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23 June 1971

Jupiter: Its Captured Satellites

Abstract. *Because of the small size and irregular orbits of the seven outer satellites of Jupiter, it is often assumed that they were derived by capture. The conditions whereby Jupiter can capture satellites have therefore been examined. Relationships derived on the basis of the three-body problem for planets in elliptical orbits enable the dimensions of the capture orbits around Jupiter to be calculated. It is found that Jupiter may capture satellites through the inner Lagrangian point when at perihelion or at aphelion. Captures at perihelion should give rise to satellites in direct orbits of 11.48×10^6 kilometers and capture at aphelion to retrograde orbits of 21.7×10^6 kilometers. The correspondence with the seven outer satellites suggests that Jupiter VI, VII, and X in direct orbits at 11.47, 11.74, and 11.85×10^6 kilometers were captured at Jupiter perihelion, whereas Jupiter VIII, IX, XI, and XII in retrograde orbits of 23.5, 23.7, 22.5, and 21.2×10^6 kilometers were captured when Jupiter was at aphelion. Examination of the precapture orbits indicates that the seven outer satellites were derived from the asteroid belt.*

There appear to be two types of satellites in the solar system. Satellites of the first type are relatively large and have approximately circular orbits in the plane of rotation of the primary with which they are associated, and they were presumably derived from the processes that led to the formation of the planets themselves. Satellites of the second type are usually very small and in irregular orbits of large eccentricity and inclination. The orbits may also be direct or retrograde. It is often assumed that this type of satellite was derived by capture from elsewhere in the solar system.

Satellite capture can be analyzed in the restricted three-body problem for planets in elliptical orbits. Relationships developed in terms only of the mass of the planet relative to that of the sun and the eccentricity of the planetary orbit enable the possibility for capture of satellites by any particular planet to be determined (*1*). It is found that for smaller planets the eccentricity becomes a critical factor determining the possibility of capture.

Satellite capture may occur through the inner Lagrangian point only when the planet is at perihelion or aphelion (*2*). Capture at perihelion usually gives rise to satellites in direct orbits and capture at aphelion usually leads to retrograde orbits. Because of their small masses most of the planets can capture satellites only when at perihelion. This is related to the fact that the relative energy required to pass through the inner Lagrangian point is least when the planet is closest to the sun. Captured satellites of the smaller planets would be expected to be in direct orbits about the primary.

It was found for Jupiter, however, that the mass is sufficiently large so that capture of satellites at aphelion into retrograde orbits is also possible.

The 12 satellites of Jupiter appear to be of two distinct types. The Galilean satellites, Io, Europa, Ganymede, and Callisto, are large, with diameters ranging from about 3000 to 5000 km; they are in circular orbits of essentially zero inclination at distances ranging up to 1.88×10^6 km from the planet (*3*).

The seven outer satellites, Jupiter VI through XII, are small, however, with diameters ranging in size from about 12 to 100 km; they are in highly inclined and eccentric orbits at distances up to 23.7×10^6 km from Jupiter. In addition, four of these outer satellites are in retrograde orbits.

The relationships developed for purposes of examining satellite capture have been developed further and are applied here to calculation of the expected dimensions of the direct and retrograde capture orbits about Jupiter.

The Jacobian constant C in the circular, restricted three-body problem may be expressed as

$$C = 2\Omega - V^2$$

Table 1. Orbital parameters of the satellites of Jupiter and predicted capture orbits. Orbital parameters and diameters are from Allen (*3*). The dimensions of the capture orbits were calculated from Eqs. 2 and 3 of this report. In the fourth column, R denotes a retrograde satellite.

Satellite	Diameter (km)	Eccentricity	Inclination (deg)	Distance from planet ($km \times 10^6$)	
				Observed	Calculated for capture orbit
I (Io)	3340	0	0	0.42	
II (Europa)	2920	0	0	0.67	
III (Ganymede)	5700	0	0	1.07	
IV (Callisto)	4720	0	0	1.88	
V	140	0	0.4	0.18	
VI	100	0.16	28	11.47	11.48*
VII	20	0.21	26	11.74	
X	14	0.14	29	11.85	
VIII	20	0.40	33 R	23.5	21.7†
IX	16	0.27	25 R	23.7	
XI	16	0.21	17 R	22.5	
XII	12	0.16	33 R	21.2	

* Direct orbits. † Retrograde orbits.

where V is the velocity in the coordinate system rotating with the uniform velocity of the primaries about the center of mass, and

$$2\Omega = \xi^2 + \eta^2 + \zeta^2 + \frac{2(1-\mu)}{r_1} + \frac{2\mu}{r_2}$$

where ξ, η, and ζ are the coordinates of the particle in the same system, and r_1 and r_2 are the distances from the primaries of mass $1-\mu$ and μ, respectively (4).

When the primaries are in an elliptical orbit, the rate of rotation of the coordinate system becomes nonuniform, and the distance between the primaries in the dimensionless system also varies. Under these conditions, the Jacobian integral of the circular restricted problem must be replaced by the trajectory-dependent expression

$$C = \frac{2\Omega}{1 + E\cos f} - V^2 - 2(1-E^2)^{3/2}\int_{f_1}^{f_2} \frac{\Omega}{(1+E\cos f)^2} \cdot [E\sin f - E^2 \sin 2f + \cdots]\, df \quad (1)$$

This expression can be transformed to a coordinate system centered upon the planet by a procedure similar to that used in deriving the Tisserand criterion for the identity of comets (5).

For qualitative evaluation of the possibilities of capture, the integral term in Eq. 1 may be omitted. However, for precise calculations of the dimensions of a captured satellite orbit, this approach is insufficient, since it neglects the fact that the primaries will cover some finite portion of their orbit, expressed by the limits f_1 and f_2 of the integral, during the process of capture.

It is therefore necessary to evaluate the integral along the path of capture. The required expansions for this have been derived and give the following relationships from which the dimensions of the capture orbits for Jupiter may be obtained. For satellites captured into direct orbits at perihelion

$$\frac{\mu}{a} = \frac{2}{1-E^2}\left(\frac{1}{1-\alpha} + \frac{\mu}{\alpha} - 1\right) + \frac{(1-\alpha)^2(1+E)^2}{1+E} - (1-E^2)^2 + 2\Omega[E - 2E^2 + E^3 - 2E^4 + \cdots] \quad (2)$$

and for capture into retrograde orbits at aphelion

$$\frac{\mu}{a} - 4\sqrt{\mu a(1-e^2)}\cos i + 4a^2 = \frac{2}{1-E^2}\left(\frac{1}{1-\alpha} + \frac{\mu}{\alpha} - 1\right) + \frac{(1-\alpha)^2(1+E)^2}{1-E} - (1-E^2)^2 - 2\Omega[E + 2E^2 + E^3 + 2E^4 + \cdots] \quad (3)$$

where μ and E are the mass ratio and eccentricity of the planet and α is the fractional distance of the Lagrangian point from the planet; Ω is derived from the value of the function Ω along the path of capture; and a, e, and i are the semimajor axis, eccentricity, and inclination, respectively, of the capture orbit.

We have $E = 0.048332$ as the present value of the orbital eccentricity of Jupiter, $\mu = 0.000954763$, and $\alpha = 0.0666931$. Also $2\Omega = 3.0978485$ and 3.0532237 for perihelion and aphelion captures, respectively. This gives a value of 0.01475 in dimensionless units for the semimajor axis of the direct capture orbits when Jupiter is at perihelion. When a value of 5.203 astronomical units (A.U.) for the semimajor axis of Jupiter is assumed, this corresponds to semimajor axes of 11.48×10^6 km for the direct capture orbits. Similarly, a value of 21.71×10^6 km is obtained for the retrograde orbits when Jupiter is at aphelion.

The 12 satellites of Jupiter are listed in Table 1, with values for the approximate diameters of the satellites and the semimajor axes, eccentricities, and inclinations of the orbits. It can be seen that the outer group, Jupiter VI, VII, and X, in direct orbits of considerable eccentricity and inclination and with semimajor axes of 11.47, 11.74, and 11.85×10^6 km, respectively, correspond closely to the predicted value of 11.48×10^6 km for capture into direct orbits while Jupiter is at perihelion.

The second group of outer satellites, Jupiter VIII, IX, XI, and XII, are in retrograde orbits of high eccentricity and inclination at distances of 23.5, 23.7, 22.5, and 21.2×10^6 km from the planet; this group probably represents satellites captured at aphelion, for which retrograde orbits having semimajor axes of 21.7×10^6 km are predicted.

The heliocentric coordinates necessary for an object to be captured by Jupiter may be derived by utilizing the criterion that the object must enter the inner Lagrangian point at perihelion or aphelion with zero velocity. It is found that the direct capture orbits at Jupiter perihelion correspond to bodies that had semimajor axes of 2.7836 A.U. and eccentricity of 0.5989. Similarly, the retrograde capture orbits are related to objects that had eccentricities close to 0.4972 and semimajor axes of 3.1517 A.U. Since this range of orbital parameters encompasses that corresponding to the asteroid belt, it seems that the seven outer satellites are probably captured asteroids.

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10 May 1971

Antarctic Bottom Water: Major Change in Velocity during the Late Cenozoic between Australia and Antarctica

Abstract. *Paleomagnetic and micropaleontological studies of deep-sea sedimentary cores between Australia and Antarctica define an extensive area centered in the south Tasman Basin, where sediment as old as Early Pliocene has been systematically eroded by bottom currents. This major sedimentary disconformity has been produced by a substantial increase in velocity of Antarctic bottom water, possibly associated with late Cenozoic climatic cooling and corresponding increased glaciation of Antarctica.*

Studies of past oceanic circulation patterns have been restricted almost entirely to those changes in surface-water distributions indicated by fossil planktonic organisms (1). Changes in distribution and activity of deep-water masses have received little attention except where they are related to broad-scale, seismically defined changes in sediment patterns (2). Antarctic bottom water, which is produced under glaciated Antarctic conditions, plays an im-