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Layers and Shells of Comets

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ABSTRACT

Comets are considered to be the most ancient and least changed objects in the Solar System. The question of the formation of these bodies may shed light on the process of evolution of the protoplanetary cloud. In this paper, we substantiate the assumption that a clearly defined layered (onion-like) structure of comets has closed gas-impermeable shells between the layers. A model is proposed that explains the possibility of the formation of space objects equipped with these heat-resistant shells. The main process of formation of space objects in this model is the accumulation of matter as a result of the adhesion of granules. This process begins at the periphery of the protoplanetary disk as temperatures drop. Volatile organic matter on the ice surface of the granules is modified by ultraviolet light, forming "glue" allowing the granules to unite. The object gains mass and, under the influence of gravity, repeatedly crosses the heated zone of the central plane, moving up and down across the entire thickness of the protoplanetary disk. In the cold zone, the substance accumulates on the object. And in the heated zone, at a distance of 3.5 to 5.0 AU from the axis of rotation (where the temperature can reach ~1000 K), closed shells are formed, separating the layers. An approximate estimate of the thickness of the layers in the cometary body has been made. It was found that at the initial stage of comet formation the thickness of the layers reached 1 - 2 m.

1. INTRODUCTION

Comets are a large group of bodies in the Solar System. Comets travelling to the Sun are believed to come from the Oort cloud and the Kuiper belt. The nuclei of all observed comets have a radius, on average, from 1 to 5 km; bodies with a radius greater than 10 km are rare. However, objects with radii of 50 - 1000 km have been discovered in the Kuiper Belt [1].

The activity of comets as they approach the Sun is expressed in the sublimation of ice and the ejection of dust from the surface. The evaporation of volatiles becomes noticeable when the comet approaches 4 - 5 AU from the Sun. The atmosphere of some comets, made of neutral hydrogen atoms, is larger than the Sun [2]. In a number of cases, fragmentation of the cometary nucleus was observed, when the object broke up into several parts. Research in recent years has shown that the comet's nucleus is extremely porous and has low strength. For example, the porosity of comet 67P/Churyumov-Gerasimenko was determined to be 75 ± 7 percent [3]. On the whole, the cometary nuclei have the ultimate tensile strength of about 2 kPa [4]. But direct data coming from Philae landing on comet 67P show that the compressive strength at different landing points varies from 12 Pa to 1 kPa [3, 5].

Comets formed early in the evolution of the protoplanetary cloud. They are believed to contain relict material that has survived since the beginning of the formation of the Solar System. The components observed in comet dust tails may have previously existed in interstellar grains. It is important to note that the composition and structure of cometary nuclei reflect the physical and chemical processes that occurred with the matter of the protoplanetary cloud.

Space missions have revealed a number of features of comets that pose challenges to models of the formation of the Solar System. For example, a study of the non-volatile part of comet 81P/Wild 2 showed [6] that comets include materials of both presolar origin and high-temperature materials that likely formed in the inner Solar System. This suggests extensive mixing of material in the early stages of the protoplanetary disk [7].

Comets are believed to have formed in conditions of extremely low temperatures. Direct measurements of molecular nitrogen (N_2) in comet 67P/Churyumov-Gerasimenko made with the Rosetta mass spectrometer have led to the conclusion that cometary grain formation occurred at temperatures < 30 K [8]. However, emissions associated polycyclic aromatic hydrocarbons, amorphous carbon, carbonates, amorphous and crystalline silicates, phyllosilicates and sulphides have been detected in comets. The presence of such a mixture of materials requires mixing of high-temperature and low-temperature components during the early formation of the protosolar nebula [9].

Crystalline silicates are formed from amorphous silicates by thermal annealing at >800 K, or as a result of evaporation and recondensation at temperatures ≥ 1800 K. It is believed that such temperatures can only occur in the inner hot disc at the stage of the collapse of the protoplanetary nebula, while the place where comets form is the outer protoplanetary disc [10]. If these crystals formed at small radii during high accretion rate phases, they would have to travel large distances to be incorporated into cometosimals [11].

The Deep Impact experiment [9] showed that about 72% of the olivines (annealing temperature 1100 - 1400 K) were crystalline, and almost all (>90%) of the pyroxenes with annealing temperature 800 - 900 K were in crystalline form. This suggests that in some places where comets were formed, the crystallization process was quite effective. In addition, it was found that about 8% of all silicates are in the form of phyllosilicates. The presence of carbonates and phyllosilicates suggests the presence of liquid water in the region of the cometary body's formation.

Thus, comets were formed under conditions of extremely low temperatures, but at the same time, part of the cometary material was subjected to high-temperature annealing, and the other part came into contact with an abundant amounts of reactive water.

Another feature of comets was their layering. The first evidence of layers was noted in comets 19P/Borrelly and 81P/Wild (Wild 2). 9P/Tempel whose images showed that layers ranging in thickness from 1 to 200 meters are widespread [12]. According to Massironi *et al.* [13], comets have a so-called "onion-like" stratification. Comet 67P/Churyumov-Gerasimenko, which is an object fused from two parts; each part has its own stratification. This led to the conclusion that early cometosimals experienced stratified accretion before they merged into a single comet [13, 14].

The origin of the layering may be primordial or evolutionary [14]. Sekanina [12] suggested the existence of isolated ice reservoirs that, on the one hand, separate the layers from each other, and on the other, help hold them together. Belton *et al.* [15] proposed the talps or "layered pile" model for Jupiter-family comets, in which the nucleus is covered with randomly stacked layers. The formation of such layers is associated with the phase transition of amorphous ice into crystalline ice [16]. Groussin *et al.* [17] suggested that as a result of the low strength of comets, the interior of the nuclei was compressed so much that diagenesis could have begun, which facilitated the formation of layers. According to Davidsson *et al.* [18], the formation of denser outer layers on porous cometary nuclei is associated with an increase in collision velocities during viscous mixing during the evolution of the protoplanetary disc. Schwartz *et al.* [19] suggested that cometary layers may not be primordial. During a catastrophic collision of cometary bodies, partial fragmentation occurs and matter is ejected, and the ejected matter is capable of collecting into a single body. Thus, cometary bodies can form at any point in the evolution of the Solar System.

This paper examines a model for the formation of comets that can explain some of the above-mentioned features inherent in comets.

2. THE SOLAR SYSTEM

The Solar System was formed 4.6 billion years ago from matter in an interstellar nebula. It is highly likely that the Sun, planets and comets formed simultaneously from the same gas and dust cloud of solar composition, called the "solar nebula". The origin of the Solar System was the gravitational collapse of a part of a giant interstellar nebula.

If the interstellar nebula is subjected to some powerful impact, such as a shock wave from an explosion of a nearby supernova, it can begin to collapse. It is believed that the elements of the Solar System were synthesized ~5 billion years ago. The impetus for the condensation of the nebula was a supernova explosion ~4.7 billion years ago. The radioactive elements of the Solar System owe their origin to this explosion. The relict matter of the original cloud, formed long before the formation of the Solar System, should have lost its radioactive elements. They should have disintegrated during the time the nebula was in a stationary state [20].

The collapse of a gas and dust cloud disturbed by some reason occurs under the influence of its own gravity. Conservation of angular momentum leads to the formation of a rotating accretion disk. Most of the matter flows to the centre and within 10^5 years a protosun is formed [21]. The remaining matter rotates around the protosun and falls onto the central plane, heating up on it. The temperature and density in the cloud decrease from the centre to the periphery and with altitude (above and below) the disk plane [21].

3. INITIAL COMPONENTS OF COMETS

The interstellar nebula material underwent significant processing before becoming a protoplanetary cloud [11]. The temperature of dust particles in interstellar space is 10 - 15 K. Streams of ultraviolet photons are the primary source of chemical reactions occurring on the surface of interstellar grains [22]. Solid organic matter, in which carbon is bound into large macromolecular compounds similar to the organic matter of carbonaceous meteorites has been discovered in comet dust particles. This substance could have formed in the interstellar medium [23].

As the comet approaches the Sun, its volatile components leave the nucleus and move into the coma. There is reason to believe that the comet's substance not only and not so much evaporates as individual molecules, but is ejected in streams. What do these streams consist of? The first experimental results were presented by Kissel and Krueger [24]. They analysed the dust composition of comet Halley's coma, which was measured by the PUMA mass spectrometer on board the spacecraft Vega 1 in 1986. As a result, it turned out that a dust particle has a fluffy mineral core with a density of 1 - 2 $g \cdot cm^{-3}$. Measurements showed that the mineral composition of the cores is close to that of chondrites and the composition of the Solar System (except for hydrogen). The core is surrounded by or embedded in a mantle of organic refractory material. The mantle is even fluffier and has a density of 0.3 - 1.0 $g \cdot cm^{-3}$ [24].

Observations of the expansion of Halley's comet's coma allowed one to conclude that CO molecules are released not only from the parent molecules of the comet's nucleus, but also from the decay of the substance already ejected from the comet's nucleus. The amount of CO in the coma showed an increase up to a distance of 20,000 km [25]. At a distance of ~1000 km from the core, the CO number density was found as $n(CO)/n(H_2O) \le 0.07$, and at a distance of ~20,000 km $0.5 \le n(CO)/n(H_2O) \le 0.15$. The most likely source of CO, according to Eberhardt *et al.* [25], are coma dust granules containing organic particles. Based on this, a model of cometary granules was proposed [26]. This model suggests that comets consist of interstellar dust particles in which silicate cores are surrounded by organic refractory mantles and outer mantles of ices, with the ices simultaneously merging with the organics of the interstellar cloud. In such granules, 26% of the mass is silicates (a combination of elements Si, Mg, Fe), 23% refractory organic matter, 9% large-molecular carbon particles, 30% water and 2% - 3% simple molecules such as CO, CO_2, CH_3OH [26].

A large amount of dust particles from comet 81P/Wild 2 was collected and brought to Earth during the Stardust mission. The particles entered the low-density aerogel with a relative velocity of 6.1 km·s^{-1}, so the original particle form could not be determined [27]. Laboratory measurements of the properties of captured dust particles have shown that they contain individual fragments of variable composition. This led to the conclusion that many of the particles represent loosely bound aggregates of different minerals [28]. According to Kolokolova and Kimura [29], cometary dust consists of aggregates of submicron grains (including organic matter, silicates and carbon) and larger solid silicate particles.

The chemical element content of dust grains from comet Wild 2 was found to be similar to that observed in anhydrous porous particles of interplanetary dust. Therefore, if comets reflect the composition of the original solar nebula, it is closer to chondritic porous interplanetary dust particles than to CI meteorites [28]. Wooden [11] argues that the original cometary particles contained significant amounts of interstellar medium grains.

The properties of dust ejected from comet 67P/Churyumov-Gerasimenko were studied for two years using the Rosetta interplanetary station equipped with the Ion Mass Analyzer COSIMA, the MIDAS atomic force microscope, and the GIADA dust detector. COSIMA has discovered dozens of solid and porous fragments of cosmic dust and made it possible to study their chemical composition. MIDAS and GIADA detected dust of different sizes (10^{-6} - 10^{-5} and 10^{-4} - 10^{-3} m), leading to the conclusion that the particles detected by MIDAS are fragments of larger particles that were detected by GIADA [30]. However, Lasue *et al.* [31] suggest that there are two distinct families of dust particles with significantly different sizes ejected from the cometary nucleus. Thus, in situ measurements of dust particles from comet 67P/Churyumov-Gerasimenko confirmed that cometary dust is characterized by a wide variety of properties and sizes, from compact individual grains to porous aggregate particles similar to interplanetary dust particles. Elongated grains of such dust may be part of the building blocks of comets [32].

This model assumes that granules are the main initial "building blocks" in the structure of comets. Moreover, each granule has a dust core consisting of metals, silicates, or carbon compounds, surrounded by a mantle of organic matter and ice (**Figure 1**). The composition of chemical elements in cometary granules is close to the composition of CI meteorites, the composition of matter in the Solar System, and the composition of interplanetary dust particles. Cometary granules contain interstellar dust particles in one form or another.

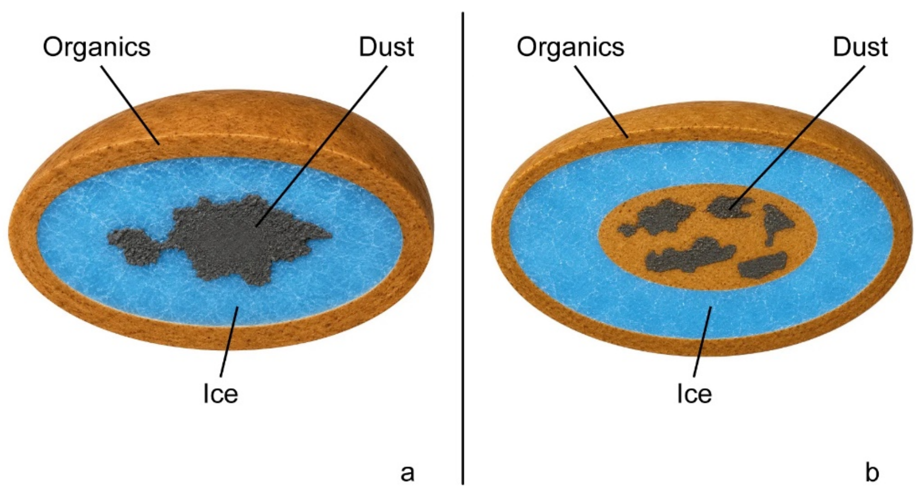

Figure 1. Schematic illustration of granules or initial "building blocks" of the comet structure.

If we assume that the interstellar nebula was initially hot and consisted only of gases, then during the process of its cooling, solid dust particles consisting of metals, silicates, etc. were first formed. As the temperature dropped further, more volatile components condensed on these dust particles, forming an icy mantle consisting mainly of water. Then simple organic compounds and gases in the form of NH_3, CO_2, H_2S, and at lower temperatures CH_4, CO, etc. settled on the ice surface. After the formation of the granule (**Figure 1(a)**), the mixture of molecules on the ice surface was exposed for a long time to flows of cosmic radiation, including ultraviolet, from various sources. In addition, thermal processes also play a certain role, that is, an increase in reaction rates when the surface layer of the granule is heated, for example, as a result of the collision of granules. Under the influence of radiation and thermal processes, simple components are polymerized and complex organic molecules are formed [33, 34].

The interstellar nebula existed for hundreds of millions of years before the formation of the Solar System. During this time, it could have been heated by shock waves from external sources. We assume that as a result of heating the granules, water and volatile compounds evaporated from them. In this case, the polymerized organic matter will remain on the dust particles or will settle on them during cooling. If this organic matter becomes viscous under certain conditions, then individual dust particles can gather (stick together), forming multi-component bodies. When the temperature drops, water and volatile compounds will settle again on the dust aggregates, and the process of polymerization of organic matter on the ice surface will continue (**Figure 1(b)**).

4. FORMATION COMETARY NUCLEI

The layered structure of comets is no longer in doubt. It has been suggested [15] that layers are elements of the internal structure of cometary nuclei in the Jupiter family. The following model for the formation of layered cometary bodies is proposed [35, 36]. This model assumes that the embryos of cometary bodies began to form on the periphery of the protosolar nebula (outside its central plane). The minimum distance from the rotation axis at which cometary bodies can form is probably ≥ 3.5 AU, since it is believed that at smaller distances, strong heating of dust particles in the protoplanetary nebula occurs, and they lose the frozen layer of water and volatile components [37]. As the nebula is compressed, its rotation increases. As the rotation accelerates, the nebula becomes flatter, and the rotating matter falls onto the disk and heats the central plane. However, at the periphery (above and below the plane of the disk), the temperature remained quite low.

Evidence for low temperatures during comet formation comes from the deuterium (D) fractionation accurately measured for comet 1P/Halley. Based on its content, it was shown that the ices of this comet, like other comets, were formed not in a protoplanetary disk, but in an interstellar nebula. A diapason for the temperature of comet assembly was established as 30 ± 10 K [38]. Measurements of the argon spectrum of comet Hale-Bopp also show that the comet's deep interior was never exposed to temperatures greater than 35 - 40 K, which are necessary to deplete the comet's primordial argon reserves [39].

Why do granules coalesce at low temperatures? The chemical reactions on the surface of the granules are caused by ultraviolet photons. According to Greenberg [22], the flux of ultraviolet photons with energies ≥ 6 eV in the interstellar medium is about 10^8 $cm^{-3}\cdot s^{-1}$. It can be assumed that on the periphery of the protosolar nebula it is almost the same. Successive decay and recombinations of organic molecules on the ice surface of the granules lead to the formation of more complex molecules. This is how the "glue" is formed, allowing the granules to stick together and form aggregates.

This glue is high molecular macromolecules. Numerous experiments have proven that under the influence of radiation and thermal processes, as well as bombardment by fast ions, the organic matter located on the surface of the ice is transformed. As a result of this irradiation and heating, polymerization and polycondensation processes (the combination of monomers into polymers) take place; that is, complex heavy molecules are formed from simple components [33, 34, 40]. A diverse range of organic compounds has been found in comets, such as in samples from comet 81P/Wild 2 [41].

Comets, and therefore granules, contain on average 30% - 33% of various organic materials [21, 42]. It is assumed [43] that when granules collide at low speeds, the temperature at the heating site rises so much that some of the frozen free radicals in the organic molecules are released and can recombine. The recombination of radicals results in the release of energy. If energy is released at a sufficient rate, a chain reaction occurs. As a result, not only does the chemical composition of the organic matter change, but the granules may also stick together. There are other theories that explain the initial process of comet formation [18], but in the model proposed here, bonding of granules takes place due to complex organic matter forming on the ice surface of the pellets.

Many authors agree that it is the interaction of gas with granules (condensation) and granules with each other that plays a significant role in the accumulation of granules and leads to the formation of solid bodies in the Solar System [44, 45]. According to Sobotovich [20], the evolution of the primary protosolar cloud proceeded through the formation of many small condensations, the embryos of which were existing dust particles. Huebner [21] suggests that ice-covered grains due to collisions were united into icy planetesimals (comets), which were the building blocks of the outer planets. The accumulation of cometary matter occurred at low collision energies and low relative velocities [2].

As the aggregates grow and their mass (m_{ob}) increases, the force (F_G) of their gravitational attraction to the centre of mass (M_{PS}) of the protosolar nebula increases (according to Newton's law) (**Figure 2**):

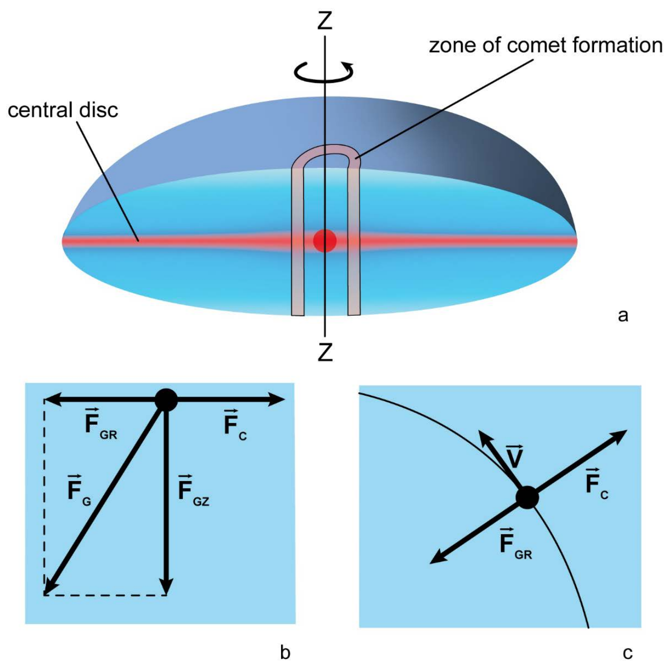

Figure 2. Comet formation in the protoplanetary nebula. (a) Schematic representation of the protoplanetary nebula with the highlighted zone between the asteroid belt and the orbit of Jupiter. Z-axis of rotation. (b) Forces, what act on a body in the plane of the rotation axis (when the body is on the periphery of the nebula). (c) Forces in the plane perpendicular to the axis of rotation.

$$F_G = G\frac{M_{PS} \cdot m_{ob}}{r^2}, \quad (1)$$

where G is the gravitational constant, r is the distance from the object to the center of mass of the nebula. The direction of force is from the object to the centre of mass nebula. It can be decomposed into forces acting parallel (F_{GR}) and perpendicular (F_{GZ}) to the central disc (**Figure 2(b)**):

$$\overrightarrow{F_G} = \overrightarrow{F_{GR}} + \overrightarrow{F_{GZ}}. \quad (2)$$

The nebula rotates, so the object is subject to a centrifugal force (F_C), which balances the gravitational force acting parallel to the plane of the central disc:

$$F_{GR} = F_C \,. \tag{3}$$

As a result, the object will rotate at speed v in conjunction with the cloud (**Figure 2(c)**) and move to the centre plane under the influence of force F_{GZ}. As it moves toward the central disc, the object will continue to gain mass from substances it encounters along the way.

As mentioned earlier, the collapse of a gas and dust cloud occurs under the influence of its own gravity. The bulk of the matter flows toward the centre, forming a protosun [21]. The remaining substance falls onto the central plane and heats it up. Thus, the temperature will be higher throughout the central plane of the protoplanetary nebula than at a distance from it. The magnitude of this temperature depends on many parameters: the accretion rate, the stage of evolution of the gas and dust cloud, etc. Huebner [21] argues that the temperature and density of matter in a protoplanetary cloud decrease from the centre to the periphery and with height (above and below) the disc plane. According to Cameron [46], the temperature of the inner layers of the collapsing cloud was about 500 K. Anders [47], based on meteorite data, calculated that meteorite accretion occurred at a temperature of 520 - 680 K.

The proposed model allows us to assume that the formation site of some comets may be the region of a gas and dust cloud located between the asteroid belt and the orbit of Jupiter (**Figure 2(a)**). In this case, the comets were formed from matter located at a distance of 3.5 to 5.0 AU from the axis of rotation of the original cloud. At the periphery of this region (far from the central disc), the temperature of the source material should not have exceeded 30 - 40 K, as shown by studies of nitrogen (N_2) [8], deuterium (D) [38], and argon [39]. While the temperature of the central disk should be ~1000 K, which is necessary for the formation of crystalline silicates [9-11]. It is believed that such temperatures could exist in the inner hot disc at the stage of the collapse of the protoplanetary nebula [10].

As an object moves from the periphery to the central plane, the temperature of the substance around it increases, and the surface of the object begins to heat up. The surface of the comet body begins to lose volatile elements and ice transforms into water. The presence of water in a liquid state could lead to formation of hydrous silicates. The question of how long liquid water remains on the surface of an object remains open. It requires further careful study, but the fundamental possibility of the formation of hydrated silicates on the surface of a cometary body exists.

As the temperature gradually increases, volatile organic matter and then water leave the surface layer of the comet. What remains is a porous structure of ~30% dust (mineral) particles and ~30% organic matter, in which a chemical transformation of organic and inorganic matter occurs. Altwegg *et al.* [48] noted that cometary organics turned out to be significantly more complex than expected. Infrared spectra of material from comet 81P/Wild 2 showed [49] that the aliphatic carbons have longer chains than those found on interstellar dust particles.

What are the membranes (shells) between layers in comets? The shells are formed when an object crosses a heated central disc. The composition of the shell substance is similar to the surface of the bark of comets. However, the shells are not a loose, porous mass like the crust of comets. Since the substance is subjected to strong heating, it becomes less friable and may fuse into a dense mass. Moreover, it should be taken into account that the object is moving, including against the flow of matter. Its surface is bombarded by an incoming flow; that is, it is subjected to mechanical compression. In this case, it can be assumed that the surface layer of the comet is transformed into a thin monolitic shell.

The shell that forms on the surface of the object must have low thermal conductivity to be capable of shielding the interior from heating. This is indirectly confirmed by sun-scratching comets. It can be assumed that it is precisely these refractory organic shells that allow comets to pass through the solar corona, the temperature of which is ~10^6 K. About 2000 sun-scratching Kreutz comets (≤100 m in size) have been observed since 1996 by SOHO, STEREO, and other instruments. Comet Lovejoy (C/2011 W3) was the first Kreutz to pass through the Sun's corona with the comet's nucleus preserved. According to estimates [50], before approaching the Sun, Comet Lovejoy was at least several hundred meters in size, its mass loss rate reached about 9.5×10^9 g·s^{-1}, and the total mass loss exceeded ~10^{13} g.

The density of the matter in the vicinity of the central disc allowed the cometary body, without losing speed, to pass to the other side of the heated plane and continue moving towards lower temperatures, collecting matter. As the object moves away from the central plane, the force of gravity, acting in the opposite direction, gradually dampens the object's vertical speed and stimulates its turnaround. Thus, during the accumulation of matter, moving in a circle around the Sun and swinging up and down perpendicular to the central plane, the comet repeatedly crosses the heated disc (**Figure 3**). Each intersection forms another shell. This model assumes that comet formation occurs in a sufficiently rarefied protoplanetary nebula, so that the drag force of the environment does not significantly affect the object's motion.

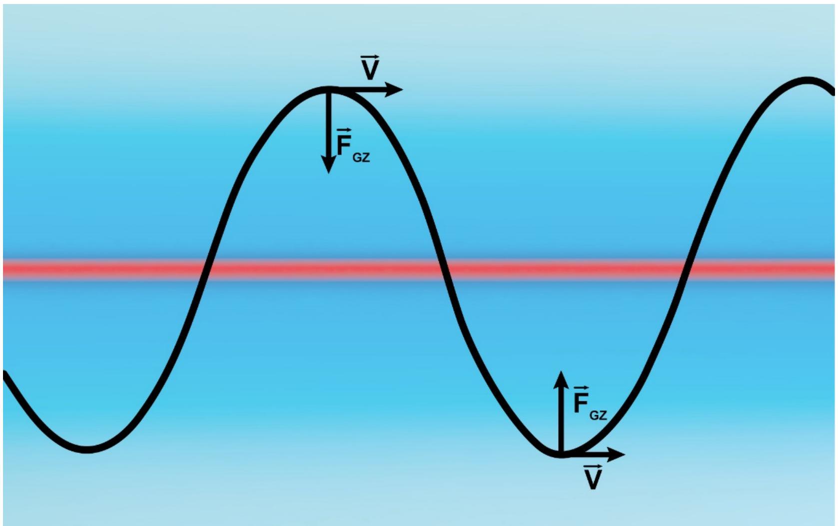

Figure 3. Schematic representation of the motion of a cometary object in a protoplanetary cloud around the central Z axis (Figure 2) with multiple intersections of the hot central disc. $\vec{V}$ is the rotation speed of the protoplanetary cloud (and the object) around the Z axis; $\overrightarrow{F_{GZ}}$ is the direction of the gravitational force.

5. THICKNESS OF LAYERS

It is possible to indirectly estimate the thickness of the layers based on observations of the Chelyabinsk object, if we consider this cosmic body to be a comet and if this comet had a shell structure, as proposed in the model. This bolide exploded over the Chelyabinsk region (Russia) on the morning of February 15, 2013 [51-53]. Several meteorites fell on the earth's surface [54]. However, there is reason to believe that we are dealing with the explosion of a comet [55], which delivered meteorites to Earth.

The atmospheric trace left by the cosmic body proved to be very specific. Over time, this trace swelled into individual bubbles (**Figure 4**). This suggests that the substance was released in separate portions during the flight [52, 55]. As noted by Pätzold *et al.* [56], the interior of the cometary nucleus is homogeneous and has a constant density on a global scale. The high porosity of the core is an inherent feature of the material. If comets are stratified and the layers are separated by shells, then as a result of heating and sublimation when the shell is damaged, the layer can be thrown off entirely. In other words, comets can shed matter in separate portions. The radiation from the flying object was comparable to blackbody emission of 6000 K [52], and the ejected material had a temperature significantly higher than the surrounding air. In places where the substance was released, the air heated up and rose upward in bubbles. The release of the substance was accompanied by sound effects. Based on the study of 18 video recordings, it was found that the explosions occurred at altitudes of: 42.7; 39.2; 37.2; 36.4; 35.5; 34.9; 33.5; 32.5; 31.9; 30.9; 29.0 and 25.8 km above the earth's surface [53].

Figure 4. The trace of the Chelyabinsk bolide (http://www.youtube.com/watch?v=Z20lnOVscpc).

We assume that during the complete destruction of the Chelyabinsk body, approximately 12 explosions occurred. We assume that each explosion corresponds to the damage of one shell and the release of one layer of matter. When the shell is damaged, a shock wave is generated due to the difference between atmospheric pressure and the internal pressure of the object. The internal pressure (in the near-surface layer) can be much lower than atmospheric pressure if it is an initial vacuum, and higher than atmospheric pressure if the shell conducts heat well, and the volatile components of the internal porous structure quickly evaporate. In any case, the result is an explosive ejection of the surface layer of matter.

The maximum glow of the object and the release of energy during its destruction occurred at the final stage of the flight at an altitude of 25 - 43 km above the earth's surface [52, 53]. The total energy (E) released during the final stage of the flight exceeded 470 kilotons of trinitrotoluene [52], *i.e.* E~ 2×10^{15} joules. To release such energy, the mass of the object (M) must be ~1.2×10^{7} kg [53]. In this case, with a body density of 250 $kg \cdot m^{-3}$, the total volume of the ejected substance will be $V = 4.8 \times 10^{4}\ m^{3}$. As a rough approximation, we assume that the thickness of every layer (h) is the same for all 12 layers. Then the total volume can be represented as the sum of volumes of layers:

$$V = \sum_{i=1}^{12} h \cdot S_i \ , \quad (4)$$

where $S_i = 4\pi(R_i)^2$ is the surface of a sphere with radius R_i. As a result of calculations, we obtain h ~1.8 m for a body density of 250 $kg \cdot m^{-3}$ and ~1.5 m for a body density of 500 $kg \cdot m^{-3}$.

If we consider the Chelyabinsk object to be a comet, it should be noted that we have no information about the density of this cosmic body. In this regard, only a rough estimate of the layer thickness can be made. Thus, based on the Chelyabinsk event, it can be concluded that near the centre of the cometary body the distance between the layers is from 1 to 2 m. The results of space experiments do not contradict the obtained layer thickness. An analysis of the layered structure of comet 67P/Churyumov-Gerasimenko showed [16] that with an average layer thickness of ~14 m, thin layers with a thickness of 1 - 3 m and spherical formations with a radius of ~1.5 m were found. As for large inclusions, they can also be explained within the framework of the proposed model. The accumulation of mass in the cometary body, where the object moves perpendicular to the central plane, allows the object to merge with bodies encountered along the way. Consequently, in the cometary body, along with granular matter, there may be larger fragments. These fragments may also be cometary nuclei and have a layered structure.

6. DISCUSSION

6.1. Why Do We Need Shells?

The main objective of the proposed model is to explain the formation of shells between layers in comets. Why are these shells needed? Considering the Tunguska event, Sekanina [57] concluded that the cosmic body that caused the catastrophe could not have been a comet. The cometary body, as a homogeneous, highly porous object, should fall apart upon entering the atmosphere at altitudes of ~70 km. And this is certainly true. As calculations [4] and direct measurements on comet 67P [3] show, the estimated tensile and compressive strength of the cometary nuclei varies from 12 Pa to 2 kPa. This allows us to assume that at a load of more than 2 kPa the comet nucleus will be destroyed. Comets enter the Earth's atmosphere at cosmic speeds and interact with atmospheric components. As a result of this, the pressure on the frontal surface of the object rapidly increases as it approaches the Earth's surface. For example, dynamic loads on the Chelyabinsk body at the altitude of ~70 km were >6 kPa [55]. Thus, a highly porous body, formed in a vacuum and lacking strong shells, cannot reach the dense layers of the atmosphere.

However, the Tunguska cosmic object could not have been an asteroid. Asteroids with a mass greater than 100 tons, as mentioned by Wood [58], are much more massive than the column of atmospheric air through which they pass. This allows large asteroids to not notice the atmosphere and not lose speed. But no crater was discovered at the epicentre of the Tunguska explosion, nor were any fragments of the asteroid found, though the remains of the cometary body were discovered in peat deposits by numerous expeditions [59-61]. Moreover, solid or fairly viscous organic matter, traces of which were found at the epicenter, could have been fragments of the comet's shells [62].

It is generally accepted that the Tunguska event exploded at an altitude of 7 - 10 km above the ground [63]. This fact casts doubt on the homogeneity of the porous material that made up the comet. And the characteristic sound noted by the Evenks at the final stage of the Tunguska body's trajectory led to the conclusion that the substance was released in separate portions. The sound resembled frequent gunfire or explosions that followed at regular intervals of several seconds [35]. This allowed us to assume that in the Tunguska event we were dealing with a comet shedding its shells.

High-resolution imaging studies of comets are consistent with the presence of shells between the layers. Comets often have predominantly smooth-bottomed pits. This has been noted by Birch *et al.* [64], for example, for comets 81P/Wild 2 and 67P/Churyumov-Gerasimenko. In the presence of shells in comets, when the outer shell is damaged and when energy enters from outside, sublimation of the substance located in the layer occurs. This substance is ejected outward in the form of a jet, however, the ejection is limited to the lower shell of the layer. As stated [65], the pits slowly expand in diameter after formation due to the retreat of the walls under the influence of sublimation. If the heating does not reach the next layer, a pit with a flat bottom and steep edges the height of the layer thickness is formed. If several shells are damaged at once, the edges of the pit may be stepped [66].

6.2. Comparison with Other Models

According to Altwegg *et al.* [67], the organics of comets are similar to protostellar material. This suggests that the material was accreted by comets virtually unchanged during the presolar stage of the protoplanetary cloud's evolution. From the preservation of a high [D_2O/HDO]/[HDO/H_2O] ratio in comets and the presence of the volatile S_2, it was concluded [67] that water ice formed before cloud compression and survived the collapse of the protoplanetary nebula as ice. Several hypotheses have been proposed to explain the fact that cometary ices have never sublimated and contain substances characteristic of interstellar dust. Weidenschilling [68] believes that comets formed from a mixture of dust and gas in the cold outer regions of the solar nebula, beyond the orbit of Neptune. Davidsson *et al.* [18] developed a comprehensive model for the formation of bodies in the Kuiper belt based on calculations by Weidenschilling [68]. Our model suggests that cometary bodies can form early in the evolution of the protoplanetary cloud at a distance of 3.5 to 5.0 AU from the axis of rotation of the original cloud. They draw unprocessed presolar material from the periphery of the nebula above and below the protoplanetary disk (**Figure 2(a)**).

It is suggested [18] that the primordial disc was cold, so that cometary bodies formed from solid bodies rather than gaseous or liquid ones [69]. It is believed that cometary embryos could have been formed by collisional coagulation [68], soft accretion of matter [67], soft gravitational collapse [70], hierarchical agglomeration, or by flow instability [18]. In the model proposed above, the cometary body is assembled from micron-sized granules with an icy mantle covered with a layer of organic matter (**Figure 1**). The main mechanism of the object's growth was the adhesion of granules, which arose due to chemical reactions between the organic components of the shells during collisions of the granules with the object and gentle heating in the impact zone.

In the Weidenschilling [68] model, as in subsequent models, coagulation and sedimentation of the protoplanetary nebula matter during collapse lead to the formation of a thin, dense layer of small aggregates in the central plane of the nebula. The formation of large solid bodies subsequently occurs due to gravitational instability, and this process does not begin until the particle sizes reach tens of metres. In other words, the accumulation of matter by comets begins when all the matter is already concentrated in the central disc. In our proposed model, cometosimals arise at an early stage of the evolution of the protoplanetary cloud and can serve as the initial building blocks for the formation of both comets and the planets of the Solar System.

To explain the presence of crystalline silicates in comets, mechanisms of radial transport and mixing of matter in the protoplanetary cloud are proposed [10, 11]. In our model, cometary bodies pass through a central disc heated by accreting matter to a temperature of about 1000 K, where amorphous silicates transform into crystalline silicates. The possibility of the existence of such temperatures in the central part of the disc is allowed [10].

Thus, the above-proposed model of the formation of cometary bodies in a protoplanetary cloud differs significantly from previously proposed models. The difference refers to both the zone of comet formation and the stage in the evolution of the protoplanetary cloud. The method of combining the substance into a single object and the method of obtaining components that require thermal treatment and interaction with liquid water also differ. In addition, in our model, comets receive shells that help them interact with the Sun's atmosphere and penetrate deep into the Earth's atmosphere.

7. CONCLUSION

The idea of comets as lumps of dirty snow, large snowflakes and other chaotic formations is largely untenable. Comets most likely represent a well-ordered structure. This structure, consisting of granules, has layers that are separated by closed, gas-impermeable shells.

7.1. Prerequisites of the Model

The following assumptions were made when constructing the model:

Granules are the main initial "building blocks" in the structure of comets. Each granule has a dust core consisting of metals, silicates, or carbon compounds, surrounded by a mantle of organic matter and ice.

This model assumes that the cometary bodies began to form on the periphery of the protosolar nebula, outside its central plane, during the initial stage of the nebula's contraction. The distance from the rotation axis at which cometary bodies can form is 3.5 - 5.0 AU. In this region, near the central plane, the temperature could reach 1000 K, and on the periphery it could be less than 30 - 40 K.

The main mechanism for the formation of aggregates from granules is the chemical bonding of granules after their collision at low speeds. The "glue" is formed on the organically coated surface of the granules due to the action of cosmic particles and ultraviolet radiation.

7.2. Main Results

The following model for the formation of comets is proposed.

1) A decrease in temperature at the periphery of the protoplanetary nebula to the level at which water condensation begins leads to a significant increase in the size of the original interstellar granules. As the temperature continues to decrease, gaseous components CO_2, CH_3, etc. settle on the surface of the ice.

2) Under the influence of external ultraviolet radiation, "organic glue" is formed on the ice surface of the granules. This glue allows the granules to stick together and the substance begins to accumulate. Thus, most of the cometary material is formed at the periphery at low temperatures.

3) As the aggregates of granules grow and their mass increases, the objects begin to move towards the central disc due to the forces of gravity. During movement, the accumulation process does not stop, and the mass of the object increases.

4) As the object moves toward the central plane, the temperature of the surrounding substance increases, and the ice in the surface layer of the object turns to water. Under these conditions, hydrated silicates can form. Crystalline silicates, what formed at high temperatures, hit the object when it crosses the high-temperature zone.

5) In the heated area of the central disc, sublimation processes are activated. Volatile gases and water are removed from the surface layer, and the rate of interaction of the remaining organic molecules increases. Under the influence of heating and flows of oncoming matter, a shell is formed on the object. It is assumed that the layer of dust and organic matter on the surface of the object conducts heat poorly and is able to protect the internal layers from destruction.

6) After passing through the hot central layer, the object, by inertia, again enters the region of low temperatures on the other side of the central plane. And again it begins to gain substance. Undoubtedly, friction acts on the object during its motion. However, since the nebula is still quite tenuous at the comet-forming stage, braking has little effect on the object's motion. Thus, the forming object is capable of scooping out matter across the entire width of the protoplanetary disk.

CONFLICTS OF INTEREST

The author declares no conflicts of interest regarding the publication of this paper.

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