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THE SATELLITES OF THE MAJOR PLANETS: WERE THEY ALL CAPTURED?

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Jupiter, Saturn, and Uranus have 15 (or possibly up to 18) regular satellites (i.e., with eccentricities and inclinations near zero) which are generally assumed to have been formed along with the planets and near their present orbits. We present evidence for their having been formed much later in the history of the solar system and in initial orbits very close to their respective planets. They then evolved to their present orbits, principally by tidal friction. Their source may be captured material, possibly of cometary origin.

If we look even in a cursory way at the planetary satellites of the solar system, there is one feature which stands out immediately, and that is the existence of families of "regular" satellites for Jupiter, Saturn, and Uranus (see Table I). By "regular" we mean that the orbits of these satellites are very nearly circular and very nearly in the equatorial planes of the planets, *i.e.*, the eccentricities and inclinations are essentially zero. Both Jupiter and Saturn also have irregular satellites with highly inclined and eccentric orbits. Their origin will not concern us here, although it is believed by many that they were captured and may therefore be related to asteroids or to cometary nuclei. For the regular satellites, however, the fact that the eccentricity and inclination are both zero is incompatible with the idea of a *simple* capture, for example by tidal friction from an inclined and initially hyperbolic orbit. In any case, the capture of even a single satellite would seem to be very improbable.

The generally accepted view about the origin of the regular satellites is that they were formed *along with* the major planets in or near their present orbits, and that their orbits have been more or less permanent for the last 4 1/2 billion years (Kuiper 1956). This impression is reinforced by the observed commensurabilities of orbital periods (resonances) which could not have been maintained under evolving orbits. The relationships between orbital distances (Dermott 1968) remind one of the Bode relationships of the planets, and therefore suggest an origin similar in some respects to that of the planets. It has even been suggested that the three planetary systems are analogous to the solar system itself, and that a similar set of physical phenomena can account for the formation of all four systems (Alfven and Arrhenius 1975).

In spite of this strong circumstantial evidence for a formation of the satellites contemporary with the planets, and for little if any evolution of their orbits, one can also make a case for the exact opposite: namely, against contemporary formation and for considerable orbit evolution. We will argue in this paper: (1) that the satellites did not form contemporaneously with the

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TABLE Ia

PLANETS OF THE SOLAR SYSTEM

Planet	Radius (equatorial) km	$R_e = 1$	Mass 10^{27} g	$M_e = 1$	Density $g*cm^{-3}$	Rotation Period (equatorial) seconds	Obliquity Degrees	Oblateness
Mercury	2420	0.38	0.317	0.053	5.3	5,068,500		0.0
Venus	6200	0.97	4.871	0.815	4.95	21,003,000 (r)		0.0
Earth	6378	1.00	5.977	1.000	5.52	86,164.1	23.45	0.034
Mars	3400	0.53	0.640	0.107	3.95	88,642.6	25.2	0.052
Jupiter	71400	11.23	1900.0	317.89	1.314	35,430	3.07	0.0599
Saturn	60000	9.41	568.9	95.18	0.704	36,120	26.74	0.108
Uranus	25400	3.98	87.3	14.6	1.31	38,880	97.93	0.0303
Neptune	24750	3.88	102.8	17.2	1.66	56,880	28.80	0.0259
Pluto	~3200	0.5	0.66	~0.11	~4.9	551,820		

Surface Gravity $cm*s^{-2}$	Escape Velocity km/s	R_{sync} R_s/R_e	Orbital Period Tropical Years	Eccentricity	Inclination degrees	Orbital velocity km/sec	$[M^{\frac{1}{2}} R^{\frac{3}{2}} P^{\frac{13}{3}} d^{\frac{13}{6}}]$
360	4.2		0.24085	0.2056	7.0043	47.90	
850	10.3		0.61521	0.0068	3.3944	35.05	
982	11.2	6.619	1.00000	0.0167	0.	29.80	
376	5.0	6.033	1.8809	0.0934	1.8498	24.14	
2288	59.5	2.268	11.862	0.0484	1.3056	13.06	7.81×10^{49}
905	35.6	1.866	29.458	0.0557	2.488	9.65	9.22×10^{48}
830	21.4	2.411	84.013	0.0472	0.772	6.80	5.21×10^{48}
1100	23.6	3.362	164.793	0.0086	1.771	5.43	
430	5.3	21.9	247.686	0.2502	17.14	4.74	

The data for the outer planets are from Newburn, R. L., and Gulkis, S. *Space Sci. Rev., 14,* 179, (1973). The data for the inner planets are from Allen, C. W. *Astrophysical Quantities.*

planets *but were formed later,* and some of them quite a bit later, from material injected by comets; and (2) that after formation near the planet each satellite evolved to its present orbit by tidal friction and by mutual gravitational interactions. This view, which goes counter to many accepted ideas, will be supported by two lines of evidence: (1) the apparent impossibility of reconciling the observed zero inclination of the satellites with the non-zero obliquities of their planets; and (2) an empirically-derived relationship involving the semi-major axes of the satellite orbits and the satellite masses, which suggests tidal evolution according to a similar scheme for the regular satellites of all three planets.

In what follows we will concern ourselves, therefore, with the Jovian satellites, J1, J2, J3, J4, and J5; with the Saturnian satellites, S1, S2, S3, S4, S5, probably S6 as well, possibly S7 (Hyperion) which would have had to have lost much of its mass recently, and S10. In the case of Uranus, all of the satellites are regular, *i.e.,* U1, U2, U3, U4, and U5.

1. WHEN AND WERE THE SATELLITES ACQUIRED?

Consider the planet Uranus. Its obliquity is more than 90° *i.e.,* its spin axis is nearly in the plane of the ecliptic. Yet its five satellites are all in equatorial orbits, *i.e.,* their orbit planes are perpendicular to the plane of the ecliptic.

Now it is generally accepted that the obliquity of planets is a consequence of the process of their formation (Safronov 1972). If the final chunks impacting on the protoplanet had a mass of a few percent of the planetary mass and impact off-center, then the angular momentum they communicate will just result in obliquities of about the observed magnitude distributed randomly. As a result of the impacts, the spin angular momentum of the planet must undergo large and rapid changes near the end of its formation period. Now if the satellites were in existence at that time, or even if the satellites cores were in existence as protosatellites, they would not be able to "follow" the angular momentum changes of the planet, and therefore the satellite inclinations would become non-zero. The satellite orbit can follow the motion of the spin axis only if that motion is extremely slow in relation to the precession period of the satellite. Only in that case will the quadrupole moment of the planet be effective in changing the satellite's inclination (Goldreich 1965). In fact this is what happens in the case of Mars where the satellites remain in equatorial orbits in spite of the slow wobbles of the Martian spin axis. But when the spin axis moves rapidly, in relation to the satellite precession period, then the satellite orbital plane cannot move to follow the spin axis.

I have in fact examined several alternative possibilities and rejected them as impossible or implausible. Therefore, my conclusion is that the satellites were acquired or were formed in place after the formation of the planet was complete (Singer 1975).

While the case of Uranus is most dramatic, in view of its large obliquity, the same argument can be applied and should hold for Saturn and Jupiter. I conclude therefore that all of the regular satellites of the three major planets were formed near or around the planets some time after the planets themselves were assembled.

2. DID THE SATELLITE ORBITS EVOLVE?

Once it is settled that the satellites were acquired *after* the planets were formed, one would like to ask the question, when were they acquired and what were their initial orbits?

It is highly unlikely that the satellites were formed or acquired in just the orbits they have at the present time. The observed commensurabilities and resonances suggest at least some slight measure of evolution. Let us assume, however, that the satellites were formed initially quite close to the planet, and that they evolved to their present orbits under the influence of tidal friction. We know that this assumption cannot be completely correct because it neglects among other things the mutual gravitational interactions between the satellites. But since no complete theory exists which would show how orbits evolve under the influence of tidal friction and mutual interactions, we will for a moment neglect the latter and examine how much of the present observations can be explained by tidal friction. This should at least give us a measure of the importance of the neglected phenomena.

The classical theory of tidal friction will suffice for our purposes. We do not consider the frequency-dependent modification which must be introduced when the satellite orbit is close to the synchronous orbit of the planet (defined as the orbit which has the same period as the planet's spin period).

4 1/2 billion years, and certainly for the depletion of comets which might have been in non-hyperbolic orbits, *i.e.*, in highly elongated ellipses.

As regards the capture itself, we should note that in order for tidal drag to be effective in capture, the comet would have to penetrate within the synchro-

After some manipulation the tidal evolution time can be expressed by the following equation (Singer 1968):

$$T_{(sec)} = (GM)^{1/2} \ (13A \ \ \sin 2\delta)^{-1} \ \ (a^{13/2} - a_o^{13/2}); \text{ or} \tag{1}$$

$$T_{(b.y.)} = 6.6 \times 10^{-31} \ [M^{1/2} \ R^{3/2} \ P^{13/3} \ d^{13/6}] \ m^{-1} \ \ [(\frac{a}{a_s})^{13/2} - (\frac{a_o}{a_s})^{13/2}$$

here T is expressed in billion years (b.y.).

The terms in the square brackets relate only to the planet with: M the planetary mass in gm; R the planetary radius in cm; P the planetary spin period in sec; d the planetary density in gm-cm^{-3}.

Note that the satellite mass, m (expressed in gm), enters inversely into the calculation of T. However, the value of T is most sensitive to the size of the satellite orbit, a. On the other hand, it is not very sensitive to the initial orbit, a_o, provided that a_o is much less than a. Table I lists the relevant values, including values of the synchronous orbit size, a_s, expressed in planetary radii by

$$a_s / R = 1.93 \times 10^{-3} \ (P^2 d)^{1/3} \tag{2}$$

and the classical Roche distance a_R, given by

$$a_R / R = 2.45 \ (d/d_s)^{1/3} \tag{3}$$

where d_s is the density of the satellite.

Figure 1 presents the log of orbit evolution time T, as calculated from Eq. (1), plotted against the present position of the satellite as expressed in units of the planetary synchronous distance, a/a_s.

Several interesting features are apparent from examination of Fig. 1, which represents really only the distances as well as *masses* of all the regular satellites, all arranged in a particular way.

a. The evolution time of J4 is 4 billion years. This value was not forced or adjusted in any way. In other words, the constant in Eq. (1) was not normalized in order to make T (J4) equal to 4 b.y. Since we don't know the internal dissipation of the planets, or equivalently the displacement angle of the tidal bulge, δ, we have used the value appropriate to the earth-moon system which leads to a tidal evolution time for the moon of 4 1/2 b.y. This value was calculated in an earlier paper (Singer 1968) and is not the higher value currently observed for the earth-moon system.

b. The points for many of the satellites appear to fall along a narrow band surrounding a straight line, independent of the planet, at least for values of orbital radius between 3 and 12 times the synchronous radius. As we approach the synchronous radius, the situation is more confused. But this may simply be a consequence of the fact that we have assumed an extremely simple model, namely tidal evolution without any gravitational interactions among the satellites, no change in the mass of the satellites during the evolution, and no change in the physical parameters of the planets themselves. In fact, even the simple formula begins to break down when a approaches a_o, as can be seen from Eq. (1), *e.g.*, the a_o term can no longer be neglected. Furthermore, during tidal evolution, satel-

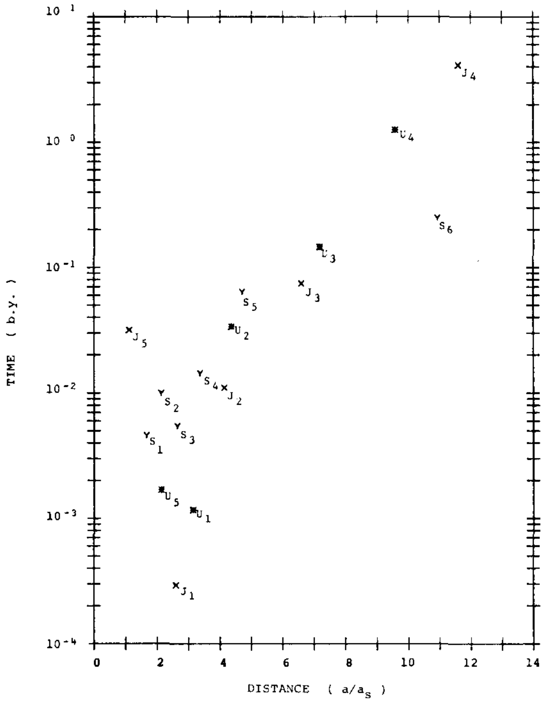

Figure 1. Orbital Evolution Time" for 16 regular satellites calculated according to eq. (1) plotted versus orbital distance (expressed in terms of synchronous distance).

required. For this reason also the very low values of evolution time indicated in Figure 1 for small values of a/a_S should not be taken too literally. Nevertheless, Figure 1 does suggest a rather dynamic picture of the solar system, with satellites being formed and acquired throughout the history of the solar system until very recent times.

(In fact, the process may still be going on. The rings of Saturn may represent a dynamic situation, just preceding the agglomeration of a satellite. It suggests also the possibility of long delays before this satellite is actually formed).

3. SOME SPECULATIONS ABOUT THE ORIGIN OF THE SATELLITES

Is capture of cometary material possible and plausible? I think the answer is yes. While comets appear to us to be rare phenomenon, this is due to an observational bias which makes comets visible only when they come close to the sun. Even today the frequency of cometary traversals in the region of the major planets is estimated to be 10,000 times greater than what is observed in the inner solar system (Rickman 1977).*

A further correction should be made for the depletion of comets over the last

The factor of 10,000 may be sufficient to explain why we don't see evidence for high comet fluxes in the inner solar system, in terms of impacts on Mars, Moon, Earth, or Mercury.

TABLE 1b

PLANETARY SATELLITES

Planet Satellite	Distance R_p	Sidereal Period Days	Inclination Degrees	Eccentricity	Radius km	Mass 10^{23} g	Density $g*cm^{-3}$
Earth							
1 Moon	60.270	27.3217		0.0549	1738	735	3.34
Mars							
1 Phobos	2.765	0.3189	1.1	0.0210	10.9 ± 0.5		
2 Deimos	6.912	1.262	0.9 - 2.7	0.0028	5.7 ± 0.5		
Jupiter							
1 Io	5.95	1.769	0.0	0	1820 ± 10	892 ± 12	3.17 ± 0.3
2 Europa	9.47	3.551	0.0	0	1550 ± 150	487 ± 12	3.08 ± 1.0
3 Ganymede	15.1	7.155	0.0	0	2635 ± 25	1490 ± 15	2.01 ± 0.06
4 Callisto	26.6	16.689	0.0	0	2500 ± 150	1064 ± 32	1.39 ± 0.35
5 Amalthea	2.55	0.489	0.4	0.003	210 - 35	0.03	
6 Himalia	161	250.6	27.6	0.158	~80		
7 Elara	165	260.1	24.8	0.207	~30		
8 Pasiphae	327	735	145	0.38	~ 8		
9 Sinope	333	758	153	0.28	~10		
10 Lysithea	164	260	29.0	0.130	~ 9		
11 Carme	314	692	164	0.21	~11		
12 *Ananke*	291	617	147	0.17	~ 8		
13 Leda	156	240	26.7	0.146	7-1		
Saturn							
1 Mimas	3.10	0.942	1.5	.0201	~200	0.37 ± 0.01	~1.1
2 Enceladus	3.97	1.370	0.0	.0044	~250	0.85 ± 0.03	~1.3
3 Thethys	4.92	1.888	1.1	0.00	~500	6.26 ± 0.11	~1.2
4 Dione	6.28	2.737	0.0	0.0022	575 ± 100	11.6 ± 0.3	1.45 ± 0.8
5 Rhea	8.78	4.518	0.4	0.0010	800 ± 125	23	~1.1
6 Titan	20.37	15.95	0.3	.0289	2500 ± 300	1401 ± 2	2.14 ± 0.8
7 Hyperion	24.68	21.28	0.4	0.1042	460 - 80	3.1	
8 Iapetus	59.3	79.33	14.7	0.0283	900 ± 100	10	~1.6
9 Phoebe	215	550.4	150	0.1633	160 - 30		
10 Janus	2.66	0.74896	0	0	~110		
Uranus							
1 Ariel	7.56	2.520	0	0.0028	1700 - 300	51	
2 Umbriel	10.51	4.144	0	0.0035	1100 - 200	15	
3 Titania	17.24	8.706	0	0.0024	2000 - 360	87 ±61	
4 Oberon	23.07	13.46	0	0.0007	1900 - 330	67	
5 Miranda	5.12	1.4135	0.0 - 3.4	.017	650 - 110	2.8	
Neptune							
1 Triton	14.3	5.877	160.0	0	3500 - 1000	3400 ± 2000	
2 Nereid	225	359.4	27.5	0.7493	600 - 100		

Data are mostly from Morrison and Cruikshank (*Space Sci. Rev.*, *15*, 641, (1974)). The data for J XII are from Kowal, C. T., Aksnes, K., Marsden, B. G., and Roemer, E. J. *A.J.*, *80*, 460 (1975). The masses for the satellites of Uranus are from Greenberg, R. *Icarus*, *24*, 325, (1975), and are relative to the mass determined for Titania.

lites can combine and increase their mass; *i.e.*, small satellites spiraling outward will be overtaken by larger ones and will be swallowed up.

We have done a series of numerical experiments to demonstrate some of these possibilities, but so far they have not been successful in explaining the deviations that are observed in Figure 1. Clearly, a more sophisticated approach is nous orbit, in which case the tidal bulge raised on the planet would exercise a decelerating effect. But for the major planets the synchronous orbit is extremely close in, but because of their high spin rates, and is therefore well within the classical Roche limit (see Table I). This feature allows us to speculate on various possibilities for enhancing capture beyond the simple tidal drag which may not create much deceleration on a single passage. We have the possibility of the impact of part of the comet on the planet creating a temporary atmosphere. We have the more promising possibility of breakup due to the gravitational gradient, with a subsequent reaction effect which aids in capture.

However the material is captured, it will be in its initial inclination, *i.e.*, non-equatorial. However, captured material broken down into small pieces will evolve into a "napkin ring" and turn into a disc, not too dissimilar from the Saturnian rings. From such a disc, it can assemble into a satellite, provided the density is large enough to allow gravitational instabilities (Goldreich and Ward 1973).

From then on the orbit will evolve under the influence of tidal friction and the gravitation perturbations of other satellites. The evolution will proceed at different speeds for different-sized satellites so that they may come to interact with each other quite strongly and even collide and combine. A detailed theoretical discussion of these processes has not yet been developed. However, the evidence from Figure 1 is certainly suggestive and persuasive that substantial orbit evolution occurred due to tidal forces and that the satellites were formed around the major planets at various times during the history of the solar system from captured material.

If this view proves correct, then all the satellites of the solar system may be formed by capture processes, including also the Saturnian rings.

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DISCUSSION

GROSSMAN: Are some of the satellites of the major planets not far too massive to be the debris of a single comet?

SINGER: A number of separate cometary events can and will combine to form a cloud around the planet which becomes a disk and later collapses into a single

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body. In addition, satellites can and will combine as their orbits evolve outward at different rates.

DELSEMME: Just for the record, since an average comet's mass is 10^{17} *grams, one* billion *cometary events would be needed to make one Moon or one Galilean satellite of Jupiter.*

GOLD: Goldreich showed that tidal friction is essential to the establishment of the commensurabilities between the satellites, and that a limit can be placed on the magnitude of this dissipation - i.e., *the "Q" of the planet - if the commensurability is not to be destroyed immediately. Within this limit, the tidal evolution of orbits continues, but leaving the commensurability intact.*

SINGER: This discussion leaves out the real possibility the satellites may have slipped in and out of different *communsurabilities as their orbits evolve. The details of the process of combined orbit evolution are of course very difficult to treat.*

GOLD: Goldreich also showed that a satellite will approach the equatorial orbit, if the rate of precession in planetary quadrupole field is faster than in the solar field.

SINGER: I have of course applied a similar principle of adiabatic variation to show that the satellites could not *have followed any reasonable change of the planetary obliquity,* i.e., *any shift of the spin axis.*

GOLD: Lastly I can see no sense in taking the Earth as a guide to the Q of gaseous bodies such as the major planets.

SINGER: Just to avoid any misunderstanding: since we don't know the value of Q of the major planets effective for tidal friction, I have used the value for the Earth-Moon-system which leads to an orbit evolution timescale of 4.5 b.y. It is interesting - and it may even be significant - that this leads directly to an evolution time of 4 b.y. for J4. Perhaps this is more than coincidence. But I am certainly not suggesting that earth rocks make up the interior of the major planets.

GREENBERG: In your plot of the time t vs. a/a_s *it appears that the J4 satellite of Jupiter would have been captured about 4 billion years ago. This seems to imply that the proportionality factors in t is one. If this is so, then some of the, say, Uranus satellites have ages of the order of million of years and shorter for other satellites. Does this allow enough time to achieve condensation of the satellites and subsequent orbit modifications to their present state of resonance?*

SINGER: You understand that I have simply plotted all of the regular satellites on one graph, using their present *masses and* present *orbital radii, and taking into account the properties of the 3 major planets: mass, radius, density, and spin period. It is remarkable that this representation leads to a single line, more or less. How to interpret this finding? On one end, the times of 4 b.y. for J4 and 1 b.y. for U4 are suggestive of tidal evolution - and these values were not forced. The interpretation of the very short "tidal evolution times" is more difficult - although not in principle - provided we are willing to accept the possibility of very recent (<1 m.y.) captures of cometary material. But - it is possible also that the simple tidal evolution equation does not tell the whole story for bodies that are either very close to the planet or relatively*

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less massive than the other satellites; for example, the neglect of the ($-a_o^{13/2}$) term may no longer be justified.

WHIPPLE: Your theory fails to account for the striking density variation among the Galilean satellites, going from meteoritic to icy in order of distance from Jupiter. This seems to be readily explicable in terms of formation when Jupiter was much hotter. This must carry the formation time back at least hundreds of millions of years, if not much more, contrary to your calculated ages.

SINGER: Perhaps I should point out that I have focused on accounting for the positions and masses of the satellites and that I find theoretical suggestions which fit those observations. As far as the chemistry is concerned, clearly one can put forward an ad hoc explanation which does not violate any physical laws. But perhaps one should wait until we have better information on the densities and compositions of the other satellites, especially those of Saturn and Uranus.

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