EARTH GENESIS

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To those who feel an interest in the evolution of the earth, it is of first moment to learn how the planet was born and what conditions controlled its growth. The other planets of our system no doubt had a birth of like nature and these, as well as the earth, bear traits that serve as signs of the family lineage. It is not clear that the sun was born at the same time, or in just the same way. There is no doubt that the sun and the planets are close akin, but this does not make it sure that they were participants in a common birth. We shall present evidence that the planets sprang from the sun, not at his birth, but later in the course of his history. The satellites might easily seem to be the offspring of the planets and this was the common view in the last century, but there are signs that planets and satellites had a common birth and that the satellites escaped being little planets only because their birth-places fell within the spheres of control of their larger sisters to whom they were forced to dance attendance as a first duty, and respond to the common call of the sun incidentally. If these relations are true, we may search the planets, planetoids and satellites for signs of the later family history, while we look to the sun for signs of their parentage and of the earlier history.

But are these real kinships? Let us look to the evidence.

If the planets were separated by centrifugal action from a nebula of which the sun is regarded as the residual mass —the view that was foremost during the last century—the planets should revolve in paths that lie in the plane of the sun's equator. But the plane of the earth's orbit is inclined 7° 15′ to it and the planes of the orbits of the other planets and planetoids diverge at other angles. These angles may not seem to imply a very wide departure from the theoretical requirement, but when the immensity of momenta of these bodies is considered the divergence is really serious.

But there are much more formidable difficulties. If the planets were separated from the parent nebula at successive stages by centrifugal action, the equatorial rotation of the nebula must have had successively the speeds of the separated parts. These speeds may indeed have been slightly altered subsequently by tidal and other actions, but Sir George Darwin has shown how trivial the tidal effects must have been at the most, and the others are negligible under this hypothesis. The velocity at the equator of the nebula must have increased from about 5.5 kilometers per second at the separation of Neptune to more than 45 kilometers per second at the separation of Mercury. Moreover its velocity must have continued to increase still further as the nebula shrank into the existing sun. As this further increase must have much exceeded that which had already taken place, it might well be supposed that material for other planets would have been separated, and this view was entertained in the last century and diligent search made for inner planets at times of solar eclipses; indeed eminent astronomers even announced the discovery of such planets, but the observations proved illusory. If the radius of the orbit of such a planet had been 1,612,900 kilometers its orbital velocity would have been 275 kilometers per second and the equatorial velocity of the nebula should have been the same at the time of its separation. To separate matter by centrifugal action at the equator of the present sun, the velocity should be 435 kilometers per second. The actual velocity is about 2 kilometers per second. This is a discrepancy so enormous as to seem fatal to the centrifugal theory.

Moreover this difficulty is supported by others not less formidable, though time will not permit us to consider them adequately. Suffice it to say that the values of the planetary momenta seem to be seriously at variance with the requirements of the centrifugal theory. Attention was directed to some of these troublesome features by Babinet a half century ago but he does not seem to have regarded them as fatal, but only as limiting conditions to which the theory must conform. Much later and quite independently Moulton carefully inquired ino the question whether the moments of momentum of the solar system were compatible with the centrifugal theory and found the discrepancies insurmountable. As his arguments rest upon the constancy of moments of momentum, a firmly established principle, they are scarcely less than rigorous.

A less technical argument may be appreciated by laymen, who may readily picture to themselves the solar nebula just before the matter of Jupiter and his satellites was separated from it according to this hypothesis. The mass of the Jovian matter was less than one-thousandth part of the mass of the nebula at that stage. A rough estimate may easily be made of the momentum that could be carried by this little outer rim of one-thousandth part compared with that carried by the remaining 999 parts. It is obvious from even a mere inspection that the moment of momentum of the thousandth part could only be some minor portion of the whole. But yet the Jovian system actually has more than nineteen times as much moment of momentum as all the inner bodies, including the sun, which were supposed to have been formed from the rest of the nebula. It seems incredible that the material for the Jovian system could have been separated in this way. A like inspection of other supposed centrifugal separations leads to analogous discrepancies, some of them proportionately more remarkable.

The cumulative force of the objections to the centrifugal hypothesis seems too grave to be escaped by any special pleading. This does not mean that centrifugal separation cannot give rise to planetary matter in any case, but merely that origin by such separation does not fit the requirements of our present planetary system.

The satellites also offer a silent protest against the pedigree assigned them by the centrifugal hypothesis. The orbital speeds of Phobos and the small bodies that form the inner ring of Saturn demur. They cannot consistently concur in the implications of the centrifugal pedigree. Particularly sharp is the dissent of three satellites recently found to revolve in directions not only contrary to the postulates of the hypothesis but opposite to their fellow satellites attending the same planets.

In the face of these serious difficulties—not to cite others—there seems to me no alternative but to abandon the hypothesis that our present planets and the sun were formed in close succession from a common nebula by centrifugal separation. Some other mode of origin must be found that better tallies with the significant facts of the system. Obviously it must also tally with the great events of cosmic evolution of which the origin of our little system was but a trivial part, however important to us. But before considering these more general relations, let us look to the terms of the hypothesis we offer to better fit the facts of the case.

It has been implied already that the genesis of our sun—and of course the genesis of stars in general—is not regarded as a part of our immediate task. The evolution of the sun is held to be an earlier event. The birth of the present planetary system is assigned to an intercurrent incident, a later episode in the sun's history. This is one of the distinctive features of the new hypothesis. This later genesis of the planets seems required because the rotational features of the sun and the revolutionary features of the planets are so out of accord as to imply origins under different conditions. This is equally implied by the discordant ratio of mass to momentum. The sun holds about 745 out of 746 parts of the total matter of the solar system, while it only carries about 2 per cent of its moment of momentum. These discordant features lead to the conviction that a new agency came in, after the original formation of the sun, and gave to a very small fraction of the solar matter—after it had been drawn out from the sun—a special endowment of momentum. This action is assigned to so simple an event as the passing of a star (or other massive body) near the sun, calling forth a very small fraction of his mass and endowing it richly with momentum from the visitor's own store. As there are a hundred million or more stars in the heavens moving in diverse directions and at varying rates, much like the molecules of a gas, many close approaches and some collisions may be regarded as inevitable, and so our appeal is made to an event of high probability. Let it be noted that no appeal is made just here to actual collisions of stars, but merely to approaches of such degrees that there must have been millions more of them than of actual collisions.

The mode of action of the passing star in calling forth a trivial fraction of the sun's substance and giving it high momentum in orbital form, rests upon an extension and adaptation of a principle enunciated long ago by Roche and confirmed by Maxwell and others. It was shown by Roche that if a secondary body were made to approach its primary, it would be torn asunder by the differential attraction of the primary body so soon as it reached a point 2.44 times the radius of the primary, provided both were homogeneous bodies of the same density, and provided cohesion, elasticity and all expansive agencies are neglected. The principle holds in other cases of close approach than the special one studied by Roche.

Now, if the Roche principle be extended to bodies affected by a strongly expansive and even explosive habit, as in the case of the sun, it is obvious that special effects must be predicated. The influence of the attraction of a passing star is of the differential kind made familiar by the tides. The differential pull of the passing star draws out the explosive body along the line joining it and the star, facilitating explosion along this line. At the same time it compresses the explosive body at right angles to this line, and so localizes and intensifies the explosive action. Thus the explosive body may be said to have become a Janus-faced piece of ordance belted and compressed about the middle, while it fires its projectiles toward and from the passing star. The projectiles shot toward the star are not only drawn toward it by its attraction during their flight, but are drawn *forward* by it in the direction of its own movement. The projectiles shot in the opposite direction suffer an opposite effect in pursuance of well known tidal laws. If the projectiles during their flight are sufficiently deviated by the passing star, they will assume elliptic, parabolic, or hyperbolic orbits instead of returning to the sun as they do in the absence of the deviating effects of the star.

If the forward pull of the passing star is relatively small, as is likely to be the case when the star is distant or small and the ejection from the sun is consequently short, the projectile will fall back to the sun, but it will carry back whatever momentum it gained from the forward pull of the passing star, and this will accelerate or retard the rotation of the sun according to the relative direction of the sun's rotation at the time. If the forward pull has a deviating effect greater than the radius of the sun, the projectile will fall into an elliptical orbit about the sun; the only exceptions being the cases in which the deviating effect is so great that it causes the projectile to pass into a parabolic or hyperbolic orbit and be lost, or else into a reversed elliptical orbit about the passing star and thus become a secondary to it. All these cases are possible, not only, but all these cases were actually encountered by Dr. Moulton in tracing out the courses of the projectiles in the first nine test cases which he followed mathematically to see the actual workings of this combination of agencies. In these cases he made no postulates relative to the mass, position, orbit or velocity of the passing star, or of the projectiles from the sun, that did not seem to lie within the probabilities of the case. In forty-eight cases later tried, he found the dispersing potency of the combination surprisingly effective, even when the passing star was not more massive than our sun, and its approach not usually as close as that of the earth to the sun, though that distance and half that distance were used in a few cases. The remarkable fact was revealed that gravitation, commonly supposed to be the supreme agency of celestial concentration, is really, under the conditions of swiftly approaching bodies of explosive habits, a very effective agency of dispersion.

It was further shown that the passing star may remain within an effective range of action for a period of twenty years in certain cases. The average period in the cases selected proved to be about five years.

During the effective period of influence a succession of explosive impulses must almost certainly take place, and these should give a stream of projectiles in the form of bunches or pulses of solar matter attended by diffusely scattered matter, the two elements constituting, by interpretation, the knots and haze so common in spiral nebulæ. These streams would of course issue on opposite sides of the sun and would curve in opposite directions, a distinctive feature also common in spiral nebulæ.

It is not difficult to see that these features would arise naturally, if not inevitably, under these conditions, but it taxes the imagination somewhat more severely to follow the composite action through the whole series of pulsations called forth successively by the disturbing star until it passes to an ineffective distance, but if done, it will appear that the arrangement of pulses at any instant takes the form of a spiral with two streams issuing opposite one another and consisting of knots and haze, the whole affected with much irregularity but retaining a general symmetry. From the nature of their origin, the streams lie nearly in the plane of the orbit of the disturbing star, and hence the whole takes on a disk-like arrangement. When seen on edge the outline is narrowly elliptical. This discoidal form is well suited to give rise to a group of planets arranged also in discoidal form as is the case with our planetary system.

The spiral feature, it is to be noted, relates to the *streams* of knots and haze, and not to the *individual paths* of each separate constituent. These paths are held to be elliptical, in the main, and to be controlled by the center of mass of the spiral. The knots must inevitably be more or less rotatory, and when large they must control the immediate movements of the matter within their spheres of influence, and so there should be revolutions about sub-centers subordinate to the general revolution about the center of the nebula.

The spiral form cannot last indefinitely. If the central mass is large and the dispersion only moderate, the inner parts must revolve much faster than the outer ones, and so the spiral streams must wrap up, growing more and more involute till they merge into a disk and thus take on one of the forms of planetary nebulæ. In some cases the spiral must merge into a disk in a short period. But if the dispersion be great and little matter left in the central part, the differences in the rates of revolution of the several scattered parts may become small and the spiral wrap up at an exceedingly slow rate and hence its endurance be long.

The mathematical tests of Dr. Moulton clearly implied that for the evolution of a spiral nebula suited to the formation of the present solar planets, the approach of the disturbing star must have been rather distant, for the explosive ejections amounted only to an extremely small part of the whole and the dispersion was relatively limited. Really close approaches of massive stars when one or both have highly explosive habits and when the velocity of approach is exceedingly high and the path at the critical stage is a sharp curve, must produce effects of a higher order, and give rise to spiral nebulæ of a much larger and more dispersed type. Consider, for example, the case of a star of the smaller order passing through the Roche limit of a star of the more massive order. Let the stars have about the mean velocities of stars of the mature type before they appreciably affect one another. As the stars approach one another these velocities will rise to such a degree that when the smaller star is passing through the Roche limit of the larger star, its velocity may reach some few hundred kilometers per second—depending upon the masses of the stars—without making the case an unusual one. Neglecting dispersion for the moment, the smaller star must swing around the larger star in a sharp conic curve and all the while be subject to extreme differences of gravitative pull from the larger star. Under the Roche principle these differences would be sufficient to wrench the small star into fragments if it were merely a passive body held together by its own gravity; i.e. its self-gravity would be somewhat more than neutralized. It follows that in the process all the expansive potency of the star is set free for dispersional work. But this is not done promiscuously nor instantaneously. The star, during its approach, has suffered tidal elongation, giving rise to tidal cones fore and aft and to compression about the middle portion. The cones have grown higher and sharper, and the middle has become more and more compressed as the approach grows closer, so that when the Roche limit is entered the star is rather a fusiform bolt than a sphere. It is moreover constantly undergoing torsion by the changing direction of the mutual pull of the two stars. The tidal cones also are constantly lagging because a gaseous body is viscous. While therefore we may say that the total explosive force of the small star has been set free by the time it has entered the Roche limit, the explosive action has all the while been directed fore and aft by the differential way in which the gravity of the large star has acted. Since the tidal cones—the two muzzles of our gigantic piece of ordnance—constantly lag, and since the curve about the larger star is sharp, the projectiles are never shot directly at or from the larger star, but at a point in its rear and at a point opposite this. The ordnance itself however, is on a rapid swing and the successive projectiles take changed paths. This may help the layman to see how the projectiles successively shot forth during the swing will be related to one another at any instant. Theoretically, under these conditions, about all the substance of the smaller star will be shot away in the form of projectiles. The ordnance is at once missile and ammunition. Only the necessary incompleteness of the theoretical action leaves matter behind to form the nucleus of the resulting spiral. Spiral nebulæ with small nuclei are occasionally seen in the heavens. Of course they should be relatively rare, for a passage through the Roche limit cannot often take place, though it is a half dozen times as likely to happen as a collision.

While the picture of the fusiform bolt is fresh in mind, it may be observed that grazing approaches and glancing collisions are not instances of the touch or the overlap of spheres pursuing straight paths, as illustrations too often imply, but of the touch or the overlap of two elongated slightly curved fusiform bolts swinging violently about their common center of gravity on sharp conic curves.

Collisions must in the nature of the case be rare compared with dispersive approaches of the different types. They need only be mentioned here to fill out the series. A glancing collision is the next step beyond a grazing approach and must quite surely give a spiraloidal dispersion. A center-to-center collision must give a radial or irregular dispersion of extreme violence.

The spiralizing whirl given to an assemblage of matter in swinging about another assemblage is probably not confined to continuous bodies like the stars, but applies also to clusters or galaxies of stars when these closely approach and swing about one another. It probably applies even more effectively when the clusters pass through one another on curved paths. And so, if the view that some of the greatest of the spiral nebulæ are only extremely distant assemblages of stars, a view not without serious objections, should yet prove true, it would perhaps only be a higher expression of the workings of the principle of disturbing and distorting approach. It is to be borne in mind that assemblages about common centers of gravity, whether continuously or disjunctively organized, do not pass one another on straight lines and at even pace, but bend their courses into elliptic, parabolic, or hyperbolic paths and greatly hasten their speeds, while differential attractions arise and increase with approach and inevitably impress their own peculiar qualities on the conjoint action.

In assigning most spiral nebulæ to the incidental effects of the close approach of stars, our hypothesis tallies well with the fact that the number of spiral nebulæ greatly exceeds that of any other form. In announcing their great preponderance, Keeler remarked that they must be due to some cause of common occurrence in the heavens. In view of the multitude of stars, the diversity of their courses and the variety of their velocities, it is difficult to assign an occurrence of a highly potential kind that is likely to be more frequent than the close approach of stars to one another. But sufficient frequency is the least significant part of the coincidence in this case, for, to meet the requirements, the occurrences must not only have had sufficient frequency, but have had such a nature as to give these peculiar results, (1) a spiral form implying at once radial and tangential action; (2) a pulsatory effect, shown in streams of knots and diffuse matter, and (3) a double outstreaming from the center, taking the form of two arms issuing from opposite sides and branching diffusely in their distal parts. The heavens do not present a more distinctive deployment than the spiral nebula, and yet it is one of singular frequency, the dominant species of the nebular type. An eccentric collision is no doubt competent to produce a certain class of highly dispersed spiral nebulæ, as already remarked, but it is doubtful whether it is competent to produce all grades and types of spiral nebulæ, or even the majority of the forms, while the probability of its occurrence is relatively small. Even so far as it is competent and adequate, it appeals to essentially the same principles of action as those that actuate dispersion in cases of approach. It thus appears to be only the last term in a long series, the less catastrophic members of which constitute the majority of actual cases. Eccentric collisions seem too rare events to give origin to so dominant and so varied a group as the spiral nebulæ. They are therefore regarded as one source of spiral nebulae but not an adequate source. Disturbing approach may have a numerical competency from one million to ten million times as great as actual collision, and yet it is not clear that it has any surplusage of competency to keep up the supply when the evanescent nature of the smaller nebulæ is taken into account. This is on the assumption that the present supply of nebulæ is to be maintained by the present galaxy of stars in their normal inter-movements. If one great cloud of stars is now passing through another, as

Kapteyn has suggested, the number of recent dispersive encounters may have been exceptionally large and the present number of spiral nebulæ abnormally great.

In thus following out in some detail our conception of the origin of spiral nebulæ, we have wandered far afield from the planetary problem with which we started; let us return to the modest nebula that was drawn out, by hypothesis, from our sun and was destined to form the family of planets on one of which we dwell. As already implied, the material was sun-substance at the start, and of course in a gaseous state for the greater part, if not altogether. This gaseous matter was shot out in successive pulses by recurrent explosive action, and these pulses took the form of irregular knots attended by much highly scattered matter.

Pulsatory action in a persistently explosive body like the sun seems to be a normal habit and is well illustrated by the sun's present action in projecting "prominences." Such action is likely to become rhythmical if there are appropriate agencies. Such agencies may be assigned in the formation of the solar nebula. Every spheroid has a period of pulsation that is normal to it, and this period is quite certain to influence the periodicity of any impulsive agency that widely affects the body. Nagoaka holds that the successive explosions of Krakatoa during its catastrophic action in 1883, substantially coincided with the pulsation-period normal to the earth. The pulsation-period of the ancestral sun may be assumed to have influenced the succession of explosions made imminent by the increasing influence of the passing star.

There was perhaps a more influential factor. It is assumed that the plane of the orbit of the passing star crossed the plane of the ancestral sun's equator obliquely, for this seems to be implied by the present obliquity of the sun's equator to the invariable plane of planetary system, and also by the anomalously low rotation of the sun which probably implies a reversal of the sun's ancestral rotation. When the tidal cones developed by the star crossed the equatorial belt of the sun, they came into coincidence with its explosive belt and the effect was intensified by this coincidence. It was also affected by the superior centrifugal components of rotation that affected this belt. The concurrent explosive action that arose at this time should therefore have been exceptionally effective. This concurrence probably also fell in with a more or less perihelion position of the star at which time its differential effect was greatest. These concurrences may be the special reason for the greater size and distance of the major planets.

Unbalanced elements in the ejective impulses naturally gave rotation to the knots, and this united with whatever rotatory property they already had as parts of the sun, so that there was a beginning of rotation at the very start. The large knots necessarily influenced the movements of the smaller knots that were shot out with them and kept near them, indeed they fully controlled any that remained within their "spheres of influence" in the technical sense. The whirl of each bunch of knots sent forth by a given explosion would naturally tend to relate itself to a common plane and the knots would generally have a common direction of revolution, but reversals in some cases might obviously arise. Herein lies the basis of origin of the satellites.

On emerging from the sun, the ejected matter suffered great expansion and consequent cooling, and this was followed by further cooling as it traversed interstellar space. Much of the material should therefore soon have been reduced from its original gaseous state to the liquid and solid states; particularly must this have been true of the more refractory material which makes up the greater part of the earth and probably of the other planets. The highly scattered matter of nebular haze could hardly have remained long in any other state than solid or liquid, but it was of course at first in minute division. As the temperature range of the liquid state is small, we may call the cooled matter solid, for convenience. The knots may have retained the gaseous state in larger degree, but the irregular forms they present in so many cases seem better to tally with the view that they too were made up largely of minutely divided solid matter in orbital motion. Doubtless gaseous matter formed some appreciable part of the knots, while a multitude of isolated molecules outside the knots doubtless pursued independent orbital courses about them.

The nebula is thus conceived to have been formed in the main of molecules and minute bodies pursuing orbital courses about the solar center, and subordinately about the gravity-centers of the knots. The movement of these minute bodies was of the same type as that of the planetoids and planets and hence they have been called planetesimals, and the theory of which they are the distinctive working element, the planetesimal hypothesis. Those minute bodies that, in addition to revolving about the solar center, revolved also about the gravity-centers of the knots, may be called satellitesimals if one wants to be specially precise, but the term planetesimal is the generic one and covers the whole class of small bodies revolving in orbits similar to those of the planets.

We have now the working mechanism for the remainder of the evolution. All the rest follows as a matter of celestial mechanics, and the details need not be pursued here. The knots, as the natural centers of growth, gathered in the haze and grew to planets, planetoids or satellites. The eccentricities, obliquities and irregularities of the original planetesimal orbits involved many crossings and thus facilitated accretion. The shiftings of the orbits by the mutual attractions within the system led on constantly to new relations and further aided aggregation until most of the planetesimals were gathered into the growing planets, planetoids and satellites. Perhaps some planetesimals remain unassembled and contribute to the phenomena of the Zodiacal Light and the Gegenschein. The combination of a multitude of bodies in somewhat eccentric and irregular orbits led inevitably to fewer and more circular orbits. The nuclei that grew most came to have the most circular orbits as an obvious consequence, and this is well exemplified in the present planetary system. The planetoids are especially eccentric, while the small planets, Mercury and Mars, have more eccentric orbits than the great planets. As a mechanical effect, each nucleus moved into a larger or a smaller orbit in proportion as more planetesimals of larger or of smaller orbits were added to it, so that the growing planets tended to space themselves out automatically towards the less occupied feeding grounds. Probably the distribution of mass in the nebula gave rise to stable and unstable zones, and the planetesimal orbits were more or less bunched in the stable zones on account of this and thus also the growth and position of the planetary nuclei were influenced. Bode's law thus perhaps comes to have a physical meaning.

But about the directions of rotations of the planets! "Aye, there's the rub."

At the time this hypothesis was first entertained, it had been, for a long time, a standard doctrine that planets formed from coherent rings would rotate in the direction of their revolution, that is forward, while planets formed from bodies moving in independent orbits would have retrograde rotations. If this law holds, our planetesimal scheme of growth, well as it seems to work in so many particulars, fails seriously here, for six of the eight planets have forward rotations. The two others probably rotate obliquely backward, at least their satellites revolve in this way. These last make trouble for the ring hypothesis, to be sure, but still it has greatly the advantage over the planetesimal hypothesis *if* the reasoning back of the alleged law is sound and applicable. It runs in this wise:

In bodies that rotate as a unit, like a ring, the outer part moves faster than the inner part, and besides, every portion of the outer part goes once around the inner parts in every rotation of the ring. If therefore the ring is made to collect into a spheroid in any normal way, the spheroid should inherit a forward rotation. On the other hand, if a ring-like belt is made up of small bodies revolving in independent orbits, as do the particles that make up the rings of Saturn, the inner bodies must move faster than the outer ones, and if these bodies are aggregated in a normal way, it was held the resulting rotation must be retrograde. Here then, there seems to be a lion in the way of all orbital hypotheses, and the planetesimal hypothesis is a most declared type of this class.

But is the reasoning applicable? In the case on which the reasoning is based, the orbits are circular. The whole line of reasoning, as well as the ring hypothesis itself, seems clearly to have had its initial suggestion in the rings of Saturn, and very naturally so, as they seem to be remnants of the process of evolution providentially left for our instruction. Roche and Maxwell, however, showed on theoretical grounds that they teach something very different, and Keeler showed by the spectroscope that Saturn's rings are formed of separate solid bodies and not of gases as was assumed in the Laplacian hypothesis. The orbits of the particles that make up these rings are nearly circular and if massed by some systematic process into single bodies these might not unlikely have retrograde rotations; that would depend however on the precise way in which the particles were brought together. But we need not dwell on this case for it is exceptional; the Saturnian rings were developed under the conditions postulated by Roche and are a peculiar feature. Most orbits in the heavens are not circular and strictly concentric, as are these, but are elliptical, and the planetesimal orbits were by hypothesis notably elliptical. Now the velocity of a body in an inner elliptical orbit is indeed on the average higher than that of one in an outer elliptical orbit of the same type, just as in the case of circular orbits, but *at the points* where an inner elliptical orbit cuts an outer orbit, and where alone the bodies in these orbits can come together, the velocity of the body in the *outer* orbit is higher than that of the body in the inner orbit, *precisely reversing the application of the law.* This may be demonstrated mathematically, but the layman may prefer to visualize it. This may be done in the simpler cases. If a notably smaller elliptical orbit is placed concentrically within a larger orbit of the same type, there can be no collision. It is only when the major axes are so moved that a more or less aphelion or distal portion of the smaller orbit is made to coincide with a more or less perihelion or proximate portion of the larger orbit that collision can occur. If the dimensions be so selected that the precise aphelion point of the inner orbit can just touch the outer orbit at its perihelion point, it is easy to see that from this point the body in the inner orbit falls back in its onward course little by little toward the central body because its velocity is insufficient to maintain its aphelion distance. On the other hand, the body in the outer orbit moves steadily farther and farther from the central body in its onward course because its velocity is more than enough to maintain its perihelion distance, i. e. the common distance of the two bodies when they were together. If the orbits appreciably cut one another, the inspection reveals similar relations of the two velocities but less clearly, and in other cases mathematical demonstration may be the only recourse. That will show, however, that this relation holds very generally but not universally.

The actual rotatory effects of the union of two bodies in elliptical orbits vary with the precise conditions of their union. Keeping in mind that the body in the larger orbit moves the faster at the critical point, it is clear that if a collision occurs when the body in the smaller orbit is *approaching* the junction, the rotational effect will be forward, but if the body in the inner orbit has *passed* the junction, the effect will be the opposite. In a large number of cases both phases are quite sure to occur. The total effect when a multitude of planetesimals are added to a knot will be determined by the mean effect of all. The areas within which collisions tend to forward rotation are greater than the areas of the opposite class, and thus the probabilities distinctly favor forward rotation, but irregular or special distributions make possible retrograde or oblique rotations.

Quite as important as the direction of rotation is the fact that velocity of rotation is not measured by the simple sum of collisional effects of like sign, but rather the algebraic sum of effects of opposite signs, and so the rotation may be low or high according to the propositions of the opposing phases of collision.

Now these features fit the case in hand, for the velocities, axes, and directions of rotation of the planets are quite various and do not conform to the systematic requirements of concentration from a common source. Rotations, slow or fast, forward, backward or oblique, with axes differently inclined, are all consistent with concentration from orbits such as are postulated by the planetesimal hypothesis. There was indeed a lion in the way, but he was chained to a very special and exceptional case.

Perhaps the most important test that can be brought to bear upon theories of the origin of the planets is found in the planets themselves, the ultimate product; in our earth in particular, because it is accessible to close inspection. The Laplacian and the planetesimal hypotheses have been carried down to their specific planetary applications, and have offered us definite stories of the early stages of the earth. These stages form the first chapter of earth history. The harmony of the stories with the later events of the self-recorded history, bear critically on the verity of these stories of earth genesis.

The series of Laplacian pictures is very familiar: (1) a globe of gas; (2) a globe of white hot lava enshrouded in a vast atmosphere; (3) a globe crusted over and covered by a nearly universal ocean overhung by a still deep moist atmosphere; and then (4), a series of slow internal and external changes. Having grown thus gradually out of the fluid state, the concentric arrangement of material normal to fluidity should have dominated the whole evolution and have had marked expression in the final product presented for inspection and verification today.

The series of planetesimal pictures departs widely from these: A nebular knot formed a nucleus at the start, partly gaseous, partly orbital, amounting, it may be, to a third or a half of the final mass. An early concentration of the knot into an earth-nucleus was followed by a very slow growth from the scattered planetesimals afterwards. The long series of infalls of planetesimals generated much heat, but chiefly in the upper zones of the growing atmosphere, whence it was easily and promptly radiated away. The magnetic and inelastic material was brought in faster than the non-magnetic and non-elastic, because magnetic attraction supplemented gravitative attraction, and because the orbital motions of the inelastic planetesimals were faster reduced by mutual collisions than those of the elastic planetesimals. And so the metals and the basic rock-material gathered more largely toward the center, while the more elastic material gathered later and more largely into the outer parts. The accessions were very heterogeneous notwithstanding. The planetesimals plunging into the atmosphere became ignited by the stroke and were largely dissipated to dust which floated at the will of the winds until gravity or precipitation brought it to the ground or the sea. This flotation had a more or less sifting effect, separating in some little degree the heavier from the lighter material, thus building into the very body of the earth a differentiation of specific gravity. This differentiation was abetted by the growing hydrosphere, and both atmosphere and hydrosphere were localized in their activities by the increasing deformations of the earth body. These united processes led thus on to continental embossments of lighter materials, and to abysmal sags of heavier materials. Radioactive matter, lodging at first promiscuously in the heterogeneous mass of the growing body, formed a multitude of self-heating centers. These, co-operating with other sources of heat arising variously in the self-compressing body, started local liquefaction in such material as was specially fusible or soluble, and these liquid parts, under the kneading strains of the earth, worked outward and initiated volcanic action, the radioactive matter partaking in the ascension and thus concentrating toward the surface. Life conditions arose early, and no doubt life soon followed and participated in the processes of growth. Thus slowly the earth grew to maturity and merged into the later history recorded in the known strata. The whole may be shortly summarized as a slow-growing earth-body, bearing a slow-growing hydrosphere, enwrapped in a slow-growing atmosphere.

Critical comparison of these two series of pictures must be left to special students of the earth and to time. Certain vital features of recent determination which will largely control future opinion relative to the genesis of the earth, are worthy of special attention: (1) the undeniable evidence of an alternation of cold and warm climatic stages following one another from the earliest date to which climatic evidences reach, now raised to demonstration by a long list of competent observers; (2) decisive evidence of the deep differentiation of the specific gravity of the earth-material, brought out by Hayford's analysis of geodetic data; (3) evidence of the concentration of radioactive material in the outer part of the earth, brought out by Strutt, Joly, Holmes, and others; (4) the determination of the earth's high rigidity, initiated by Kelvin and others, supported by seismic data gathered by a host of observers, supported also by the pendulum studies of Hecker, and now brought to a full demonstration by the brilliant co-operative work of Michelson, Gale and Moulton on new lines. All these new developments are welcome from the viewpoint of the planetesimal hypothesis. Whether the terms of the older hypotheses can be revised to fit them or not, it does not fall to me to say.

The foregoing relates to the origin of our present planets and satellites. A few words may be added relative to other forms of planetesimal genesis, and to the origin of the comets and meteorites. Elsewhere I have endeavored to show that, on the surface of a great rotating body of hot gases, the molecular activities necessarily give rise to krenal flights of molecules, i. e. elliptical excursions outward from the body, which are checked by gravity and returned to it without the collisions that usually terminate molecular flights within a body of gas. These krenal flights are especially promoted in the equatorial belt when centrifugal separation is imminent. Occasional collisions are inevitable in the course of the krenal flights, and some of these flights are thereby converted into orbital flights. Thus the dominant types of molecular flights are: (1) *within* the atmosphere, intercollisional; (2) at the *summit* of the collisional atmosphere, krenal, (3) in the *outermost* zone, orbital. The orbital atmosphere can only be formed from those molecules that have exceptional velocities, and hence its molecules carry exceptional energy and moment of momentum. The transfer of these exceptionally endowed molecules from the collisional atmosphere to the orbital atmosphere makes relatively heavy drafts on the energy and moment of momentum of the rotating spheroid. The transfer is accelerated by every acceleration of rotation, and the draft of energy and moment of momentum is thus accelerated as the critical point of centrifugal separation is approached. This accelerated draft seems to be such that the equatorial velocity never quite reaches the stage at which separation *en masse,* or even partitively, can take place by simple centrifugal action, but only by this indirect mode. The molecules that pass thus individually into orbits have paths that vary much from one another and are scattered widely throughout the sphere of control of the spheroid. They do not form a simple ring close about the shrinking spheroid, as in the familiar Laplacian conception, nor do they follow closely the analogy of the small bodies that make up the Saturnian rings. They constitute a variety of planetesimals, with elliptical orbits promiscuously crossing one another, and subject to aggregation in much the same ways as the planetesimals of the spiral nebulae, save that there are here no nebulous knots to serve as collective nuclei. This last is a vital point, for, in the absence of collecting nuclei, the aggregates are likely to be many and small, rather than few and large as in our planetary system. The planetary family thus separated from a gaseous nebula in the course of its condensation should consist of a multitude of small planetoids of eccentric orbits and rather diverse planes. A family of this type, on the near approach of a star at some later time, might be thrown into inextricable confusion and its members be liable to pass through the Roche limit of some other body of their own system, or of the new system, and to be torn into fragments which, as clustered groups, would be given very eccentric orbits. Such clustered groups of fragments are thought to constitute the nuclei of comets and from these gaseous emanations, developed by the heat of the sun, form comas and tails. Later, by dispersion, the fragments are scattered into meteorites.

This, in hasty terms, is the planetesimal conception of the origin of a family of planets, or rather planetoids, generated by centrifugal action from a spheroidal gaseous nebula while it is condensing into a sun. Such an origin belongs to the planetesimal genus of hypotheses in being strictly orbital, but the mode is distinctly different from that initiated by a passing star, and evolved through the form of a spiral nebula.

Early in this paper it was intimated that the special problem of the planetesimal hypothesis was the origin and growth of the present planets only, but that the concept must, none the less, be in accord with the greater events of cosmic evolution. A few words on this point seem required to fill out our theme.

The origin of our sun, and of suns in general, was definitely set aside as not falling within the special problem for whose solution the planetesimal hypothesis was offered. The origin of suns must probably, none the less, be related, in some suggestive way, to the processes and principles on which the planetesimal hypothesis is based. It will have been noted that the planetesimal hypothesis postulates an orbital state of the nebular matter. It is thus founded declaredly on orbital dynamics. In the phraseology of the naturalist, it belongs to the orbital genus. It is perhaps entitled to be regarded as the type of that genus, since it found its field by throwing down the doctrinal bars that shut off the orbital state from competency to give rise to forward rotations.

But suns are the great examples of gaseous bodies, and as such, are controlled by gaseous dynamics in contradistinction to orbital dynamics. There do not therefore seem to be obvious grounds for supposing that the stars came into being by an orbital process. Certain of the stars may indeed be concentrations of the large knots of the great spiral nebulæ, but these great knots are assigned to explosive separation from still greater gaseous bodies, and the real genesis of the gaseous state of the knot goes back to the origin of the great suns from which the nebulæ are supposed to have sprung. The suggestion of Kapteyn ("Scientia," Vol. XIV, N. XXXII-6, pp. 345-357) that the irregular nebula of Orion has qualities that fit it for an initial place in the helium series of stars, seems to tally well with the view, entertained earlier in this paper, that center-to-center collisions of stars, or other massive bodies, would give rise to irregular or radiant nebulæ. When one considers the prodigious velocities at which the great stars must collide, it is perhaps not too much to suspect that extreme dissociation attends the collision, and that this may be sufficient to give rise to the spectral effects which appear in the hydrogen-helium-nebulium nebulæ, and these may lead on to the spectral characters that appear in the helium stars and in the series that follows them. This speculative conjecture seems to find a measure of support in the succession of spectra observed in the Novæ. If this be warranted, the origin of this class of stars falls into the final place in the series of stellar approaches, the supremely close approaches, the head-on collisions. This brings the whole into a series of harmonious relationships. The dynamics of the last term, however, are of the collision-rebound or gaseous type, not of the orbital. A center-to-center collision is, however, an event much less frequent than are such approaches as are held to give rise to spiral nebulæ, and yet the stars greatly outnumber the known spiral nebulæ. Perhaps a reconciliation of this discrepancy may be found in the probable fact that the stars endure longer than the nebulæ, and in the multiplication of stars by spiraloidal separation into great knots that later condense into suns of a smaller order.

A further respect in which the stars seem to fall concordantly in with the orbital scheme of evolution, though not themselves of the orbital genus, seems to be disclosed by the recent discovery that the velocities of the stars are correlated with their spectral types, and these, in the opinion of some, are correlated with their ages, and in the opinion of others, with their masses. In either case, the relation is referred to the mutual influence of the stars in their approaches to one another as time goes on, these approaches not being usually near enough to call forth dispersive action. This class of approaches may be assigned a place at the distal end of the series of approaches, while the less distant order of approaches form the smaller spiral nebulæ, the still nearer approaches the larger spirals, the penetrations of the Roche limit, the grazing approaches, and the glancing collisions, the still more effective members of the spiraloid series, while the center-to-center collisions form the extreme climax of the series, giving rise to irregular and radiant dispersions attended by extreme dissociation. The center-to-center collisions obviously destroy a large part of the motion of translation of the colliding stars by converting the energy of translatory motion into energy of dispersion. If, as suggested, the attendant dissociation develops the primoidal spectral state appropriate to a new stellar cycle, the coincidence is suggestively happy.

The evolution of suns is of a higher order than the evolution of planetary systems. The evolution of organized star clusters and stellar galaxies is of a still higher order. In these, suns are but the units. In the dynamic organization of star clusters and galaxies there is a return to the orbital realm. And here again, the fundamental agency may prove to be the Janus-faced function of gravity acting paradoxically and partitively as a dispersive as well as centralizing agency. It has already been mentioned in passing that galaxies swinging near one another, or interpenetrating one another eccentrically, may develop spiraloid configurations on principles closely like those assigned to the origin of spiral nebulæ. If this view is justified, or so far as it is justified, our planetary hypothesis finds a correlative in an undeveloped gallactic hypothesis.

It will perhaps be generally conceded that the energies that express themselves in orbital activities transcend those that express themselves in gaseous activities. In like measure, orbital cosmogony seems to transcend gaseous cosmogony in dynamical potency. But there are interchanges between them and no doubt an equilibrium between them. That both have fields whose immensity and intricacy transcend all human grasp goes without the saying.