisiana and
Washington state
LIGO, NSF, Illustration: A. Simonnet (SSU)
First 5 BH-BH mergers
BHs and NSs with known masses

- LIGO-Virgo Black Holes
- X-ray Binary Black Holes
- Known Neutron Stars
- LIGO-Virgo Neutron Stars

Solar Masses
First NS-NS merger, explosion also seen