JUPITER AND SATURN EVOLUTION BY GAS ACCRETION ONTO A SOLID CORE.

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Introduction: The formation of Jupiter and Saturn is of increasing interest, not only for themselves, but to understand the differences and the similarities between our solar system and what had been observed of extra-solar planets. Because Jupiter and Saturn are mostly gaseous and probably accreted a large part of their masses from the Solar Nebula (SN), when the gas was still abundant [1], their existence sets interesting constraints on the properties of the SN and the boundary conditions for terrestrial planet formation. Two scenarios are generally proposed for the formation of giant planets: the first one assumes that cores are formed first, by accumulation; similar to the mechanism generally accepted for the formation of the terrestrial planets [2], [3], and [4]. As the core grows, 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 second scenario assumes that giant planets are formed by gravitational instabilities in a massive SN [6] with solar chemical compositions and masses probably larger than the present masses. Here we report new results from our development of a complex hydrodynamic code able to model the process of giant planet formation, starting from a solid core able to collect the surrounding gas.

Constraints on Formation Models: The formation models must take into account several observationally inferred constraints, such as timescales and lifetime of the SN, the size (if present) of a solid core in each planet, the bulk chemical composition of the planet, and its moons, and the architecture of the satellite system. Most of these constraints are at best imperfectly know. The gaseous accretion mechanism is possible only if the timescale of gas dissipation in the protosolar nebula is longer than formation time of the central core. A key constraint is, therefore, the presence of central cores; however, while for Saturn the existence of this core could be confirmed or excluded by the Cassini mission, for Jupiter is still an open problem after Galileo and asks for new measurements. Other important constraints are the abundance anomalies observed in the giant planets with respect to solar and/ or interstellar abundances. General enrichment of C N O with increasing distance from the Sun are observed in the solar system, accompanied by helium depletion both in Jupiter and Saturn. Finally the presence, structure and chemical properties of systems of regular satellites can be used to infer the final phases of the accretion process of giant planes. Current theories on the evolution and accretion of the solid component of SS [2], [7] make likely the presence, in the giant planet formation 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. Only when the core has reached a certain value of the mass can it accrete efficiently the nebular gas in its sphere of influence. 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 infall rate inside the protoplanet's 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 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.

Nucleated instability: 3D accretion model: While our model, updated from [1], intends to treat the problem of the accretion onto the growing planet in the most general possible way, some approximations must be considered. A 3D mesh simulates the rotating Keplerian feeding zone, with the structure of the grid constructed to take into account the two main gravitational attractors (Sun and protoplanet). The gas accretion is studied in 3D scheme, without making any special assumption on spherical symmetry. Boundary conditions are given on the external edge of the SN, in the radial and vertical directions, and in the particular mesh point corresponding to the protoplanet. Quasi-hydrostatic equilibrium spherical structures for the envelope are computed at each time step, to define standard physical parameters as protoplanet mass, luminosity, effective temperature, and the effective radius of the region in quasi-hydrostatic equilibrium.

Model and results: 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). The structure of the protoplanet is computed, instead, 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. In some of our model runs, disk-like structures form around the protoplanet that can be identified as primordial satellite disks. Comparison between Jupiter and Saturn shows that the accretion of material proceeds almost in the same way for the two planets and that part of the gas external *to* the Hill lobe is collected in both cases. However this effect is more pronounced in the case Jupiter. Moreover the Saturn disk is larger and more regular than the Jupiter one, due to the larger scale length of the solar gravity

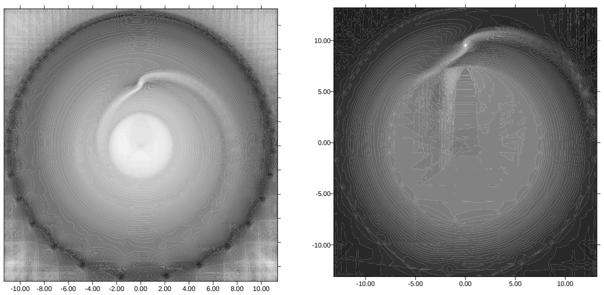

Figure 1 Jupiter and Saturn imbedded in the PSN at the end of the accretion

In the Saturn case a core of 15 M_{Earth} collects gas up to M_{Saturn} in ~ 10^4 years for a “Minimum Mass” Solar nebula. Similar results are obtained in the Jupiter case. The pulsation instability mechanism seems to be insufficient to stop the accretion: The typical accretion velocity, v is greater than the sound velocity ($v>c_s$) well inside the envelope and in the strongly distorted flow paths near the Hill boundary the gas finds channels to fall onto the core. The cooling time is a dominant effect on the accretion process, and flattens the curve (accretion time –SN mass). It is possible to achieve runaway accretion of the envelope, but this is strongly dependent on the model parameters. During the protoplanet growth the region from which the gas can be collected enlarges, and more and more matter is potentially able to reach the Hill lobe of the protoplanet. For M(SN)=0.02 M(Sun), the feeding zones between 3.9 AU and 8.7 AU (in the case of Jupiter) and between 7 AU and 13 AU in the case of Saturn, contain matter enough for several planets like Jupiter or Saturn. The most probable stopping mechanism is the global evolution of the Protosolar Nebula, that was gradually depleted of light elements, during all the evolution of Jupiter, and particularly Saturn and the outer Solar system, as indicated by their present composition (photoevaporation) [2], [8]. Another possible mechanism is the pulsational instability of the outer regions of the envelope. Moreover the accretion efficiency is strongly decreased by overheating of the envelope (runaway growth of outer planetesimals accretion due to planetary migration). Tidal confinement of the feeding zone and formation of a gap (leading to gas depletion around the protoplanet are also possible). 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 figure 2 is shown the structure of the prograde disk when the mass for the protosaturn at the end of the accretion.

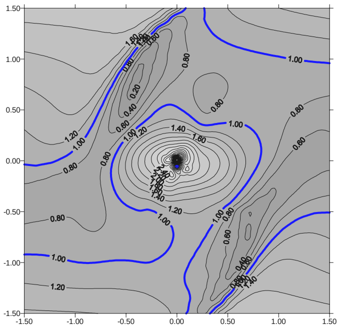

Figure 2 v_{gas}/v_{sound} when $M_{planet} = M_{saturn}$

Such A disk model allows us to predict the molecular carriers of nitrogen and carbon in the satellite disk around Saturn, and thereby the initial abundances of ammonia, methane, nitrogen and carbon monoxide in Titan and the other natural satellites.

References:

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