Lecture 2

What is a star?

A huge ball of ionized gas (plasma) producing energy (light) by nuclear fusion.

The visible surface of the sun (photosphere) is ~5700K. An object at this temperature emits most of its energy as visible light

Light is electromagnetic radiation emitted at various wavelengths

- Because of its electric and magnetic properties, light is also called **electromagnetic radiation**
- Visible light falls in the 400 to 700 nm range
- Stars, galaxies and other objects emit light in all wavelengths

An opaque object emits electromagnetic radiation
according to its temperature

Experiments show that solids, liquids, and dense gases (like our sun) emit continuous spectra due to temperature – thermal or blackbody emission

Experiments show that dilute gases produce either emission or absorption lines instead of a continuous spectrum

Experiments with gases and prisms showed that substances can absorb parts of any light that shines on them. These substances can re-emit that absorbed light at a later time. An emission line spectrum is equivalent to thermal emission by the cloud of gas.

Spectral lines are produced when an electron jumps from one energy level to another within an atom

- The nucleus of an atom is surrounded by electrons that occupy only certain orbits or energy levels
- When an electron jumps from one energy level to another, it emits or absorbs a photon of appropriate energy (and hence of a specific wavelength).

The spectral lines of a particular element correspond to the various electron transitions between energy levels in atoms of that element.

Each chemical element produces its own unique set of spectral lines

Hydrogen lines will be the most important for stars

Photosphere is a thin layer (~300-500 km thick) of the sun which is opaque – so is "visible surface" of sun. Temp of photosphere ranges from ~4000-8000K, but mostly is 5700K (~10,000F). When we talk about the "temperature of a star", we mean its photospheric temperature

Limb darkening – at limb, light is coming

from upper part of photosphere, not base

On large scale, sun produces continuous spectrum. Photosphere is cooler than interior – so see faint absorption lines (Fraunhofer lines) – use to determine chemical composition of photosphere (and

presumably whole sun). Note: for all stars, the temperature and chemistry determined from spectra is for PHOTOSPHERE. Interior is theory.

We can figure out the chemical composition of the sun by matching each of the sun's absorption lines to a spectra measured in a laboratory for a particular element or molecule

A star's color depends on its surface temperature

The spectra of stars reveal their chemical compositions as well as surface temperatures

The "Harvard Classification" of stars which we use today was generated by teams of women astronomers in the late 1800s (who were paid less than Harvard's secretaries). They sorted stellar spectra into 7 classes based on color (and thus **temperature**) and spectral features

O B A F G K M

Hottest ----------------------→Coolest

$L = \sigma T^4 A$, where $A = 4\pi r^2$

L = brightness (luminosity) of star

σ = a constant

T = temperature

A = area which depends on two contants (4 and π) and the radius (size)

of the star)

So, a bright star can be HOT, or it can be COOL BUT VERY VERY BIG

Two guys named Hertzsprung and Russell compare the spectral class (temperature) and brightnesses (luminosity) of all the stars for which they had data – the diagram they created is called an H-R diagram

What they found is that most stars fall in a narrow band called the "main sequence", but that some stars were big but cool or small but hot. Why?

To understand the H-R diagram, you need to look at the life cycle of stars

Stars are born, they live for a while, then they die – in the process, they create the chemical elements of the periodic table.

The life of a star is a constant battle against gravity – and gravity always wins

Stars form from immense regions of gas and dust called a nebula (plural nebulae or nebulas

It's all about MASS

Anything with mass is affected by gravity

Gravity tries to pull objects of mass towards each other

In a gas (nebula), THERMAL PRESSURE is what keeps atoms and molecules from all moving towards the center of mass

What do we mean by thermal pressure?

In a gas, the molecules are always in motion. The hotter the gas, the faster the motion, with many molecules trying to move away from the center (the gas tries to expand).

When a gas is compressed, it heats up, and so its thermal pressure increases.

If a nebula is not actively contracting or expanding, then gravity is in balance with thermal pressure

Need a trigger (perturbation) to cause nebula to collapse (feel more gravity than thermal pressure)

Triggers include:

Supernova

Collisions between nebulae

Solar wind pressure from nearby O and B stars

Other? Anything that disturbs balance

In order to be dense enough to collapse from a slight perturbation, need to be molecular cloud

Stages:

Free-fall contraction

Kelvin-Helmholtz contraction – slows contraction

Protostar or YSO before it reaches main sequence

Center of protostar becomes hot enough to glow in visible at some part – cool, but very large, so very luminous – HOWEVER, surrounded by exterior of protostar, so we don't actually see star at this point

Different types of YSOs:

1) IR stars

2) Proplyds

3) Herbig-Haro objects

4) T-Tauri stars

Range from protostars

to newly-formed stars

IR stars:

infrared protostars

- **show excess emission in IR compared to visible wavelengths**
- **explained by dust cocoons surrounding protostar**
- **these cocoons obscure the visible light from the central star-like object, but are warmed by that visible light and so radiate in the IR**

Proplyds: protoplanetary disks

- **dusty cocoons seen around YSOs**

first seen clearly in the Orion Nebula

Herbig-Haro

Objects--

- YSOs with

disks & bipolar

outflows

Solar Nebula - a spinning disk of gas and dust surrounding the newly forming sun.

T-Tauri star:

catchall term for many types of YSOs

- **YSO has not yet achieved H to He fusion and is not yet on the "Main Sequence" trend of luminosity & temperature**
- **can show evidence for rapid rotation, strong magnetic field, strong stellar winds, short-lived brightness outbursts (FU-orionis outbursts), excess IR emission**

Eventually interior of star becomes hot enough for nuclear fusion – star becomes main sequence star

Nebulae are huge – as they collapse, they break into numerous fragments – each of which will become a star system – star must be between ~0.1 solar masses to ~60 solar masses.

So tend to form CLUSTER of stars

High mass stars take less time to go from start of collapse to main sequence than do low mass stars

Eventually interior of star becomes hot enough for nuclear fusion – star becomes main sequence star – either proton-proton chain or CNO cycle

CNO cycle – more efficient method, but requires higher internal temperature, so only for stars with mass higher than ~1.1 solar masses

12C + p -> 13N 13N -> 13C

13C + p -> 14 N

14N + p -> 15O 15O -> 15N

15N + p -> 12C + 4He

Net reaction: 4 hydrogen converted to 1 helium

A more massive star must produce more energy to support its own weight – reason there is a correlation

of mass and luminosity on main sequence

Internal structure of main sequence star varies with mass

Reminder – Life Cycle thus far:

Nebula → collapse

Protostar YSO, Herbig Haro, T-tauri

Main Sequence

Main sequence stars have mass > 0.1 solar masses

and < 60 solar masses

Main sequence – thermal pressure from hydrogen

fusion in core (either proton proton chain

or CNO cycle) – balances gravity

Mass-luminosity relationship – in order to balance gravity,

must have

$$L = M^{3.5}$$

So a 4 solar mass star will be 128 times brighter than sun

Lifetime on main sequence = fuel/rate of consumption

$= M/L = M/M^{3.5} =$

$1/M^{2.5}$

So a 4 solar mass star will have a main sequence lifetime 1/32 as long as our sun

What do we mean by "lifetime"? The length of time over which there is Hydrogen available in the core

Eventually, all of the material in the core in converted to Helium and all of the Hydrogen is outside the core and too cool to fuse.

The Sun has been a main-sequence star for about 4.56 billion years and should remain one for about another 7 billion years

During a star's main-sequence lifetime, the star expands somewhat and undergoes a modest increase in luminosity

This is because we've converted part of the core into Helium, the core has contracted, causing the gas to heat up, heating and expanding the gas outside the core

So main sequence is not a line on an H-R diagram, but a band

So, what happens when the core runs out of hydrogen?

No fusion = thermal pressure doesn't balance gravity = star begins to collapse (contract) = get additional heating by Kelvin-Helmholtz contraction

Additional heat from contraction raises temperature of a shell of hydrogen outside core to high enough for hydrogen fusion – “shell burning”

Fusion of 4 hydrogen to form helium in a shell provides enough heat to support outer layers of star, but doesn’t do anything for core

Core keeps shrinking – producing heat from contraction (way above amount need to fuse hydrogen, but there is no hydrogen in core). This heat is added to that of “shell burning”, so outer layers of star have more thermal pressure than needed to balance gravity

Outer layers of star expand while core continues to contract → RED GIANT

When core hydrogen fusion ceases, a main-sequence star becomes a red giant

Concept – ideal gas – pressure depends on temperature (PV=nRT), so hot gas has higher pressure (and expands)

Electron degeneracy – we have an ionized gas (electrons not attached to nuclei) - gravity pushes electrons and nuclei close together – electrons cannot get any closer together without having same energy (violating pauli exclusion principle).

An electron degenerate gas will not expand as temperature increases

STELLAR LIFECYCLE:

What happens next depends on mass

For stars < 0.4 solar masses, core stops contracting due to degeneracy pressure before becoming hot enough to fuse He.

For stars > 3 solar masses, core becomes hot enough to fuse He before matter becomes degenerate.

In between, stars become degenerate before getting hot enough to ignite He → Helium Flash

Helium Flash – core gets hot enough to fuse He, but doesn't expand (so not offsetting gravity), so fuses faster and faster, until temperature becomes so high that electrons can move away from nuclei and are no longer degenerate. Star's core rapidly expands (helium flash) and then settles down to steady rate of helium fusion – can lose outer layer of tenuous stellar atmosphere in a ring called a planetary nebula

Helium fusion – 3 helium nuclei fuse to form one carbon nuclei (triple alpha process)

$^{4}He + ^{4}He \rightarrow ^{8}Be$ + gamma rays

$^{8}Be + ^{4}He \rightarrow ^{12}C$ + gamma rays

Expansion of core absorbs some of energy that went to expanding the outer layers, so outer layers shrink slightly

Can use **turnoff point** for a star cluster to determine age of cluster

- A low-mass star becomes
  - a red giant when shell hydrogen fusion begins
  - a horizontal-branch star when core helium fusion begins
  - an asymptotic giant branch (AGB) star when the helium in the core is exhausted and shell helium fusion begins

Dredge-ups bring the products of nuclear fusion to a giant star's surface

- As a low-mass star ages, convection occurs over a larger portion of its volume
- This takes heavy elements formed in the star's interior and distributes them throughout the star

Low-mass stars die by gently ejecting their outer layers, creating planetary nebulae

- Helium shell flashes in an old, low-mass star produce thermal pulses during which more than half the star's mass may be ejected into space
- This exposes the hot carbon-oxygen core of the star
- Ultraviolet radiation from the exposed core ionizes and excites the ejected gases, producing a planetary nebula

The burned-out core of a low-mass star cools and contracts until it becomes a white dwarf

- No further nuclear reactions take place within the exposed core
- Instead, it becomes a degenerate, dense sphere about the size of the Earth and is called a white dwarf
- It glows from thermal radiation; as the sphere cools, it becomes dimmer

High-mass stars create heavy elements in their cores

- Unlike a low-mass star, a high mass star undergoes an extended sequence of thermonuclear reactions in its core and shells
- These include carbon fusion, neon fusion, oxygen fusion, and silicon fusion

- In the last stages of its life, a high-mass star has an iron-rich core surrounded by concentric shells hosting the various thermonuclear reactions

The sequence of thermonuclear reactions stops here, because the formation of elements heavier than iron requires an input of energy rather than causing energy to be released

- A high-mass star dies in a violent cataclysm in which its core collapses and most of its matter is ejected into space at high speeds
- The luminosity of the star increases suddenly by a factor of around 10^8 during this explosion, producing a supernova
- The matter ejected from the supernova, moving at supersonic speeds through interstellar gases and dust, glows as a nebula called a supernova remnant

Lots of stuff without text

So why are we talking about star formation and nucleosythesis?

Because we think the universe had a beginning.

Our current understanding of the origin of the universe indicates that the only elements that formed were Hydrogen and Helium, with perhaps small amounts of Li, Be, and B. You can't make planets or life from just this.

The very first stars would have had no heavy elements, and they would have been massive – so they are exactly the type of stars that are born quickly, live fast, and die spectacularly, spewing heavier elements out into the universe via supernova explosions. Lower mass stars would have formed in a region already contaminated by the material provided by the deaths of these higher mass first generation stars.

The lowest mass (M stars) have main sequence lifetimes longer than the age of the universe—every one that has ever formed is still with us today as a main sequence star

Type I = population I star (chemically like our sun)

Type II = population II star (fewer “metals” than our sun)

We see these older stars—they have less heavy elements than our sun

If we look at star forming regions today (such as the Orion nebula), we notice that the new stars have more heavy elements than our sun.

Without the life and death of stars, there would be no rocky material from which to make terrestrial planets, there would be no oxygen to make water, and there would be no carbon, nitrogen, oxygen, or other materials with which to make life – we wouldn’t be here to take this class.