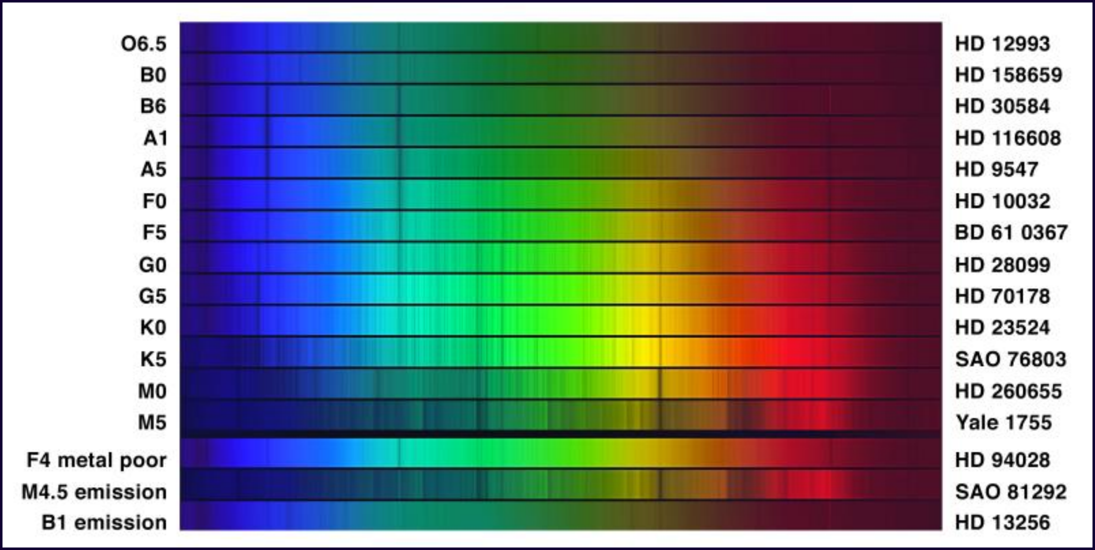
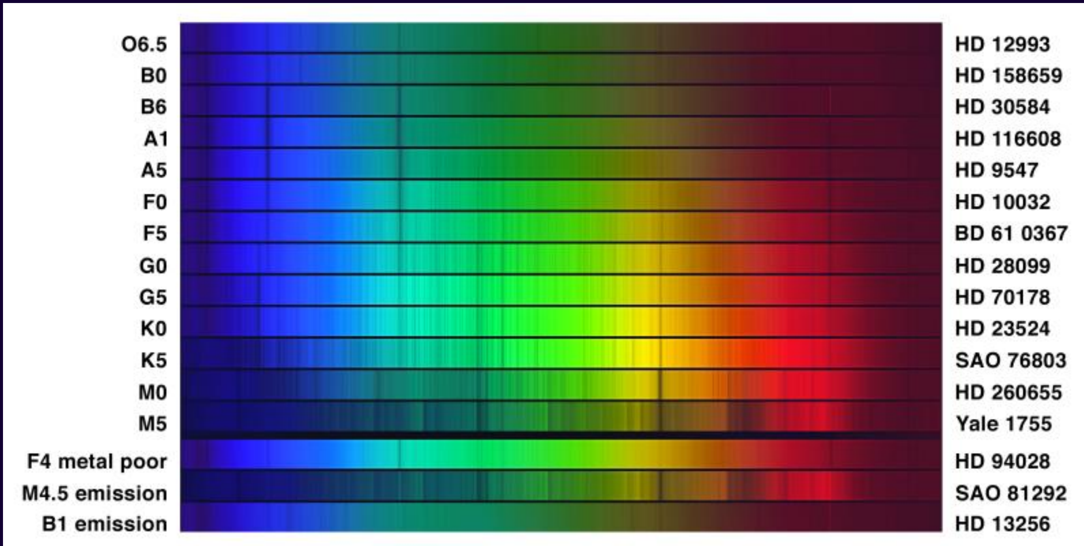
The Sun

Astronomy 101
Syracuse University, Fall 2020
Walter Freeman

October 27, 2020



All the stars are made of the same stuff – the same stuff as we are.



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“The cosmos is also within us. We are made of star-stuff. We are a way for the universe to know itself.”

–Carl Sagan, *Cosmos*

Announcements

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Discussion hours today: 4:00-5:30, steps of Hendricks Chapel or on Zoom.

Come talk to me about:

- ... problems with your groups
- ... last-minute questions about Paper 2
- ... questions about anything!

A review: thermal radiation

All objects with a temperature emit light: hotter objects emit more light, shifted toward shorter wavelengths.

Keep in mind that an object may *mostly* emit light outside our visible range...

	T (Kelvin)	Peak wavelength	Visible light?
Deep space	3	Microwave	None
Freezing ice	273	Infrared	None
People	300	Infrared	None
Boiling water	373	Infrared	None
Hot stove, candle, etc.	1500	Near infrared	A little red
Incandescent lamp	2400-2800	Near infrared	Mostly red/orange
The Sun	5700	Visible	Mix of all colors (looks white)
Hot stars	10000+	UV	Mostly blue

A review: spectroscopy

Every chemical element has a unique *spectrum*: the colors of light that it can emit and absorb.

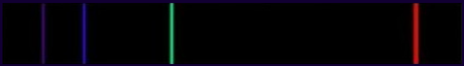
Other colors simply pass through.

(Molecules have these spectra too: their electron energy levels are more complicated.)

Review: emission and absorption spectra

If you excite a diffuse gas, it will *emit* light of particular colors that correspond to its transitions. (We do this electrically in lamps.)

H + electricity



Emission spectrum

But that same gas can *absorb* those same colors, too.

Hot object

Continuous spectrum

Light from hot object passing through H gas

Absorption spectrum

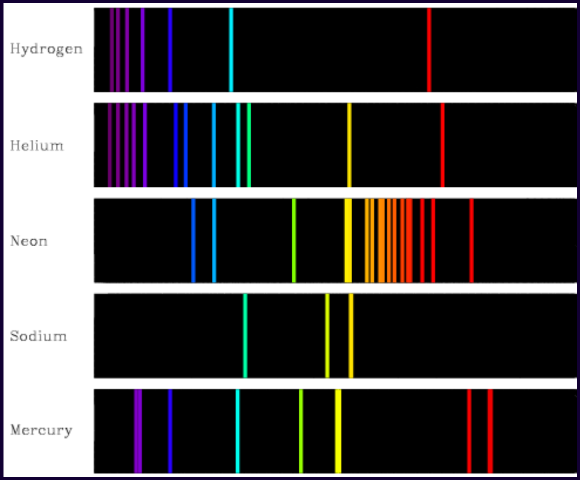
Spectroscopy

How do we use this to learn about astronomy?

Every element has its own “fingerprint”, based on its unique energy levels.

We can measure those fingerprints easily on Earth with emission lamps.

Then, if we see them in the sky – either in emission or absorption – we know where they came from!



We can figure out what chemicals are in anything in the sky by looking for lines in its spectrum!

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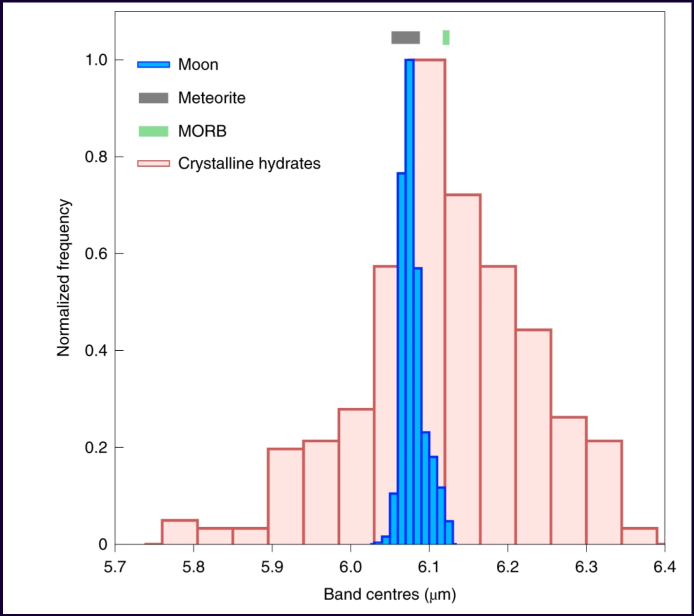


Image from Honniball et al., "Molecular water detected on the sunlit Moon by SOFIA", *Nature Astronomy* (2020)

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.

The Sun's history and the source of its power

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

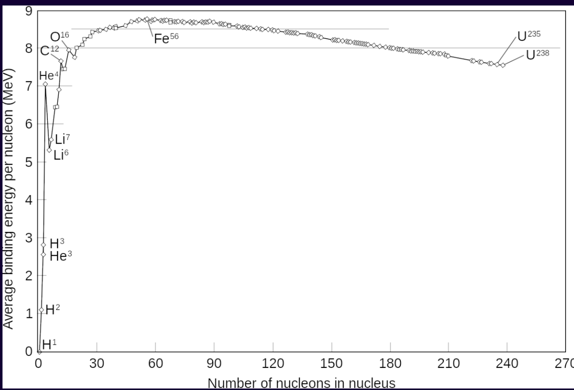
$$(P) + (P) + (P) + (P) \rightarrow (NNPP) + 2e^{+} + 2\nu$$

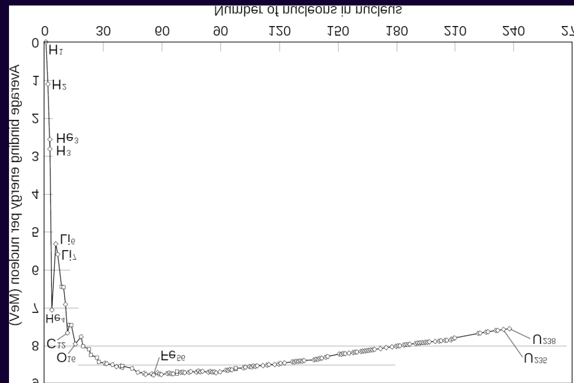
How much energy? We can calculate it...

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.

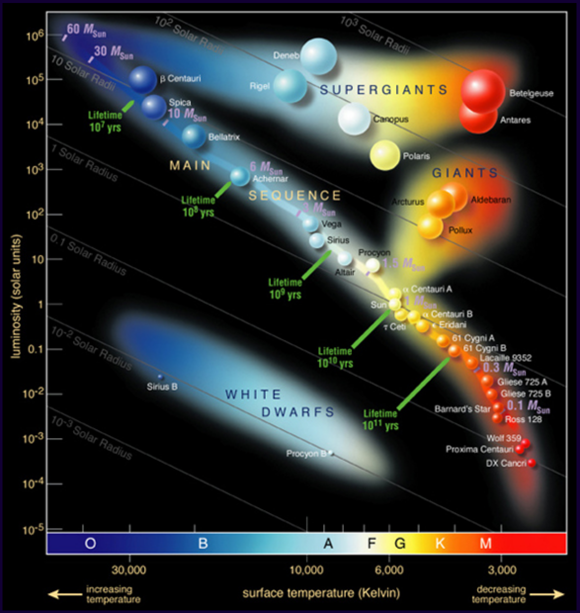




A star's life

- 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	3.6 years	
Coal	20 seconds	
Natural gas	45 seconds	



(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.

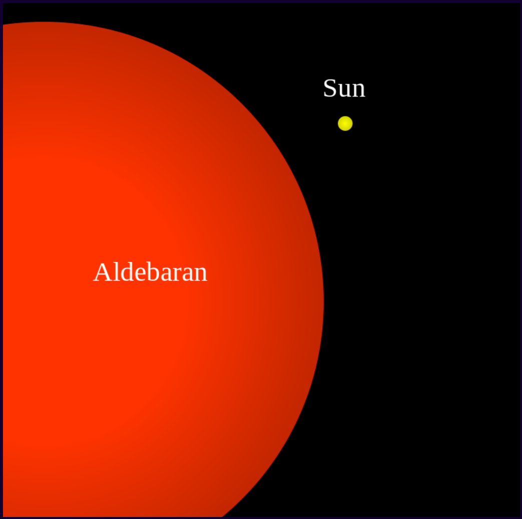
They are too faint for us to see without telescopes, but they contribute to the Milky Way glow. (Our nearest star is a red dwarf.)

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

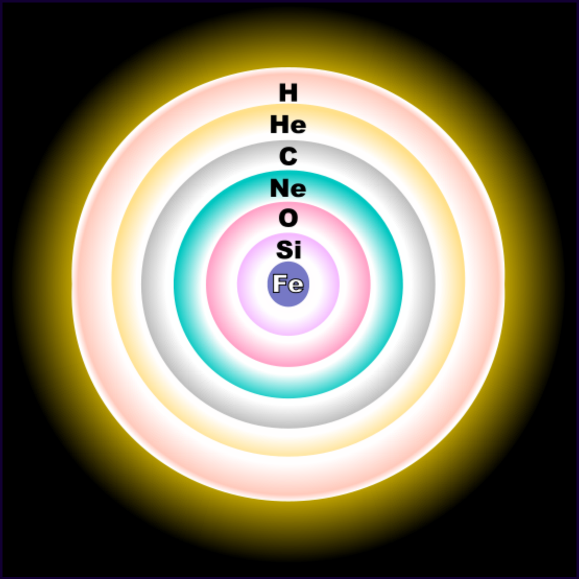
- When the Sun runs out of hydrogen in its core, the core contracts, while the outer layers puff up: it becomes a red giant. (5 billion years in the future, lasting for 1 billion years)
- Eventually the core gets hot enough to fuse helium into carbon, and the core ignites in a "helium flash".
- When 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)

- Quantum mechanics limits how tightly you can pack particles together. *“Pauli exclusion principle”*
- Our Sun, when it dies, will be crushed by its own gravity into a ball of carbon atoms – a white dwarf.
- The quantum exclusion principle, acting on the electrons in the carbon, holds it up.
- It will sit there forever, slowly cooling down, unless something else hits it.

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.

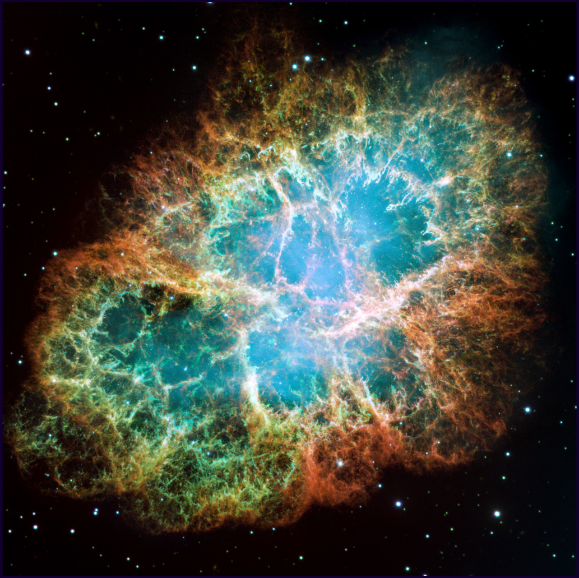
This process releases less energy than even helium fusion, so it doesn't last as long.

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!

Neutron stars

What about the heavier cores left behind by these supernovae?

- The exclusion principle, holding up the white dwarf left behind on the Sun, acts more weakly on heavy particles.
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- If a star is massive enough, its gravity is strong enough to crush positive protons and negative electrons together to make neutrons.
- These can be packed incredibly tightly, since the exclusion principle is weaker.
- They are a hundred million billion times denser than water! (10^{17})