ASTR 1020

Look over Chapter 16 and 17

Star Stuff and Star Birth

Things to Know

- Protostar Life Track
- Bipolar Flow
- Core-Hydrogen Burning
- Hydrogen-Shell Burning
- Subgiant Branch
- Triple-Alpha Process
- Pauli Exclusion Principle
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Where Stars Form

Star formation begins when part of the interstellar medium starts to collapse under its own weight.

The cloud fragment heats up as it shrinks, and eventually its center becomes hot enough for nuclear fusion to begin. At that point, the contraction stops and a star is born.

Three Things that Hamper Star Formation

Gravity tries to bring matter together in a nebula. but three things opposes this.

- Heat
- Rotation
- Magnetism

Heat

When atoms cluster together they will disperse as quickly as they form as a result of their heat (which is their random motion).

Clusters need nearly 10^{57} atoms to form a cluster that can withstand gravity. This is more then all the all the sand on all the beaches of Earth.

Spin

As a cloud contracts, it must spin faster (to conserve its angular momentum), and it starts to bulge as material on the edge tends to fly off into space. Eventually the cloud will form a rotating disc.

The more rapid the rotation, the greater the tendency for the gas to escape, and the greater the gravitational force needed to retain it.

Magnetism

Magnetism can also hinder a cloud's contraction.

Magnetic fields can exert electromagnetic control over charged particles. In effect, the particles tend to become "tied" to the magnetic fields they are free to move along the field lines, but are inhibited from moving perpendicular to them.

Stage 1 An Interstellar Cloud

The first stage in the star-formation process is a dense interstellar cloud containing thousands of times the mass of the Sun, mainly in the form of cold atomic and molecular gas.

Breaking up is Hard to Do

If such a cloud is to be the birthplace of stars, it must become unstable and eventually break up into smaller pieces. The initial collapse occurs when a pocket of gas becomes gravitationally unstable.

An interstellar cloud can produce either a few dozen stars, each much bigger then our Sun, or a whole cluster of hundreds of stars, each comparable to or smaller then out Sun.

Stage 2 A collapsing Cloud Fragment

The process of continued fragmentation is eventually stopped by the increasing density within the shrinking cloud.

As fragments continue to contract, they eventually become so dense that radiation cannot get out. The trapped radiation casues the temperature to rise, the pressure to increase and the fragmentation to cease.

Stage 3 Fragmentation Ceases

The inner regions now become opaque to their own radiation and so have started to heat up considerably.

The dense, opaque region at the center is called a **Protostar** an embryonic object at the dawn of star birth.

After stage 3 we can distinguish a "surface" of the protostar its photosphere.

Stage 4: A Protostar

As the protostar evolves, it shrinks, its density grows and its temperature rises, both in the core and at the photosphere.

Still much larger then the Sun, our gassy heap is now about the size of Mercury's orbit.

The motion of the point representing the star on the H-R diagram is known as the star's **Evolutionary Track** or **Life Track**.

Stage 5 Protostellar Evolution

Events proceed more slowly as the protostar approaches the main sequence.

The causes of this slowdown is heat–even gravity must struggle to compress a hot object.

Stage 6 A Star is Born

Some 10 million years after its first appearance, the protostar finally becomes a true star.

Protons begin fusing into helium nuclei in the core, and the star is born.

Stage 7 The Main Sequence at Last

Over the next 30 million years or so, the stage 6 star contracts a little more.

Pressure and gravity are finally balanced, and the rate at which nuclear energy is generated in the core exactly matches the rate at which energy is radiated from the surface.

Star Time

The time required for an interstellar cloud to become a main sequence star also depends strongly on its mass.

The most massive fragments heat up to the required temperature and become O-type stars in a mere million years.

The opposite is the case for prestellar objects having masses less then that of our Sun. A typical M-type star requires nearly a billion years to form.

Brown Dwarfs

Low-mass interstellar gas fragments simply lack the mass needed to initiate nuclear burning.

Small, faint and cool (and growing ever colder) they are known collectively as Brown Dwarfs.

Gaseous Planet or Brown Dwarf?

	Gaseous Planet	Brown Dwarfs	Star
Diameter compared to Jupiter	1	2	10
Mass compared to Jupiter	1	55	1,000
Properties	Only partial convection. No deuterium burning	Full convection. Deuterium burning	Full convection. Thermonuclear Burning

Bipolar Flow

Strong heating within the turbulent disk and a powerful protostellar wind combine to produce **Bipolar Flow**, expelling two “jets” of matter in the directions perpendicular to the disk. As the protostar wind gradually destroys the disk, blowing it away into space, the outflow widens until, with the disk gone, the wind flows away from the star equally in all directions.

Leaving the Main Sequence

On the main sequence, a star slowly fuses hydrogen into helium in its core. This process is called **Core-Hydrogen Burning**.

As the main-sequence star ages, its core temperature slowly increases and both its luminosity and radius increase.

Eventually, as the hydrogen in the core is consumed, the star’s internal balance starts to shift and both its internal structure and its outward appearance begin to change more rapidly: the star leaves the main sequence.

Evolution of Sun-Like Stars

We are going to start by looking at the end of smaller stars like our Sun

Helium Core

As nuclear fusion proceeds, the composition of the star's interior changes.

The star's helium content increases fastest at the center, where temperatures are highest and the burning is fastest.

Running on Empty

About 10 billion years after the star arrived on the main sequence hydrogen becomes completely depleted at the center and the location of principal burning moves to higher layers in the core.

An inner core of non-burning pure helium starts to grow.

Changes

Without nuclear burning to maintain it, the outward-pushing gas pressure weakens in the helium inner core. However, the inward pull of gravity does not.

As the hydrogen is consumed, the inner core begins to contract.

Twice the Protons, Twice the force Needed

Helium nuclei have two protons each, carrying a greater positive charge so their electromagnetic repulsion is larger, and even higher temperatures are needed to cause them to fuse—at least 10^8 K.

The shrinkage of the helium core releases gravitational energy, driving up the central temperature and heating the overlying burning layers.

Hydrogen-Shell Burning

Hydrogen is now burning at a furious rate in a shell surrounding the non-burning inner core of helium "ash" in the center. This phase is known as the **Hydrogen-Shell Burning** stage.

Becoming Red a Giant

The gas pressure produced by this enhanced hydrogen burning causes the star's non-burning outer layers to increase in radius.
Not even gravity can stop their expansion.

The Red Giant Path

The star's roughly horizontal path from its main-sequence location (stage 7) to stage 8 on the figure is called the **Subgiant Branch**. By stage 8, the star's radius has increased to about three times the radius of the Sun.

A Red Giant

The red giant is huge—about the size of Mercury's orbit. In contrast, its helium core is surprisingly small—only about 1/1000 the size of the entire star, making the core just a few times larger than Earth.

Helium Fusion

For a star like the Sun, this simultaneous shrinking and expanding does not continue indefinitely. A few hundred million years after a solar-mass star leaves the main sequence, something else happens—helium begins to burn in the core.

The reaction that transforms helium into carbon occurs in two steps.

The Triple-Alpha Process

First, two helium nuclei come together to form a nucleus of beryllium-8 (^{8}Be).

$$^{4}\mathrm{He} + {}^{4}\mathrm{He} \rightarrow {}^{8}Be + \mathrm{energy}$$

Soon after another helium comes zooming in and combines with the beryllium to make Carbon 12.

$$^{8}Be + {}^{4}\mathrm{He} \rightarrow {}^{12}C + \mathrm{energy}$$

Helium-4 nuclei are traditionally known as *alpha particles.* Three alpha particles are required foregoing reaction is usually called the **Triple-Alpha Process**.

Electron Degeneracy Pressure

Under the conditions found in the red-giant core, a rule of quantum mechanics known as the **Pauli Exclusion Principle** prohibits the electrons in the core from being squeezed too close together.

This condition is known as **Electron Degeneracy**, and the pressure associated with the contact of the tiny electron spheres is called **Electron Degeneracy Pressure**.

Building Pressure

In the electron-supported core of a solar-mass red giant the pressure is largely independent of the temperature. When burning starts and the temperature increases, there is no corresponding rise in pressure, no expansion of the gas, no drop in the temperature, and no stabilization of the core.

Finally able to react to the energy dumped into it by helium burning, the core expands, its density drops, and equilibrium is restored as the inward pull of gravity and the outward push of gas pressure come back into balance. The core, now stable, begins to burn helium into carbon at temperatures well above 10^{8} K.

The Horizontal Branch

It resides in a well-defined region of the H–R diagram known as the **Horizontal Branch**, where core-helium burning stars remain for a time before resuming their journey around the H–R diagram.

Red Giant Again

As helium fuses to carbon, a new inner core of carbon ash forms

The star now contains a shrinking carbon core surrounded by a helium-burning shell, which is in turn surrounded by a hydrogen-burning shell.

By the time it reaches this stage the star has become a swollen red giant for a second time.

Red Supergiant

Our star is now a red supergiant. The carbon core grows in mass as more carbon is produced in the helium-burning shell above it but continues to shrink in radius, driving the hydrogen-burning and helium-burning shells to higher and higher temperatures and luminosities.

No Carbon Burning

Before the carbon core can attain the high temperatures needed for carbon ignition, the electrons in the core once again become degenerate, the contraction of the core ceases, and its temperature stops rising.

A spoonful of the core would weigh a ton on the surface of the Earth.

Isolations

Now, the burning becomes very unstable. The helium-burning shell is subject to a series of explosive helium-shell flashes.

Compounding the star's problems, its surface layers are also becoming unstable. As the temperature drops to the point at which electrons can recombine with nuclei to form atoms, each recombination produces additional photons, which tend to push the outer envelope to greater and greater distances from the core.

Planetary Nebula

The "star" now has two distinct parts.

At the center is a small, well-defined core of mostly carbon ash. Well beyond the core lies a spherical shell of cooler, low-density matter spread over a volume roughly the size of our solar system. Such an object is called a **Planetary Nebula**.

White Dwarfs

Formerly concealed by the atmosphere of the red-giant star, the core becomes visible as the envelope recedes.

The core has a white-hot surface when it first becomes visible, although it appears dim because of its small size. The core's temperature and size give rise to its new name **White Dwarf**.

The End of The Road

The star continues to cool and eventually becomes to dim to see. It will eventually become a **Black Dwarf** a cold, dense, burned-out ember in space.

Stars Bigger Then The Sun

Stars leave the main sequence for one basic reason they run out of hydrogen in their cores.

A high-mass star leaves the main sequence on its journey toward the red-giant region with an internal structure quite similar to that of its low-mass cousin. Thereafter, their evolutionary tracks diverge.

Life Track of Massive Stars

In stars having more than about 2.5 times the mass of the Sun, helium burning begins smoothly and stably, *not* explosively—there is no helium flash.

A much more important divergence occurs at approximately 8 solar masses. These high-mass star can fuse carbon, oxygen, and even heavier elements as its inner core. They are destined to die in a violent supernova explosion soon after carbon and oxygen begin to fuse.

Binary-Star Systems

Each star in a binary system is surrounded by its own teardrop-shaped “zone of influence,”. Any matter within that region “belongs” to the star. The two teardrop-shaped regions are called **Roche Lobes.**

The Roche lobes of the two stars meet at a point on the line joining them called a **Lagrangian Point**. This Lagrangian point is a place where the gravitational pulls of the two stars exactly balances.

Detached Binaries

Normally, both stars lie well within their respective Roche lobes, and such a binary system is said to be **Detached Binary**.

Semidetached Binary

If gas begins to flow from one companion through the Lagrangian point. The stars in this case are said to be a **Semidetached Binary**. Because matter is flowing from one star onto the other, semidetached binaries are also known as **Mass-Transfer Binaries**.

Contact Binary

If, for some reason, the other star also overflows its Roche lobe the surfaces of the two stars may merge. The binary system then consists of two nuclear-burning stellar cores surrounded by a single continuous common envelope a **Contact Binary**.

The Death of very massive stars

Very massive stars will explode toward the end of their lives. There are two three ways that stars can explode.

One type of star, called a **Nova**, may increase enormously in brightness by as much as a factor of 10,000 or more in a matter of days.

The word *nova* means “new” in Latin, and to early observers these stars did indeed seem new, because they appeared suddenly in the night sky.

How to Get a Nova

The white-dwarf stage represents the end point of a star's evolution. This is end for an *isolated* star, such as our Sun.

However, should the star be part of a *binary* system, an new ending is possible.

Mass Increases

If the distance between the two stars is small enough, then the dwarf's tidal gravitational field can pull matter primarily hydrogen and helium away from the surface of its main-sequence or giant companion. The system becomes a mass-transferring binary.

Flare Up

As it builds up on the white dwarf's surface, the stolen gas becomes hotter and denser. This surface-burning stage is as brief as it is violent.

The star suddenly flares up in luminosity then fades away as some of the fuel is exhausted and the remainder is blown off into space.

The End of Large Mass Stars

A high-mass star, can fuse not just hydrogen and helium but also carbon, oxygen, and even heavier elements as its inner core continues to contract and its central temperature continues to rise.

As each element is burned to depletion at the center, the core contracts, heats up, and starts to fuse the ash of the previous burning stage. A new inner core forms, contracts again, heats again, and so on.

Iron Cores

Once the inner core begins to change into iron, our high-mass star is in trouble. Iron is the most stable element there is.

Iron nuclei are so compact that energy cannot be extracted by combining them into heavier elements or by splitting them into lighter ones.

Photodisintegration

The core temperature rises to nearly 10 billion K. At these temperatures, individual photons, according to Wien's law, have tremendously high energies, enough to split iron into lighter nuclei and then to break those lighter nuclei apart until only protons and neutrons remain.

This process is known as **Photodisintegration** of the heavy elements in the core. As nuclei are destroyed, the core of the star becomes even less able to support itself against its own gravity. The collapse accelerates.

Neutronization

Now the core consists entirely of simple elementary particles—electrons, protons, neutrons, and photons at enormously high densities, and it is still shrinking. As the core density continues to rise, the protons and electrons are crushed together, forming neutrons and neutrinos. This process is sometimes called the **Neutronization** of the core.

$$\mathrm{p} + \mathrm{e} \rightarrow n + \mathrm{neutrino}$$

Neutron Degeneracy Pressure

There is now nothing to prevent the star from collapsing all the way to the point at which the neutrons come into contact with one another. They then produce enormous pressures that strongly oppose further gravitational collapse.

This **Neutron Degeneracy Pressure**, akin to the electron degeneracy pressure that operates in red giants and white dwarfs, finally begins to slow the collapse.

Rebound

By the time the collapse is actually halted, however, the core has overshot its point of equilibrium, Like a fast-moving ball hitting a brick wall, the core becomes compressed, stops, then rebounds—with a vengeance!

Core-Collapse Supernova

At that point the core rebounds. An enormously energetic shock wave sweeps through the star at high speed, blasting all the overlying layers—including all the heavy elements just formed outside the iron inner core—into space.

For a period of a few days the exploding star may rival in brightness the entire galaxy in which it resides. This spectacular death rattle of a high-mass star is known as a **Core-Collapse Supernova** (Type II).

Supernova and Novas

Like a nova, a supernova is a star that suddenly increases dramatically in brightness, then slowly dims again, eventually fading from view.

The most important difference is that a supernova is more than a million times brighter than a nova.

A second important difference is that the same star may become a nova many times, but a star can become a supernova only once.

In addition to the distinction between novae and supernovae, there are also important observational differences *among* supernovae.

Type I and II

Astronomers divide supernovae into two classes, known simply as Type I and Type II. **Type I Supernovae**, are hydrogen-poor and have a light curve somewhat similar in shape to that of typical novae.

Type II Supernovae, usually have a characteristic “plateau” in the light curve a few months after the maximum.

Carbon-Detonation Supernova

What is responsible for these differences among supernovae?

To understand the alternative supernova mechanism, we must return to the processes that cause novae and consider the long-term consequences of their accretion–explosion cycle.

Nova explosions eject matter from a white dwarf's surface, but they do not necessarily expel or burn all the material that has accumulated since the last outburst.

Chandrasekhar Mass

There is a limit to the mass of a white dwarf, above which electrons cannot provide the pressure needed to support the star. The maximum mass of a white dwarf is about 1.4 solar masses, a mass often called the **Chandrasekhar Mass**.

Carbon-Detonation Supernova

If a white dwarf exceeds the Chandrasekhar mass, the pressure of degenerate electrons in its interior becomes unable to withstand the pull of gravity, and the star immediately starts to collapse.

Carbon fusion begins everywhere throughout the white dwarf almost simultaneously, and the entire star explodes in another type of supernova—a **Carbon-Detonation Supernova** (Type I) comparable in violence to the "implosion" supernova associated with the death of a high-mass star, but very different in cause.

Stellar Nucleosynthesis

We currently know of 115 different elements, ranging from the simplest—hydrogen, containing one proton—to the most complex, called ununoctium and discovered in 1999, with 118 protons and 181 neutrons in its nucleus.

How and where did all these elements form? The hydrogen and most of the helium in the universe are primordial dating from the very earliest times. All other elements in our universe result from **Stellar Nucleosynthesis** that is, they were formed by nuclear fusion in the hearts of stars.

the Proton–Proton Chain

Stellar nucleosynthesis begins with the proton–proton chain. A series of nuclear reactions occur, ultimately forming a nucleus of ordinary helium (^{4}He) from four protons (^{1}H):

Triple-Alpha Reaction

When the temperature exceeds about 100 million K, helium nuclei can overcome their mutual electrical repulsion, leading to the triple-alpha reaction.

The net result of this reaction is that three helium-4 nuclei are combined into one carbon-12 nucleus releasing energy in the process.

Magnesium Formation

At higher and higher temperatures, heavier and heavier nuclei can gain enough energy to overcome the electrical repulsion between them. At about 600 million K (reached only in the cores of stars much more massive than the Sun), carbon nuclei can fuse to form magnesium

Helium Capture

The formation of most heavier elements occurs by way of an easier path. The repulsive force between two carbon nuclei is three times greater than the force between a nucleus of carbon and one of helium. Thus, carbon–helium fusion occurs at a lower temperature than that at which carbon–carbon fusion occurs.

As a star evolves, heavier elements tend to form through **Helium Capture** rather than by fusion of like nuclei.

Very Heavier Elements

Under intense heat, some silicon-28 nuclei break apart into seven helium-4 nuclei. Other nearby nuclei that have not yet photodisintegrated may capture some or all of these helium-4 nuclei, leading to the formation of still heavier elements

S-Process

If the alpha process stops at iron, how did heavier elements, such as copper, zinc, and gold, form? That process is **Neutron Capture** the formation of heavier nuclei by the absorption of neutrons.

Researchers usually refer to this as “slow” neutron-capture or the **S-Process**. It is the origin of the copper and silver in the coins in our pockets, the lead in our car batteries, the gold in the rings on our fingers.

R-Process

There must be yet another nuclear mechanism that produces the very heaviest nuclei. This process is called the *r-process* (where r stands for “rapid,”). The r-process operates very quickly, occurring during the supernova explosion that signals the death of a massive star.

Because the time available for synthesizing these heaviest nuclei is so brief, they never become very abundant.