ADVANCES IN SPACE DYNAMICS 4: CELESTIAL MECHANICS AND ASTRONAUTICS,
H. K. Kuga, Editor, 103-112 (2004).
Instituto Nacional de Pesquisas Espaciais – INPE, São José dos Campos, SP, Brazil.
ISBN 85-17-00012-9

MODEL OF A GIANT IMPACT ON SATURN

Mirta Gabriela Parisi
Adrián Brunini
Facultad de Ciencias Astronómicas y Geofísicas,
Universidad Nacional de La Plata and CONICET.
Paseo del Bosque s/n (1900) La Plata, ARGENTINA.
e-mail: gparisi@fcaglp.fcaglp.unlp.edu.ar

ABSTRACT

The origin of the obliquities of the giant planets is one of the fundamental questions of cosmogony. Large stochastic impacts are believed to play a key role during the last stage of the formation of the planets and have been considered as a possible explanation to account for the planetary spin obliquities. We assume that the obliquity of Saturn (26°.7) is due to a giant off-center impact with another protoplanet. We obtain that the impactor mass required to tilt Saturn is 6-7.2 $m_\oplus$. This range of masses set a constraint for the mass of the planetary embryos in the outer Solar System. In order to get dynamical constraints, we study the possible scenarios taking into account the mechanisms of satellite formation and the physical and dynamical characterisitcs of the saturnian moons.

INTRODUCTION

The origin of the spin obliquities of the giant planets is one of the fundamental questions of cosmogony. The rotation of the planets is connected with the process of planetary formation. Current theories of giant planet formation are based in the knowledge of the present interior structure of these planets. However, the way to probe the deep regions of these planets is by calculating interior models matching their observed gravitational field, a method that can only yield information on quantities that are averaged over a significant fraction of the planetary radius. After the discovery of extrasolar giant planets orbiting very close to their parent star (*e. g.* Mayor and Queloz 1995), the formation of giant planets by gas instability (Cameron 1978), which had been abandoned to the profit of the nucleated instability model (*e.g.* Pollack *et al.* 1996), has been reborn from its ashes, and been proposed as a mechanism that led to the rapid formation of Jupiter and Saturn (Boss 1998). A giant planet may be formed only far from the star in the framework of the gas instability model, as well as, in the standard nucleated instability model, but the gas instability model has the advantage to allow rapid giant planet formation and then, migration of a giant planet towards the star by viscous torques until the dissipation of the circumstellar disk. However, Bodenheimer *et al.* (2000) carried out the first calculation of the formation *in situ* of close-in extrasolar giant planets in the frame of the nucleated instability model. A primordial distribution of particles enhanced with respect to that of our Solar System makes this scenario plausible.

Although new observations of Saturn relevant to studies of its internal structure have to await the arrival of the Cassini- Huygens space mission in 2004, constraints from the interior and evolution models inferred from Voyayer mission, indicate that a significant fraction of the heavy elements lie in the dense core and in the metallic envelope, which is difficult to reconcile with the formation of this planet by gaseous instability (Guillot 1999). Thus, we favour the usually accepted nucleated (core) instability scenario for the formation of Saturn in the framework of the planetesimal hypothesis.

During the process of accumulation, planets acquire rotational angular momentum from the relative motions at collision of the material from which they accrete. Lissauer and Kary (1991), Dones and Tremaine (1993) and Lissauer *et al.* (1997), computed the rotation rate of a planet which accretes from a disk composed by a large population of small, solid planetesimals with ordered motions. This seems to be the origin of the systematic component of planetary rotation. Due to the symmetry of the problem about the plane of the planet's orbit, there is no systematic preference for positive or negative L_x and L_y. An ordered component to L_z is possible, producing a net planetary spin angular momentum either in the same direction as the orbital angular momentum (prograde rotation) or in the opposite direction (retrograde rotation).

The giant planets contain significant quantities of gas, most of which must have been accreted by hydrodynamic gas flows. Such hydrodynamic flows produce prograde rotation (*e.g.* Miki 1982).

The systematic component of planetary rotation and gas accretion do not account for the spin obliquity of the giant planets. However, the stochastic nature of planetary accretion from planetesimals allows for a random component to the spin angular momentum of a planet in any direction (Safronov 1969). As planets might accumulate a significant fraction of their mass and angular momentum from only a very few large impacts, stochastic effects may be very important in determining planetary rotation and spin obliquities (Lissauer and Kary 1991, Lissauer and Safronov 1991, Brunini 1993).

Large stochastic impacts occur during the final stages of the formation of the planets. The self-limiting nature of runaway growth implies that protoplanets form at regular intervals in semimajor axis. In such a configuration, protoplanets are not sufficiently isolated one another to be dynamically stable for long periods of time. Agglomeration of these protoplanets into a small number of widely spaced planets requires a stage characterized by large orbital eccentricities, radial mixing, close gravitational encounters, and giant inelastic impacts (Lissauer 1993, Levison *et al.* 1998).

Giant impacts are believed to be events that played a key role in the formation of the planets. The idea of the formation of the Moon from the debris resulting from the impact of a Mars-sized body has grown in popularity because it naturally provides the large angular momentum of the Earth-Moon system and can easily account for the lack of volatiles and iron on the Moon (*e.g.* Canup and Asphaug 2001). A giant impact is also proposed as the origin of the Pluto-Charon binary system (*e.g.* Stern 1991) and as the mechanism to explain Mercury's massive iron core (Benz *et al.*

1988). The large spin obliquity of Uranus (98°) may be attributed to a great tangential collision with another protoplanet when Uranus was at the end of its formation process (Korycansky *et al.* 1990, Brunini 1995a, Parisi and Brunini 1996, 1997), or maybe, significantly later in the evolution of the planet (Slattery *et al.* 1992). Saturn may owe its obliquity to an impact by a very large protoplanet (Lissauer and Safronov 1991).

Other theories able to explain the origin of the spin axis inclination of the planets were investigated. The obliquities of the planets may be strongly modified by passing through secular spin-orbit resonances, *i. e.*, when the spin axis precession rate of the planet matches one of the frequencies describing the precession of the orbit planet. The chaotic obliquity of the planets was carefully investigated by Laskar and Robutel (1993). They showed that the inner planets could have started with nearly zero obliquity, in a prograde state, and the chaotic behaviour of their obliquity could have driven them to their current value. They also found that the obliquities of the giant planets are essentially stable along all their evolution. Harris and Ward (1982) found that if a slow change in either the axial or the orbital precession frequencies occurred since the formation of the solar system, then the resulting resonances might have altered the direction of the spin axes of the giant planets. For a giant planet to pass through a secular spin-orbit resonance it is necessary an external agent. Hamilton and Ward (2002a) stated that Saturn's obliquity is a post-formation trait due to a secular spin-orbit resonance with Neptune and that Saturn is still locked into this state. They proposed the depletion of the Kuiper belt as the external agent which produced the slow decrease of Neptune's nodal frequency required for the capture into this resonance. They found that this mechanism requires a small initial obliquity which might be attributed to the same resonance due to the slow contraction of Saturn. In the past, planetary spin axis precession rates should have been much faster due to the circumplanetary disks from which the satellites formed. Circumplanetary disk dispersal could drive the giant planets to slow adiabatic passages through secular spin-orbit resonances (Hamilton and Ward 2002b). The differential expansion of the planetary orbits during the late stages of the formation of the Solar System (Brunini and Fernandez 1999) should force the passages of the giant planets through regions of dynamical instability generated by three- and four-body mean-motion resonances as well as secular resonances (Michtchenko and Ferraz-Mello 2001). During this process, the giant planets could also pass through spin-orbit resonances. However, Brunini and Parisi (2003) found that the large obliquity of Uranus was not achieved by the dynamical coupling between the torque exerted by the sun and the perturbations generated by the other giant planets during the post-formation planetary migration process in the outer Solar System. Nevertheless, several factors not considered in their simulations might affect the evolution of Uranus' obliquity. The possible chaotic evolution of the obliquities of the giant planets in a formation scenario deserves future studies.

In this paper, we carry out a simple model of a giant impact on Saturn to account for its spin obliquity. We study the possible scenarios taking into account several factors, such as, the timescales of formation and evolution of Saturn, the mechanisms of formation of regular satellites' accretion disks, the existence and origin of irregular satellites, and the physical and dynamical characteristics of the saturnian moons.

POSSIBLE SCENARIOS

We further assume that the spin obliquity of Saturn is due to a great tangential collision with another protoplanet. It is usually accepted that the accretion disk precursor of regular satellites could have been formed in four different ways (Pollack *et al*. 1991). The disk may have formed directly from gases and solids in the surrounding Solar nebula that flowed into the Hill sphere around Saturn (accretion-disk model), from the outermost portions of the planetary envelope that rotated rapidly and so was left behind as the planet contracted (spin-out model), from the blowout of part of the planet's envelope that accompanied the impact of a massive planetesimal (blow-out model), and from the collision of planetesimals inside the Hill sphere (co-accretion model). However, the co-accretion model does not seem to provide the required amount of disk mass to account for the formation of the regular satellites of Saturn (Parisi and De Elia 2003, in preparation). These satellites orbit in the equatorial plane of the planet. If satellites had been orbiting around Saturn before this large impact had taken place, the impulse imparted at collision would have produced a shift in the orbital velocity of the satellites (Parisi and Brunini 1997). The satellites could suffer ejection or change into more or less bound orbits depending on the geometry of the impact and the orbit and velocity of the satellite at the moment of impact. Regular satellites would have been transferred to prograde or retrograde orbits acquiring different eccentricities and inclinations (Brunini *et al*. 2002). It is not possible that the present regular satellites of Saturn existed before collision, since if they had existed, the equatorial bulge of the planet would have tended after collision to pull the retrograde orbits of the satellites around, travelling in a direction opposite to the planetary spin. Prograde orbits had travelled in the same direction as the spin, but in any case, the satellites' orbital plane would have reached the planet's equatorial plane in a timescale longer than the age of the Solar System (Hamilton, private comunication).

There are three possible scenarios for a giant collision on Saturn:

1) Collision during the accretion process: The planet accretes solid and gas and interacts with the nebulae where L_z is not conserved due to angular momentum exchange, but L_x and L_y may be considered as due to the stocastic event. Material ejected by the blowout at collision would be reaccreted instead of orbiting behind, which makes the blow-out model for satellite formation implausible. The accretion model and the spin-out model should be investigated in the frame of a scenario with planetary obliquity. Outer satellites would collide with the planet due to gas drag. The present outer saturnian satellites should have been captured later in the evolution of the planet.

2) Collision at the end of the accretion process: Since runaway gas accretion, gap formation and envelope contraction are very quick processes, a collision just at the end of the accretion process is an event of very low probability.

3) Collision after the formation of the planet: Since the contraction of the planetary envelope is very quick, the collision probably ocurred when the planet had reached its present structure. Regular satellites might be formed only in the frame of the blow-out model. Outer satellites probably existed at the time of collision and where transferred to new orbits at impact. This scenario is presented in the following section.

MODEL OF THE IMPACT

We assume that the spin obliquity of Saturn ($26°.7$) is due to a giant off-center impact with another protoplanet. Such impactor may have been formed via runaway growth in a zone which was dynamically isolated until Saturn's gravitational reach expanded due to accretion of a large amount of gas (Lissauer and Safronov 1991) or may have been formed in the region of Uranus and Neptune being ejected by these planets into the region of Saturn. Once Saturn accreted its present core mass, runaway gas accretion and envelope contraction occurs on a timescale of years (Korycansky *et al*. 1991). Thus, the collision is assumed to occur when the planet had reached its present structure. The regular satellites of the planet are formed from an accretion disk as a result of the blow-out at collision. Since $L_s/L \sim 0.01$ (where L_s is the present orbital angular momentum of the regular satellites of Saturn and L is the rotational angular momentum of the planet), it is assumed that only a very small amount of the total mass and angular momentum is transferred to the accretion disk. While regular satellites accreted within circumplanetary disks, the irregular satellites are thought to have been captured from orbits around the sun involving any dissipative process. Most capture theories for irregular satellites favour permanent captures not after the final stages of the accretion process (Pollack *et al*. 1979, Heppenheimer 1975, Byl and Ovenden 1975, Heppenheimer and Porco 1977, Brunini 1995b). Since the collision is assumed to have occurred very late in the history of Saturn's formation, it is assumed that the outer satellites of Saturn existed at collision and were transferred to its present orbits by the impulse imparted at impact. The angular momentum added to the planet by the impact is:

$$\vec{l} = m\vec{v}b, \tag{1}$$

where m and $\vec{v}$ are the impactor mass and relative velocity at collision, and b is the most probable impact parameter, *i.e.*, $b = 2/3R_s$, where R_s is the present radius of Saturn. After collision, the rotational angular momentum of the planet $\vec{L}$ is:

$$\vec{L} = \vec{L}_0 + \vec{l}, \tag{2}$$

where $\vec{L}_0$ is the rotational angular momentum of Saturn before collision. Using Eqs. 1 and 2, it is possible to obtain an expression for $\vec{v}$ as a function not only of Saturn's mass and its present period, which are known quantities, but also as a function of the initial period of the planet (the period before the impact) and the impactor mass, which are unknown. In order to set constraints, we calculated the initial period that minimizes the impact relative velocity $\vec{v}$, which resulted to be approximatly equal to the present period of the planet. Thus, we further assume that the period of rotation of the planet remains the same after and before the impact, which allows us to get the required $\vec{v}$ to tilt Saturn's spin axis as a function only of the impactor mass m. To obtain constraints on the impactor incident speed, we considered that the impactor had a hyperbolic orbit with respect to Saturn before the impact. The maximum allowed incident impactor velocity was taken as that of an initially heliocentric parabolic object lying in the same orbital plane as Saturn and moving in a direction opposite to Saturn's motion, including the acceleration caused by the planet. This maximum allowed value of v is ~ 42 km s^{-1}. The minimum allowed impactor incident velocity corresponds to a null relative velocity at infinity. Due to the acceleratoin caused by the planet, the minimum value of v is ~ 35.5 km s^{-1}. Using these contraints, we obtain that the required impactor mass to tilt Saturn's spin axis is 6-7.2 $m_{\oplus}$. This range of masses set a

satellite	e_{min}	e_{med}	e_{max}
S 1	0.32	0.43	0.55
S 2	0.13	0.36	0.65
S 3	0.11	0.31	0.56
S 4	0.41	0.58	0.75
S 5	0.16	0.31	0.51
S 6	0.16	0.33	0.54
S 7	0.52	0.63	0.72
S 8	0.16	0.24	0.34
S 9	0.22	0.28	0.35
S 10	0.44	0.61	0.78
S 11	0.20	0.31	0.43
S 12	0.06	0.09	0.13

Table 1: Variation of the eccentricity of the outer saturnian satellites due to Solar perturbations.

constraint for the mass of the planetary embryos in the outer Solar System.

Motivated by our previous results (Parisi and Brunini 1997, Brunini *et al*. 2002), we have explored if the rich system of outer satellites of Saturn recently discovered (Gladman *et al*. 2001) could set constraints in this scenario.

The impulse imparted at collision may be expressed in the following form:

$$(m + M)\Delta\vec{V} = m\vec{v}, \tag{3}$$

where M is the mass of Saturn before the impact ($M+m$ is the present Saturn's mass) and $\Delta\vec{V}$ is the orbital velocity change suffered by Saturn. The right hand of this equation may be estimated from the angular momentum considerations at collision. Then, it is possible to obtain $\Delta\vec{V}$.

Any satellite orbiting the planet would suffer the same orbital velocity change $\Delta\vec{V}$ with respect to the center of mass of the planet. If $\vec{v}_1$ and $\vec{v}_2$ are the orbital velocity of the satellite before and after the impact, and $\vec{v}_{e1}$ and $\vec{v}_{e2}$ are the escape velocity at the satellite's position before and after the impact, the following equations are fulfilled:

$$\vec{v}_2 = \vec{v}_1 + \Delta\vec{V}, \tag{4}$$

$$\begin{aligned} v_1^2 &= A v_{e1}^2 \\ v_2^2 &= B v_{e2}^2, \end{aligned} \tag{5}$$

where A and B are arbitrary coefficients ($0 < A \leq 1$, $B > 0$). If $A < B$ then the satellite is transferred to an outer orbit. In the special of B=1, the satellite is unbound. If $A > B$ the satellite is transferred to an inner orbit. The minimum eccentricity of the satellite's orbit before

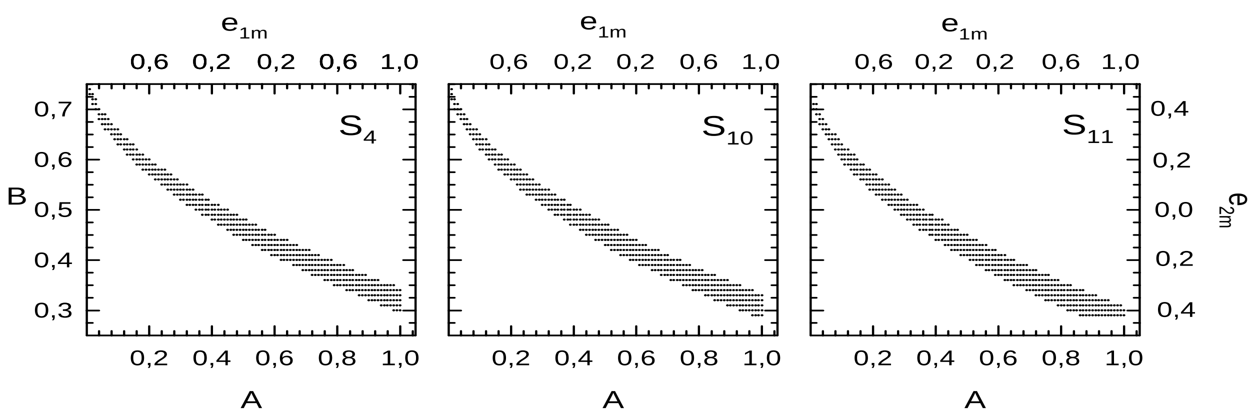

Figure 1: The permitted transfers capable of producing the actual orbits of the saturnian outer satellites for the inclination group $i : 34^o$

collision is $e_{1m} = 2(1-A) - 1$ if $A \leq 0.5$, or $e_{1m} = 1 - 2(1-A)$ if $A \geq 0.5$, while the minimum eccentricity after collision e_{2m} is given changing A by B. For each A it is possible to obtain the value of B required to transfer a satellite to the present orbit of each one of the saturnian outer satellites. This value of B provides the minimum eccentricity e_{2m} acquired by the satellite at collision. If this value of e_{2m} is less than the actual maximum eccentricity of the satellite e_{max}, tabulated in Table 1, the satellite could have been transferred to the initial condition A to its present orbit. But if the resulting e_{2m} is greater than e_{max} the transfer is not permitted. Brunini *et al.* (2002) obtained that in the case of Uranus, one of its satellites has no permitted transfers. They concluded that this satellite could not exist before collision, which set strong constraints into the usually accepted scenario of a giant collision on Uranus to account for its large obliquity. However, in the case of Saturn, all the outer saturnian satellites have several permitted transfers for any initial condition as is shown in Fig.1. The main difference between Saturn and Uranus is that in the case of Saturn, we have assumed an impact parameter b much larger, which allows the orbits of the satellites to remain more tighten to the planet. This is due to the fact that for Uranus we carried out the model at the end of the accretion process while in the case of Saturn we assumed that the planet had its present structure at collision. We based our models in the timescales and conditions stated on current models of giant planets formation (*e. g.* Pollack *et al.* 1996).

The outer saturnian satellites fall into just three different inclination groups: three at $i = 34°$, four at $i = 46°$ and four at $i = 165° - 175°$, with only one satellite having an inclination of 153°. Very recently, a new outer satellite of Saturn (S/2003 S1) was disovered by Sheppard (2003). The preliminary orbital inclination of this object is 136^o.

In Fig.1, we show only the first cluster, since for the other satellites, we obtain similar results.

CONCLUSIONS

We present our first model of a giant impact on Saturn to account for its spin obliquity. We obtain that the mass of the impactor should be in the range 6-7.2 $m_\oplus$. Although it was not possible to set constraints in this scenario from the knowledge of the actual orbital properties of the recently discovered saturnian outer moons, this model needs improvement and will be revisited in a forthcoming paper. Other scenarios discussed in Section 2 should be examined, where the regular satellites could be used to set constraints.

ACKNOWLEDGMENTS

We thank A. Paola for useful comments and discussions.

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