Stellar death:
White dwarfs, Neutron stars & Black Holes
**E5.2x Stellar Evolution**

Stars, including the Sun, transform matter into energy in nuclear reactions. When hydrogen nuclei fuse to form helium, a small amount of matter is converted to energy. These and other processes in stars have led to the formation of all the other chemical elements. There is a wide range of stellar objects of different sizes and temperatures. Stars have varying life histories based on these parameters.

<table>
<thead>
<tr>
<th>E5.2e</th>
<th>Explain how the Hertzsprung-Russell (H-R) diagram can be used to deduce other parameters (distance).</th>
</tr>
</thead>
<tbody>
<tr>
<td>E5.2f</td>
<td>Explain how you can infer the temperature, life span, and mass of a star from its color. Use the H-R diagram to explain the life cycles of stars.</td>
</tr>
<tr>
<td>E5.2g</td>
<td>Explain how the balance between fusion and gravity controls the evolution of a star (equilibrium).</td>
</tr>
<tr>
<td>E5.2h</td>
<td>Compare the evolution paths of low-, moderate-, and high-mass stars using the H-R diagram.</td>
</tr>
</tbody>
</table>
What happens when fusion stops?

- Stars are in balance (hydrostatic equilibrium) by radiation pushing outwards and gravity pulling in.

- What will happen once fusion stops?

- The core of the star collapses spectacularly, leaving behind a dead star (compact object).

- What is left depends on the mass of the original star:
  - $< 8 \, M_\odot$: white dwarf
  - $8 \, M_\odot < M < 20 \, M_\odot$: neutron star
  - $> 20 \, M_\odot$: black hole
Forming a white dwarf

- Powerful wind pushes ejects outer layers of star forming a planetary nebula, and exposing the small, dense core (white dwarf)
- The core is about the radius of Earth
- Very hot when formed, but no source of energy – will slowly fade away
- Prevented from collapsing by degenerate electron gas (stiff as a solid)

\[ M \approx 1.0 \, M_{\text{sun}} \]
\[ R \approx 5800 \, \text{km} \]
\[ V_{\text{esc}} \approx 0.02c \]
Planetary nebulae
(nothing to do with planets!)

THE RING NEBULA
Planetary nebulae
(nothing to do with planets!)

THE CAT’S EYE NEBULA
Death of massive stars

- When the core of a massive star collapses, it can overcome electron degeneracy.
- Huge amount of energy released - big supernova explosion.
- **Neutron star**: collapse halted by neutron degeneracy (1934: Baade & Zwicky).
- **Black Hole**: star so massive, collapse cannot be halted.
1967: Pulsars discovered!

* Jocelyn Bell and her supervisor Antony Hewish studying radio signals from quasars
* Discovered recurrent signal every 1.337 seconds!
* Nicknamed LGM-1 now called PSR B1919+21

Observation of a Rapidly Pulsating Radio Source

by
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J. D. H. Pilkington
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R. A. Collins

Mullard Radio Astronomy Observatory,
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Unusual signals from pulsating radio sources have been recorded at the Mullard Radio Astronomy Observatory. The radiation seems to come from local objects within the galaxy, and may be associated with oscillations of white dwarf or neutron stars.
1967: Pulsars discovered!

- Beams of radiation from spinning neutron star
- Like a lighthouse
Neutron stars: key facts

- **Mass:** About 1.5 times the mass of the Sun
- **Radius:** 10 - 15 km
Neutron stars: key facts

HUMANITY in a SUGAR CUBE

ABOUT 10 TIMES MORE DENSE THAN ATOMIC NUCLEI
Neutron stars: key facts

HUMANITY IN A SUGAR CUBE

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NEUTRON STARS CONTAIN:

DENSET DIRECETLY OBSERVABLE MATTER IN THE UNIVERSE
Neutron stars: extreme objects

- **Magnetic field:**
  - about trillion times Earth’s!

- **Surface gravity:**
  - > 100 billion times Earth’s

- **Rotation:**
  - spin up to 700 times a second (60 million times faster than Earth)
Why do neutron stars rotate so quickly?

- Conservation of angular momentum means that smaller objects will rotate more quickly.
What are neutron stars made of?

**Atmosphere:** Hydrogen

**Crust:** Solid lattice (of iron?)

**Core:** Mostly neutrons, or something more exotic?
NEED TO MEASURE NEUTRON STAR MASSES AND RADII
Measuring a neutron star radius is......

like measuring the width of a DNA helix on the Moon
How/where do we see neutron stars?

**THE ELECTROMAGNETIC SPECTRUM**

- **Penetrates Earth Atmosphere?**
  - Y: Radio, Infrared, Ultraviolet, X-ray, Gamma Ray
  - N: Microwave, Visible, Ultraviolet

- **Wavelength (meters)**
  - Radio: $10^3$
  - Microwave: $10^{-2}$
  - Infrared: $10^{-5}$
  - Visible: $.5 \times 10^{-6}$
  - Ultraviolet: $10^{-8}$
  - X-ray: $10^{-10}$
  - Gamma Ray: $10^{-12}$

- **About the size of...**
  - Buildings
  - Humans
  - Honey Bee
  - Pinpoint
  - Protozoans
  - Molecules
  - Atoms
  - Atomic Nuclei

- **Frequency (Hz)**
  - $10^4$ to $10^{20}$

- **Temperature of bodies emitting the wavelength (K)**
  - 1 K
  - 100 K
  - 10,000 K
  - 10 Million K
Where do we see neutron stars?

Youngest neutron stars are at the centre of supernova remnants.

But, to see neutron star need to look in X-rays!

Crab nebula: 1054 AD
RED: OPTICAL
BLUE: X-RAY
Where do we see neutron stars?

**NEUTRON STAR & SUN-LIKE STAR ORBITING EACH OTHER**

- Gravitational field of neutron star pulls gas towards it
- Form a **very hot** disc of in-spiralling gas
- They are some of the brightest X-ray sources in the sky!

**X-RAY BINARY**
All-sky X-ray image

The brightest X-ray sources in the sky come from accretion onto black holes and neutron stars.

From MAXI onboard the ISS
Black Holes

- First suggested by John Michell in 1783! *A object whose gravity is strong enough that even light cannot escape*
- Einstein’s General Relativity (1916): mass bends space and time
- Karl Schwarzschild (1916): discovered a ‘singularity’ - what we now call black holes
- John Wheeler coined the phrase ‘black hole’ in 1960s
- *How might we see indirect evidence of black holes?*
Quasars
Quasi-stellar radio sources

• Bright stellar-like objects that were also bright radio sources
• But, weird **non-stellar** spectra
• Realized they were **redshifted** so must be a huge distances (U is expanding, bigger the redshift, further the distance)
Very bright and very small

- **Quasars are extremely luminous** (> 100 billion Suns)
- **Highly variable** - size of light emitting region must be a few light-minutes across!
- **What is the power source?!**
Powered by what?

- Nuclear fusion?  
  - No

- Dense star cluster?  
  - No

- Accretion onto a massive black hole?  
  ✓ Yes!

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Diagram with text:

GAS CLOUD $\rightarrow$ star formation $\rightarrow$ DENSE STAR CLUSTER $\rightarrow$ stellar coalescence $\rightarrow$ CLUSTER OF $\gtrsim 100 \, M_\odot$ STARS

- supernovae
- CLUSTER OF NEUTRON STARS OR STELLAR-MASS BLACK HOLES

SUPERMASSIVE STAR

- contraction
- collisional disruption of stars
- 'new stars' form

- collapse and/or accretion
- nuclear explosion
- post-Newtonian instability
- bar-mode instability

BLACK-HOLE BINARY

- spiral together via gravitational radiation
- slingshot ejection

- $\gtrsim 3$ MASSIVE BLACK HOLES

- one black hole grows spectacularly by accretion
- N-body evolution
- TIGHTLY-BOUND SYSTEM OF FEW BODIES

- contraction catalyzed by gas in system that radiates binding energy
- relativistic instability or gravitational radiation

massive black hole

Martin Rees (1984)
Accretion

- Accretion is seen on many scales in the Universe
- *Infall of gas releases gravitational potential energy as radiation*
- Angular momentum lost through friction in a disk
- As mass accretion rate varies, brightness varies
- 10 times *more efficient* than nuclear fusion!

Credit: CXC/NASA
Black holes at the center of every galaxy?

- Look at the stars at the center of our own Galaxy (Milky Way)
- Orbits include a black hole with mass of 4 million Suns!
Different types of black holes

- Stellar-mass black holes: formed in supernovae
- Supermassive black holes: at the centers of galaxies

**Key Questions:**

- How do black holes grow?
- How do supermassive black holes form?
- How do they affect their environment?
Indirect evidence for black holes

• So, why we can’t see them directly we know they exist
  - we can see evidence of them ‘feeding’
  - we can see stars orbiting around an ‘empty’ place at the center of our own Galaxy