The Sun

Astronomy 101
Syracuse University, Fall 2022
Walter Freeman

November 10, 2022

Dead the new astronomy calls her, ...
Dead, but how her living glory lights the fall, the dune, the grass!
Yet the moonlight is the sunlight, and the sun himself will pass.

–Alfred, Lord Tennyson (1886)

Announcements

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- We are working on grading your Exam 3's; you should get them back next week
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- Don't forget your takehome labs
- A reminder about final projects

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- Could there be life there?

The puzzle of the Sun's energy

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The Sun's thermal radiation converts its heat into light.

But what energy source supplies that heat?

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- Early 1900's: radioactive dating showed the Earth was definitely older
- ... we need a new idea to fuel the Sun!

New ideas in the 1920's

Chemists noticed something weird in the masses of hydrogen and helium:

	Mass	Energy ($E = mc^2$)
One mole of hydrogen	1.008 grams	
Four moles of hydrogen	4.032 grams	
One mole of helium	4.002 grams	
Difference	**0.030 grams**	**3 trillion joules**

If hydrogen could be converted into helium, it would release an enormous amount of energy!

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In 1925 Cecilia Payne used spectroscopy to show (in her doctoral thesis!) that the Sun was almost completely hydrogen.

This explains the source of the Sun's power!

The Sun's history and the source of its power

(Hubble Space Telescope image: NASA + ESA / Judy Schmidt)

Clouds of gas – mostly hydrogen but with a few heavier elements – collapse under their own gravity to form stars.

If you smash hydrogen nuclei together hard enough, they fuse to make helium plus a *lot* of energy.

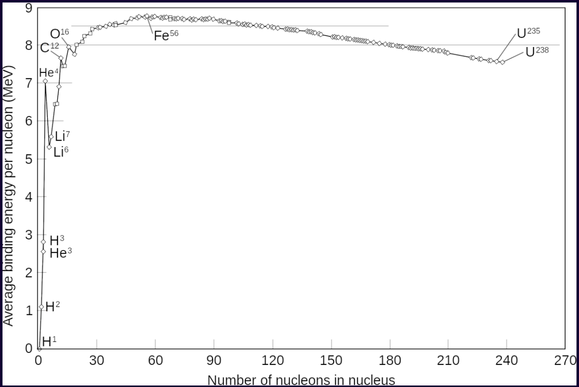
$$(P) + (P) + (P) + (P) \rightarrow (NNPP) + 2e^{+}$$

How much energy? We can calculate it...

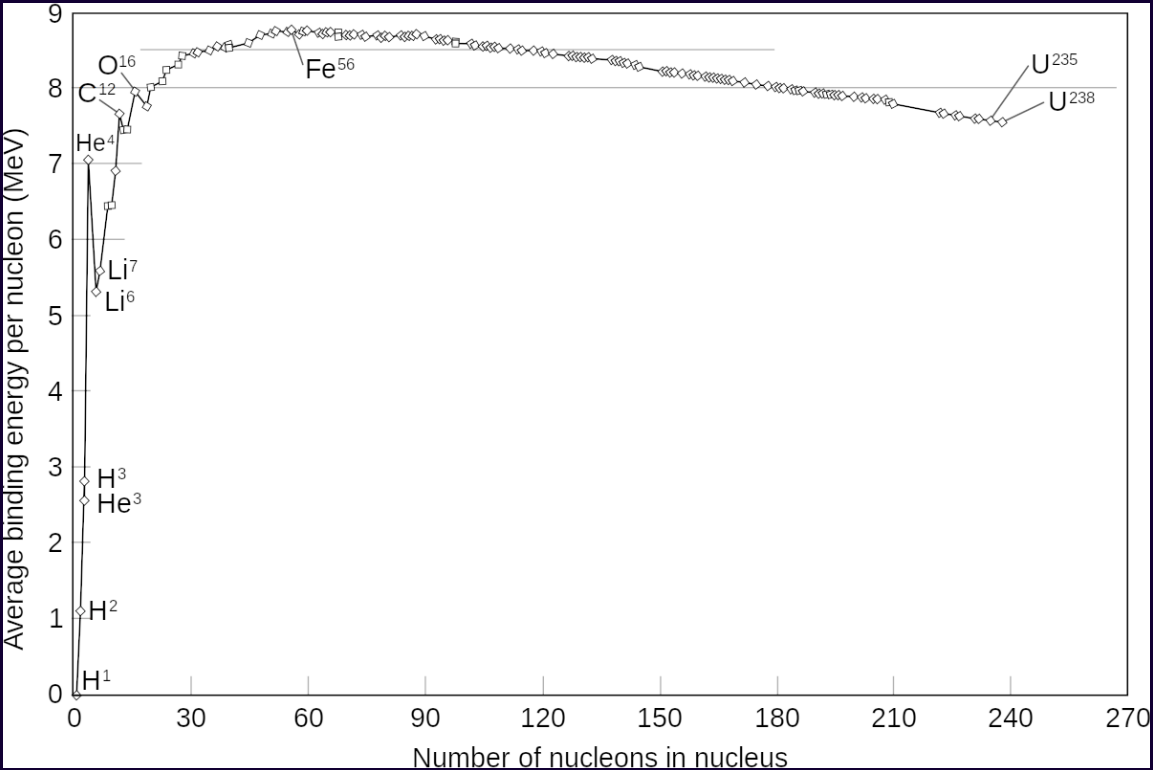
Nuclear potential energy

There is potential energy associated with the *arrangement of protons and neutrons in nuclei*.

We can calculate how much energy is associated with nuclear fusion by looking at how much potential energy there is.



- Moving upward on this graph *releases* energy
- Moving downward on this graph *requires* energy
- Moving rightward combines smaller atoms to make bigger ones (fusion)
- Moving leftward splits larger atoms to make smaller ones (fission)

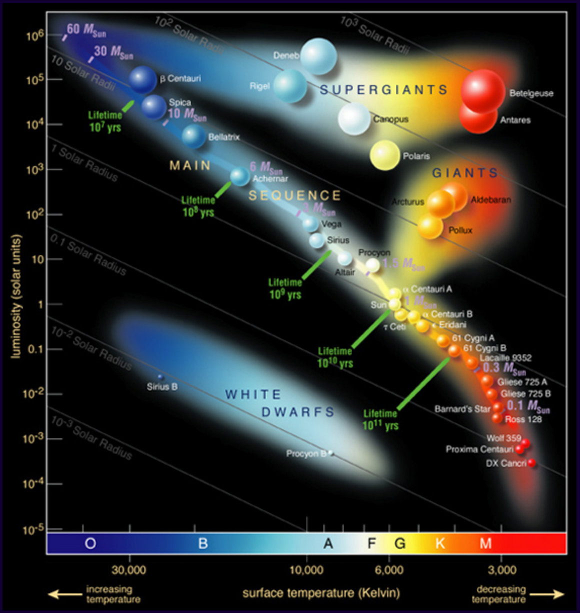

Average binding energy per nucleon (MeV)
Number of nucleons in nucleus
0
1
2
3
4
5
6
7
8
9
0
30
60
90
120
150
180
210
240
270
H1
H2
H3
He3
He4
Li6
Li7
C12
O16
Fe56
U235
U238

A star's life

- Gravity compresses a star's core, heating it up
- Nuclear fusion starts, pushing back against gravity
- Once the nuclear fuel is depleted, gravity takes back over
- Once it reaches even higher temperatures, the next stage of fusion starts

	Energy produced (power plant time per ton)	Temperature required (Kelvin)
Hydrogen to helium	20 years	10 million
Helium to carbon	2 years	100 million
Carbon to neon	1 year	500 million
Neon to oxygen	5 days	1 billion
Oxygen to silicon	1.5 years	2 billion
Silicon to iron	10 months	3 billion
Uranium to fission products	2-3 months	(Nuclear power)
Coal	20 seconds	
Natural gas	45 seconds	

The life of the Sun



(European Southern Observatory)

Most stars are less massive than the Sun.

These "red dwarfs" lead long, cool, boring lives, slowly fusing hydrogen to helium, emitting red and infrared light.

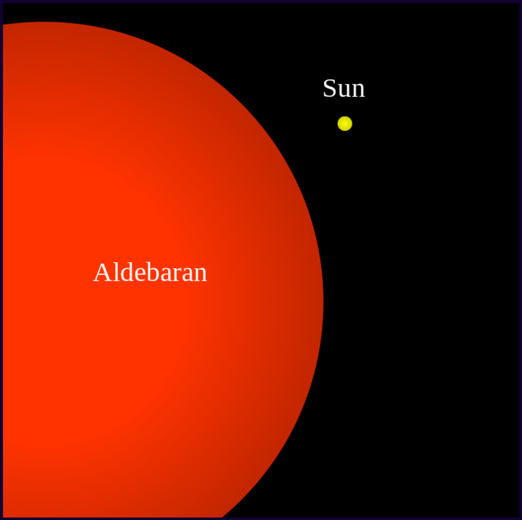
They are too faint for us to see without telescopes, but they contribute to the Milky Way glow. (Our nearest star is a red dwarf.)

They will live 10-100 times as long as the present age of the universe – a trillion years.

They will burn their hydrogen until it is all gone, then slowly fade away as brown dwarfs made of helium.

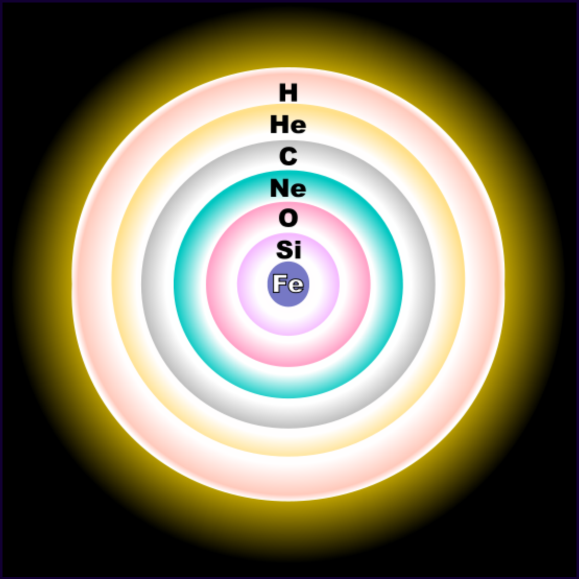
The Sun's fate

- When the Sun runs out of hydrogen in its core, the core contracts, while the outer layers puff up: it becomes a red giant. (5 billion years in the future, lasting for 1 billion years)
- Eventually the core gets hot enough to fuse helium into carbon, and the core ignites in a "helium flash".
- When the helium is depleted, that's it: the Sun isn't heavy enough to fuse carbon.
- The carbon core will be left behind as a white dwarf, slowly cooling – a dying ember in the sky, called a brown/black dwarf.
- Its outer layers will be blown out into interstellar space, briefly forming a nebula.



(Wikimedia Commons)

Other stars



Wikimedia Commons / R. J. Hall.
Image not to scale.

More massive stars have enough weight to compress their carbon cores and fuse it to (mostly) Ne, Na, Mg, and O.

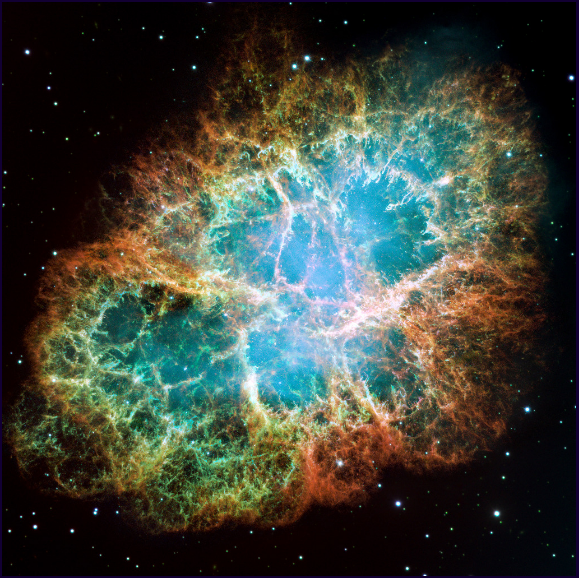
This process releases less energy than even helium fusion, so it doesn't last as long.

Elements fuse into heavier and heavier elements, releasing less energy each time, until they reach iron in the heaviest stars.

Iron is "stellar ash" – it can't release any more energy by fusion.

In some of these heaviest stars, once their iron cores grow too much, gravity crushes them into one enormous atomic nucleus – a neutron star.

Supernovae



(Hubble Space Telescope/NASA)

The resulting explosion destroys the rest of the star.

It causes a flurry of nuclear reactions, forging elements heavier than iron.

It also scatters the heavy-element-rich contents of the star out to space. This is why the Earth has so much iron in it – and where our heavy elements come from.

It releases massive amounts of energy, forming a bright flash in the sky.

This is the Crab Nebula, the remnant of the 1054 supernova.

It was hundreds of times further away than most visible stars, but could be seen even during the day!