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Formation of Giant Planets and their regular satellites

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Abstract. The problem of giant planets formation is central in term of understand the Solar System Origin. We are dealing with this problem since a long time, and we have refined, in the last years, our work. Presently we study the evolution of giant planets starting from the assumption that they are formed in two stages: first the central core is formed. When this central core reaches a critical value, then it becomes able to collect the surrounding gas. A rapid accretion then starts. The body temperature increases and the internal structure evolves. The first rapid accretion period is followed by a slower accretion period, during which the planet atmosphere expands. A disk is also formed that is feed by the protosolar nebula gaseous material. This disk is - at the beginning - embedded in the large planet atmosphere, but, as the planet contracts, gradually emerges from it. In disk accretion disk satellite formation can take place

Key words. Planets Origin, Regular satellites Formation

1. Introduction

In this work we present a detailed simulation of the so-called nucleated instability model. Two scenarios are generally proposed for the formation of giant planets: the core-accretion one, also called the nucleated instability and the direct gas instability. In the core-accretion approach, first the Jupiter and Saturn cores were formed, and then the nebular gas was captured, probably through a hydrodynamical instability. The mechanism of gas flow onto the protoplanets was responsible for the timing of the protoplanet formation and for the structure of the accretion disk around it. The mechanism of core formation is assumed to be similar to the one giving origin to terrestrial planets (Safronov 1969, Safronov and Ruskol 1982, Coradini et al., 1981). As the core grows larger, more and more nebular gas is captured in its sphere of influence, until a large and massive envelope is formed. At this time a rapid accretion phase begins. The mechanism of nucleated instability works only if the following conditions are present:

- The collapse of gas onto a solid core asks for the pristine presence of such a core, and the growth of solid bodies of planetary or sub-planetary was a common process in our Solar System.
- Current theories on the evolution and accretion of the solid component of Solar

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System. (Safronov, 1969) make likely the presence, in the GP region of bodies of several Earth masses, growing with timescales from 10^5 to 10^7 years.

- Cores are formed first, through an accumulation mechanism, similar to the mechanism generally accepted for the formation of the terrestrial planets
- As the core grows larger, more and more nebular gas is collected in its sphere of influence, still holding quasi hydrostatic equilibrium, until a large and massive envelope is formed.

Usually simulations shows that, the first phase of the accretion, the accretion rate of gas is nearly proportional to the accretion rate of the core. The first models of core-accretion mechanism were performed by Mizuno et al. (1978) and Mizuno (1980) that showed that it is possible to construct series of equilibrium models of cores surrounded by gaseous envelopes. Wuchterl (1991 a,b) tried to make consistent models of the equilibrium structure of the giant planets but found several difficulties, in particular that a large portion of the envelope was located in regions of vibrational instability. In a paper by Ikoma et al. (Ikoma et al.2000),it has been shown that the rapid gas accretion of gaseous envelopes, in the nucleated instability model, is regulated essentially by core accretion rate and grain opacity in the outermost envelope. The conventional critical core mass 5-12 Earth Masses, however, is based on some nominal values of these quantities. Ikoma et al (2001), through numerical simulations of quasi-static evolution of the gaseous envelope, have also investigated the characteristic growth times of the envelope mass for wide ranges of core accretion rate and grain opacity.Their results, combined with the /recent planetary accretion theory, suggest surface density of solid materials twice as massive as that of the minimum-mass solar nebula model and the longer lifetime of the nebula than the about hundred million years are needed to form Jupiter and Saturn. Usually, in the papers on the nucleated instability, most of the attention is put on the structure of growing planet: the formation process of giant planets can be divided into two stages in terms of the dominant energy source that maintains the envelope in hydrostatic equilibrium. In the earlier stage, the dominant energy source is the potential energy released by incoming planetesimals (Mizuno 1980), whereas in the later stage, i.e., after the core mass reaches the critical core mass, energy release caused by contraction of the envelope itself is needed to support the envelope against the massive core and inner envelope. Rapid gas accretion occurs as a result of the contraction of the outer envelope (Bodenheimer & Pollack 1986; Pollack et al. 1996). As readily conjectured, the onset time of the rapid gas accretion depends on the core accretion rate. Furthermore, the opacity is also an important quantity since it governs the . thermal response of the envelope. The opacity sources are gas and grains in our problem. The envelope gas is almost identical to that of the Sun, the opacity of which is well investigated, whereas the grain opacity is poorly understood because we have no precise knowledge of either the abundance or the size of grains in the ancient envelope. In our simulation, instead, we have computed a detailed way the modalities through which the gas is accreted by the central core. We have also treated with great detail the way in which the gas is incorporated into the nebula. In order to do that we have developed a complex hydrodynamic code able to follow the evolution of the planet, starting from the phase i which only a solid core is present already able to collect the surrounding gas and taking into account the geometry of the accretion. We have verified that , at the beginning, quasi hydrostatic equilibrium is maintained, until a large and massive envelope is formed. The gas accretion rate depends on feedback mechanisms that drive the rearrangement of the boundary of the gaseous envelope and hence the gas accretion rate inside the protoplanets gravitational sphere of influence (Hill lobe). The rearrangement time of the structure, during the core instability accretion can be much shorter than the cooling time of the whole planet. This is because the accretion rate is driven essentially by the thermodynamics of the gas near the boundary of the Hill lobe, and not by the cooling time of the planet that could

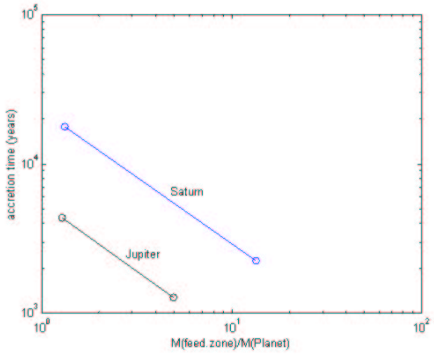

Fig. 1. Accretion time of Jupiter and Saturn as function of the mass present at the beginning of the accretion in the feeding zone. The accretion time when the mass in the feeding zone is equal to the present mass of the central planet can be considered as an asymptotic value

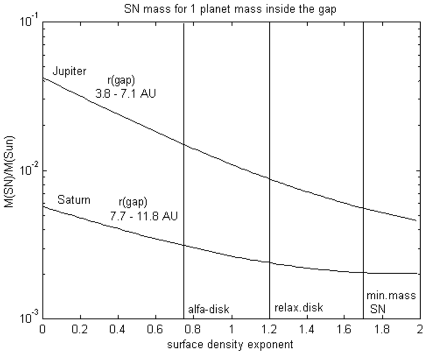

Fig. 2. Structure of the nebula needed to support the accretion of Jupiter and Saturn as a function of the exponent of the surface density distribution. The more distribution is flat, small negative exponent it α, the larger is the mass needed in SN in order to have sufficient mass in the feeding zones. the total mass present in the nebula.

be very long. On the contrary, the luminosity of the protoplanet depends on the thermodynamical conditions of the infalling gas. So, we can argue that the thermal structure of the gas strongly drives the terminal evolutionary phases of the protoplanet as the accretion tails off. When the radius has contracted to some tens of Jupiter radii, the protosatellite accretion disk is formed. In general, the larger is the mass in the feeding zone, the shorter is the accretion time. In figure 1 is shown the accretion time as function of the mass of the feeding zone. For a feeding zone containing a mass equal to the present mass of the planet, the accretion time is about 4500 years for Jupiter and 18.000 years for Saturn. In this timescale the planet reaches about 90% of its present mass. the further accretion is much slower.

The mass present in the feeding zone depends on the assumptions on the structure of the Solar Nebula (SN) at the time when the accretion onto the pre-existing core starts. One of the most important parameters characterizing the SN is the surface density distribution σ. In general, σ can be expressed as follow:

$$\sigma(r) = \sigma_0 R^{-\alpha} \tag{1}$$

here the exponent α describe the way in which the average surface density decreases when moving outward and σ_0 is the surface density at one AU. In order to obtain a sufficient quantity of mass in the feeding zones respectively of Jupiter and Saturn, is more convenient have a disk relatively concentrated in a "small" area, therefore characterized by a large negative exponent. Otherwise, when the exponent is smaller, then the nebula is more extended. In the simulation presented here we have made the following assumptions:

- The accretion zone of Jupiter extend from 3.8 to 7.1 AU, and the one of Saturn from 7.7 AU to 11.8 AU
- The total mass in the Protosolar Nebula is $\approx 2 \times 10^{-2} M_\odot$

2. The Model

The model (Magni and Coradini 2004) that we have developed intends to treat the problem of the accretion onto the growing planet in the most possible general way, even if the physical treatment must be simplified. We have considered a 3D mesh, that simulates the rotating Keplerian feeding zone, with the structure of the grid that takes into account the two main gravitational attractors (Sun and protoplanet) The spherical symmetry is abandoned

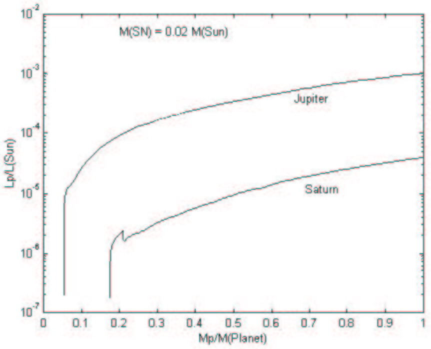

Fig. 3. Luminosity of Jupiter and Saturn as function of the mass of the planet

everywhere, and the Hill lobe is only virtually present. Boundary conditions are only in the external edge of the SN, in radial and vertical direction, and in the mesh point corresponding to the protoplanet. However, quasi-hydrostatic equilibrium spherical structures for the envelope are computed at any time step, to define standard physical parameters as protoplanet mass, luminosity, effective temperature, effective radius of the region in quasi-equilibrium.

Tidal interaction of a planet with the SN leads to the formation of spiral density perturbations that, because of the differential rotation, lead the planet in the inner region, and trail it in the outer region. Inner part of SN loses and outer disk gains angular momentum. Thus, the planet can progressively deplete of gas and solid matter an annular region along its orbit. The angular momentum exchange is asymmetric and the net balance can produce a torque that usually drives the planet to migrate inward. There is a strong connection between planet migration, gap onset, physical and thermodynamical conditions inside the protoplanetary disk, and evolutive history of the central star, that strongly influence the evolution of the Giant Planets as in the case of extrasolar planets. In our case, we have verified that the gap formation, even if present, is very limited.

Another important aspect of our work is related to the treatment of the interaction between the growing planet and the surrounding gas in terms of its thermodynamical properties. The planet is always contained in the central cell. We have introduced quasi-stationary equilibrium structure for the planet and in each time step we have verified if the gas accretion rate is compatible with the assumption that the central body is in hydrodynamic equilibrium. If the equilibrium is attained, then the gas can continue to freely enter in the cell, thus contributing to the planet growth; if not, the structure is relaxed, until a new equilibrium is attained, and the accretion can continue.

3. Results and Conclusions

The results of the accretion can be summarized as follows: as already mentioned the central planets accretion is a rapid process, once the gas collapse onto the core starts. Our model proceeds as follows: the thermal structure of the feeding zone and, in particular of the region surrounding the growing planet, is computed taking into account adiabatic and radiative exchanges among the different cells in which the fluid is divided, by solving the time-dependent radiative equations (computed with ADI method). For each time step the structure of the protoplanet is computed taking into account radiative and convective transport, and the luminosity is produced by the energy released in infalling gas and planetesimals, under the approximation of homologous variation of the structure. The planet luminosity increases, as it is shown in figure 3. The luminosity increases first, and further, when then planet evolves attaining its final equilibrium structure, it decreases again. In some of our model runs, disk-like structures form around the protoplanet. The Structure of the disk in horizontal and vertical section, both for Jupiter and Saturn, is shown in figure 4. During the final phases of the accretion the large envelope surround the evolving planet gradually shrinks and an extended disk emerges where the satellites can form. In this disk satellite can form. The disk chemistry - that will be studied in a next paper-depends on the thermodynamics conditions of this nebula.

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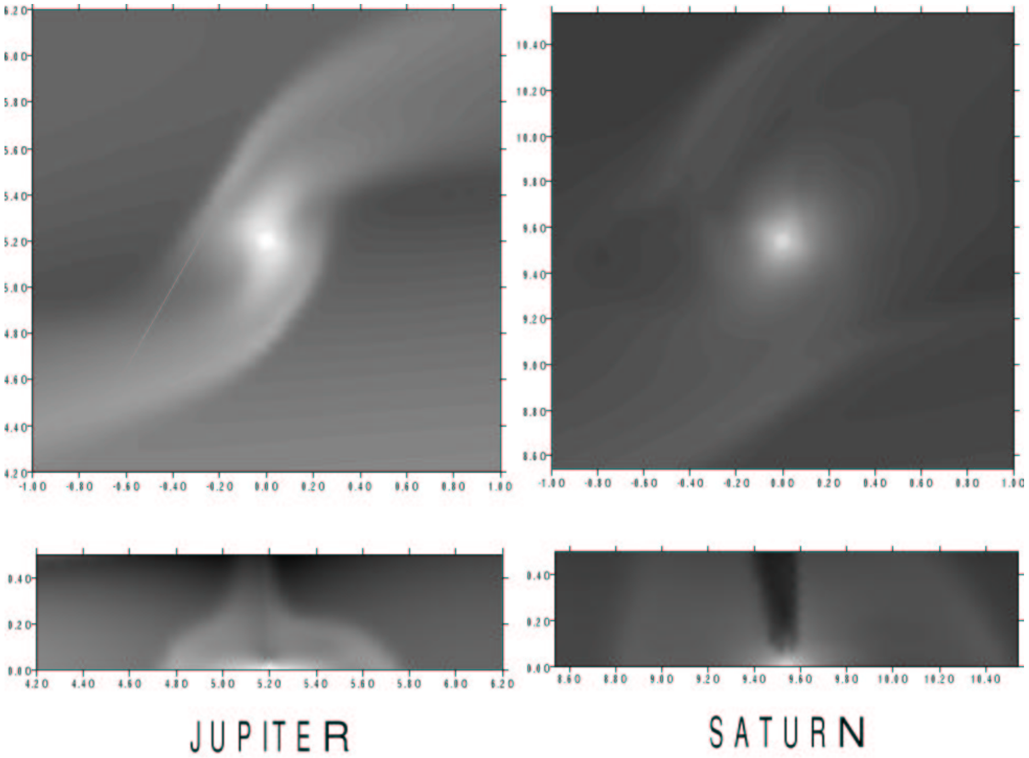

Fig. 4. Jupiter and Saturn surrounded by the growing disk. In the figure the following assumptions were done: (white) corresponds to $log\rho \leq -9$ and (black) corresponds to $log\rho \geq -12.6$

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References

Bodenheimer, P., & Pollack, J. B. 1986, Icarus, 67, 391

Chambers, J. E., and G. W. Wetherill 1998, Icarus, 136, 304

Coradini, A., Federico, C. and Magni,G. 1981, Astron. Astrophys., 98, 173

Ikoma,M. Nakazawa, K. and Emori, H. 2000, The Astrophysical Journal,537, 1013

Ikoma,M. H Emori, and Nakazawa, K. 2001, The Astrophysical Journal 553, 999

Magni, G. Coradini, A. 2004, PSS, 52, 343

Mayer, L, J. Wadsley, T, Quinn and Stadel, J. 2005, Mon.Not.Roy.Astr.Soc.,363,641

Mayer, L., T. Quinn, et al. 2002, Science, 298, 1756

Mizuno H., Nakazawa K., Hayashi 1978, Prog. Theor. Phys. 60, 699

Mizuno, H. 1980, Prog. Theor. Phys., 64, 544

Pollack, J. B., Hubickyj, O., Bodenheimer, P., Lissauer, J. J., Podolak, M., & Greenzweig, Y. 1996, Icarus, 124, 62

Safronov, V. S. 1969, NASA TT-F-677, 206

Safronov, V.S. and Ruskol, E.L. 1982, Icarus, 49, 284

Shu, F., Johnstone, D. and Hollenbach, D. 1993, Icarus, 106, 92