# All the stuff that happened before there was an Earth to study…

## 1. Formation of the Universe, Galaxies, Stars and Elements…

*"We are made of starstuff" – Carl Sagan*

When children ask, "where do I come from," you can tell them this story and avoid the whole stork thing…

### THE BIG BANG

12-15 billion years ago, the universe we live in formed in an event commonly referred to as the **Big Bang**. All mass exploded from an infinitely small point, called a "**singularity**."

Evidence for the Big Bang comes from studies that show universal expansion: Edwin Hubble determined in 1929 that observable galaxies are "**red-shifted**," meaning that light from these objects is shifted toward the red (the lower-frequency) end of the visible spectrum – this indicates that these objects are all moving away from our galactic neighborhood. When he began to catalogue the relative velocities of these distant galaxies it became apparent that the more distant objects had much greater velocities and nearer objects had lower velocities.

Hubble published a graph showing the recessional velocity versus distance for a number of galaxies. The points on the graph traced out a straight line, indicating a direct linear relationship between the two quantities (this relationship is known as **Hubble's law**). The constant that relates these quantities (known as the **Hubble constant**, or "H") determines the slope of this line and its exact value is not precisely known. If you trace this line back toward its zero point, all of the galaxies move closer and closer together until they all occupy the same space.

In 1948 George Gamow predicted that this Big Bang would have generated copious amounts of high frequency radiation; Ralph Adler and Robert Herman then pointed out that this radiation would be red-shifted to very low apparent frequencies. These predictions sat on the shelf until the mid-1960's when Arno Penzias and Robert Wilson were able to measure this primordial cosmic ray background radiation (*you can do this also: Unplug the cable from your television and adjust the brightness to its lowest level and the contrast to its highest level; the few bright specks that flicker on the screen are all due to impacts of cosmic rays on the phosphors; about 1 in 100 of these are original photons generated by the Big Bang*).

### THE EXPANSION OF THE UNIVERSE AND FORMATION OF LIGHT ELEMENTS

Within the first few seconds after the Big Bang the universe expanded at an inconceivable rate, cooling as it expanded. As expansion and cooling continued, energy began to congeal into matter (remember E = mc2?). Most of the matter consisted of **neutrons**. As individual neutrons are unstable, they began to spontaneously decay, producing **protons** (hydrogen nuclei) and **electrons**.

At pressures and temperatures we are familiar with, atomic nuclei never encounter one another because they are always surrounded by a cloud of electron orbitals. Within this early cosmic soup however, high temperatures prevented protons and electrons from hooking up to form atoms. Still, the like positive charges would normally keep protons from encountering one another (this repulsion is known as the **coulomb force**).

Protons that overcome this force can stick together like Velcro, creating heavier nuclei in a process known as **fusion**. Fusion requires a unique type of environment: the protons must be moving fast enough to overcome the coulomb force (this requires extremely high temperatures); and there must be so many protons in a small space that collisions are highly likely (requiring high mass density, i.e. high pressure).

The universe at this point was still dense and hot enough that protons could collide at high velocities, fusing together to produce helium nuclei and, to a lesser extent, lithium nuclei. By the end of the first half-hour fusion slowed to a stop, and the universe consisted of ~75% individual protons (i.e., hydrogen nuclei) and 25% helium nuclei. After about 1 million years things had cooled enough that these nuclei could combine with free electrons to form stable atoms.

## THE FORMATION OF GALAXIES, STARS AND HEAVIER ELEMENTS

Heterogeneous distribution of matter ("clumping"), working with the force of gravity, led to the formation of massive rotating disks of hydrogen and helium gas (galaxies). Within these galaxies smaller clumps of gas collapsed to form stars.

Stars are made of hydrogen and helium (~75:25 ratio). The average star is a million times as massive at the earth – the extreme gravity causes the gasses to squeeze together tightly, especially within the core (for perspective, the core of our Sun is about twice the Earth's diameter, or about 2% of the Sun's diameter). Densities in the core exceed 150 grams per cubic centimeter, or 50 times the density of rocks, yet temperatures are so high the material still behaves as if it were a gas.

Within the stellar core, extreme temperatures and pressures overcome the coulomb resistance between protons, leading to further fusion of hydrogen into helium, which releases copious amounts of energy (the heat generated by the fusion of one gram of hydrogen would be enough to vaporize a small iceberg). This energy creates an outward pressure on the star, preventing further gravitational collapse and maintaining the star's diameter.

When the core region runs out of hydrogen, fusion stops and the gravitational collapse of the star continues, causing an increase in core pressures and temperatures. Eventually the pressure and temperature are great enough that helium nuclei can be fused to form heavier elements such as carbon, nitrogen and oxygen. When helium runs out further collapses occur and these elements are eventually fused into heavier elements such as sodium, silicon, sulfur, etc…

Small to average stars might go through two or three of these collapse/re-ignition cycles. Their final collapse occurs when internal pressures are not great enough to create additional fusion. In the end they eject their outer most layers and shrink into a "**white dwarf**." Giant and super giant stars can go through this process of dying, then rising again from their ashes, many times. All stars eventually run out of fuel though. When this occurs large stars go through a final collapse and the outermost layers explode as a **supernova**, creating even heavier elements and distributing these materials throughout the galactic region, adding roughly 1% heavier elements to the hydrogen/helium mix in the interstellar clouds.

### WHERE DO WE COME FROM?

All of us (even the extraterrestrials among us) are linked together by the chain of events that had its beginning when the universe popped into being 12-15 billion years ago. The subatomic particles that make up the atoms in your body, the atoms that make up the metal, wood, concrete, plaster and paint that make up this building and the rocks upon which this building stands, the atoms that make up the other 6 billion people on the planet as well as every animal, insect and plant, even the atoms that make up the plastics and chemicals that we think of as "artificial," were created simultaneously in the Big Bang. We are made, quite literally, of starstuff.

## 2. Nebular Accretion Theory

### WHAT WE KNOW (OBSERVATIONS)

So we've created a universe of galaxies and stars, and stars have taken the hydrogen and helium they were allotted and begun turning them into a diverse array of elements. Earth is not a star. None of the other objects orbiting the Sun is a star. From where did all of these objects come, and how do they fit into the universe we've created?

First of all, any model of the formation of our solar system needs to explain the following observations:

1. All planets orbit the sun in the same direction (counter clockwise when viewed from above the north pole), and all orbit within a planar disk known as the **plane of the ecliptic** (Mercury diverges about 7 degrees from this plane but no other planet diverges by more than 3 degrees).
2. Planetary orbits are predominantly circular (they are slightly elliptical but eccentricity is very low).
3. The Sun rotates in the same direction that the planets orbit.
4. All of the planets rotate in the same direction that they orbit except for Venus, which rotates very slowly in a clockwise direction (this is called **retrograde**), and Uranus whose rotational axis is tilted sideways.
5. All of the large moons in the solar system orbit their planets in the same direction as planetary orbit and rotation, and their orbits lie very close to the ecliptic plane.
6. Though the sun contains >99% of the total mass in the solar system (75% of the rest is contained in Jupiter), it has only about 30% of the total **angular momentum** in the system.
7. The inner four planets (and the asteroid belt, between Mars and Jupiter) contain little mass and are terrestrial (that is, they are constructed of rock and metal, with very low volatiles).
8. The outer four planets are quite massive, and they are composed primarily of volatiles.
9. Beyond these eight planets lies a ring of small bodies (known as the Kuiper Belt) composed primarily of ices (frozen volatiles), the largest of which is Pluto and its sister, Charon.
10. Surrounding the entire system is a halo of small icy bodies (known as the Oort Cloud) that extends outward for at least a few trillion miles, perhaps several light-years.

### THE BUILDING BLOCKS AND NEBULAR COLLAPSE

First generation stars were the first in the universe to form, thus they contained only the elements hydrogen and helium. Our sun is a second (or possibly third, maybe even fourth) generation star, formed from Hydrogen and Helium plus the detritus of old supernovae (i.e., it contains about 1%

elements other than H and He). Because we sometimes name things before we completely understand them, first generation stars are known as **population II** stars while 2nd, 3rd, etc. generation stars are called **population I** stars…

Our solar system began as part of a cloud of gas and dust that collapsed upon itself. I emphasize here (because I rarely see it mentioned elsewhere) that star formation occurs *en masse*: many hundreds, even thousands, of stars (and probably planetary systems) formed from the same cloud, thus our sun has many sister stars scattered around the galaxy.

### ANGULAR MOMENTUM AND THE FLATTENING OF THE SYSTEM

As our part of the cloud began to collapse its rate of rotation began to increase due to **conservation of angular momentum**:

$$\boldsymbol{m * \omega * r = P_a} \tag{1}$$

where $m$ is the total mass of the system, $\omega$ is the rate of rotation, $r$ is the radius of rotation, and $P_a$ is the angular momentum. Conservation of angular momentum says that angular momentum stays the same unless energy is added to or taken away from the system. In the case of our system there is no mass added from the outside or taken away from the system.

As the cloud collapses, the rotational radius shrinks. Since $m$ and $P_a$ stay the same, then as $r$ shrinks the only way to keep the right side of the equation the same as the left side is for $\omega$ (the rotation rate) to increase.

$$\boldsymbol{m} * {\Large \boldsymbol{\omega}} * {\scriptstyle \boldsymbol{r}} = \boldsymbol{P_a} \tag{1a}$$

This is the same effect that you see when an ice skater goes into a spin. As she draws her arms inward her radius decreases and her rate of rotation increases. When she extends her arms back outward her radius increases so her rate of rotation decreases.

Because the system was spinning it collapsed more rapidly at its poles, while **centripetal force** slowed its collapse in the equatorial plane. As a result this amorphous cloud self-organized into a disk shape with a central bulge where the **proto-sun** was accumulating (so called because it was not yet dense enough at its core for nuclear reactions to occur).

### COOLING, CONDENSATION, CLUMPING AND COLLISION

Due to its large gravitational well, most of the mass within the system fell into the proto-Sun. Within the **proto-planetary disk**, less than 1% of the original material remained. The proto-Sun was very hot due to compaction and friction, so the disk was hot at its center and quite cold at in the outer reaches.

Close to the system's center it was hot enough that most elements could only exist in atomic form, as gasses (or even as plasma). Further from the center some elements began to combine and crystallize into liquid droplets and into solids. The first solids to form were oxides of titanium, aluminum, silicon (known as "**silicates**") and iron. These high-temperature materials are known as "**refractory compounds**". As these compounds can exist at quite high temperatures they existed everywhere, from very near the proto-sun to the outer reaches of the system, though because they were composed of elements that were rare (relative to hydrogen) there wasn't much there.

Beyond what came to be known as the "**frost line**" it was cold enough for ices to form: materials such as water ($H_2O$), methane ($CH_4$), carbon dioxide ($CO_2$), and ammonia ($NH_3$). These low temperature compounds typically exist as gasses in our environment, and we call them "**volatile compounds**." Since the silicates form early, dust particles in the outer part of the system consist of tiny silicate particles, often coated by a layer of carbon, surrounded by a coating of ice.

Encountering each other the dust particles stick together due to static electricity (much in the same way that dust bunnies form under your bed). Eventually the inner solar system consists of homogeneous blobs of sediment the size of boulders or small asteroids and the outer solar system consists primarily of somewhat larger "dirty snowballs."

When these objects get large enough that their gravity becomes nontrivial the collisions become somewhat more energetic (for instance, an object crossing the earth's orbit is traveling about 30 km/second). Some collisions cause particles to break up, while other collisions lead to **accretion** of the **impactors**. Through time some objects grew large enough that they became difficult to destroy. We call these objects **planetesimals**. As these planetesimals gained mass, their increased gravity swept up other objects they encountered, increasing their mass even further.

The size of these early planetesimals depends on their distance from the star and the density and composition of the accretionary disk. Theories suggest diameters of up to a few thousand kilometers in the inner solar system, and an order of magnitude greater in the outer solar system. Accretion is believed to have taken a few hundred thousand to a few tens of millions of years.

### THE SOLAR WIND

At some early point the core of the proto-Sun became dense enough that nuclear reactions began, and the Sun became the Sun. Observation of this process elsewhere in the galaxy suggest that this process is accompanied by an explosion of energy and particles from the star, known as the **T-Tauri wind**. The energy from this blast is enough to blow most of the remaining gasses and finer particles out of the inner solar system. Close to the sun the remaining planets were fairly small, but beyond the frost line the planets grew from particles of rock and ice, thus they grew larger, faster. Eventually these had enough gravity that they could hold onto even the lightest gasses.

Collisions between these objects continued and the objects became fewer and more massive. Since objects with highly eccentric orbits are more likely to cross the paths of other planetesimals, natural selection tends to favor the survival of planetesimals with more or less circular orbits. Where there may have been millions or billions of large objects circling the proto-sun at one time, this was gradually pared down to thousands, then to hundreds, then to dozens.

After a few tens to a hundred million years, our solar system was left with fewer than ten planets, about half rocky (**terrestrial** or earth-like) and half gaseous (**Jovian** or Jupiter-like). Jupiter's gravity was apparently great enough that it seems to have prevented the accretion of a fifth terrestrial planet between itself and Mars. Accretion was limited beyond 5 billion kilometers from the sun due to the low density of material, thus instead of a fifth or sixth Jovian world beyond

Neptune there is naught but a cometary ring known as the Kuiper belt (though Pluto, the largest of these objects, is big enough to have been classified as a planet).

This accretion model has gone through much revision since first proposed by Kant. In its current form it accounts for most of the observations noted above. It falls short in explaining the current distribution of angular momentum in the system, but extra-solar observations suggest that stars similar to the Sun lose much of their angular momentum during their T-Tauri phase.

## 3. Planetary Formation

MAKING PLANETS FROM ROCKS

In accretion the largest planetesimals had a distinct growth advantage, as they were less likely to suffer a world-destroying impact. As they grew larger their gravitational wells deepened and they swept up all of the smaller bodies in their paths.

In the outer system the planets accumulated significant volatile compounds in addition to refractories; since refractories accounted for less than 1% of the mass of the nebula the outer planets grew much larger than the terrestrial worlds. In any case in the early stages of formation the planets were homogeneous bodies.

SEGREGATION OF MATTER

As the planets grew, gravitational compression caused them to heat up. Other significant heat sources included the kinetic energy of the impacts and the decay of radioactive elements (which were in much greater supply at the time). Since the volume of a sphere increases in proportion to the cube of the diameter

$$\boldsymbol{V_{sphere}} = \frac{1}{6} * \boldsymbol{\pi} * \boldsymbol{D}^3 \tag{2}$$

while the surface area increases only as the square of diameter

$$\boldsymbol{A_{sphere}} = \boldsymbol{\pi} * \boldsymbol{D}^2 \tag{3}$$

larger bodies have a difficult time radiating away excess heat (for instance, a large cake takes longer to cook, and to cool down, than does a cookie or a cupcake).

This build up of heat in the interior eventually led to some melting. In the terrestrial planets this led to some separation of **siderophile elements** (those that prefer to associate with metallic iron) from lithophile elements (which prefer to form silicate minerals). Most of the siderophile elements, being heavy, migrated toward the Earth's center forming the core, while the lighter **lithophile** elements floated upward to form the mantle. Friction associated with this movement increased melting and thus the rate of segregation. The larger bodies thus became chemically layered into a rocky mantle and a metallic core.

LATE-PERIOD IMPACTS

Within the first few hundred million years after planet formation impacts with relatively large bodies were still common, and some are believed to have altered the fates of the terrestrial planets:

Mercury suffered at least one large impact that created the Caloris Basin, a large complex crater that is more than ¼ the diameter of the planet itself. This impact was large enough that seismic waves generated significant disruption of the terrain at its antipode (the side of the planet opposite the impact site). An earlier large impact is hypothesized to have vaporized much Mercury's mantle (after core segregation), leaving it with a metallic core about 75% of the planet's diameter.

The planet Venus is unusual partly because of its **retrograde** rotation. While most of the planets rotate counterclockwise (when viewed from the north) one time every 10-30 hours or so, Venus rotates clockwise once in about 5800 hours (a period slightly longer than a Venutian year). This is also commonly attributed to a late-period, low angle impact.

Earth is also believed to have experienced late-period impacts. In fact, meteorites are discovered on Earth's surface every day. Though most of the extraterrestrial material that currently lands on our planet is no bigger than dust grains, objects the size of softballs or even basketballs are common. The Allende meteorite, which landed in Chihuahua, Mexico in 1969, was originally more than a meter in diameter. And there is, of course, strong evidence for an asteroid perhaps 10 kilometers in diameter having struck the Earth just off the Yucatan peninsula 65 million years ago and killing off roughly half of all the species of plant and animal living on Earth at the time.

### FORMATION OF THE MOON

The largest post segregation impact experienced by the Earth probably occurred about 4.4 to 4.45 billion years ago, and the impactor may have been half as large as the Earth itself (this would make it as large as Mars). According to computer models this collision was a very low angle, glancing blow, and probably ejected a large percentage of the mass of the proto-Earth's mantle into space.

The body of the impactor (including its core) were incorporated into the Earth. The rest of the excess material formed a ring around the planet. Some of this material eventually fell back to Earth. The rest gradually accreted to form the Earth's moon, making our planet the only terrestrial body with a large moon (Mars' two small moons were captured bodies that originated in the asteroid belt).

Evidence supporting this model of the moon's formation comes from the moon's surface. Rocks returned by Apollo missions in the 1970s show the moon to be chemically very similar to the Earth's mantle, to the extent that the ratios of oxygen isotopes on the two bodies are similar. This indicates that the materials from which both bodies are formed originated at approximately the same distance from the Sun.

Also, the low density of the moon indicates that its metallic core is either absent or extremely small. If the moon had accreted simultaneously with the Earth, at the same distance from the sun, we would expect it to have a core of a similar composition, about half the diameter of the moon. Absence of a significant core, coupled with similarity of composition between the moon and the Earth's mantle, implies that the moon formed from materials taken from the Earth, after the Earth had become segregated.

## ASTEROIDS, METEOROIDS AND COMETS

In the asteroid belt, most of which lies between Mars and Jupiter, we find remnant materials from the formation of planets. **S-class asteroids** are made primarily of silicate materials (S = Stony) while **M-class asteroids** are made primarily of metals (predominantly iron) – these bodies appear to represent pieces of a small planet that accreted and segregated, but was subsequently destroyed by late-period impacts. A third type of asteroid, the **C-class** (for chondritic) is thought to represent proto-planetary material that was never part of an accreting body, or if it was it never reached temperatures necessary to be melted or segregated.

Though we've not visited the asteroids until very recently, their compositions are amply represented by meteors that fall to Earth periodically: **stony meteorites**, **metallic meteorites**, and **carbonaceous chondrites**.

Comets share a common origin with C-class asteroids, in that they both represent clumps of unaltered solar nebula material. The primary difference between the two is that comets formed beyond the solar system's "frost line," where it was cool enough for ice to crystallize along with dust. Some models of the solar system claim that C-class asteroids and carbonaceous chondrites are merely the remnants of comets that have burned all of their volatiles in many passes by the Sun.

## COMMON ORIGINS

The dating of rocks by the use of **radionuclides** such as uranium and potassium has been done for the past century. In that time we've determined ages for rocks from all over the Earth. Since tectonic processes recycle crustal rocks through the mantle, most rocks are quite young (geologically). The oldest rocks in north America come from the Canadian shield (around Hudson Bay) and are about 3.2 billion years old. The oldest Earth sample found to date is a zircon crystal from a metamorphic rock in Australia that is just over 4 billion years old. So the Earth is *at least* this old.

Rocks brought back from the moon by Apollo astronauts were age-dated. Samples from the **Maria** (the large flat basaltic plains – Galileo thought they were oceans) vary from 3 to 3.8 billion years, while rocks from the lunar highlands are as old as 4.48 billion years. This is a minimum age for the moon, and for the Earth since it must have formed first. Clearly the Earth's crust has been melted and recycled a lot more than has the moon's (this is also apparent from the pristine nature of most of the impact craters on the moon).

The few meteorites we have that have been clearly identified as having come from Mars (known generally as **SNC meteorites**) vary in age from 1.3 to 3.8 billion years, a minimum age for that planet.

Finally, we've dated many different types of meteorites. The oldest of these are the carbonaceous chondrites at 4.56 billion years. As carbonaceous chondrites are believed to be unmelted (thus unaltered) samples of original nebula material, this age is commonly quoted as the age of the solar system, the Sun and the Earth.