EVIDENCE FOR LUNAR-TYPE OBJECTS IN THE EARLY SOLAR SYSTEM

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Objects of the solar system, in addition to the Sun, can be classified into four groups – the planets, objects of lunar mass, smaller objects of variable mass and the comets.

If the solar proportion of gases relative to non-volatile compounds of the variety in the terrestrial planets, namely about 300 times the mass of these elements, were added to the terrestrial planets, they would have masses comparable to those of the major planets. Mercury is low in mass but has a high density, indicating that it has lost several times its mass of silicate materials relative to high density metallic iron. If this were restored and then the component of gases were added, it would also fall into the group rather naturally. Mars appears to be rather small. Uranus and Neptune have rather high densities indicating some loss of gases, probably hydrogen and helium. When we attempt to estimate the mass of primitive solar material from which the planets were evolved, we conclude that they evolved from very similar masses. Later, I shall argue that the process was a very inefficient one.

Schmidt (1944) suggested that the planets accumulated from many small objects, and, in this case, one might reasonably suggest that the axes of rotation might be oriented in a vertical direction to the invariant plane. Only for Jupiter is this true, and this may indicate that large objects such as of lunar mass were present, and were part of this accumulation process. Table I gives the orientation of planetary axes. Tidal effects have probably slowed the rotations of Mercury and Venus, though the reverse rotation of Venus can hardly be explained in this way. As Singer (1970) has pointed out, the reverse rotation could be explained by a collision of an object of lunar mass with the planet in which the relative angular momentum of planet and lunar object could be sufficient to reverse the direction of rotation. Also, the somewhat erratic orientation of the axes of the other planets could be explained by similar processes.

A second group of objects in the solar system consists of seven satellites having the mass of the terrestrial Moon within a factor of 2. Table II gives the masses of these satellites in units of the Moon's mass, the densities of the satellites and the fraction of lunar type material, assuming that they consist of material of this type and a material of density 1.0 g cm^{-3}, presumably water, and the masses of lunar type material so calculated in units of lunar mass. If it is assumed that low densities are due to admixtures of water, the masses become even more constant. A third group of objects consists of the smaller satellites of the planets and the asteroids, the largest of which have masses of a few percent of a lunar mass. It is interesting and probably informative that a group of seven objects of nearly lunar size exists in the solar system, and that a distinct discontinuity in masses exists within the planetary satellites.

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It is interesting that Triton moves in a very nearly circular orbit with an axis tilted 160° to the ecliptic plane. If Pluto is an escaped moon of Neptune, as suggested by Lyttleton, this large tilt of the axis is explained, but is it not surprising that the orbit was left with a very small eccentricity? Possibly Triton was captured in a circular orbit lying in the plane of the equator of Neptune, and a lunar object was subsequently captured into the body of Neptune, thus tilting its axes but leaving Triton approximately in its original orbit. Possibly Pluto is a lunar object which has not been captured. Possibly other such objects exist and have not been observed as yet. A fourth group of solar objects are the comets which may be the source of some meteorites.

If this evidence for a substantial number of objects of lunar mass is to be taken as valid, it is necessary to assume that these objects were captured by the planets, and, hence, originated in the solar nebula as independent objects. This is a popular assumption in regard to the origin of the terrestrial satellite, mostly because of chemical arguments. Urey (1958, 1966) has postulated such an origin and has proposed that gravitational instability in a gaseous solar nebula was a suitable physical mechanism for producing such objects, and that the Moon was one of these. The formulae for such masses have been given in previous publications (Urey, 1958, 1966). Using the theory of Chandrasekhar (1955), it was postulated that early in the history of the solar system, there existed a nebula in quiet rotation about the Sun with variable

TABLE I

Inclination of axes

Mercury	–
Venus	180°
Earth	23°27′
Mars	25°12′
Jupiter	3°7′
Saturn	26°45′
Uranus	98°
Neptune	29°

TABLE II

	Mass	Radius	Density	Lunar solid %	Mass
Io	0.985	1.00	3.22	98.4	0.969
Europa	0.641	0.89	3.02	95.5	0.612
Ganymede	2.112	1.60	1.73	60.2	1.271
Callisto	1.316	1.44	1.48	46.3	0.609
Titan	1.87	1.40	2.31	80.9	1.513
Triton	1.85	1.08 ± 0.37	$4.8^{+12}_{-2.8}$		
Pluto	?	?	?		
Moon	1.00	1.00	3.34	100	1.00
				Av.	0.994

temperatures as a function of distance from the Sun, but constant temperatures in directions perpendicular to the nebula plane. In this case, the variation of density vertical to the plane is given by:

$$\varrho = \varrho_0 \operatorname{sech}^2\left(\frac{x}{H}\right), \qquad H = \left(\frac{RT}{2\pi G\mu\varrho_0}\right)^{1/2},$$

where ϱ_0 is the density at the median plane, x is the distance vertical to this plane, μ is the mean molecular weight of the gas and here assumed to be 2.4. The mass per unit is found to be $2\varrho_0 H$. Chandrasekhar's formula for the minimum unstable wavelength in a direction perpendicular to the axis of rotation is:

$$\lambda = \left(\frac{\pi\gamma RT}{G\mu\varrho}\right)^{1/2} \left(1 - \frac{\Omega^2}{\pi G\varrho}\right)^{-1/2},$$

where γ is the ratio of heat capacities, C_p/C_v, and Ω is the angular velocity of rotation. Using the mass of the present Sun to calculate Ω and assuming that the value of ϱ to be used is $\varrho_0/2$, the quantity in the second parenthesis is 0.819 for all distances. If the field due to the nebula is included, a massive nebula would decrease this somewhat. The minimum unstable mass is:

$$m = 2\varrho_0 \left(\frac{RT}{2\pi G\mu\varrho_0}\right)^{1/2} \left(\frac{2\pi\gamma RT}{G\mu\varrho_0}\right) \left(1 - \frac{2\Omega^2}{\pi G\varrho_0}\right)^{-1}.$$

We use the Roche density for ϱ_0, namely

$$\varrho_0 = \frac{M_\odot}{2\pi R^3 \times 0.04503} = \frac{2.10 \times 10^{-6}}{c^3},$$

where c is the radial distance in astronomical units.

These formulae are very approximate when applied to a real solar nebula instead of an idealized gas of uniform density in all directions. One does not believe that cubes of gas, in the three dimensional case, nor that square areas of gas, in the two dimensional case, collapse to spheres. Also, the presence of solids, which may have been of various sizes and might have settled to the median plane of the nebula, will surely modify the results deduced from these formulae. In particular, the temperatures that have been calculated in previous papers are probably not realistic as has been noted previously. Radioactive substances will be present in the solar nebula, and, hence, some electrical conductivity will be present and magnetic fields may be trapped and considerably modify the behaviour of gases.

If solids accumulate in the median plane of the nebula, one could expect a development of variable densities of solid masses. Such variable accumulations would seem to be most probable, and, in fact, these may constitute the way that planetary growth occurred. If such variable masses occurred and by chance became more concentrated in some area, gravitational instability of the gases would be promoted and a gas sphere with solids accumulating at the center would probably be promoted. Hence, higher temperatures and lower densities than those required by the theory of gases would be required.

In past discussions of this problem, it was assumed that objects of lunar mass, plus the quota of gases based on estimated solar abundances, were formed throughout the solar system. With this hypothesis and the assumption of the Roche density at the median plane, the temperature and densities at the median plane can be calculated. These are presented in Table III. It is immediately evident that the temperatures are very low. In fact, at Uranus and Neptune, only helium would remain in the gaseous state. The assumption of lunar masses was justified on the assumption that all satellites of approximately lunar mass throughout the solar system accumulated in this way, and that they were captured by their planets. The table also shows the value of ϱ_0 for the different planetary distances. Kusaka *et al.* (1970) have recently discussed the accumulation of the planets from a solar nebula, and their values for the temperatures and densities are given in the last two columns. These data apply to the stage of solar development when the Sun had a luminosity of 10 $L_{\odot}$ at which time the solar nebula was present. Their temperatures fall off approximately with $c^{-1/2}$, and these temperatures apply to the outer surface of the nebula which are illuminated by the high temperature Sun. Table III, in the last two colums, gives the nebular masses for each planetary region and the total masses. Our total mass for the nebula of 0.6 $M_{\odot}$ is only three times the value of 0.2 $M_{\odot}$ preferred by Herbig (1971) in order to account for the dust in space. The Kusaka *et al.* (1970) nebula has about one fourth of Herbig's preferred mass. On either model a high temperature process occurred as the nebular material left the contracting solar mass followed by the cooling of this nebula to lower temperatures. Probably the fine dust to produce the T-Tauri stage was formed at this time. This was followed by other processes which formed the planets, here assumed to have occurred through gravitationally unstable masses. Table III also shows the densities per unit area of the nebula to secure lunar masses of 2.2×10^{28} g for the lunar gas mass and the values assumed by Kusaka *et al.* (1970). These latter masses are based on the assumption that the solar nebula had exactly the masses needed to produce the planets with no excess planetary matter lost to space. It seems reasonable to suppose that a contracting mass of gas with excess angular momentum would throw off a nebula in a rather continuous way without such gross minimum and maximum amounts of material at neighbouring radii, and that the apparently erratic varying masses of planetary bodies are due to methods of accumulation of these bodies.

If such gas spheres were formed, the solids would settle to their center. If the solids were present as very small particles, they would settle slowly, and if as larger objects, more rapidly. The energy of accumulating a lunar object would be absorbed by the great heat capacity of the gas so that the lunar object would be formed at a low temperature. If the energy of accumulation were distributed uniformly through the gas sphere, its temperature would be raised by less than one degree. If the gas sphere lost energy by radiation, it would contract and temperatures would increase at the

TABLE III

	AU	$m = 2.2 \times 10^{28}$ g			KNH		$m = 2.2 \times 10^{28}$ g Urey	KNH
		T	ϱ_0, g cm^{-2} ($\times 10^{-3}$)	H km ($\times 10^{-5}$)	T	g cm^{-2}	Neb. masses ($\times 10^{-32}$ g)	Neb. masses ($\times 10^{-30}$ g)
Mercury	0.3871	106.15	1127.0	1.56	405	1600	1.3543	0.2159
Venus	0.7233	56.81	323.0	2.91	274	11000	1.1240	3.434
Earth	1.	41.09	169.0	4.02	225	7200	0.8793	4.024
Mars	1.5237	25.97	72.7	6.12	176	2200	1.2272	0.4245
Asteroid	2.7673	14.85	22.0	11.13	130	0.22	1.4695	0.00161
Jupiter	5.2028	7.84	6.24	20.92	97	1500	1.4547	37.08
Saturn	9.5388	4.31	1.85	38.36	73	130	1.5587	12.19
Uranus	19.191	2.14	0.458	77.18	54	36	1.3692	10.02
Neptune	30.07	1.39	0.196	120.93	45	28	0.8704	23.69
Pluto					40	1		0.6372
						Total	11.3078×10^{32} $\sim 0.6\,M_\odot$	91.172×10^{30} $\cong 0.45\,M_\odot$

center. Thus, one could expect that the surface might melt and a rather thick layer of liquid would form if the surface were agitated by massive storms which would be expected. The formulae for the central temperature and pressure for a sphere of mass M and radius R as calculated from Emden gas spheres (1929) are:

$$T_0 = 1.16 \times 10^{-15} \frac{M}{R}$$

$$P_0 = 1.09 \times 10^{-7} \frac{M^2}{R^4} \text{ dyn cm}^{-2},$$

providing the mean molecular weight is 2.4 and the value of $\gamma(=C_p/C_v)$ is 1.5. If the mass is 2.2×10^{28} g and $R = 8.5 \times 10^{10}$, $T_0 = 300$K and $P_0 = 1$ bar, and if $R = 2 \times \times 10^{10}$, $T_0 = 1276$K and 330 bar. More exact calculations have been made by Janet Bainbridge (1962). Thus, objects could be accumulated at low temperatures and be melted later at the surface. Later, as the gas sphere was dissipated by a high temperature Sun, the surfaces of such lunar objects would be subjected to a thermal history appropriate to their distance from the Sun. It is to be expected that all such objects at some particular distance from the Sun's center would not be of the same mass and would not proceed through the same thermal history. We should note that the gas spheres would be on the verge of instability due to the solar field, but they must not have too great stability for the gases might not be removed when the high temperature Sun with its sweeping magnetic field became effective.

Again, it should be noted that the theory is a very approximate one. It assumes that square areas in the nebula became gas spheres of equal mass and that the suspended solids had no effect on the process. Not all masses accumulated at the same time, all did not have the same mass, and they did not go through the same identical history.

Some became hot at their surfaces, some remained at low temperatures and some may have become melted throughout. The solid objects collided with each other and produced fragments of metal and silicate which fell on other objects. The great complications of the meteorites attest to such complications.

If these seven objects of approximate lunar mass were captured by the Earth and other planets, there is the serious problem of the mechanism of capture. Several suggestions in regard to the capture of the Earth's Moon have been made, i.e. dissipation of energy through tidal effects, collision with many smaller objects previously captured, and dissipation of energy in a terrestrial gaseous nebula, and possibly others will be proposed. Capture by interaction with other objects or with gaseous nebula might be applied to the satellites of other planets, but tidal effects could hardly be a general mechanism.

There have been serious difficulties with the suggestion that the Moon was accumulated in a primitive gas sphere because of its low density and the general belief that the carbonaceous chondrites represent the solar abundance of iron. This abundance of about 0.9 relative to silicon in numbers of atoms would lead one to expect a density of the non-volatile fraction of solar material considerably higher than that of the Moon, and would require a considerable amount of water in the lunar interior. Since the lunar rocks are remarkably free of water, this has not seemed probable. The high abundance of iron in the Sun, as determined a few years ago based upon Whaling's (1970) oscillator strengths, depends upon solar data on strong lines which are markedly affected by damping in collisions with hydrogen atoms in the Sun's atmosphere. Brueckner (1971) has shown that damping constants are larger than previously estimated, and, hence, that the abundances reported have been too high. Gilbert *et al.* (1974) and his associates have determined the oscillator strengths of weak lines, and these criticisms do not apply to abundances determined using these data. These latter determinations give a solar ratio of iron to silicone of about $\frac{1}{3}$, and the density of the solar material of low volatility agrees rather closely with that of the Moon. Thus, after considerable uncertainty, this particular objection to the Moon being a primitive object may possibly be resolved.

The difference in chemical composition of the Moon and terrestrial planets is a serious problem. The density of Mars is about 5.5, indicating that it is about 65% iron by mass while the Earth and the Moon must consist of about 30% and 15% of iron respectively. Some fractionation of this density element relative to magnesium and silicon and other elements must have occurred. Of course, we do not know whether other satellites of similar masses to that of the Moon have the composition of the Moon relative to these low volatile elements.

The hypothesis that there were many objects of lunar mass in the early solar system was advanced some years ago in an attempt to understand the differences in chemical composition of the Moon and Earth. The capture of the Moon by the Earth appears to be improbable, and this improbability seems to be relieved if many Moons were present. Also, the tilt of the axes of the planets is readily explained by this hypothesis, and other features of meteorites, variation in densities of the terrestrial planets, etc., are explained by this hypothesis. If many moons were not present in the early solar system, this student of the subject would prefer to believe that the Moon escaped from the Earth and would prefer to try to explain the chemical differences between the Earth and Moon rather than to assume that capture of one lone Moon by the Earth occurred, and would ascribe the irregular tilt of planetary axes to some unknown process. The 'Many Moon' hypothesis is viewed with disfavor by many students of solar origin, but it seems to me as being no less probable than the many asteroid hypothesis, and, in fact, I have assumed that many objects of both kinds were present.

One of the major problems of this 'Many Moon Theory' is the formation of regularly spaced satellite orbits. However, it seems probable that Mars had a nebula (Urey, 1972), and, if so, it seems likely that the other planets also had nebulae and that the capture and spacing of satellites were determined by the action of such nebulae. Describing such processes in detail is a very difficult problem. In discussing such complicated problems, it is desirable to be able to have observational data. This paper is an attempt to apply observational data to the problem.

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