The Evolution of the Universe

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Introduction

The universe, of which our domicile the planet Earth forms but a minuscule part, has an architecture that changes and has been changing in time. In other words, it has a history of evolution. Lack of experimental evidence denies us the knowledge of what the universe was like "at the time of its origin," as discussed by Hubert Reeves in the preceding chapter. Neither do we know much about its geometry, simply because our observatories are concentrated, for all practical purposes, vanishingly close to a single point in an immensity whose size can only be measured by the billions of years required by light to go from one extremity to another!

Two sets of clues give us a fairly precise idea, however, about how the first-order shape of the universe has been changing and what sort of processes may have created its material wealth. The change of shape is betrayed by the behavior of light from very distant stars, and the growth of the material wealth by our knowledge of nuclear physics and chemistry.

The shift toward the red in the spectra of light reaching us from the distant galaxies tells us that they are speeding away from us , with the remotest receding at speeds approaching the speed of light! In other words, the universe is expanding. The magnitude of this shift is dependent on how far away a galaxy is from us, known by calibrating the "brightness" of the stars in the galaxies and correlating it with distance, which shows that the farthest galaxies are moving away with the highest velocity. If we reverse this "explosion" and bring all the galaxies back to an imaginary point where they all had the same speed, we end up with the "origin" of the universe some fifteen billion years ago, although we cannot pinpoint the place of its origin, because not all the relative motion parameters are available to us.

Formation of the Elements as the Building Blocks of Planets

Within a minute of the initial "Big Bang" that commenced the expansion of an original very dense, hot substance consisting entirely of the elementary particles, the atomic nuclei began forming (Tayler, 1988). In the next 10^5 years the expanding universe cloud cooled to a point where the individual atomic nuclei and the electrons could combine into atoms mainly hydrogen (H), helium (He), and Lithium (Li) atoms.

The cloud began to break up into numerous clusters in the next billion years. Once formed, these clusters remained stable, owing to the mutual gravitation of their constituent particles, and evolved into a billion galaxies that form the basic units into which the universe matter is now subdivided. Within the galaxies, gravity led to further subdivision of the gas to form stars with extremely high core temperatures and pressures (the core temperature of our own Sun, for example, is close to 1.4 x 10^{7}°K)[1] that led to nuclear fusion. Reactions do not produce nuclei of elements beyond Fe, because their production requires energy rather than the release of energy. This explains why their total quantity in the universe is relatively small. These heavier elemental nuclei are thought to be produced by the capture of neutrons and perhaps even protons. (See Table 1.)

Once produced in stars or in more massive objects, the elements are turned into interstellar space through either relatively mild or violent processes. The large stars implode catastrophically once they run through their nuclear fuel. These implosions disrupt the star and cast its remnants into the surroundings during what is known as supernova explosions. It is in these supernova explosions that most of the elements heavier than iron are produced. In our galaxy, supernova explosions occur once a century. Since our galaxy is 10×10^9 years old, 10^8 such events must have contributed to its wealth of elements.

The Origin of the Solar System and the Construction of the Planets

How to go from a subregion of the galactic nebula to the present Solar System remains, by contrast, a mystery. Rb-Sr and Nd-Sm isotopic age measurements on very primitive meteorite material tell us that the initial Solar System mass began forming 4.56×10^9 years ago. There are again two sets of clues as to how this event may have happened: one set consists of the physical parameters,

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[1] 273°K = 0°C.

Table 1: Relative abundance of the first 28 elements and their fates during the formation of the terrestrial planets (after Boecker, 1985).

Element Number	Element Name	Compound Solid	Compound Gas	Rel. Abundance In Sun*	Fate†	Rel. Abundance in Chondrites**
1	Hydrogen		H_2	40,000,000,000	(1)	-
2	Helium		He	3,000,000,000	(1)	trace
3	Lithium	Li_2O		60	(3)	50
4	Beryllium	BeO		1	(3)	1
5	Boron	B_2O_3		43	(2)	6
6	Carbon		CH_4	15,000,000	(1)	2,000
7	Nitrogen		NH_3	4,900,000	(1)	50,000
8	Oxygen		H_2O**	18,000,000	(2)	3,700,000
9	Fluorine		HF	2,800	(1)	700
10	Neon		Ne	7,600,000	(1)	trace
11	Sodium	Na_2O		67,000	(2)	46,000
12	Magnesium	MgO		1,200,000	(3)	940,000
13	Aluminum	Al_2O_3		100,000	(3)	60,000
14	Silicon	SiO_2		1,000,000	(3)	1,000,000
15	Phosophorous	P_2O_5		15,000	(3)	13,000
16	Sulfur	FeS	H_2S	580,000	(2)	110,000
17	Chlorine		HCl	8,900	(1)	700
18	Argon		Ar	150,000	(1)	trace
19	Potassium	K_2O		4,400	(2)	3,500
20	Calcium	CaO		73,000	(3)	49,000
21	Scandium	Sc_2O_3		41	(3)	30
22	Titanium	TiO_2		3,200	(3)	2,600
23	Vanadium	VO_2		310	(3)	200
24	Chromium	CrO_2		15,000	(3)	13,000
25	Manganese	MnO		11,000	(3)	9,300
26	Iron	Feo,FeS,Fe		1,000,000	(3)	690,000
27	Cobalt	CoO		2,700	(3)	2,200
28	Nickel	NiO		58,000	(3)	49

*Relative to 1,000,000 silicon atoms.
†(1) Highly volatile; mainly lost;
(2) Moderately volatile; partly captured;
(3) Very low volatility; largely captured.
**Plus metal oxides.

such as the orbits, volumes, and masses of the planets; the other includes the compositional data from the various members of the solar system.

All planets revolve around the Sun in orbits that are nearly coplanar, Pluto showing the largest deviation with 17.2^0. They all resolve in the same sense as the rotation of the Sun and the planets conform to the revolution of the original nebular cloud from which they condensed. However, a major problem here remains in accounting for the fact that although the Sun has almost 99% of the mass of the Solar System, 98% of the angular momentum of the system resides with the planets.

The density of the planets, corrected to subtract the condensing effect of the planetary gravity, gives a clue to their chemical composition, when viewed in the light of the observational evidence provided by the meteorites. Depending on whether they contain millimeter-sized spherules which are called chondrules and consist of once-molten material with bulk chemical compositions similar to that of the Sun, meteorites are divided in two classes: chondritic and achondritic. It is generally believed that the chondritic meteorites have never been through a planet-making cycle and thus reflect the original composition of the objects that congregated to form the planets. By contrast the achondrites clearly have been melted at least once to separate metallic iron from stony substances. These are interpreted to be remnants of now disrupted planets or asteroids.

Four elements, viz. oxygen (O), silicon (Si), magnesium (Mg), and iron (Fe), dominate the composition of the chondrites. Aluminium (Al), calcium (Ca), nickel (Ni), and sodium (Na) form a second group, and chromium (Cr), potassium (K), manganese (Mn), phosphorous (P), titanium (Ti), and cobalt (Co) constitute a third. Table 1 shows a summary of why these elements constitute the building blocks of the terrestrial planets near the sun, and especially why O, Si, Mg, and Fe dominate their composition.

Once we know what to expect in terms of compositions, the densities of the planets give us a rough idea of what percent of each consists of "stony materials" made up mainly of O, Si, and Mg, and what percent of Fe. For instance, Mars has a corrected density of 3.7 gr/cm^3 corresponding with such "stony minerals" as γ-olivine and garnet, suggesting that it consists mostly of stony matter. Mercury has a density of 5.4 gr/cm^3, falling half-way between the ordinary chondritic meteorites with average densities

Table 2: Simple Earth model based on cosmic abundances (after Anderson, 1989, table 2-2).

Oxides	Weight Fraction
MgO	0.250
SiO_2	0.354
Al_2O_3	0.026
CaO	0.021
Na_2O	0.011
Fe_2O	0.339
Total	**1.001**

just under 3.5 gr/cm^3 and the iron meteorites with an average range between 7.8 and 7.98 gr/cm^3, suggesting that it may be composed of half iron and half "stone." Earth and Venus have compositions halfway between the "all-stone" mercury. Thus, the Earth is expected to consist crudely of about 25% of iron and 75% of stone.

The information outlined so far is unfortunately still insufficient to support a unique model of planetary formation. The model currently in vogue, the one proposed by Safronov (1972), assumes that the Sun initially had a uniform gas-dust nebula. This first developed into a torus and then into a disk (Fig. 1) that was sufficiently hot in its inner regions that only elements forming compounds volatilizing above about 1000°C condensed into solid bodies, while the outer regions were cold enough to allow condensation of compounds that solidify only below 0°C. As the disk got denser it became unstable and broke up into numerous dense aggregates where self-gravitation exceeded the disruptive tidal forces of the Sun. Dust was progressively removed by attraction to larger bodies, the disk became transparent, and a large temperature gradient was established.

A large number of planetesimals (about 500) that had condensed much of the original nebular gas eventually may have coalesced into a small number of terrestrial planets. It was toward the end of this coalescence process that the earth may have been hit by a Mars-size object and fissioned to create the Moon (Fig. 2). This model[2] has been criticized recently, because of its low intrinsic dynamic probability, because such a late collision would have

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[2] For an excellent overview of the data and ideas on the origin of the Moon, see Hartmann et al. (1986).

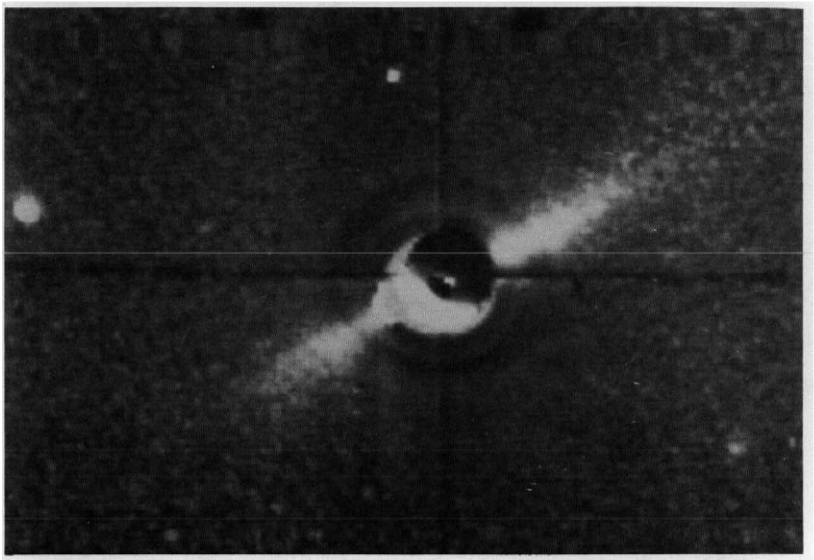

Figure 1: The disk of dust surrounding the star Beta Pictoris, which is thought to be an embryonic planetary system (from Broecker, 1985, p. 66).

entirely re-melted the earth, generating geochemical signatures quite different from those that are actually observed, and because the model requires that the Moon be made from the stony outer layer of the impactor, while the actual geochemistry of the Moon suggests that it was made from material derived from the earth's own mantle. Another model suggests instead that a giant impact may have occurred after the earth had accreted only to ~ 70% of its present size to generate the high angular momentum of the Earth-Moon System, and that later collisions with much smaller (0.001 to 0.01 of the earth-mass) high-velocity planetesimals may have ejected the protolunar material from the earth's mantle.

Currently, the Moon revolves around the earth with an almost perfectly circular orbit that has a present radius of 384,400 km. This radius is growing at a current rate of 4 cm/year, a rate that has been diminishing since the Moon formed. Earth's water bulges ("tides" caused by the gravitational pull of the Moon and the Sun) exert a gravitational pull on the moon that speeds the Moon's journey around the earth. This pull, by contrast, slows down Earth's own diurnal motion. For instance, some 360 million years ago there were 400 days in a year instead of the current 365! Thus, our only

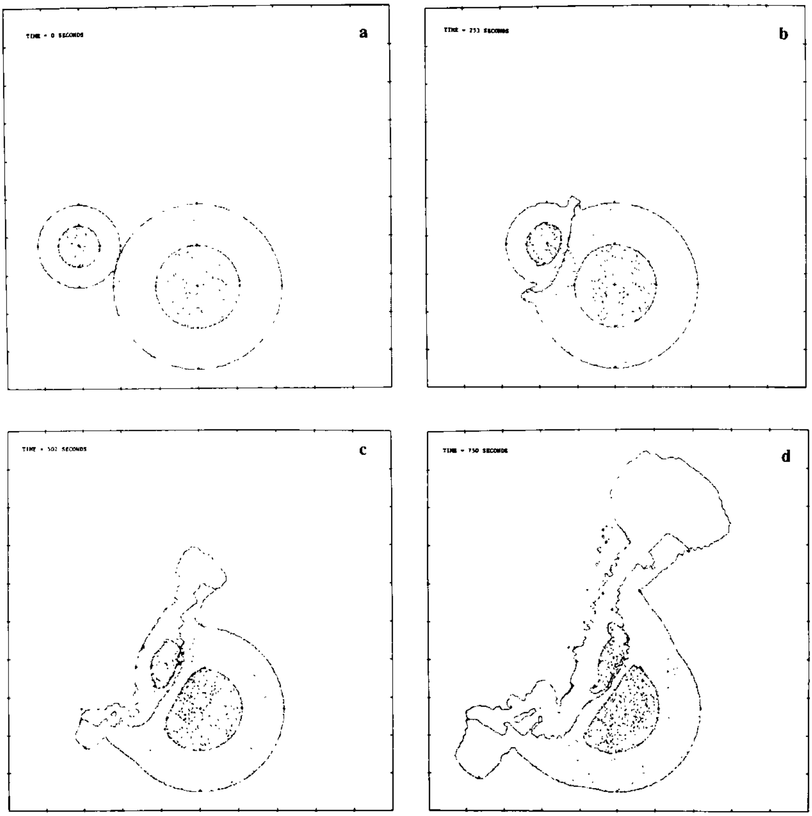

Figure 2: A computer simulation of the formation of the Moon as a result of the collision of a large asteroid with the earth (after Kipp and Melosh, 1986).

natural satellite exercises from afar long-term and profound controls on terrestrial affairs.

Our knowledge about the structure and history of the universe is limited by what we can now observe, both in the universe itself and in our laboratories. Our models concerning its evolution are constructed entirely on the basis of what we know of nuclear physics and chemistry, and of celestial mechanics. We thus have a fairly good idea of how the elements have formed and how they were used in the construction of the stars and planets, although we still face a problem in explaining the distribution of the angular momentum in our own solar system (the only planetary system of which we have observational evidence).

As we go away from the processes of which we have direct knowledge toward the early infancy of our universe, the testability of our conjectures and thus our ability to know decreases dramatically. As Hubert Reeves points out in the preceding chapter, the Planck temperature (10^{28} degrees) seems to be the present limit of "actualistic methodology" (i.e., the methodology that investigates the past on the basis of our knowledge of the present-day processes) of the astrophysicists, much as the oldest accessible rocks delimit the present temporal domain of the geologists.

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