THE ORIGIN OF THE SOLAR SYSTEM

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Abstract. This paper considers a possible history of the evolution of the solar system with an emphasis on the formation of asteroids, comets, planets, and the Oort cloud.

This paper considers a possible history of the evolution of the Solar System. One of the most striking aspects of this subject is the lack of agreement among authors. I have attempted to take information from several sources and assimilate it into some sort of "average" theory.

The universe is thought by virtually all astronomers to have started about 15 billion years ago as a very, very dense concentration of energy expanding out in all directions. This explosion is called the "Big Bang". After a few hundred million years of complicated interactions between matter and energy the Big Bang left mainly a universe full of gas that was almost entirely made of hydrogen and helium. This is enough raw material for about 100 billion galaxies.

Many people believe that slight variations in density occurred at this point that were eventually to become clusters of clusters of galaxies, or more simply superclusters. These could be called proto-superclusters. There were thousands of these proto-superclusters of galaxies each of which became many protoclusters of galaxies. These split into protogroups of galaxies. One of these protogroups became what we call the Local Group—this includes our own Milky Way Galaxy, the well known Andromeda Galaxy, and about twenty other galaxies. The local protogroup then became a local group of protogalaxies. Now consider only the protogalaxy that will become ours.

From the complicated previous motion of the protogalaxy it will soon become approximately spherical due to statistical "averaging out" of the chaotic motion within the gas. The cloud is now likely to collapse under its own gravitation. It will tend to spin faster as it shrinks. This is because angular momentum must be conserved—just as when an ice skater pulls his arms in he must spin faster. When it spins fast enough it starts to throw off some material in the form of a disk.

For material that is above (or below) the plane of the disk the centrifugal force due to rotation can cancel the gravitational force in the direction parallel to the disk. Since this is not the case for the gravitational force perpendicular to the disk, this means that there is a net gravitational force toward the plane of the disk. This results in a small, massive sphere with a large, very thin disk around it.

The disk is not solid so particles at different distances from the center orbit around the center in different amounts of time. This differential rotation is approximately described by Kepler's Third Law: "*The ratio of the radius-cubed to the period-squared is the same for all points in a given system*". Points that are

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farther from the center move more slowly. This differential rotation gives rise to spiral arms that are waves of increased density that move through the galaxy at about half of its overall rotation rate.

Small regions of higher than average density may be caused to collapse as a density wave goes by. The differential rotation will tend to give the region a spin. These regions will generally break up to form about 1,000 stars each. The matter that these form from is called the interstellar medium. At that stage it is practically all hydrogen and helium. Soon after the formation of stars the most massive stars explode in supernovas that produce many heavy elements and spew them out into the interstellar medium. This not only provides the much needed heavy elements—it also is another type of shock wave that can trigger a stable system to collapse.

Now consider a concentration of interstellar medium that was in a spiral arm of high density about 4.7 billion years ago. A nearby star becomes a supernova and the shock wave causes the region of gas to collapse. The gas has a little dust mixed in that has condensed from the heavier elements. The gas and dust cloud then breaks into a few hundred smaller ones. The one that we are interested in is about twice the mass of the sun.

This is now the protosolar nebula. It is a somewhat turbulent bunch of gas and dust. The density of the nebula increases due to its collapse and molecules start to form because of the higher frequency of collisions.

The most common elements in the cloud are hydrogen, helium, carbon, nitrogen, and oxygen. This means that molecules such as H_2O, CO, CO_2, NH_3, and many others can form. Helium does not react readily with anything. This shows that organic compounds do not need a completed solar system in order to exist. There is also some silicon, calcium, iron, nickel, magnesium, calcium, and aluminum present. The cloud also contains small amounts of all the other elements.

At this point the cloud breaks into smaller clouds due to turbulent motion in the system. Each cloud gets its own spin and they all move around each other in a complicated manner. They will change size due to collisions and eventually one will become significantly larger than the rest. When this happens the systems will tend to orbit around the biggest one in large, very eccentric ellipses. Each of these small systems will then collapse independently.

There could of course also be more than one main cloud. This was apparently *not* the case for our solar system. It is, however, a very common case. A multiple main cloud system would probably exclude the formation of a “normal” solar system—although it would explain the formation of multiple stars.

We now return to the system with a single main cloud. The density increases and this helps to keep the radiant energy from nearby bright young stars from heating most of the cloud. This decreases the temperature. These conditions favor the condensation of volatiles such as water-ice, ammonia-ice, and methane-ice—with some silicate-type dust mixed in. Small dust grains serve as condensation nuclei for the ices—in much the same way that dust in the Earth’s atmosphere helps raindrops to form.

Then as the dirty snowflakes move through the cloud they can collide and merge to become larger. This process is called accretion. This happens in all of the sub-clouds—which are in elliptical orbits around the main cloud. The result is about 10^{15} dirty snowballs in highly elliptical orbits around the main cloud. The planes of their orbits are randomly oriented so that they form a spherical “cloud” that is about 100,000 astronomical units in diameter. This is called the Oort Cloud. It is the home of the comets. The mass of the entire cloud is about 1,000 times the mass of the Earth.

As the Oort Cloud forms the large sub-cloud collapses. This is the solar nebula. As with all the other collapses the solar nebula is spinning and must leave behind a disk to conserve angular momentum. The result is a disk of gas and dust with a collapsing sphere of gas and dust at the center—with the Oort Cloud far outside of it.

The sphere is about twice the Sun's present mass and is now the protosun. The disk is about 3% of a solar mass. The protosun and the disk both spin in the same direction. The disk now has a large surface area compared to its volume which causes it to radiate energy very quickly in the infrared part of the spectrum. This—combined with the increases in density from infall to the disk—causes more condensation to occur.

As the protosun collapses half of the energy of collapse is radiated away—while the other half is turned into kinetic energy that raises the temperature of the protosun. This is a consequence of the virial theorem from statistical mechanics. The radiated energy warms the inner part of the disk but it has little overall effect since it hits the disk edge-on.

Eventually the temperature in the center of the protosun reaches about 10 million kelvins (10^7 K). At this point it begins to have violent enough collisions between protons to start converting hydrogen to helium. This reaction releases great amounts of energy—a star is born.

This new source of energy causes a temperature difference across the disk. It is now significantly hotter near the Sun than at great distances away. For this reason ices of water, methane, etc. cannot survive as solids in the inner part of the disk. This tends to separate different chemical compositions into different regions of the disk. The inner disk has dust grains of metals and rocky silicates—while the outer disk has ices with silicate dust in them.

When these solids have averaged out to nearly circular orbits they start to collide slowly enough to merge together through chemical bonding. As a particle gets larger it has a greater chance of acquiring more mass—and greater size—through accretion. This is because it sweeps out a greater fraction of the available volume of particles.

Because the disk is comprised mostly of volatiles there is more solid material to accrete in the outer part of the disk. This means that planetesimals in the outer part of the disk are likely to get quite large.

Throughout the disk there tend to be certain zones that get dominated by the largest planetesimal that is in that area. As it grows it sweeps out a bigger and bigger area. This makes it grow even faster. When it gets to around 1,000 meters in diameter it starts to sweep out an even larger area due to its gravitational interactions with the smaller planetesimals.

Eventually the sweep areas start to overlap. That is about the end of that stage except in the outer disk where the masses are great enough to trap gases. These planetesimals may be large enough to undergo gravitational collapse. They then follow their own evolution and form miniature "solar systems" of orbiting moons.

A large mass like Jupiter can cause severe gravitational perturbations. The proto-Jupiter planetesimal increased the collision velocities in the asteroid belt to the point that the planetesimals there would break up instead of accreting each other. This is the reason that there is no planet there. The asteroids are basically a bunch of planetesimals that never made it to the planet stage.

Because of the chemical differentiation in the disk the inner planets are very dense. They have a lot of nickel and iron and rocky materials in them. The Moon is possibly a captured planetesimal.

The asteroids still collide today and the fragments from these collisions are the source of most of the meteorites that reach the surface of the Earth.

At about the same time that most of the accretion ends the Sun becomes very active. It is spinning very quickly and it starts to emit a very strong "solar wind" of charged particles. At this time it loses close to one solar mass of matter. This brings it close to its present mass.

Radiation pressure forces the solar wind particles to move radially outward from the Sun. The charged particles are constrained to follow the magnetic field lines of the Sun. The Sun's magnetic field rotates along with it causing the particles to rotate as they go out. Their angular momentum increases as they get farther away from the Sun. This causes a transfer of angular momentum from the Sun to the solar wind—thus causing the Sun to spin much more slowly. The radiation pressure and solar wind also clear any gas and dust that is not caught up in planets or other large bodies.

The comets come from the Oort Cloud. When they are far out in their orbits they are very weakly bound to the Sun. Nearby stars can therefore gravitationally perturb a comet's orbit. This results in some comets being thrown out of the solar system—it also results in some comets being thrown into the inner solar system. This means that some of the comets may have been formed in a system associated with another star.

Once comets are near the Sun they melt on the surface and radiation pressure and the solar wind push back a tail that we can see from the Earth. These comets may return to the Oort Cloud, or they may be trapped in the inner solar system because of gravitational interactions with a large planet such as Jupiter.

When the Earth passes through the orbit of a comet it encounters debris from the tail of the comet—this debris enters the upper atmosphere and is seen as bright "shooting stars" in the sky. These burn up and never reach the ground intact. The material does, however, eventually fall down to the surface. This is interesting since some of this material may be from another star's "solar system". Although it is a very small amount—and it is not fundamentally a different type of material—it is still quite a thought!!

If a comet has been broken up by a close encounter with a large planet—or the Sun—then a huge number of meteorites enter the atmosphere when the earth passes through the part of the orbit where most of the remnants are.

These facts explain why meteorite showers happen yearly and why some years have more spectacular ones than others.

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