20 September 2017

How Were The Stars Formed?

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The Milky Way galaxy was once ablaze with bright young stars. Today, star formation has calmed down, but we glimpse intense pockets of gas, such as in Orion, that are forming massive stars and testify to the brilliant past. Stars form throughout the Milky Way in clouds of interstellar gas that orbit their host galaxy. The clouds acquire more mass as gas accumulates, and the gaseous nebulae are soon massive enough to become unstable to the inexorable tug of their own gravity. The clouds collapse, and their central regions fragment into dense clumps of cold gas that condense to form stars. The gas is dusty, and the dust particles are the key ingredients that eventually coalesce to form a disk-like structure of snowball-like bodies within which are rocky cores. These orbit the forming sun, and in turn agglomerate into planets. Comets and asteroids are relics from the past. The earth, and the entire solar system, was formed out of interstellar grit.

A galaxy is an agglomeration of tens or hundreds of billions of stars. Its fate devolves around knowing the mass of a star. Why should a star like the sun weigh in at two billion trillion trillion tons? And all other stars, countless in number, are between a tenth and a hundred times the mass of the sun. Arthur Eddington once famously wrote that a physicist on a cloud-bound planet could predict that there are stars. His argument was based on stability considerations. Consider a series of giant balls of hydrogen gas. Their stability is a result of completion between gravity and pressure, the centers of the clouds heating up under the immense pressure of the surrounding layers of gas. Make the ball more than a hundred times the mass of the sun, and the pressure of the radiation alone would drive the cloud apart. Make it less than a tenth of a solar mass, and the central pressure could not compete with the fatal attraction of gravity.

Once we converge on the notion of the mass of a star, we inevitably wonder how it formed. We have a clue: some stars are much younger than the sun. Some are much older and some are being born today. All of these stars, young and old, nascent and dying, we see around us, just as a city contains people of all ages.

The mass of a star is the key determinant of its age. A massive star is hot in its core and burns hydrogen prolifically. A low mass star is cooler and is more conservative in consumption of its fuel. Massive stars are short-lived, low mass stars live for an eternity. The sun, somewhere in between, has lived for some 4.6 billion years, and is now in middle age. The typical star is a third of the mass of the sun. It will live for a hundred billion years. It almost certainly has a planetary system. It's definitely a better place to be near when our sun dies, five billion years from now.

Let us begin with the nearest star, our Sun. How did it form? We need to go back in time, to see how a giant gas cloud evolved, fragmenting into stars. Before this remarkable event, let us consider the history of the parent cloud. It was much like the clouds we observe today, swirling around the interstellar medium on quasi-circular orbits about the centre of our Milky Way Galaxy.

From clouds to stars

First, a cloud of gas developed and grew in mass. The Milky Way Galaxy has something like a hundred billion solar masses in stars, and about a tenth of this mass is in gas. The gas swirls around the galaxy, most of it contracting into a relatively thin disk. The clouds orbit the galaxy and occasionally run into each other. Interstellar clouds coalesce and grow, just like storm cloud formations that develop on an initially sunny day. Once a cloud has aggregated enough mass, perhaps a hundred thousand or a million solar masses of hydrogen gas, gravity becomes so powerful that the cloud collapses.

Interstellar clouds are highly turbulent and their collapse is chaotic. This results in fragmentation into dense clumps of cold gas. Many of these give birth to stars. The gas clumps are highly obscured by dust, and are seen in the optical bands as regions of darkness in the Milky Way. One needs to use infrared telescopes to peer inside the dusty gas clouds that are found throughout the interstellar medium. These telescopes are usually in space as the Earth's atmosphere is opaque, especially in the far infrared where the coldest dust is found. We observe interstellar clouds at different stages by observations at radio, optical, infrared and microwave wavelengths. The longer the wavelength, the more penetrating is the radiation.

The densest clouds consist mostly of interstellar molecules, and are best viewed with the ALMA telescope (Atacama Large Microwave Array) in Chile, with 73 antennae at 16000ft altitude.

The interstellar medium is dusty. The heavier elements in the gas condense into tiny grains of dust. The tiny grains of dust act as seeds for icy deposits that grow in dense cold interstellar clouds and constitute the pervasive dusty component of the interstellar medium. The cores of the observed dust particles are initially formed in the outflows from evolved stars, that is, stars which have generated elements like carbon and silicon in their hot interiors. As the star ages, layers of enriched gas are ejected in outflows. Tiny dust grains condense in the outflows flakes of graphite and quartz.

The dust grains are covered with icy mantles and are microns in size. It is these that are responsible for absorbing starlight, and for the vast dark patches one sees in the Milky Way. The recompense for observers is that the energy emerges in the far infrared, and space telescopes, notably the Spitzer and Herschel observatories, have imaged the infrared sky. With their aid, we can peer into the dark hearts of the densest molecular clouds and see star formation at work.

The clusters of young stars shine like beads on a string, strung out into a spiral pattern and demarcating the regions where the differential rotation of the galaxy has perturbed the orbital motions. The outer regions take longer to orbit than the inner regions, since the orbital velocity does not change much, and this has the effect of producing a spiral pattern of shocked gas that is lit up by ensuing star formation. The shock compression of the gas is caused by passage of our nearest neighbour, the Large Magellanic Cloud galaxy that perturbs the gas cloud orbits and causes them to crash into each other. A competing driver of cosmic traffic jams is caused by the tumbling of the central bar of stars in the Milky Way. The orbiting clouds pass through a traffic-like diversion spread out into a spiral density wave pattern. Clouds crash into each other and coalesce. The over-massive clouds collapse under their own gravity and fragment into stars before they have escaped from the spiral shock pattern. This leads to the beautiful spiral arms common to disk galaxies, provided they contain enough gas to form stars.

Barriers to fragmentation: the cooling problem

There are two hurdles a collapsing cloud must overcome in order to fragment into stars.

Firstly, it must cool dramatically to get rid of the thermal energy acquired as the cloud compresses during collapse. Atoms and molecules are effective coolants, but do not suffice. Atoms, and at high density their molecular counterparts, have internal energy levels. These are excited by atomic collisions. The lifetime of excited levels is generally short. De-excitations result in emission of radiation that escapes from the cloud, as long as the cloud is transparent to these photons. In this way, the thermal energy of atoms and molecules is radiated away. The cloud cools and continues to collapse.

A problem arises at high densities. The cloud becomes entirely molecular, and the molecular radiation, which is at discrete frequencies corresponding to the energy levels of the excited molecules, is absorbed by the far more common intervening molecules which are unexcited. This is because the lifetime of the excited states is short.

The cooling radiation is trapped. In effect the cloud is opaque and cannot cool. So it cannot collapse and fragment.

Dust comes to the rescue. The molecules trap the radiation but it is the dust that absorbs it. The dust emits radiation continuously, in the far infrared. The radiation leaves the cloud, and the cloud collapses. Dense interstellar clouds were studied extensively with the far infrared Herschel 6.5 m space telescope. They fragment into proto-stars. These highly embedded forming stars are seen as bright infrared sources within the dusty wombs of dense clouds. Massive stars form and emit intense ionizing radiation that creates molecular cavities in the clouds. The edges of the cavities glow in ionized gas. Eventually the dust and gas disperse and we are left with a new-borne cluster of stars

Barriers to fragmentation: the angular momentum problem

Our galaxy is rotating. This means that all interstellar clouds, as they condense within the galaxy, also spin. As a cloud collapses, it conserves its angular momentum and spins faster and faster. How can one possibly collapse to form a star? One has to transfer the angular momentum. The answer lies in coupling the exterior of the cloud with its core by magnetic fields.

Magnetic fields to the rescue

The interstellar medium is magnetized. The dust grains spin about lines of magnetic force that trace the field, just as one sees when one scatters iron dust around a magnet. The light from stars is polarized. The interstellar grains that scatter starlight are needle shaped and systematically aligned. They contain iron, and spin, like tiny magnets, and their spin axes line up perpendicularly to the field lines. The scattered light is polarized. By looking at stars with a polarimeter, or polarizing filter, we can trace the topology of the field and even infer its strength.

Interstellar clouds spin faster and faster as they collapse. The magnetic field gets tangled, and this creates magnetic forces that oppose the rotation. The result is that the core of the cloud spins down as the cloud collapses, and its angular momentum is transferred to the cloud envelope, its outer regions. This is how the angular momentum barrier is overcome.

A similar phenomenon of magnetic braking repeats on the scale of the proto-star, allowing the star itself to form with modest spin. One observes outflows as gas is ejected from proto-stars in the so-called T Tauri phase that demarcates the settling down of the proto-star to a stable equilibrium. A dusty disk is formed around the proto-star by the gas and dust with excess rotation. This is the site where planets will form.

All stars do rotate, but relatively few are rapid rotators. Likewise, all stars are weakly magnetized, but very few proto-stars have strong magnetic fields. It is when the stars collapse to form white dwarfs or neutron stars that highly magnetized, rapidly spinning objects are formed. In these very dense and short-lived phases, magnetic braking is less efficient.

The onset of thermonuclear power

Proto-stars are powered by gravity. Gravitational energy is released by contraction. This phase lasts only a hundred million years or so. In the late nineteenth century, astronomers debated the contradiction between the gravitational settling age of a star and the inferred age of the earth. In the early twentieth century, astronomers worried about the apparent contradiction between the age of the earth and the age inferred for the stars from the newly discovered expansion rate of space. These debates were resolved with the discovery of thermonuclear fusion of hydrogen in stellar cores.

The nucleus of a helium atom consists of two protons and two neutrons. An isolated neutron decays after just under 15 minutes into a proton and an electron, along with a nearly massless antineutrino. A neutron is slightly heavier than a proton by about 0.1%. Mass is a form of energy. So if we can generate a helium nucleus via combining protons, we have to release energy in order for mass to be conserved. Einstein famously told us that mass and energy are equivalent. We have an energy source. This is thermonuclear fusion. It occurs naturally in the cores of hydrogen stars that are sufficiently hot in their centres. In practice this means above 0.07 solar masses. Smaller objects are called brown dwarfs, and they glow dimly because they are contracting very slowly under gravity. They are discovered at infrared wavelengths.

Release of internal energy from thermonuclear reactions in the centre of the sun is how the sun battles gravity. Thermonuclear energy supplies the thermal pressure that supports the sun. For the Sun, the fuel supply is good for billions of years. On the other hand, massive stars have a much more accelerated evolution. Stars burn up its nuclear fuel at a rate that goes as the cube of their mass. This means that the lifetime of a 30 solar mass star may be as short as a few million years before it exhausts its hydrogen fuel supply.

These are tiny time-scales in the grand scheme of things; many such events occur over the ten billion year time span of our galaxy. So we can use our galaxy as an astronomical zoo: it contains stars at all stages of their evolution, from birth to death. We can visualize the birth, adolescence, maturity and death throes of stars.

When the hydrogen fuel supply in the core of the sun, where it is hot enough to burn, is exhausted, the sun contracts and the core heats up. Helium in turn is ignited, and it burns by thermonuclear reactions into carbon. This reaction releases so much luminosity that the outer part of the sun will swell up into a red giant. Our sun is fated to become a red giant in about 4 billion years. About a percent of the stars in the Milky Way are red giants.

At the time of red giant formation, the sun's atmosphere would encompass the orbit of the earth, burning any surface organic material into ashes. Life at this point would be difficult, making the worst envisageable climate change scenario seem like a holiday. Once the helium energy supply is exhausted the core contracts into a white-hot star about the size of the earth, but a million times denser. We call this a white dwarf. The atmosphere is ejected in the beautiful phenomenon that we see as a planetary nebula. The white dwarf gradually cools down. Our galaxy is teeming with old white dwarfs, descendants of sun-like stars.

Exploding stars

Very massive stars explode, after exhausting their nuclear fuel, because their masses are so large that there is no stable endpoint. The cores collapse to form neutron stars, objects that are a thousand times more compact than white dwarfs. So much energy is released in this final collapse that a huge explosion blows off the outer layers of the star. This is a supernova explosion. The light released in this immense explosion, heralding the death throes of a massive star, is about that of the luminosity of an entire galaxy, some tens of billions of suns. The impact of such a violent explosion on the surrounding interstellar gas results in beautiful images of shock waves igniting quiescent gas clouds into glowing ribbons of hot gas that extends over hundreds of light years.

Black holes

The most massive stars of all actually collapse into black holes. Black holes must be the most mysterious objects known to man. In their modern incarnation, they were conjectured to exist by Einstein in 1916 and discovered by the LIGO interferometer in the US almost a century later in 2015. The LIGO experiment detected gravitational waves, ripples in the fabric of space caused by the sudden and powerful change in the gravity field as two black holes merged to form a more massive black hole.

From stars to planets

The forming star is surrounded by a nebula of cold gas and dust that has too much rotation to collapse. Instead, the nebula cools and forms a dusty gaseous disk that spins around the central object, which we refer to as a proto-star, destined, as it shrinks further, to become a star. The proto-stellar disk has its own destiny: it will fragment into icy asteroid-like rocks which in turn coalesce into planets. This sequence of planet formation is not fully understood, but of course we have our solar system as a test bed of theory. The missing link is the transition between a dusty disk and a proto-planetary system.

We observe disks around young stars. It is thought that under sufficiently cold conditions, dust particles coalesce and rain down into the disk's central plane. The particles are thought to be amorphous aggregates of compressed grit that orbit the proto-star and continue to collide with each other, fusing into lumps of rock, rather like Saturn's rings. Far away from the forming sun, the particles are largely icy with rocky cores. Near the proto-sun, the ices sublimate, and rocky particles prevail. A system of asteroid-like planetesimals develops: these are the building blocks of the planets, and asteroids and comets are the relic debris. The many smaller dust particles are blown away by the activity of the emerging sun. We know that proto-stars powered by gravity produce vigorous outflows that can sweep clean much of the remaining dusty debris. By the time the central star has settled into a steady state as it begins its use of thermonuclear fuel, the planetesimals in their nearly circular orbits have merged into distinct bodies that orbit the sun. The outer planets are predominantly icy and massive, the inner planets have few remaining volatiles, and are rocky and of lower mass. Beyond the outer planets is the realm of the asteroids, identified as Kepler's belt, in the outer solar system. There are inner regions where asteroids dominate, especially between the orbits of the massive planets, where gravity disrupts the formation of rival planets.