FORMATION AND GROWTH OF EMBRYOS OF THE EARTH AND THE MOON. S. I. Ipatov, Vernadsky Institute of Geochemistry and Analytical Chemistry, Kosygina st., 19, Moscow 119991, Russia, siipatov@hotmail.com.

Introduction: According to Galimov and Krivtsov [1], solid embryos of the Earth and the Moon have been formed from the same rarefied dust condensation. The authors presented arguments that the giant impact concept [2] of the formation of the Moon has several weaknesses. Formation of massive (up to $0.1M_E$-$0.6M_E$, where M_E is the mass of the Earth) condensations was considered by several scientists (e.g. [3]). Ipatov [4-7] and Nesvorny et al. [8] studied formation of trans-Neptunian satellite systems formed by contraction of rarefied condensations. In my opinion, models of formation of trans-Neptunian satellite systems and of formation of the Earth-Moon system can be similar.

Formation of solid embryos of the Earth-Moon system at the stage of rarefied condensations: To my estimates [9], the angular momentum K_s of a condensation used by Galimov and Krivtsov [1] in their computer simulations of the formation of the embryos of the Earth-Moon system as a result of contraction of a rarefied condensation could not be acquired during formation of the condensation from a protoplanetary disk. I showed that the angular momentum K_{sEM} of the present Earth-Moon system could be acquired at a collision of two rarefied condensations with a total mass not smaller than $0.1M_E$. The mass of the condensation that was a parent for the embryos of the Earth and the Moon could be relatively small ($0.02M_E$ or even less), if we take into account the growth of the angular momentum of the embryos at the time when they accumulated solid planetesimals.

The angular momentum of the condensation needed for formation of the Earth-Moon system could be acquired by accumulation only of small objects. In this case, there could be K_s=K_{sEM} for a parental condensation with mass m>$0.2M_E$. However, for such accumulation of only small objects, other terrestrial planets would have large satellites. Probably, the condensations that contracted and formed the embryos of the terrestrial planets other than the Earth did not collide with massive condensations, and therefore they did not get a large enough angular momentum needed for formation of massive satellites.

In the above estimates of K_s, the radius of the parental condensation with the angular momentum needed for the formation of the embryos of the Earth-Moon system was comparable with the Hill radius r_H of the system and was greater than the radius of the parental gas-dust condensation equal to $0.023r_H$ considered in [1]. At such small radius of the condensation, Galimov and Krivtsov [1] obtained evaporation of FeO from dust particles and the formation of embryos of the Earth and the Moon depleted in iron. In order to get the angular momentum needed for formation of a satellite system, the condensation considered by Galimov and Krivtsov had to be a result of a compression of the condensation with a larger size than that considered in [1]. After the compression of the condensation to radius equal to $0.023r_H$, it could contain objects greater than dust. Some scientists (e.g., [10]) consider that condensations in the feeding zone of the terrestrial planets could consist of objects of decimeter size, which were greater than dust. Could the above evaporation of FeO take place for such objects, e.g. if they had fractal structure?

There could be also the second main collision (or a series of similar collisions) of condensations or solid bodies that changed the tilt of the Earth. For the second main collision of condensations, the radius of the Earth embryo condensation had to be smaller than the semi-major axis of the orbit of the Moon embryo.

Growth of solid embryos of the Earth-Moon system: The solid embryos of the Earth-Moon system formed from the parental condensation grew by accumulation of smaller objects, e.g., planetesimals. In the case of small relative velocities of planetesimals, effective radii r_{ef} of the embryos are proportional to r^2, where r is the radius of a considered embryo. In this case, $m_{Mo}^{-1/3}=m_M^{-1/3}+k_2m_{Eo}^{-1/3}-k_2m_E^{-1/3}$, (1)
where $k_2=k_d^{1/3}$, k_d is the ratio of the density of the growing Earth of mass m_E to that of the growing Moon of mass m_M (k_d≈1.65 for the present Earth and Moon), m_{Mo} and m_{Eo} are initial values of m_M and m_E. For m_M=$0.0123m_E$, m_{Eo}=$0.1m_E$, m_E=M_E, the above equation is true at k_2=1 and m_{Mo}=$0.00605M_E$, and also at k_2=1.65 and m_{Mo}=$0.0054M_E$. For such data, the mass of the Moon embryo grew by a factor of 2 – 2.3 while the Earth embryo grew by a factor of 10. At r_{ef} proportional to r^2, the embryo of the Earth grew faster than that of the Moon. For large enough eccentricities of planetesimals, the effective radii of proto-Earth and proto-Moon were proportional to r. In this case $m_{Mo}^{1/3}=m_M^{1/3}+k_1m_{Eo}^{1/3}-k_1m_E^{1/3}$ (where $k_1=k_d^{2/3}$) and the increase of m_M/m_{Mo} is greater than that of m_E/m_{Eo}.

According to Galimov and Krivtsov [1], initial embryos of the Earth and the Moon were depleted in iron, and the Earth got a larger fraction of iron than the Moon because it grew faster by accumulation of dust. To estimate the maximum growth of m_M, let us consid-

er the following simple model: The initial embryos didn't contain iron, and the incoming material contained 33% of iron. For a considerable growth of the mass of the Earth embryo, the final fraction of iron in the embryo can be close to the present 32%. The fraction of iron in the Moon would be equal to 0.33(1-m_{rMo}), where m_{rMo} is the ratio of the initial mass of the Moon embryo to the present mass of the Moon. Taking the present fraction of iron in the Moon to be equal to 8% and solving 0.33(1-m_{rMo})=0.08, (2)
we get m_{rMo}=0.76 and the growth of the Moon embryo mass by a factor of 1.3. This estimate is in accordance with the estimates by Galimov and Krivtsov [1] of the growth of the Moon embryo mass by a factor of 1.31 at the growth of the mass of the Earth embryo by a factor of 26.2. For the formula (2), the fraction of iron in the Earth is 0.33(1-1/26.2)=0.317. In [1] the increment dm of the embryo mass m was proportional to m^2, i.e. to r^6. At r_{ef} proportional to r^2 from formula (1), we can obtain that for the growth of the mass of the Moon embryo from M_M/1.3 to the present mass M_M of the Moon, the mass of the Earth embryo grew (to M_E) by a factor of 2.4 or 2.7 at k_d equal to 1.65 and 1, respectively. In this case for the above simple model, the fraction of iron in the Earth does not exceed 0.33(1-1/2.7)≈0.21 and is less than the present value. May be at the gas/dust stage the relative growth of m_E was faster than at r_{ef} proportional to r^2?

Besides direct collisions with planetesimals, the Moon embryo could also grow by accumulation of almost iron-free material ejected from the Earth embryo at impacts of planetesimals with the Earth embryo. It allows one to consider smaller (than in the above estimates) initial masses of the embryos. In the case of such accumulation, the fraction of iron in the initial embryos could be close to that in the present Earth. This model differs from the known multiple impact models (e.g., [11-13]) by that the initial embryo of the Moon in my model was formed from the same rarefied condensation, as the Earth embryo, but not from a disk of material ejected from the Earth embryo. The model of the formation of a solid planet with a large satellite can also work for some exoplanet.

Delivery of water to the Moon embryo. Orbits of those Earth-crossing objects that migrated from outside of the Jupiter's orbit are typically highly eccentric. For such eccentric orbits of the objects, the effective radii of the Earth and the Moon are approximately proportional to their radii. The square of the ratio of radii of the Earth and the Moon is 13.48. Based on our runs of migration of planetesimals from the feeding zone of Jupiter and Saturn [14] and of migration of Jupiter-crossing objects [15-16], I calculated probabilities of collisions of such planetesimals and objects with the Moon. Such probabilities were typically smaller than probabilities of collisions with the Earth by a factor of 16 or 17 for planetesimals and many Jupiter-family comets. However, in some runs for some Jupiter-family comets, the factor was up to 25. Based on the above results, we can conclude that the amount of the material, including water, delivered to the Moon from outside of the Jupiter's orbit could be smaller by about a factor of 20 than that delivered to the Earth from this region.

Conclusions: The embryos of the Earth and the Moon could form as a result of contraction of the same parental rarefied condensation. A considerable fraction of the angular momentum of such condensation could be acquired at a collision of two rarefied condensations. The present angular momentum of the Earth-Moon system could be acquired at the collision of two identical rarefied condensations with sizes of their Hill spheres, which total mass was about 0.1 of the mass M_E of the Earth and which heliocentric orbits were circular. The initial mass of the rarefied condensation that was a parent for the embryos of the Earth and the Moon could be relatively small (0.02M_E or even less) if we take into account the growth of the angular momentum of the embryos at the time when they accumulated planetesimals. The Moon embryo could get more material ejected from the Earth embryo than that fell directly on the Moon embryo.

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References: [1] Galimov E.M., Krivtsov A.M. (2012) *Origin of the Moon. New concept*. De Gruyter. Berlin, 168 p. [2] Canup R.M., et al. (2013) *Icarus, 222*, 200-219. [3] Lyra W., et al. (2008) *Astron. Astrophys*, *491*, L41-L44. [4] Ipatov S.I. (2010) *Mon. Not. R. Astron. Soc.*, *403*, 405-414. [5] Ipatov S.I. (2014) *Proc. of the IAU. V. 8. Symp. S293*, Cambridge Univ. Press. 285-288. http://arxiv.org/abs/1412.8445. [6] Ipatov S.I. (2017) *Solar System Research*, *51*, 321-343. [7] Ipatov S.I. (2017) *Solar System Research*, *51*, 409–416. [8] Nesvorny D., et al. (2010) *Astron. J., 140*, 785-793. [9] Ipatov S.I. (2015) *Proc. of "SPACEKAZAN-IAPS-2015"*, Kazan University, 97-105, http://arxiv.org/abs/1607.07037. [10] Johansen A., et al. (2007) *Nature, 448*, 1022-1025. [11] Rufu R., et al. (2017) *Nature Geoscience*, *10*, 89-94. [12] Gorkavyi N.N. (2004) *BAAS*, *36*, 861. [13] Svetsov V.V., et al. (2012) *LPS XLIII*, Abstract #1808. [14] Ipatov S.I., Marov M.Ya (2016) *LPS XLVII*, Abstract #1458. [15] Ipatov S.I., Mather J.C. (2006) *Advances in Space Research*, *37*, 126-137, http://arxiv.org/format/astro-ph/0411004. [16] Ipatov S.I., Mather J.C. (2007) *Proc. of the IAU Symp. No. 236*, Cambridge Univ. Press, Cambridge, 55-64, http://arxiv.org/format/astro-ph/0609721.