Cosmic Chemistry: Planetary Diversity

Solar Nebula Supermarket

STUDENT TEXT

GENESIS: IN THE BEGINNING

Most cosmologists believe that the universe was created about 15 billion years ago with the Big Bang, a cosmic explosion that resulted in an expanding cloud containing only the two lightest elements—hydrogen and helium. At that time there would have been only one period in the periodic table! That's even better than earth, fire, air, and water! But wait! The plot thickens!


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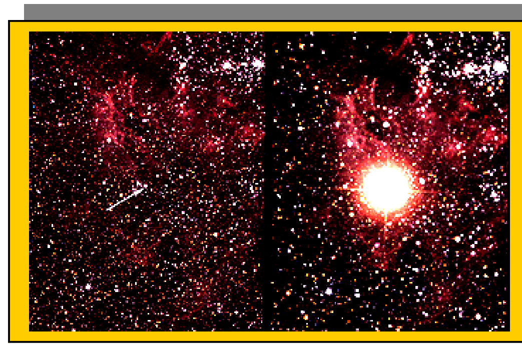
In places where there were higher concentrations of these gases, mutual gravitational attractions among the gas molecules led to the formation of the first generation of stars. When enough material had fallen into a new star, the pressure and temperature at its center became high enough to start the process of nuclear fusion, in which the nuclei of hydrogen and helium merged to form heavier elements. These fusion reactions released light energy—and the stars began to shine!

As stars lived out their lives, their structures and properties changed as their nuclear fuels were depleted. When the stars' hydrogen and helium reserves were depleted, their cores began to contract rapidly, causing a dramatic increase in temperature. If the stars had sufficient mass, their core temperatures were high enough to trigger fusion cycles in which their helium atoms fused to make neon, manganese, oxygen, silicon, and sulfur. (See Appendix A, "The Nuclear Fire of the Sun" in the Genesis module *Cosmic Chemistry: The Sun and Solar Wind*). The most massive stars employed other fusion reactions, successively burning carbon, neon, oxygen and silicon. The ultimate products of such reactions were elements near iron in the periodic table—V, Cr, Mn, Fe, Co, and Ni.

Since fusion between nuclei cannot produce nuclides heavier than the iron-group elements, these elements probably were formed by capture of neutrons, produced by helium burning. Subsequent decay of these neutrons into final stable products (protons and electrons) resulted in elements with greater atomic numbers than iron-group elements.

As these stars became unstable, their lives ended as supernovae, at which time they either exploded violently, rapidly creating even heavier elements, and spewing much of their stellar material into space, or released the nuclear material from their interior zones to the surface where it was lost to space when the outer layers were blown off.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The end results of these two processes were similar, however. The space among the stars was enriched with heavy elements, some of which condensed to form small solid grains out of which some new stars were possibly formed. As this process occurred over and over, each generation of stars contained higher abundances of heavy elements than the previous generation. These heavy elements, in turn, provided the building blocks of planetary beginnings in the form of dust and gas.

Our hydrogen-burning sun belongs to a generation of stars created about 4.5 billion years ago from a cloud of interstellar dust, ice crystals and gas that collapsed to form the nebula from which the sun and the rest of the solar system grew. This cloud contained most of the elements of the periodic table, the result of material accumulated from several generations of supernovas and their related nuclear processes.

CURRENT COMPOSITION OF THE SUN

Figure 1

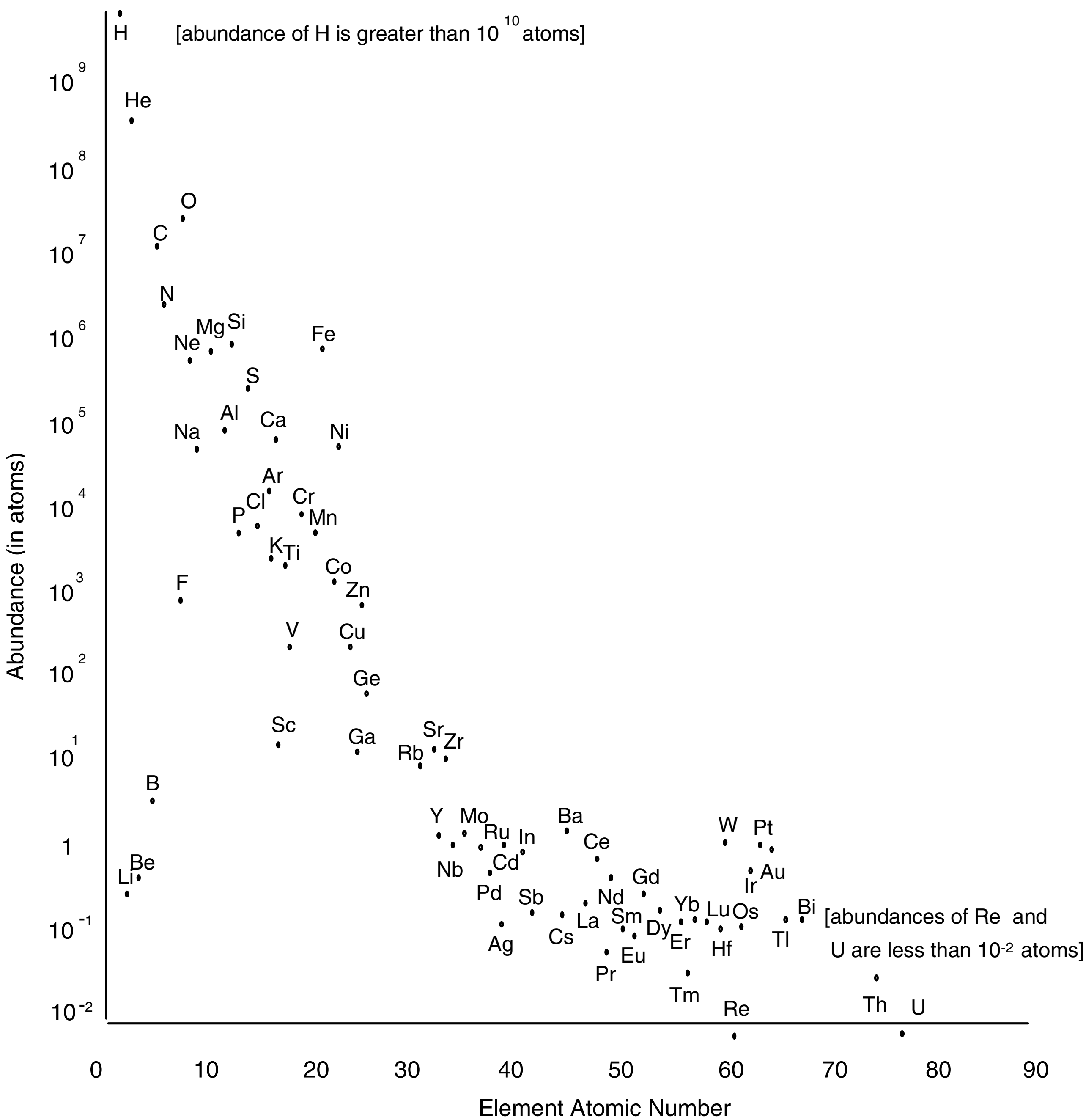
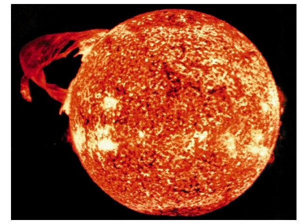


Figure 1. Spectroscopically derived concentrations of chemical elements in the solar atmosphere plotted on a logarithmic scale *vs.* their atomic numbers. Note. The data in Figure 1 are from Geochemistry Pathways and Processes by S. M. Richardson & H. Y. McSween Jr., 1989, Englewood Cliffs, NJ: Prentice Hall and Solar System Evolution: A New Perspective by S. R. Taylor, 1992, Cambridge, MA: Cambridge University Press.

Almost seventy of the currently known elements have been observed in the sun's **photosphere**, **chromosphere**, or the corona. The relative atomic abundances of most of these observed elements in the sun are shown in Figure 1.

Clearly hydrogen and helium are the dominant elements because only these two emerged from the "Big Bang," and, in most cases, subsequent fusion reactions formed the elements between helium and the iron-group. Note that when the abundances of these elements are plotted logarithimically against their atomic numbers (as they are in Figure 1), there is a rapid exponential decrease with increasing atomic number, reflecting decreasing production in the more advanced fusion cycles. Our sun presently is burning only hydrogen, so the heavier elements must have been inherited from an earlier generation of stars. (See Student Activity "Where Does It Fit?" in *Cosmic Chemistry: The Sun and Solar Wind*.)



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The abundances of the elements Li, Be, and B, may be abnormally low because they have been reduced by bombardment with neutrons and protons the sun's lifetime. The fact that elements with even atomic numbers are more likely to be stable may account for higher abundances of elements with even rather than odd atomic numbers.

SOLAR NEBULA COMPOSITION

Most of the theories of the origin and development of the solar system depend on a knowledge of the original composition of the material from which the sun and planets were formed. How can current data from our sun help reconstruct the composition of the solar system's elemental composition 4.5 billion years ago?

Most of the mass (99%) of the original solar nebula has been preserved in the outer layers of the sun, so the constituents in those layers are presumed to be very similar to that of the whole solar system. Although nuclear processes have modified the composition at the sun's core, little mixing has occurred among the surface layers and the inner layers, so the original elemental nebular composition has, for the most part, been preserved. (*See* Appendix C, "The Structured Sun," in Genesis module, *Cosmic Chemistry: The Sun and Solar Wind*.) The abundance of those elements thought to be major constituents of the primordial solar nebula, are listed in Table1 below.

Hydrogen and helium are thought to have been the most prevalent elements in the primordial gas. By mass, the mixture was probably 74% hydrogen and 24% helium. At temperatures below 200 K, hydrogen was found as molecules, rather than as charged particles—protons and electrons—as is now the case in most of the sun's interior.

The remaining two percent of elements present included carbon, nitrogen, and oxygen. At temperatures no higher than 200 K, these elements would most likely be found bonded to available hydrogen to form methane, ammonia, and water. Other noble gases, such as Ne and Kr, were present in such low abundance as to be negligible.

In the colder portions of the nebula, carbon probably would form "ices," such as solid CO and CO_2 rather than methane. About one fourth of the condensed material contained metals and silicate "rock," with the metals probably including iron, magnesium, calcium, aluminum, nickel, chromium, manganese, potassium, and titanium.

Current abundance of chemical elements observed in the sun—Table 1

Element	Current Abundance (percent of atoms)	Constituents of Cool Primordial Nebula* (percent by mass)	
Hydrogen	92.1	Hydrogen	74
Helium	7.8	Helium	24
Oxygen	.061		
Carbon	.030	**Condensed Solids**	
Nitrogen	.0084	Water	.95
Neon	.0076	Methane	.5
Iron	.0037	Rock	.5
Silicon	.0031	Ammonia	.05
Magnesium	.0024		
Aluminum	.00026		
Sulfur	.0015		
Potassium	.000012		
Calcium	.00019		
Titanium	.0000074		
Chromium	.000042		
Manganese	.000029		
Nickel	.00015		

Note. The data in Table 1 are from The New Solar System by J. K. Beatty & A. Chaikin, (Eds.), 1990, Cambridge, I Cambridge Publishing Press; Geochemistry Pathways and Processes by S. M. Richardson & H. Y McSween Jr., 1989, Englewood Cliffs, NJ: Prentice Hall; and Solar System Evolution: A New Perspective by S. R. Taylor, 1992, Cambridge, MA: Cambridge University Press.

The nebula, which can be considered the transition state between the remains of our stellar ancestors and the new planetary objects, including our sun and the planets that evolved from it, had some rotational motion. As it rotated, the cloud flattened until it was shaped like a very large compact disk, about 10^{10} kilometers in diameter, about the distance from the sun to Pluto. The density of the cloud at this distance may have reached 1000 g cm^{-3}.

At some point the disc reached a steady state, where the gravitational forces balanced the combined forces of gas pressure and outward centrifugal force. Near the center of the disc, where most of the nebular mass resided, the infant sun formed and nuclear fusion began, heating nearby regions by radiation.

THE CONDENSATION THEORY

From the data given in the student activity it appears that every planet has a different elemental and molecular composition. Planetary scientists have explained these differences using many theories, models, and assumptions about the evolution of the solar system, but which of these is accurate? In this activity we will consider only whether or not the varying composition of the planets could be explained by differences in temperatures at which the nebula condensed.

According to the condensation theory, the heat produced by the contraction of the nebular cloud evaporated the ice crystals, dissociated hydrogen molecules into hydrogen atoms, and left micro grains of nebular materials that continued to orbit the immature sun. The physical and dynamic conditions accompanying the collapse of the solar nebula suggest that temperatures of almost 2000 K and pressures of 10^{-2} atmosphere probably were achieved. These conditions would lead to at least partial, if not complete, evaporation of solids.

Subsequent condensation of nebular constituents, upon cooling, could have been an important process in establishing the chemical characteristics of the early solar system. At a certain point the rotating nebular disc began to cool by infrared radiation, leading to condensation of different components.

The nebular components that condensed first, the theory continues, were the most *refractory*—hard materials able to withstand high temperatures. The first substances condensed were metallic oxides, such as aluminum oxide and calcium titanium oxide. (See Figure 2.) Grains began to form at rates that could have been as much as 1 cm/yr. As temperatures began to drop iron/nickel alloys condensed and at temperatures below 1600 K, magnesium silicates formed as rocky particles.

As the nebular cooling continued, sodium and potassium silicates, now called feldspar materials, formed. At even lower temperatures, there were reactions between the mineral grains and residual gases, forming iron minerals. Next in order of condensates were the hydrated minerals, formed when water in the gas cloud reacted with some of the grains of calcium, iron, and magnesium minerals. Water ice and ices of methane and ammonia formed at temperatures below 200 K.

Because of gravitational attraction between solid grains, the solids migrated very quickly in astronomical terms (probably over a period of one hundred years) to the equatorial plane of the disc and the chances of inelastic collisions among particles grew. Small grains started sticking together to form larger planetesimals. Still larger protoplanets, which had diameters of several hundred kilometers and which consisted primarily of solids, continued to form over an estimated period of 10^8 years. When the protoplanets stopped growing, most of the planetesimals had joined together to form the nine stable planets.

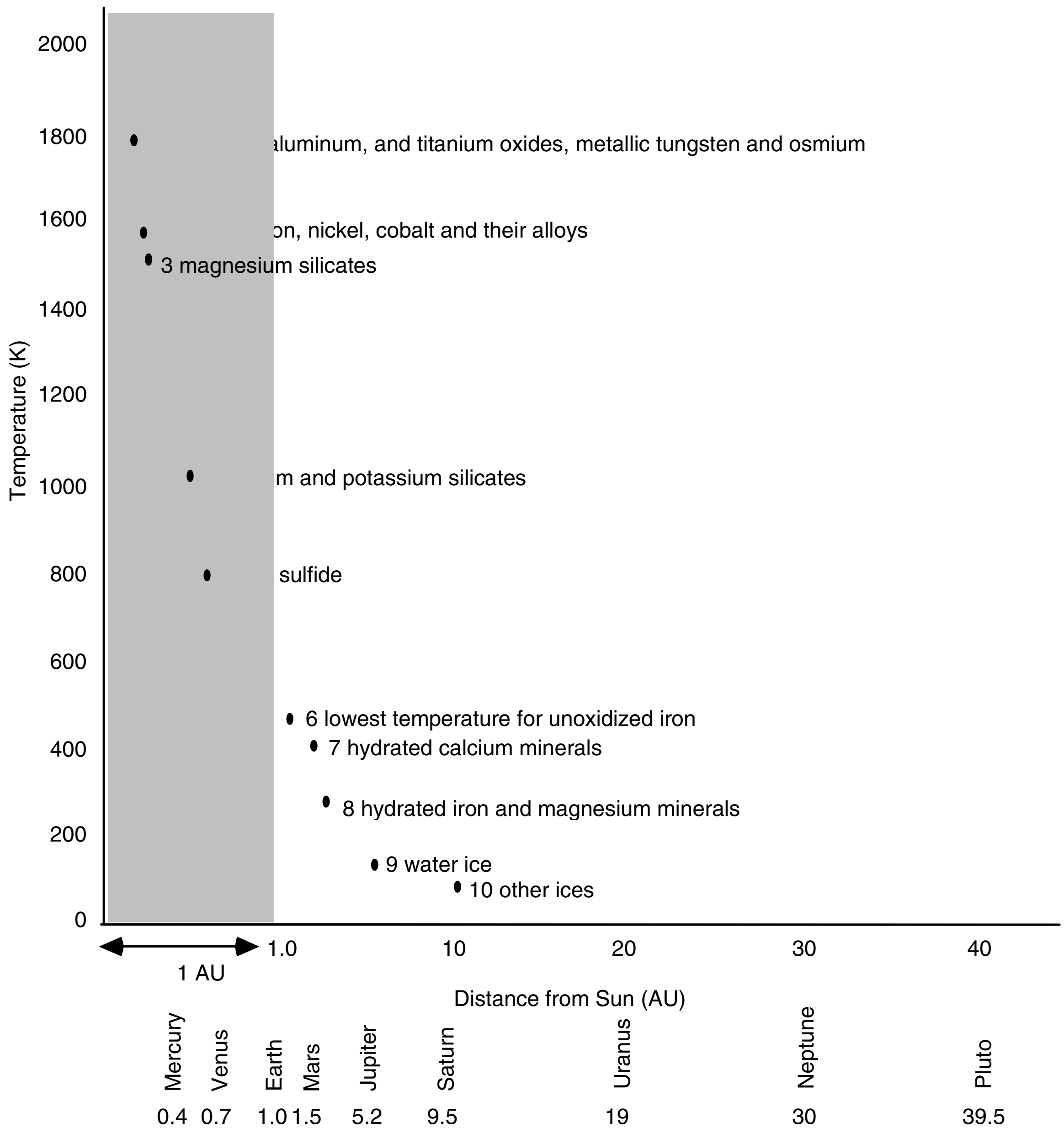
It follows from the above scenario that planetesimals made of rock from grains of dust probably were the first to be formed because they were made from components with higher freezing temperatures. These included calcium, aluminum, and titanium oxides; metals like iron, nickel, cobalt; and magnesium silicates. They were probably surrounded by an atmosphere of lighter gases, such as hydrogen and helium, which did not condense but were gravitationally attracted to the protoplanets. According to the theory under consideration, the four rocky planets—Mercury, Venus, Earth, and Mars—formed closest to the sun in this way. (See Figure 2)

The temperature of the outer solar system, where the giant planets were forming further from the sun, probably was between 100 to 200 K. The condensation in the outer parts of the nebula occurred in a manner similar to that described for the rocky planets, although there probably were larger numbers of ice crystals present in this portion of the nebula. The rocks and metals in the planetesimals were, again, probably the first to aggregate because of their higher freezing temperatures, giving the giant planets their rocky cores. As these protoplanets grew sufficiently large they attracted large amounts of hydrogen and helium gas from their surroundings.

When the larger bodies were being formed, the nebular cloud dissipated and sunlight sublimed any unshielded ice to the outer reaches of the solar system. It is theorized that, during this time, that the solar wind of the still immature sun had an intensity of approximately 10^8 times its current value, so it could have acted as a solar whisk broom, sweeping away particles smaller than a few centimeters in size.

Figure 2 shows the temperatures and distances from the sun at which planetary components from the primordial solar nebula would be expected to condense.

Figure 2



<u>Figure 2.</u> Temperature (K) and distance from sun (AU) at which major planetary constituents would condense from primordial solar nebula. <u>Note.</u> [*Note that the shaded region on the horizontal axis represents only 1.0 AU, whereas the other axis units are 10 AUs.*] The data in Figure 2 are from <u>The New Solar System</u> by J. K. Beatty & A. Chaikin, (Eds.), 1990, Cambridge, MA: Cambridge Publishing Press; <u>Geochemistry Pathways and Processes</u> by S. M. Richardson & H. Y McSween Jr., 1989, Englewood Cliffs, NJ: Prentice Hall; and <u>Solar System Evolution: A New Perspective</u> by S. R. Taylor, 1992, Cambridge, MA: Cambridge University Press.

If the condensation theory has any validity, each planet should reflect the composition of solid particles present in the solar nebula corresponding to its distance from the sun. Planets should become less metallic and posses more ice as one goes farther from the sun and the mineral composition of rocks also should vary predictably among the planets. Because of the characteristic high density of metals, one would predict a direct relationship between the abundance of metals in a planet's structure and its density.

As you answer the questions that are part of this activity, you will be making the same kinds of decisions about the validity of this model that scientists have been making for decades.