ON THE FORMATION OF SATELLITES NEAR GIANT PLANETS.


The formation of satellites and the early evolution of their primary giant planets are closely connected. Many authors suggested a hot stage in Jupiter's history as an explanation of the composition change with distance among the galilean satellites. But the hot stage may be obtained by several ways which are not indifferent for the satellite growth. One of us has shown that the growth of Jupiter and Saturn modelled as a spherically symmetrical accretion leads to the surface temperatures 17000° and 3600°K respectively[1]. High temperatures of the planets result also for the contraction models with the constant mass found from the evolutionary tracks of stars with small masses[2–4]. However the study of the evolution of gas–dust protoplanetary cloud[5] has shown that the most reliable model of formation of giant planets had two stages: the accumulation of planetary embryos from condensed (solid) particles for 10^7–10^8 yr and the accretion of non-condensable gases (chiefly H and He) onto the embryos (10^5–10^6 yr). The mass of the embryo sufficient for the beginning of the accretion is about 1–3 Earth masses for Jupiter's distance from the Sun. One can distinguish also a third stage- the sweeping up of solid bodies remaining in the planetary zone with the simultaneous ejection of many others from the solar system and partly to its periphery (~10^8 yr)[6,7]. Assuming that the massive satellites of all planets have originated from circumplanetary swarms[8], we conclude that the main contribution of the material into the swarms is connected with the second stage, i.e. accretion of gas. Some part of the material could be also acquired at the third stage.

The accretion of gas onto the embryo signifies the flow of gas from the whole feeding zone which in the case of Jupiter represents a circumsolar rotating torus with R_{min} = 5–6·10^3 R_{J}, R_{max} ≈ 15·10^3 R_{J} and the thickness 1–2·10^3 R_{J}, where R_{J} is the ra-
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dius of Jupiter. But only inside the sphere of action of Jupiter with the radius of 740 \( r_J \) (\( r_J \)-current radius), the gas motion is governed by Jupiter's gravitational field, being directed toward the embryo. Outside the sphere the gas rotates differentially around the sun with the heliocentric velocity slightly lower than the Keplerian velocity of the embryo. The models of gravitational contraction and of accretion are quite different and lead to different time-scale and temperature distribution along the radius. Important difference is also in the dynamics of satellite swarms because in the accretional model the increase of the mass of the planet is accompanied by the proportional decrease of the orbital radii of all particles from which the satellites accumulate. Therefore the conclusions about satellite formation made for the contraction model\([9,10]\) cannot be extended to the accretional model favoured by us. Only the last stage of gravitational contraction (after the end of accretion) is somewhat similar in the two models.

The hydrodynamics of the accretion of differentially rotating gas is very complicated. A simplified picture of gas motion may be found considering a steady spherically-symmetric accretion perturbed by a slight rotation\([11]\). The boundary conditions "at infinity" we must replace by the conditions at the radius of the sphere of action. Putting the averaged angular velocity around the planet equal \( \frac{1}{4} \dot{\omega}_c \), where \( \dot{\omega}_c \) is circumsolar angular velocity, we find that the gas is accreted mainly in polar regions and that in the equatorial plane the accretion is prevented and a circumplanetary disc to \( \approx 20 R_J \) is formed. The conclusion about the accretion mainly in polar regions was also made earlier \([12]\). The rate of accretion is essentially less than the maximum one, usually assumed for the spherically symmetric accretion in infinite medium. The planet easily accretes the gas only from the region near its orbit. However the gas from other heliocentric distances did
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not come to fill this region — due to small viscosity the gas conserved its angular momentum relative to the sun. As a result the value of $f_{\infty}$ (near the sphere of action of the planet) in the expression for the rate of accretion highly decreased with time. Nevertheless the accretion at its maximum caused high temperatures of the surface of planets ($\approx 3000^\circ$K) securing the evaporation of volatiles in the region of galilean satellites.

The evaluation of density and velocity of gas and of the maximum dimension of solid particles dragged by gas permits to estimate the contribution of condensable matter into the satellite swarm due to drag by gas and due to "free-bound" collisions of particles. The contribution by "free-free" collisions is negligible. The evaporation-condensation process in the swarm resulted in the fractionation of chemical composition of satellites. The possibility of the origin of gaseous thorus on the orbit of Io as the remnant of gaseous disc during the accretion process is discussed.

References.