Simulation of the explosive origin of a planetary satellite

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Abstract. Explosion in the planetary interior and the ejection of the part of outer layers of the planet into orbit to form a satellite makes it possible to explain the elemental and isotopic composition of the Moon. Satellite formation has been simulated for a two-dimensional geometry using molecular dynamics methods for up to hundreds of thousands particles. The particles are asteroid-size bodies (diameter of about 100 km) which interact with each other according to Newton’s law. The properties of the compact material are described by a short-range potential. A number of calculations with varying initial conditions have shown the scenario of the explosive origin of the Moon to be realistic and preferred over other hypotheses.

1. Introduction

The hypotheses according to which the Earth and the Moon were formed from one region of a protoplanetary gas–dust disk, the Moon arriving from outside was captured by the gravitational field of the Earth, or the Moon separated from the rapidly rotating Earth without additional impact do not explain the elemental and isotopic composition of the Earth and the Moon and do not agree with the results of computer simulations [1]. The more recent hypothesis first proposed in [2], according to which the Earth–Moon system formed as a result of a collision of the planets, experiences difficulties in explaining the similarity of the isotopic compositions of terrestrial and lunar rocks [3].

The origin and composition of the Moon can be adequately explained by assuming that it was formed from terrestrial material as a result of an explosion in the planets deep interior. Due to the explosion, a large mass of the Earth upper stone with a relatively low content of iron and the unchanged isotopic composition of the elements was ejected at a high velocity into outer space. A power source required for such an explosion could be a chain nuclear reaction [4, 5]. Another source of energy for the explosive scenario is assumed to be the gasification of fluids leaving the interior [6]. However, the efficiency of gasification is much lower compared to nuclear reactions, so that an ejection on an unbelievable scale is required.

The traditional classification of uranium and thorium as lithophile elements did not allow their significant concentration in deep interior of the Earth and, hence, the possibility of an explosion. However, the latest data on the registration of geoneutrinos emitted by the reacting actinides, are proved that despite the radioactive decay during for billions years, a substantial portion of actinides at the present is in the Earth deep interior [7, 8]. Such settling of actinides as
refractory high-density compounds, as oxides or carbides can be attributed to the gravitational differentiation of planets matter after their formation and melting. It is believed that iron and nickel are allocated from the rocks and as heavier fell toward the center, forming a iron–nickel core, central part which could harden due to high pressure. Actinides as oxides or other high-density refractory compounds, due to less concentration in the molten ocean of magma, formed separate particles large enough later, so, presumably, settled on an already formed solid inner core.

According to estimates, the energy of ejection of the Moon is of the order of $10^{29} - 10^{30}$ J [5]. This corresponds to a chain reaction of up to $10^{16}$ kg of U-235 or $5 \times 10^{16}$ kg of natural uranium dioxide at the time of Earth formation, when the fraction of fissile U-235 reached 20%, which is no more than a few percent of the expected total content of actinides in the Earth interior [9]. Billions of years ago, natural nuclear reactors and nuclear chain reactions in the surface layers of the Earth occurred, in particular, in West Africa [10]. However, the possibility of concentration and explosion of actinides deep in the Earth interior remains debatable [11].

Another unresolved component of the problem of the explosive origin of the Moon is the explosion mechanics involving mass ejection into orbit and satellite formation. In the simplest case of ejection of a small point mass, it either moves away from the Earth with a velocity higher than the escape velocity or returns to the Earth due to the closedness of orbits in the gravitational field. However, interactions between ejected fragments of large mass will lead to an exchange of energy and momentum, so that some of the material may remain in orbit. In addition, the influence of the Sun and other planets is significant, and this may also cause bodies ejected to large distances to leave closed orbits.

The rapidly rotating proto-Earth could have an angular momentum sufficient to explain the present angular momentum of the Earth–Moon system. For this, the rotation rate should be five times higher than the present one [5], which also significantly facilitates the ejection and reduces the required explosion power. This rate of diurnal rotation of the planet does not seem improbable. For example, the present Jupiter, which is several times larger than the Earth, makes one revolution in ten hours in spite of the possible spin-down over billions of years.

Thus, the explosion and ejection of the Moon are not a priori impossible.

The complexity of the problem does not allow the use of reliable analytical approaches. Therefore, the objective of this study was to perform a computer simulation of the mechanical component of the process to show that the formation of a large satellite of a terrestrial-type planet by explosion is in principle possible.

2. Formulation of the problem

The problem of a deep explosion was solved for the two-dimensional case. It is assumed that the body has a dense core (the mass of the core particles is three times larger than the mass of the remaining particles). The rotation of the body is such that the velocity on the surface is equal to the Earth orbital velocity $v_1 = \sqrt{GM/R}$, where $G$ is the gravitational constant, $M$ is the mass of the planet, and $R$ is the radius of the planet. The explosion products (particles in the more bright on the picture area on the border of dense core and less dense shell) are instantaneously brought to a high temperature, and their kinetic energy increases (i.e., an explosion occurs).

3. Solution method

The two-dimensional computer simulation of the formation of a planetary satellite, such as in the mega-impact hypothesis [2], was performed using a method similar to the molecular dynamics method with a number of particles of the order of $10^5$ (individual particles corresponded to bodies of about 100 km in size). Properties of substances in a compact state asked short-range potential, such that more realistically describe the planet density with depth as a result of
gravitational compression. Interaction at a distance taken to Newton’s law:

\[ U(r) = 4\varepsilon \left( \frac{b}{r} \right)^{12} - \left( \frac{b}{r} \right)^{6} - \frac{Gm^2}{r}, \]  

(1)

where \( \varepsilon \) is the depth of the Lennard-Jones potential well, which for bodies with a size of about 100 km was assumed to be equal to \( 4 \times 10^{20} \) J; \( G = 6.67 \times 10^{-11} \) m\(^3\)kg\(^{-1}\)s\(^{-2}\); \( b = 96 \times 10^3 \) m; \( m = 3 \times 10^{18} \) kg.

In the calculations, the values of \( \varepsilon, b, \) and \( m \) were varied depending on the number of particles into which the body of the planet was broken up.

The main difficulty of the calculations was to select the required power and location of the explosion, the rate of the diurnal rotation of the planet before the explosion, and other characteristics from the values of which depended more than results from a sort of short-range potential.

The entire computational domain was divided into cells. The cells have several levels. Each cell of levels other than the lowest level have references to four daughter cells and the parent, and all particles are contained only in cells of the lowest level.

In the calculations, we used a system of units in which \( \varepsilon = b = G = 1 \). The whole grid is divided into cells: the minimum cell size is \( 3b \). The computational domain has no boundaries and increases as the particles move away from the center (all particles are always considered regardless of how far they have moved away from the center).

The forces of gravitational interaction between particles do not allow the spatial truncation of the potential. It is necessary to take into account the contribution of all pairs of particles, even distant ones. The fast multipole method was used to speed up the calculations and correctly account for gravitational interactions [12]. The interaction of particles in cells at the lowest level was calculated by relation (1). The interaction with particles in distant large cells was calculated as with point masses located in the center of the cells.

The above approach to the molecular dynamics simulation of the explosion on the scale of a space object does not have a rigorous justification. On spatial flow scales of more than 10x10 atoms, the parameters of individual particles manifest themselves weakly and the flow regime is continuum flow.

An apparent advantage of the approach is the simplicity of the problem statement and the reasonable equation of state taking into account phase transitions, which makes it possible to distinguish between the condensed and gaseous phases of the material ejected from the planet.

4. Calculation results

Different results were obtained depending upon the geometry, the explosion power, the rotation rate of the planet and the particle interaction potential. Thus, at a relatively low explosion power, most of the fragments fall back. The higher the power, the more fragments remain in orbit and the more fragments irreversibly leave the planet. The results show the possibility of the ejection of large enough nearly-continuous blocks of condensed material to form parts of the proto-Moon.

The successive steps of one of the calculations are shown in figure 1. In the explosion, an expanding bubble forms on the surface of the planet core. The dimensions of the bubble increase and its walls become thinner. Due to the flow heterogeneity and gravitational forces, the mantle breaks up into fragments held together by the intrinsic gravity field. Most of these fragments fall back and get captured by the planet, but some of them remain in orbit. The two largest fragments seen in figure 1 are about one thousand km in size each. The numerous smaller fragments, which, in aggregate, exceed in mass the large fragments, are not visible on the scale of the figure.
Figure 1. Result of the molecular dynamics simulation of the explosion in the planetary interior and the formation of satellites; the time from the beginning of the explosion is 0, 0.5, 1.0, 1.5, 2.5, 8 h (from left to right, from top to bottom).

A similar flow was obtained by simulating the explosive origin of the satellite with the use of the hydrodynamic model [13]. Both approaches provide similar general structures of the explosive flow, but there are also significant differences. The problem of the origin of the Earth satellite cannot be considered solved.

5. Discussion
The calculation results presented in figure 1 show that the arrival of a part of the fragments on the stationary orbit is facilitated by the exchange of the angular momentum of large masses scattered in different directions by the expanding explosion products.

Simulation of the explosion showed the possibility of multiple satellites origin of various sizes within the first few hours. Grouping many bodies in one or several satellites in orbit may take
many years. Such prolonged modeling was not our task. However, the obtained result is not in
doubt, as confirmed by the entire history of the evolution of the Solar system, with the merger
of the smaller bodies into larger, then in the body of a planetary dimension. In the modeling of
Moon origin by the megaimpact [2] when released into orbit even smaller fragments than in our
case, it also assumes their subsequent consolidation into a larger body.

The solid cores of the planets of the Solar system presumably have similar composition of
elements, including actinides. Therefore, explosions were possible not only in the Earth, but also
in other planets. However, our calculations have shown that the results of these explosions could
be different depending on the mass of the planet, the amount of locally accumulated actinides,
and explosion geometry. For example, for the Venus, the power of such an explosion (if it was)
could be insufficient for satellite formation. For the large planets Jupiter and Saturn, explosions
could lead to the formation of the plurality of observed satellites.

Under the influence of a shock wave, the medium contracts, heats up, and therefore masses
thrown into the rarefied space partially lose volatile chemical elements, enriching with refractory.
This may explain the observed volatile-element depletion of lunar rocks and their enrichment in
refractory chemical elements in comparison with terrestrial rocks.

6. Conclusions

The flow mechanics during a nuclear explosion in the planetary interior was studied by molecular
dynamics simulation. The possibility of ejection of compact condensed fragments into the low
orbit of the planet and the formation of satellites has been shown.

The obtained results suggest that the hypothesis of the explosive origin of the Moon provides
an adequate and consistent explanation for the elemental and isotopic composition of the Moon
and, perhaps, the satellite systems of other Solar System planets [14].

From the hypothesis of the explosive origin of the Moon it follows the possibility of periodic
chain reactions in the remnants of actinides in the Earth core and at present time [15]. These
manifestations may be periodic amplification of convective heat flow from the core to the mantle
and to the surface, resulting in the restructuring of the magnetic field of the planet and to changes
in the Earth climate.

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