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# STRUCTURES OF THE TERRESTRIAL PLANETS

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# Structures of the Terrestrial Planets

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The origin of the Earth and other planets of the solar system poses one of the great central problems of astronomy. The famous nebular hypothesis of Laplace, which dominated ideas for nearly a century, considered all the planets to be initially gaseous. It provided no origin for the nebula itself, but the ultimate central body to which the nebula contracted would have had far too rapid rotation to be identified with the Sun. It may be noted even at this point that the Moon and Mercury can hold no appreciable atmosphere now, and Mars barely so, and they can never therefore have been in all-gaseous form, as in fact also turns out to hold for the Earth and Venus. The Sun being central to the system led theorists to turn to tidal or collisional encounters with a passing star, but this also implied initially gaseous planets, and also failed by a very large factor to account for the enormous scale of the system compared with the Sun -- Jupiter moves at a distance of 1000 solar radii and Neptune at 6000. This difficulty was overcome by the hypothesis that the Sun originally possessed a companion-star moving at a distance of planetary order from it, and by means of a close encounter of this body with a passing star would the incipient planetary material now be released. The encounter itself could speed up the companion-star sufficiently to break its weak gravitational binding to the Sun and cause it to escape. In a variation of this binary theory, the companion was supposed to be sufficiently massive to have evolved rapidly to a supernova-explosion stage, the Sun capturing a mere wisp of the vast amount of material (several sun-masses) thereby thrown off into spacce, the slightest asymmetry of recoil enabling the remnant star to be set free from the Sun. The captured gaseous material would expand and cool, some into dust, and settle into a pre-planetary nebular disc in rotation round the Sun, and this material would proceed to develop into a set of planets. These processes of formation would imply that other planetary systems than are own would be extremely rare.

Up to this stage, interstellar space had always been regarded as practically empty, apart from a few calcium atoms, but the situation was completely changed by the steady discovery of vast quantities of gas-clouds and dust-clouds, mainly in association, that go to constitute the main form of the galaxy and occupy about 15 per cent of its overall volume. Such clouds have dimensions of parsecs and masses several times that of the Sun, and pursue orbits in the galaxy just as do the stars, so that in addition to the huge general galactic rotational velocity they have superposed more or less random velocities of a few kms/sec relative to adjacent objects -- stars and clouds. Now it is dynamically possible for a star such as the Sun to acquire material from one of these gas-and-dust clouds. As our planets have total mass only 1/700th that of the Sun, it is evident that to provide for such an amount the Sun would need to have captured only the merest wisp of material from such a cloud. Capture could easily result through intervention of another comparably near star in slowing just part of the cloud relative to the Sun. Such a star would not have to come unusually close to the Sun for the effect to operate, since the clouds themselves have dimensions of interstellar order. The exact amount of material captured and its angular momentum about the Sun, which latter is what would determine the eventual scale of the resulting system, would depend on more or less chance factors. But the interesting point now emerges that planetary systems so formed may be extremely numerous in the galaxy, and other galaxies, though usually with orbital scale and total mass different from our own, and each with a variety of planets physically as in our own system. Similar dynamical action would lead to planetary systems in the very numerous external galaxies that are seen to contain gas-and-dust clouds, the latter component in particular being essential for production of planets of terrestrial type.

There is a second more direct way that a star such as the Sun would collect interstellar gas and dust without the action of another star, and this is by the process of accretion through gravitational focussing of material towards the axial line behind the Sun as it passed through the cloud. At one extreme, if the star were at rest within such a cloud, its attraction would draw in material radially, but if the cloud had vorticity or rotatory momentum as such clouds do, this would be conserved and the cloud could contract down only to an extent limited by centrifugal force. At the other extreme, if the star moved through the cloud at very high speed, it would collect little more than just the material it ran into bodily, and the mass captured would be negligibly small and have no orbital motion. However, somewhere between these extremes would exist a relative speed that would allow capture of a mass comparable with the mass of the planets. Depending on the density of the cloud, the requisite speed is of order 1 km/sec, and this is small compared with the relative velocities of stars and clouds, which have distributions averaging about 20 km/sec. But in the accretion process, the star interacts with the <u>whole</u> cloud, not merely with the little it captures, and this results in a a strong braking-action reducing its speed relative to the cloud, with the rate of capture increasing as the inverse-cube of the speed. Thus an initial speed such as 5 km/sec could well be slowed almost to zero by this braking-action during passage of a star through a large cloud and hugely increase the total capture. In this way, perhaps 1 star in 100 has undergone an encounter enabling capture of a mass of planetary order later to aggregate into planets, but even this could mean that $10^9$ planetary systems are associated with stars in our galaxy. That such a process frequently is undergone by the Sun is shown by the existence of myriads of comets, of which several million are in orbits about the Sun at present. There are of the order of a hundred groups of these that come in towards the Sun from almost identical points of the celestial sphere for each group. The groups are widely spread over the whole sphere, but show a strong belt-like distribution parallel to the galactic plane and also concentration towards the ant-apex of the motion of the Sun. The comets are vast swarms of widely spaced dust-particles forming in passages of the Sun through dust-clouds at higher speeds, though still below average, and only a small amount of material compared with the planets is captured at each such encounter with a dust-cloud.

As aforesaid, these galactic clouds are in slow rotation sufficient to prevent them collapsing down under their self-gravitation, which means angular velocities of a few time $10^{-15}$ per sec. Even this seemingly minute rate implies considerable angular momentum for the captured material, and it may be shown to be of the same order as that carried by the orbital motions of the planets. But there is possibly a stronger source of such momentum, for not only are clouds quite irregular in form and density, but a star would be most unlikely to pass symmetrically through one. The amounts of material converging towards the accretion-axis from opposite sides of some plane through it would usually be quite unequal, and a difference as small as 1 per cent would be adequate to account for the planetary angular momentum, and could be more effective than any intrinsic vorticity in the cloud.

Once captured by the Sun, the development of such a gas-dust nebula is readily determined. The 1 or 2 per cent by mass of its dust-particles will rapidly take up the form of a flat annular disc as thin as possible with its areal elements all in Keplerian orbits round the Sun. This is easily proved, but it is actually exemplified in nature by Saturn's rings whose particles are confined to circle the planet in an extremely thin plane annulus. The particles cannot coagulate to form moons of Saturn as they are closer to the planet than the Roche-limit at which distance differential orbital rotation overcomes their mutual gravitation. However, this is by no means so for the planetary dust-disc at far greater proportional distance from the Sun, and which would have flattened to a thickness of only a few centimetres at the distances where the terrestrial planets would then come to form. Incipient planets can grow by gravitation from chance accumulations within this disc and progressively increase in mass till all the material of the disc has been absorbed into them to produce the primitive terrestrial planets. By such means the Earth could gradually grow practically to its total mass in about $5 \times 10^4$ years. Moreover, growth of a planet by such means from a thin disc has two highly important consequences, as is next explained.

First, captured material would necessarily fall to its surface only in a very narrow circumferential band just a few centimetres wide and not to all parts of the surface. When the mass becomes sufficiently great for the infalling impact with the surface to produce melting, which would occur for an object the size of the Moon or greater, the material thereby liquefied would not pile up where it fell but flow sideways from the narrow band in polarward directions. This spreading on the surface would be especially conducive to rapid cooling of the material to solid form, and thus even the Earth and Venus would originate in all-solid form, as has already been seen so must have the Moon, Mercury, and Mars originated.

Second, because of their orbital motions, small areal elements of the disc will possess vorticity with axis perpendicular to the plane of the disc, and as mass is drawn in to a growing planet the vorticity is conserved, and thereby rotation is imparted to the body. Planets formed in this way would initially have rotation-periods of order 4 - 5 hours about parallel axes. This close parallelism still halds for a large proportion of planetary mass, which is mainly carried by Jupiter and Saturn. The excpetions to this rule can be accounted for by subsequent large additions of mass, and by tidal and dynamical action. There is also evidence from the excessive radioactive content of the outer layers of the Earth, which also is found on the Moon, that a second capture of interstellar material of such nature by the Sun took place, to be gradually swept up onto the already existing planets, and if the initial plane of the disc of this material, which would have had mass of order 1 per cent of the planets, its angular momentum would disturb the axes of rotation of the planets by amounts of the order of a degree or so, as they presently exhibit for the most part.

At the distances of the Earth and other terrestrial planets the solar-maintained temperature would be too high for hydrogen, the main interstellar constituent captured, to be collected in by such small planets. Even further out, at the distance of Jupiter and beyond, there would first be needed aggregation of a solid planetary core of mass comparable with that of the Earth, and at the lower temperature there prevailing this core could then go on to retain hydrogen and other light gases, and gradually accrete the whole of the primal captured gases. This explains why the great planets not only have masses some two orders of magnitude greater than the inner planets but mean densities only of the order of unity (g $cm^{-3}$) because of their high content of hydrogen, compared with about 3 - 5 g $cm^{-3}$ for the terrestrial planets.

A further important consequence of the inner group of planets from a well-mixed dust-cloud is that they must all have similar chemical composition. There could be no possibility, for example, of the Earth first forming an iron core and then going on to surround this by purely rocky material, as is often supposed to be its structure. The well-established seismic data for the Earth reveal all its physical properties at every depth, apart from the temperature and chemical composition, and these known elastic properties can be applied to the earlier forms of the Earth and to the present and earlier forms of the other inner planets and the Moon, and fully account for their principal features and interior mass-distributions. Thus when the Earth was all-solid, in which form it remained for about $10^9$ years, its radius would have been about 370 kms greater than at present. But as a result of internal radioactive heating there occurred intermittent epochs of rapid overall contraction, at times of the order of $10^8$ years apart, which occasions correspond to eras of intense mountain-building, of which there are known to have been more than twenty such eras during the age of the Earth.

It is also possible using the seismic data to calculate the initial moment-of-inertia of the Earth, and when the crucial stage of mountain building was first started about $3 \times 10^9$ years ago, the value would have been $9.78 \times 10^{44}$ cgs units compared with the present value of $8.15 \times 10^{44}$ cgs. It follows that the average rate of decrease during the past three aeons has been $\dot{C} = - 1.70 \times 10^{27}$ cgs. Now dynamical analysis of the ancient-eclipse data, which as yet cover only the past 3300 years, inescapably requires a changing moment-of-inertia, and the rate emerging from the most accurate values of the secular accelerations of the Moon and Sun is $\dot{C} = - 1.67 \times 10^{27}$ cgs, a value in remarkably close agreement with the average rate during the whole life of the Earth.

This theoretical approach to planetary formation enabled it to be predicted, before any space-missions to planets, that unlike the Earth there would be found no folded and thrusted mountains on the Moon, Mercury, and Mars, but that such mountains would be found on Venus. All these predictions have now been proved correct. Much has been made of the longstanding general acceptance of a high density for Mercury, which is widely believed to be almost as high as that of the Earth at a figure of 5.4 g $cm^{-3}$, implying an iron content of about 60 per cent. This result rests ultimately on a value promulgated by Newcomb in 1895, but investigation of his work has revealed that after an extensive study over a period of several years, which gave a closely accurate and acceptable value for the mass of Venus, he abandoned its implications for the mass of Mercury and quite unjustifiably adopted on no valid basis a value of Sun/6000000, when his actual arithmetic if followed out would have led to a mass of Sun/8,500,000, which latter value would bring the density and hence the composition of the planet into line with the other terrestrial planets and the Moon. There is urgent need for a thorough re-discussion of the Mercury-mass which can in fact now be accurately determined far more straightforwardly and precisely from the Viking data than by any other means.

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