### Topics for this week

- What can we learn about stars from their spectra?
- How does the Sun generate the energy that is radiated from its surface?
- Describe the first reaction in the proton-proton chain of nuclear reactions in the Sun.
- What is the overall result of the nuclear reactions in the Sun?
- How does Einstein's equation, E = m c<sup>2</sup>, help explain how nuclear reactions generate energy?
- Describe how neutrinos allow us to observe the interior of the Sun, and say what was found.

## Information in spectra

What can we learn about stars from their spectra?

composition: different atoms emit and absorb light at different wavelengths.

motion: from the shift in wavelength caused by the Doppler effect we can measure a star's motion toward or away from us. We can also measure their rotation this way.
temperature: hot stars emit their light at shorter wavelengths than cooler stars do. They also have

different patterns of absorption and emission lines.

age

size

mass

#### Spectra of stars

- The deep layers of the atmospheres of stars emit light according to the rules for radiation from solids (although they aren't actually solid).
- The outer layers of atmospheres of stars produce emission and absorption line spectra.
- Studies of the spectra of stars tell us about both the temperatures and the compositions of their atmospheres.
- The simplest effect of temperature is that hotter stars appear bluer and cooler stars appear redder, but temperature changes spectra in other ways too.

## Spectra of Stars

- Hot stars emit more short wavelength light than cooler stars do because atoms in hot stars have more energy than atoms in cooler stars do, so they can emit higher energy photons, which have shorter wavelengths.
- The explanation of the pattern of absorption lines is more complicated.
- For example, cool stars show a strong absorption line of sodium, whereas hotter stars do not.
- What causes absorption lines?
- Is there more sodium in cooler stars? (No.)

## **Absorption lines**

- A photon can be absorbed by an atom if the photon has the right amount of energy to cause an electron to jump from a low energy orbit to a high energy orbit.
- But the visible lines of hydrogen occur when electrons jump from level 2 up to level 3, 4, or 5.
- The atoms had to have enough energy to be in level 2 or they couldn't absorb visible photons. Only the warmer stars show the hydrogen absorption lines.
- Sodium atoms absorb orange photons when they jump from their lowest energy levels to the next higher level.
- So cool star have sodium absorption lines.
- But it isn't hard to ionize a sodium atom. In hotter stars the sodium atoms are ionized and absorb different energy photons.

# Quiz

It is hot inside of the Sun because of ...

- A. chemical reactions
- B. combining of light elements to make heavier ones
- C. breaking apart heavy elements making lighter ones
- D. contraction that occurred when the Sun formed
- E. contraction that continues to occur

The Sun did originally heat up by contraction (D), but that only generated enough energy to account for its first few million years of luminosity. The energy it radiates from its surface is now being replaced by energy from fusion.

#### Energy from the Sun

- The Sun radiates tremendous amount of energy from its surface. Where does this energy come from?
- Nuclear fusion inside the Sun generates energy while fusing hydrogen nuclei to make helium nuclei.
- The reaction chain is referred to as the proton-proton chain because the first reaction is the fusion of two protons.
- The best way to explain how nuclear reactions generate energy is to note that a helium atom has less mass than the 4 hydrogen atoms that were fused to make it.
- Einstein's famous equation,  $E = m c^2$ , says that mass can be converted into energy (or energy into mass) and to calculate the energy generated by destroying a mass m you multiply m by the square of the speed of light.



# Masses and Energies

electron	e⁻	9x10 <sup>-31</sup> kg	511 keV
proton	p+	1836 e⁻	938.3 MeV
neutron	n	1839 e⁻	939.6 MeV
deuteron	d+	3669 e⁻	1875 MeV
helium	$\alpha^{++}$	7292 e⁻	3727 MeV

n → p<sup>+</sup> + e<sup>-</sup> + 
$$\overline{v}$$
 + 0.8 MeV  
n + v → p<sup>+</sup> + e<sup>-</sup> + 0.8 MeV  
p<sup>+</sup> → n + e<sup>+</sup> + v - 1.8 MeV  
p<sup>+</sup> + p<sup>+</sup> → p<sup>+</sup> + n + e<sup>+</sup> + v - 1.8 MeV → d<sup>+</sup> + e<sup>+</sup> + v + 1.4 MeV  
4p<sup>+</sup> →  $\alpha^{++}$  + 2e<sup>+</sup> + 2v + 26.6 MeV

## The rate of fusion

If we know the rate of energy generation, and the amount of energy generated for each helium nucleus made, we can calculate the rate at which helium nuclei are made.

helium nuclei made / second

energy made / second

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energy made / helium nucleus made

# Quiz

- A 100 Watt light bulb uses 100 Joules (10<sup>2</sup> J) of electrical energy each second.
- A typical photon from a light bulb has about 10<sup>-19</sup> J of energy.
- How many photons does a 100 W light bulb emit each second?
- A. 10<sup>-21</sup>
- B. 10<sup>-17</sup>
- C. 10<sup>17</sup>
- D.  $10^{21}$  photons/s =  $(10^2 \text{ J/s}) / (10^{-19} \text{ J/photon})$

#### Fusion of hydrogen to make helium

1 hydrogen atom: 1.673 x 10<sup>-27</sup> kg 4 hydrogen atoms: 6.693 x 10<sup>-27</sup> kg 1 helium atom: 6.646 x 10<sup>-27</sup> kg Mass lost: 0.047 x 10<sup>-27</sup> kg (0.7% of 6.693x10<sup>-27</sup>) Energy created = Mass lost  $x c^2$ : 4.29 x 10<sup>-12</sup> J / He atom formed Total power (energy radiated per second) from Sun: 3.90 x 10<sup>26</sup> J / s Helium atoms formed / s = (Energy / s) / (Energy / He atom):  $9.09 \times 10^{37}$  He atoms formed / s Mass destroyed / s = (Energy generated / s) /  $c^2$ :  $4.33 \times 10^9$  kg / s =  $4.33 \times 10^6$  tonnes / s

#### Forces that cause nuclear reactions

- We know of four types of forces or interactions between particles:
- gravitational: an attraction between any masses
- electromagnetic: an attraction or repulsion between charged particles. (opposites attract)
- weak: an interaction which can convert one kind of a particle into another. e.g.,  $p^+ \rightarrow n + e^+ + v$
- strong: an attraction between the particles (protons and neutrons) in a nucleus. only occurs if the particles are very close together.

Steven Weinberg (in U.T. Physics department) showed that electromagnetic and weak forces are related.

Others are trying to find a theory combining all forces.

#### Is it 'Just a Theory'?

Fusion only occurs very close to the center of the Sun. How can we be sure this is how the Sun generates energy?

- The neutrinos created when protons became neutrons and positrons during fusion are very unlikely to collide with anything while leaving the Sun.
- When they get to the Earth they can cause neutrons to become protons and electrons.
- Since 1965 Ray Davis has been observing the solar neutrinos through the conversion of neutrons into protons in a tank of dry cleaning fluid ( $C_2CI_4$ ) in a gold mine in South Dakota.
- He received the Nobel prize in Physics for this work.

#### **Detection of Solar Neutrinos**

n + v → p<sup>+</sup> + e<sup>-</sup>  ${}^{37}Cl + v → {}^{37}Ar + e^{-}$ ...with a half-life of 34 days  ${}^{37}Ar + e^{-} → {}^{37}Cl + v + 0.82$  MeV

By bubbling Ar through the tank of cleaning fluid every week or so, the <sup>37</sup>Ar can be collected and measured through its radioactive decay.

But the number of neutrinos detected is only about 1/3 the number expected.

What happened to the other neutrinos?

## **Neutrino Oscillations**

- The favored explanation for the lack of solar neutrinos is that they changed to something else before getting to Davis's tank of dry cleaning fluid.
- There are 3 families of leptons (light-weight particles):

electron	e⁻	$v_{e}$
muon	μ	$\mathbf{v}_{\mu}$

tau  $\tau$   $v_{\tau}$ 

Just like there are 3 families of quarks:

u	d
S	С
t	b

Maybe some of the electron neutrinos turn into the other types on their way here.

## **Quantum Field Theory**

Neutrinos can transform from one type into another if the neutrinos formed from electrons, muons, and taus are not the mass eigenstates (the normal modes) of the neutrino field.

Whatever that means.