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PART 1

Planetesimals and stellar encounters

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1.1

Introduction

Two hundred years ago there were many theories about how the world began. They were assessed by different criteria – astronomical, geological, dynamical, and theological (Miller 1803). Pierre Simon de Laplace and William Herschel proposed theories that were linked together to form the "Nebular Hypothesis," connecting the origin and development of the Solar System with the condensation of stars from diffuse matter. The development of this hypothesis in the 19th century is discussed in my book *Nebulous Earth.*

In Part 1, I describe how, after dominating cosmogonic speculation for a century, the nebular hypothesis failed the geological, dynamical, and astronomical tests of 1900 (by then, theology was no longer considered relevant to the evaluation of scientific cosmogonies). Rival theories proliferated but by 1940 most of them had also been found inadequate, though a few of their components – especially the "planetesimal" hypothesis of T. C. Chamberlin – survived.

In the meantime the foundations for a new improved Nebular Hypothesis had been constructed with the help of nuclear physics (see my *Transmuted Past*). The development of the modern theory is presented in Parts 2 and 3; special theories for the origin of Earth's Moon are discussed in Part 4. Astronomical, physical (including dynamical), and chemical criteria rule; geology is secondary. I follow the story only to about 1985; for surveys of more recent research the reader should consult works such as the compendium edited by Levy and Lunine (1993), the papers published in the November 1993 issue of *Icarus,* and the brief overview by Ahrens (1994).

1.1.1 Nebulae, planetesimals, and the big bump

At the end of the 19th century most astronomers accepted the Laplace–Herschel Nebular Hypothesis. According to Laplace, the atmosphere of the primeval Sun extended throughout the entire space now occupied by planetary orbits; it was a hot, luminous, rotating cloud of gas, similar to the nebulae that Herschel thought to be the progenitors of stars. As the nebula cooled it contracted; conservation of angular momentum then required it to rotate more rapidly. By hypothesis, the gas rotated like a rigid body in the sense that the angular velocity was the same at all distances from the center, so that the linear velocity would be greatest at the periphery. Eventually the centrifugal

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force on the outer portion of the nebula would exceed the gravitational attraction toward the center, and a ring of gas would separate and remain at the same distance while the inner part continued to contract. By hypothesis, again, the gas in the ring would collect into a single large sphere, which would then gradually cool and condense to a liquid or solid planet. Meanwhile the contracting nebula would spin off additional rings at regular intervals, until finally only the Sun was left at the center. Satellites could be formed by a similar process of ring separation as the protoplanetary sphere cooled down and condensed.[1]

The Nebular Hypothesis was closely connected with 19th-century geological theories, which generally presumed that the Earth had been formed as a hot fluid ball and then cooled down, solidifying on the outside first. According to the "contraction theory," the solid crust would not contract as rapidly as the fluid interior, so it would have to wrinkle in order to adjust its diameter to that of the shrinking core; in this way one could explain various geological formations.

Lord Kelvin, the most influential British physicist of the 19th century, adopted the general scheme of a cooling Earth but attacked two features that geologists relied on for their explanations. First, he estimated the time required to cool down from an initial hot fluid state and found it to be only 20 to 100 millions years compared with the hundreds of millions of years geologists assumed to have been available for slow processes like erosion to produce the observed effects. Second, Kelvin showed that the fluid interior could not be so large as to extend to within 30 or 40 miles below the surface (as the geologists thought it should); in fact he went to the other extreme and concluded that the entire Earth is now solid.[2]

The debate between Kelvin and the geologists on the age of the Earth was, of course, eventually settled by the discovery of radioactivity, which not only provided a source of heat to replace that which was lost from the original store (thereby invalidating Kelvin's conduction calculations), but also furnished a direct method for estimating the ages of some surface rocks. By 1905 Rutherford and his colleagues were proposing a time scale of billions of years, as part of the revolution that was sweeping through science (Brush 1979a).

But even before the implications of radioactivity had been generally understood, the American geologist T. C. Chamberlin challenged Kelvin's theory of the cooling Earth in an assault so successful and far-reaching that it overthrew the nebular hypothesis itself.[3] Today it is hard to appreciate what a

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[1] For further details see my *Nebulous Earth,* chapter 1.2. Hereafter, chapter and section numbers alone, without "chapter" or "section" will be used in cross-references to this volume and to *Nebulous Earth* and *Transmuted Past.*

[2] See *Nebulous Earth* 2.2 and 3.3.

[3] Thomas Chrowder Chamberlin (1843–1928) studied geology with Alexander Winchell at the University of Michigan, then taught science at a normal school in Wisconsin. He was appointed to the Wisconsin Geological Survey in 1873 and headed the glacial division of the U.S. Geological Survey from 1881 to 1904. By the end of the 19th century he had established a considerable reputation as a geologist and educator. Chamberlin served as president of the University of Wisconsin from 1887 to 1892, then was called to the newly established Univer-

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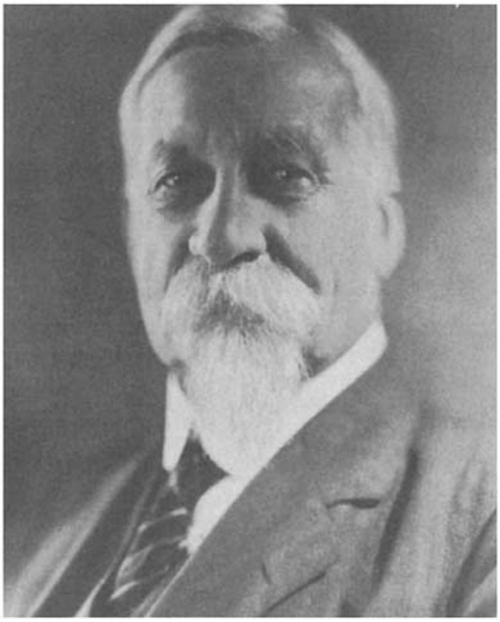

Figure 1. Thomas Chrowder Chamberlin (*Biographical Memoirs of the National Academy of Sciences,* vol. **15**, 1934).

tremendous feat that was, because we now realize the hypothesis had some serious flaws that had already been pointed out decades earlier. Yet no one had persuaded astronomers that patching up Laplace's theory was less fruitful than looking for a fundamentally different hypothesis; no one had shown geologists that the evidence for a hot primeval Earth a few tens of millions of years ago was really quite flimsy; and no one had dared to tell Lord Kelvin that he was wrong in his basic assumptions about Earth history. Chamberlin, a geologist who ventured into the apparently more difficult and prestigious field of theoretical astronomy in his 50s, was hailed as the brash American who pulled the tail of the British lion and liberated geologists from the tyranny of the truncated time scale. At the same time he introduced into planetogony a hypothesis – accretion of cold solid particles – that, despite temporary rejection, has become an essential feature of most modern theories.

Chamberlin's original objection to the Nebular Hypothesis was based, as one

sity of Chicago, where he headed the geology department from 1892 to 1918. As founder-editor of the *Journal of Geology* (1893–) he continued to exert considerable influence on U.S. geology through the 1920s. He was also well known for his "method of multiple working hypotheses" – his 1890 article on that subject was so often cited that it was reprinted in *Science* in 1965.

The most comprehensive source of information on Chamberlin is the dissertation by Schultz (1976). See also the memoir by his son, R. T. Chamberlin (1934), and articles by Winnik (1970), Leith et al. (1929), and Willis (1929). Rainger (1993) discusses his attempt to move invertebrate paleontology into the Geology Department at Chicago.

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might expect, on geological considerations. Having studied the glacial formations in North America, he examined the contemporary attempts to explain the cause of the Ice Age, in particular the hypothesis that the Earth originally had an atmosphere rich in carbon dioxide. A drop in the carbon dioxide content supposedly reduced the absorption of solar heat and thus lowered global temperatures. But when Chamberlin learned of calculations, based on the kinetic theory of gases, showing that gases at high temperatures would have molecular velocities great enough to escape the Earth's gravitational field, he realized that the notion of a dense carbon dioxide atmosphere was inconsistent with the assumption that the Earth had once been a hot fluid ball; not only carbon dioxide but all the other gases in the atmosphere would have escaped at temperatures high enough to melt rocks.

When Chamberlin looked into the possibility that the Earth had been formed by accretion of cold solid particles, he found that this idea had indeed been discussed by astronomers under the name "meteoritic hypothesis." But it seemed to have a fatal defect: Planets formed by combining solid particles moving in adjacent circular orbits would have retrograde rotation. The reason is that according to Kepler's Third Law, linear velocity decreases with distance from the Sun, so the particle in the inner orbit would be moving faster than the one in the outer orbit just before they collided, and the combined body would have a net backward rotation. Since it was thought that all planets (with the possible exception of Uranus and Neptune) have direct rotation, accretion from solid particles did not look very promising.

But the astronomers who rejected the meteoritic hypothesis on the basis of Kepler's Third Law had forgotten to apply Kepler's other two laws. In general the particles would move in elliptical orbits (first law), and a given particle would move faster in the part of its orbit which is closer to the Sun (second law). Chamberlin showed by analyzing several examples that unions of particles moving in intersecting elliptical orbits would be more likely to leave the resulting particle with direct rotation.

Here and elsewhere Chamberlin had the assistance of a young astronomer, F. R. Moulton, who was completing his Ph.D. research at the University of Chicago, where Chamberlin headed the Geology Department.[4] In addition to reviewing and working out the details of Chamberlin's ideas, Moulton put together the objections to the Nebular Hypothesis in a comprehensive paper

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[4] Forest Ray Moulton (1872–1952) received his B.A. degree in 1894 from Albion College (Albion, Michigan), then went to the University of Chicago as a graduate student, and was appointed assistant in astronomy in 1896. He was awarded a Ph.D. in astronomy and mathematics in 1899, and later became professor of astronomy at Chicago. He published several articles and books on topics in astronomy, in addition to his work with Chamberlin on the origin of the Solar System. He retired from Chicago in 1926; he served as executive secretary of the American Association for the Advancement of Science from 1936 to 1940.

Biographical details may be found in an anonymous article in the Albion alumni magazine (Achates 1947) and in the *DSB* article by H. S. Tropp (1974). Both date Moulton's collaboration with Chamberlin from 1898, but the documents to be cited later indicate that it had begun at least as early as summer 1897. Achates also confuses T. C. Chamberlin with his son Rollin. See also Gasteyer (1970).

Figure 2. Forest Ray Moulton (*Io Triumphe,* vol. **12**, 1947. Reproduced by permission of Albion College).

published in 1900. While his name became attached to Chamberlin's theory, Moulton's major contribution to planetogony was to convince astronomers that the Nebular Hypothesis must be abandoned.

The major defect of the Nebular Hypothesis in 1900 was its failure to explain the distribution of angular momentum in the Solar System. Laplace's spin-off of successive rings should have left the Sun with much greater rotational speed than it now has. In fact Jupiter has most of the angular momentum of the Solar System, contrary to what one would expect from any reasonable estimate based on the Nebular Hypothesis. On a smaller scale, the discovery in 1877 that Mars has a satellite (Phobos) that goes around it in only one-third of the rotation period of the planet contradicts the assumption that satellites have formed from rings spun off by the planet's nebula.

Chamberlin was primarily interested in the thermal and mechanical development of the Earth rather than the rotation of the Sun. He suggested that the accumulation of particles by the growing Earth might have been so slow that the heat released by conversion of mechanical energy would be mostly dissipated into space and would never produce a large amount of melting. Thus, he agreed with Kelvin that the Earth is now entirely solid, a view that prevailed until 1926 when the British geophysicist Harold Jeffreys established the existence of a liquid core.[5]

Nevertheless, once Chamberlin had become interested in astronomical problems he could no longer confine himself to geology. Looking at James

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[5] See *Nebulous Earth,* 2.3.

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Keeler's photographs of spiral nebulae, he speculated that the two prominent arms belonged to two previously distinct celestial objects. From this thought, and contemplation of solar prominences, he was led to the idea that a planetary system could be generated when another star passed close to the Sun. He did not require an actual collision though this was being suggested by others. The tidal force of the intruder would cancel the gravitational force holding in the solar gases on the near and far sides of the Sun, allowing two filaments of material to flow out; the filaments would then be curved by the continued action of the intruder as it recedes. Chamberlin assumed that the filaments would eventually condense into small solid particles that would be captured into orbits around the Sun.

The Chamberlin–Moulton theory thus consisted of two distinct hypotheses: (1) close encounters of two stars, drawing filaments of gaseous material out of one of them to form a spiral nebula; (2) condensation of the gases to small solid particles, called "planetesimals" (i.e., infinitesimal planets), which accrete to form planets and satellites (Chamberlin 1905, 1906; Moulton 1905, 1906a). When it later became clear that the spiral nebulae are galaxies rather than objects that could be as small as planetary systems, Chamberlin dropped this part of the first hypothesis but retained the assumption that two stars interacted in order to release into space the material from which planets formed.

A decade after the publication of the Chamberlin–Moulton theory, Jeffreys and the British astronomer-physicist J. H. Jeans independently adopted the first hypothesis of the American theory, but rejected the second. Jeffreys (1916a, 1917a, 1918) argued that high-velocity collisions among the planetesimals would vaporize them so quickly that the material would remain gaseous until it collected into planets; thus, he proposed to return to the 19th-century assumption that the Earth was originally a hot fluid ball and has been cooling down. Jeans (1917, 1919) was more interested in developing idealized mathematical models to represent the initial ejection of material from the Sun under the tidal influence of the other star. Thus, Jeans concentrated on the astronomical side of the theory, while Jeffreys developed it from a geophysical viewpoint.

The tidal theory, whether the Chamberlin–Moulton or the Jeans–Jeffreys version, was generally accepted by astronomers until 1935, even though it was never worked out in sufficient detail to provide a convincing explanation of the quantitative properties of the Solar System. Its supporters believed that the tidal theory could overcome the major defect of the nebular hypothesis by showing at least qualitatively how most of the angular momentum could have been given to the major planets rather than to the Sun.

In the meantime, the French mathematician Henri Poincaré had demonstrated a theorem that seemed to provide another serious objection to the nebular hypothesis: If the present mass of the planets were spread out over the entire volume of the Solar System, this material would be of such a low

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density that it would dissipate into space before condensing. The filaments postulated in the tidal theory would not have to be spread out over such a large volume, so this difficulty would be avoided.[6]

Of course, astronomers recognized that any theory that required the encounter of two stars to form planets would entail an extremely small frequency of planetary systems in the universe. This was consistent with the failure to find any convincing evidence for nonsolar planetary systems. Jeans at one time seemed to take perverse pleasure in the idea that we are the result of a chance event that has happened only once in the universe and (because the stars are decaying and thinning out by expansion) will probably never happen again (Jeans 1932: 2–5). Later he changed his mind and postulated that stars were much larger in the past so the frequency of collisions and hence of planetary systems was correspondingly larger (Jeans 1942).

1.1.2 Astrophysics strikes back

In 1796 Laplace proposed his nebular hypothesis, not in one of his technical papers on celestial mechanics, but in a nonmathematical book on astronomy intended for the layman. Similarly, the American astronomer H. N. Russell in 1925 began to think about the origin of the Solar System when working on a textbook and presented his criticisms of the tidal theory in *Scientific American*, *Saturday Review*, and finally in a series of public lectures in 1934 (Russell 1935), but he never discussed the subject in an astronomical journal.[7] Did astronomers still think that cosmogony was not quite an appropriate subject for serious research, and does this attitude account for the slow rate of progress?

Russell found two major objections to the assumption that material extracted from the Sun by a passing star would condense into the planets of the present Solar System. First, theories of stellar structure developed by A. S. Eddington and others in the 1920s indicated that gases from the interior of the Sun would be at such a high temperature – on the order of a million degrees – that they would dissipate into space before they could condense into planets. Second, a simple dynamical calculation showed that it would be impossible for the tidal encounter to leave enough material with the necessary angular momentum in orbits at distances from the Sun corresponding to the giant planets.

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[6] Poincaré's career, his research on cosmogony, and related topics are discussed in *Nebulous Earth*, 1.7. For his own survey of selected theories see Poincaré (1913).

[7] Henry Norris Russell (1877–1957) earned his Ph.D. at Princeton University in 1900 and taught astronomy there from 1905 to 1947. He was director of the University Observatory from 1912 to 1947. His research on stellar evolution was associated with the "Hertzsprung–Russell" diagram universally used by astronomers. His research on spectral analysis led to the theory of Russell–Saunders (L–S) coupling, well known in atomic physics, for atoms with more than one valence electron.

Although R. A. Lyttleton, with Russell's encouragement, attempted to rescue the encounter theory by introducing a third star, most astronomers seemed to think after 1935 that there was *no* satisfactory theory of the origin of the Solar System. Russell had refuted the encounter theory, yet the fatal objections to the Nebular Hypothesis remained, and no other alternative seemed very plausible. Jeffreys in particular continued to insist that we simply have no adequate explanation for the existence of the Solar System.

Russell indirectly helped to demolish another argument that had previously been used by planetogonists to account for the near-circularity of most planetary orbits. If the planets are initially formed with highly eccentric orbits, one must find some mechanism to reduce the eccentricity. A popular choice was the hypothetical "resisting medium," that part of the dust and gas from the original nebula that did not condense into planets. Theoretically its viscous resistance should have helped elliptical orbits to evolve into more nearly circular ones. Russell was skeptical about this mechanism, pointing out that the medium would consist mainly of hydrogen and would be accreted by the planets if they interacted with it; it would thus be hard to explain why the Earth's atmosphere and oceans contain so little hydrogen. Russell also encouraged H. P. Robertson at Princeton to look into the old claim by J. H. Poynting that the absorption and re-emission of solar radiation by small bodies in the Solar System would decrease their angular momentum and eventually cause them to fall into the Sun. There had been some dispute as to whether Poynting's result, derived from the ether theory in 1903, was consistent with Einstein's theory of relativity. Robertson (1937) showed that there is indeed a dragging effect (though Poynting's formula is not accurate) and that particles less than 1 cm in radius in the vicinity of the Earth's orbit would be swept into the Sun in less than 40 million years. Thus, the "Poynting–Robertson effect" makes it unwise to invoke a resisting medium to round up planetary orbits except under carefully defined conditions.

In addition to knocking out the encounter theories, Russell also participated in an important discovery that later removed one of the objections to the Nebular Hypothesis and substantially influenced its modern form. In the 1920s astronomers believed that the Sun had roughly the same chemical composition as the Earth; this would be consistent with the hypothesis that the Earth was formed from material drawn out of the Sun by a passing star. Thus, the Sun should contain substantial amounts of elements such as iron, silicon, and oxygen but relatively little hydrogen and helium. In 1929 Russell, confirming an earlier finding of Cecilia Payne (1925a, 1925b), showed that hydrogen is by far the most abundant element in the Sun's atmosphere, and other astrophysicists in the 1930s established that the same is true for many other stars and probably for the universe as a whole.

If one assumes that the Earth was formed from a cloud of material characterized by the typical "cosmic abundance" of elements, then most of the hydrogen originally present in this cloud – now called the "solar nebula" – must have been lost. Hence, its original mass must have been much greater

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than that of the present planets, and its density could have been great enough to satisfy Poincaré's criterion for condensation.

Of course, one still has to deal with the other long-standing objections to the Nebular Hypothesis, and in addition explain the chemical processes that produced planets with compositions radically different from the cosmic abundance table.

1.1.3 Intermission

In the decade following Russell's refutation of the encounter theory, no single theory was supported by more than a handful of astronomers. Nevertheless, there were some significant developments in this decade that influenced later work: (a) revival of the planetesimal hypothesis; (b) the concept of "magnetic braking" of the Sun's rotation; (c) suggestions that the Sun had encountered an interstellar cloud and captured from it the material that later formed planets; (d) claims for discovery of extrasolar planetary systems; (e) research on cosmic abundances of the elements. I will summarize these briefly.

(a) The Swedish astronomer Bertil Lindblad showed that partly inelastic collisions between particles initially moving with different speeds in eccentric orbits with different inclinations will tend to make all the particles move at similar velocities in circular orbits lying in a flat ring.[8] Collisions between the particles would then occur with small relative velocities, thereby avoiding Jeffreys's argument that collisions would vaporize the particles. Lindblad (1934, 1935) suggested that a cold particle immersed in a hot gas would tend to grow by condensing the gas on its surface. Dirk ter Haar (1944, 1948) in Leiden elaborated this idea by using the Becker–Döring kinetic theory of the formation of drops in a saturated vapor and reinforced Lindblad's proposal that solid particles could grow initially by nongravitational forces.

Jeffreys himself began to reconsider his objection to the planetesimal hypothesis and suggested that the vapor pressure of solids at very low temperatures might be below the pressure in the surrounding medium, so that condensation would outweigh the vaporizing effect of collisions (1944). Alfred Parson (1944, 1945) published an estimate of the vapor pressure of iron ($10^{-46.7}$ atm at 273°K), which indicated that condensation would be favored in interstellar space, and Jeffreys (1948) admitted that his original objection to the planetesimal theory had thereby been answered.

The American astronomer Fred Whipple proposed in 1942 that radiation pressure acting on particles in a dust cloud would tend to push them together; each of a pair of nearby particles would shield the other from the radiation,

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[8] Bertil Lindblad (1895–1965) studied at Uppsala University, receiving his Ph.D. in 1920 with a dissertation on the theory of radiative transfer in the solar atmosphere. After a few years of research at the Lick and Mt. Wilson Observatories in the United States and at Uppsala, he was appointed director of the Stockholm Observatory in 1927 and stayed there for the rest of his career.