Chapter 19 Star Formation

Star Forming Regions

Our universe is constantly renewing itself through star formation. Billions of stars have been born, lived and died. We don't see the lives of stars since the shortest lived stars live for several million years. In spite of all this we can see plenty of evidence for ongoing stellar evolution.

Young Stars in the Universe

Our Sun and most of the nearby stars were all probably formed several billion years ago. Yet when we look in the Milky Way and other nearby galaxies we can see emission nebulae that contain young hot stars in them. Some of these regions are only a few million years old. The galaxy M33 has such a nebula called NGC 604. Inside it there is massive star formation going on. The cloud is some 500 pc across. These regions are called *stellar nurseries*. Whatever the size of the nebula, the emission nebulae are the stellar birthplaces throughout the universe. How and where do stars forms? Stellar formation starts when one of these cold dark clouds starts to collapse. As it collapses, it starts to heat up due to friction and eventually it becomes hot enough in the center that nuclear fusion begins. It becomes a full fledged star at this point. The collapse stops and the new star will grow in size due to the outward pressure from inside. If this is true, then why hasn't all the clouds collapsed already? We need to look at a few more factors first to see why this is true.

Gravity and Heat

What can withstand the pull of gravity and keep a cloud from collapsing? As a cloud begins to collapse the atoms are pulled closer together and they start to bump into one another. When this happens heat is generated and the force caused by the heat is greater than the pull of gravity and they are pushed apart. Even as large numbers of atoms do this, heat will still prevail. (Remember that the heat is just a measure of the energy that the atom has.) To overcome the heat with gravity, you must have 10^{57} atoms in the cloud. That is much more than all the grains of sand on the Earth, 10^{25} grains.

Some Complications

Besides heat, the rotation of a cloud can cause it to keep from contracting. Think of this: as the cloud collapses, what happens to the spin rate? What happens to an ice skater that is spinning and they pull in their arms? Well the same thing is happening to that cloud. As it gets smaller, it spins faster which then throws the material outward and it slows down.

Magnetism may also affect the pull of gravity and keep the cloud from collapsing. Most clouds have a magnetic field. As the cloud starts to contract, it heats up and ionizes some of the atoms. These charged particles become tied up in the magnetic field lines in the cloud and can only move along the lines. This can distort the contraction of the cloud. As the cloud continues to contract, this causes the magnetic field to increase in strength and ties up the ions in the cloud keeping the contraction from occurring the way it should for a star to form.

Modeling Star Formation

We are going to discuss the modern theories of star formation. These have been solved on supercomputers from what we know about stars. This theory has evolved over the years to what it is now from the information that we knew.

The Formation of Sun Like Stars

The star formation begins when gravity dominates over the heat of the cloud. At this point the cloud will contract on its way to becoming a real star.

Stage 1: An Interstellar Cloud

In the first stage you take an interstellar cloud, maybe tens of parsecs in size with a temperature of only 10 K throughout and start to collapse it. These clouds seem to have enough internal pressure to withstand gravity. As this happens the cloud must break up into smaller clumps. Many astronomers think that there is some sort of trigger that sets off the collapse. This could be the shock wave from a supernova, or the high solar wind from near-by hot young stars. Whatever the reason, it is thought that once the collapse begins, fragmentation naturally follows. The cloud could break up into thousands of smaller fragments, each possibly becoming a star. This process from large cloud to many smaller fragments takes a few million years. There is little evidence of one star born from one cloud. It apparently just doesn't happen.

Stage 2: A Collapsing Cloud Fragment

Let's talk about just one fragment now. To form a star like our Sun the cloud will contain between 1 and 2 solar masses. The cloud is probably 100 times the size of our solar system. Even though the cloud has shrunk down in size, it is still about the same temperature. The reason for this is that the gas radiates large amounts of energy into space. The material is still very thin. The only place where the temperature goes up is in the center. Here the temperature is about 100 K instead of 10 K like the rest of the cloud. As they continue to condense, they become more dense and now the energy doesn't escape them so easily. It is here that the temperature starts to go up in the cloud.

Stage 3: Fragmentation Ceases

By now several tens of thousands of years has passed since the process started. The inner density is to a point where it is opaque to the radiation that it emits which causes the temperature to go up in the center. The temperature is about 10,000 K, but the outer temperatures have not increased much. At this point you have what is called a *protostar*. This is the beginning of star birth. The material on the outside is falling in on the protostar making it more massive and it heats up even more. At the end of stage 3 we can distinguish a surface of the protostar. This is its photosphere.

Stage 4: A Protostar

It has now taken about 100,000 years to reach this point. It has shrunk down and the temperature is about 1 million K. It is about the size of Mercury's orbit. The surface temperature is around a few thousand K. If we know the radius and surface temperature we can calculate the luminosity. It is actually several thousand times the luminosity of the Sun. The main reason is that it is hundreds of time larger than the Sun. This luminosity is due to gravitational energy. Now we can plot the protostar on the H-R Diagram. As the protostar finds itself on the H-R Diagram it plots out its *evolutionary track*. This red track shows what is happening to the protostar. The early track is called the *Kelvin-Helmholtz contraction phase*. As the protostar collapses, it spins faster to conserve angular momentum. When this happens, it forms a flat disk around the protostar called a *protostellar disk*. This disk maybe 100 AU in diameter. It is from here that planets would form. The heat from the core starts to diffuse outward from the center to the cooler surface. It radiates into space and now the contraction starts to slow, but it doesn't stop. At this point it moves down on the H-R diagram. It becomes less luminous. As it drops towards the main sequence it is said to be on the *Hayashi track*. Stars on the Hayashi track exhibit violent surface activity which leads to strong protostellar winds. This is the *T Tauri phase*, named after the protostar T Tauri.

Stage 5: Protostellar Evolution
At this stage the protostar is only 10 times the size of our Sun. It has a surface temperature of only 4000 K and the luminosity is about 10 times that of the Sun. The core temperature is about 5 million K. The gas in the core is completely ionized. It is still not hot enough for nuclear fusion. Things have slowed down now. Gravity is now struggling with the internal heat as it pushes closer to becoming a star.

Stage 6: A Newborn Star
After 10 million years we now have a full fledged star. As our 1 M_{sun} reaches a size of 1 million km the core temperature reaches 10 million K and ignites the hydrogen fuel. The surface temperature is 4500 K.

Stage 7: The Main Sequence at Last
Over the next 30 million years very little changes occur in the star. The central temperature increases to 15 million K and the surface temperature reaches 6000 K. Gravity and the outward pressure from the heat are now balanced. This will all take about 40 – 50 million years to reach this point. It will establish itself on the main sequence and it will remain virtually unchanged for the next 10 billion years.

Stars of Other Masses
We just looked at what would happen to form a 1 solar mass star like our Sun. But this is not how stars of other masses form up. Let's look at some of these.

The Zero Age Main Sequence
Figure 19.8 shows the tracks for a .3, 1 and 3 solar mass star and where they enter the main sequence. Mass will determine how long they are a protostar. For example and O or B class star will take about $1/50^{th}$ the time it took our Sun to become a main sequence. For less massive protostars, it will take them much longer than our Sun. Whatever the mass, the end product is the main sequence. The main sequence line where a star's properties settle down is called the *zero-age main sequence*.
We know that mass is a main drive to what happens in a stars life, but there is one other thing that affects it. The composition of the cloud will also determine what happens. This will affect the temperature of the protostar. If they have a higher proportion of

heavy elements, it will be cooler and less luminous. Remember that the main sequence is not an evolutionary track. Stars do not move along it. Once on the main sequence the star will remain at that spot for its life until it moves off.

Failed Stars

Sometimes the cloud fragment is too small to ignite the hydrogen fusion. What you have is a failed star. Jupiter is a good example of this. Jupiter formed up and contracted and heated up but didn't start the nuclear fusion. The heat is still detectable from Jupiter. These objects will collapse until they become cold, dark clinkers, orbiting another star or just wandering through space. Astronomers think that a protostar needs to be about .08 solar masses or 80 times the mass of Jupiter to ignite the nuclear fuel. It is thought that there may be a vast number of these objects in space, but they give off no light so we don't see them easily. These small, faint, cool objects are called *brown dwarfs*. These are thought to be prestellar fragments of at least 12 solar masses, so Jupiter is not a brown dwarf.

Observations of Cloud Fragments and Protostars

How do we know what is really happening during star birth? The time frame is too long for humans to see the whole thing, so we do the next best thing. We watch many objects that are in different stages of their birth.

Evidence of Cloud Contraction

In stages 1 and 2 there is no emission of light for us to look at so we must use radio telescopes to peer into the clouds. The Trifid Nebula (M20) is an example of star birth. We look for the emission nebulae to watch star birth. M 20 seems to contain gas that is contracting. By using radio telescopes we can see the invisible gas that surrounds the nebula. These are the contour lines for formaldehyde gas. It seems that parts are contracting and fragmenting and on their way to becoming stars. The huge dark cloud surrounding the visible nebula is in stage 1. It has a temperature of about 20 K. Regions A and B are much denser cloud fragments and they have temperatures of about 100 K. Fragment B has been shown by Doppler studies that it is contracting. Its mass is about 1000 solar masses. This is somewhere between stage 1 and 2. The visible nebula itself is a star forming region. In the center you already have young stars that have formed. This is somewhere around stage 6 or 7.

Evidence of Cloud Fragments

Other regions of the Milky Way show us cloud fragments between stages 3 and 5. The Orion nebula is lit by several O type stars. There are several smaller areas in the cloud fragment that are showing intense radiation. These areas are thought to be on their way to stage 3. The temperatures can't be reliably determined because they are buried in the cloud.

Evidence of Protostars

As we look for objects at stages 4, 5, and 6 we find that radio telescopes no longer work. This is due to higher temperatures which emit shorter wavelengths. They shine intensely in the infrared. One of these objects was found in Orion. The luminosity is about 1000 times greater than the Sun. This puts it around stage 4. In the 1980's we launched the IRAS satellite that showed us some of these objects closer to home than we thought. Figure 19.11 shows 2 low mass star forming regions found in Orion by the HST. These are around stage 5. Some of these infrared objects have their energy sources hidden. A young hot star is hidden down in the dust and is giving off ultraviolet radiation. It is absorbed by the dust and emitted as infrared. These are called *cocoon nebulae*. They are near stage 6.

Protostellar Winds

Protostars often exhibit strong winds. In the Orion Nebula gas molecules have been found to be expanding at 100 km/sec. These winds have been linked to protostars in the area. Around the protostar you have a protostellar disk from which planet may form. Strong heating and a powerful protostellar wind combine to form a *bipolar flow*. This is perpendicular to the disk. As the winds destroy the disk, the outflow widens and then when the disk is gone the outflow expands outward in all directions. One such example is seen in the Orion Nebula in figure 19.14. The 2 lobes of the outflow are called HH1 and HH2. The HH stands for Herbig-Haro who were the investigators that discovered them.

Shock Waves and Star Formation

Star formation is really much more complex than we have just discussed. One of the things that can happen is that the outflow from the emission nebulae can cause the thin material in space to be compressed just like a *shock wave* going through the material. This compresses the material until it too may collapse and fragment and form stars. This is one trigger to the formation of other stars. Other triggers are: 1)the gentle deaths of stars that form a planetary nebula, 2)the more violent death of large stars in a supernova, 3)spiral density waves moving through a spiral galaxy and 4)the interaction between galaxies. Supernovae are by far the most energetic and efficient way of causing star formation, but they are few and far between, so the other methods must play a major part.

Star Clusters

If a large cloud collapses at the same time you will produce a group of stars at nearly the same time. These are called *star clusters*. Figure 19.17 shows a good look at one such cluster. Since they were all born at about the same time, the only differences between them are due to mass, which allows us to look and see how they are evolving.

Clusters and Associations

There are several types of groups of stars. One such grouping is called an *open cluster*. It is a loose, irregular cluster found mainly in the plane of the galaxy. The Pleiades is one such cluster. By putting them on the H-R diagram we can determine that they are less than 100 million years old, so they are youngsters. Less massive, but more spread out groups are called *associations*. They will contain only a few hundred stars over a few tens of parsecs. They are usually rich in young stars. The last type is very different from the other 2 types. It is called a *globular cluster*. Figure 19.19 They are all more of less spherical in shape, found away from the plane of the Milky Way and contain a few hundred thousand to millions of stars. They may be spread out over 50 parsecs. Looking at the H-R diagram you can see that they lack the upper main sequence stars. All of the O through F type stars have exhausted their fuel and died off. Most of the stars left a probably a little smaller than the Sun. This means that they are old, maybe 10 billion years old. These are probably the oldest stars in the galaxy. The stars show a lack of heavy elements which means that they formed a long time ago.

Clusters and Nebulae

We really don't know what happened in the cloud to form an object like a cluster. As time goes on, though, we are learning more and more. The formation is quite complex. How much of the cloud actually became stars is one of those questions. If O and B class stars were formed up first, their strong winds would have blown away much of the cloud surrounding them. This would affect the efficiency of star formation. You will find that there are smaller stars than large stars out there, which may be a consequence of the big stars forming first.

Cluster Lifetimes

At some time the clusters will no longer be clusters. The stars will become individual stars in space. It might be because when the dust and gas gets blown out of the cloud, there is not enough gravity to hold on to the stars it has. If they survive the loss of gas, then the lightest stars usually find themselves thrown out by the bigger brothers. The tidal gravitational field of the Milky Way may strips the outlying stars from the galaxy. Encounters with giant molecular clouds can pull the outlying stars away. Because of these influences, open clusters only last a few hundred million years. Some of the very massive open clusters may last 5 billion years. Loosely bound associations may only last a few tens of millions of years. The road from gas cloud to a single star like the Sun is a long and tortuous one indeed.