On the origin of asteroid (2867) Steins.

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The enigmatic appearance of asteroid Steins is proved to be the result of its formation inside parent body's crust and throwing out of it. Steins' diamond-like cone shape, rotational axis, fractures, chains of craters, evolution trends, etc. are consistently explained from the point of view of explosive ejective orogenesis. The implications for asteroids and satellites are discussed.

Contents

1 Introduction

On 5 September 2008 ESA's Rosetta spacecraft on its way to comet 67P/Churyumov-Gerasimenko encountered 5km-wide main belt asteroid Steins [1,2]. During seven minutes fly-by at 800km distance cameras of the probe acquired about half thousand of Steins' detailed views (e.g. fig.1). Ultraviolet to mm spectra, light curves, and data on the environment were taken as well.

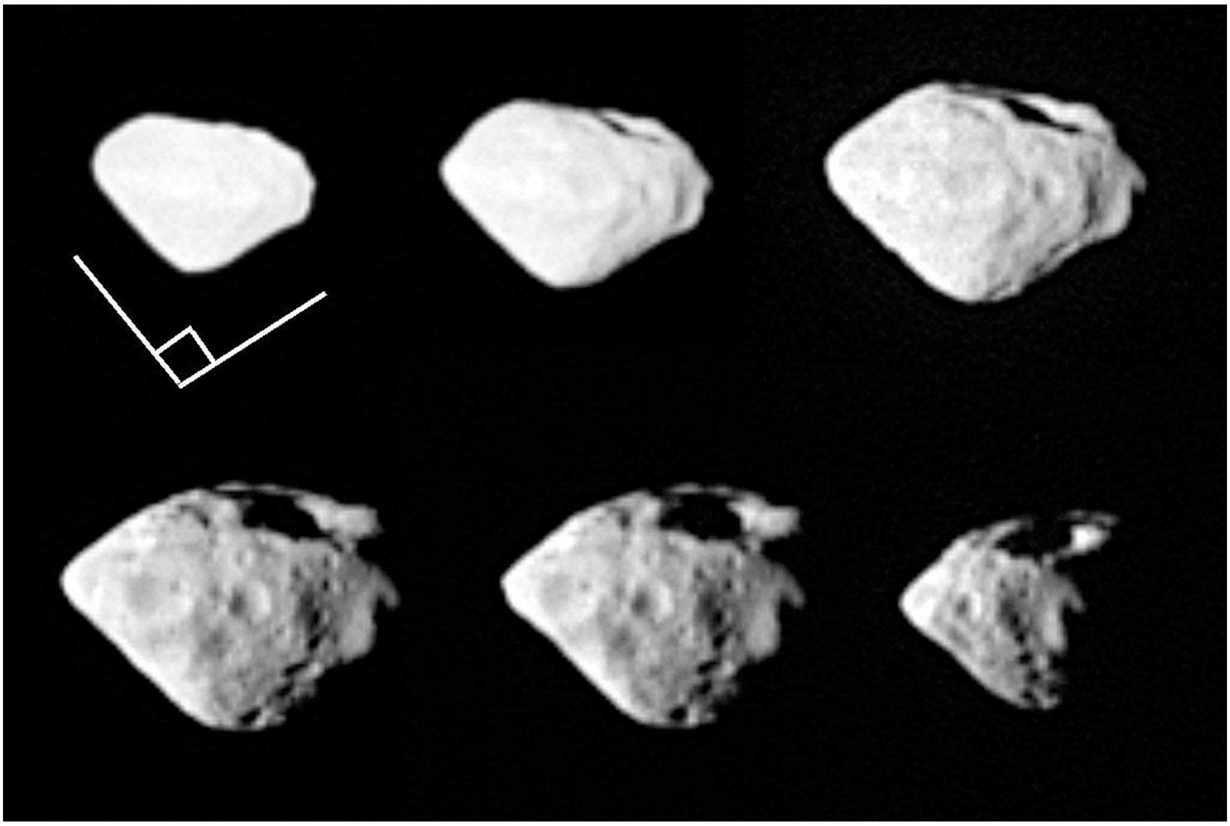

Fig.1. Six views of approx two thirds of Steins' surface acquired by OSIRIS imaging system before, during, and after the close encounter. White sketch was added by us to emphasize ca. 90° northern pole summit angle. (http://www.esa.int/spaceinimages/Images/2008/09/Asteroid_Steins_A_diamond_in_space)

Brilliant cut appearance and astounding morphology of Steins have been actively discussing by astrophysical research community. Public opinion was intrigued by the speculations on artificial origin of the asteroid. A decade after the fly-by the coherent explanation of Steins' characteristics is still lacking.

In the following we are giving an integral account of the observational data. The essence of our point of view is the phenomenon of explosive ejective orogenesis. In its course a cone or pyramid mountain forms by fracturing crust of a rigid celestial body and explosively jumps out of it to fall down nearby. The phenomenon was earlier described on example of the largest main belt asteroid Ceres [3] . To examine Steins and other cosmic bodies we put forward only one main assumption. It is that a mountain ejected by a huge explosion is sometimes able to overcome gravity pull of the primary to become its satellite or to leave it. This way formed rock offspring bears the genetic features of its parent body as well as universal characteristics of ejective orogenesis.

2 The phenomenon of ejective orogenesis

Let us briefly review the features of explosive ejective orogenesis as the foundation for further considerations. The stages of the phenomenon ubiquitous among rigid celestial bodies are the following. A cone or pyramid mountain is shaped by fault development inside parent body's crust, then it is explosively ejected rotated, and at last drops down near or above the newly formed crater. Thrown out mountains are also possible to be destroyed into several parts or lose their integrities to form rock debris. On Ceres the process of ejective orogenesis proceeded on different scales, at least up to hundreds of kilometers. Examples of geologically fresh Ceres' craters and ejected mountains of different shapes and sizes are shown in fig.2.

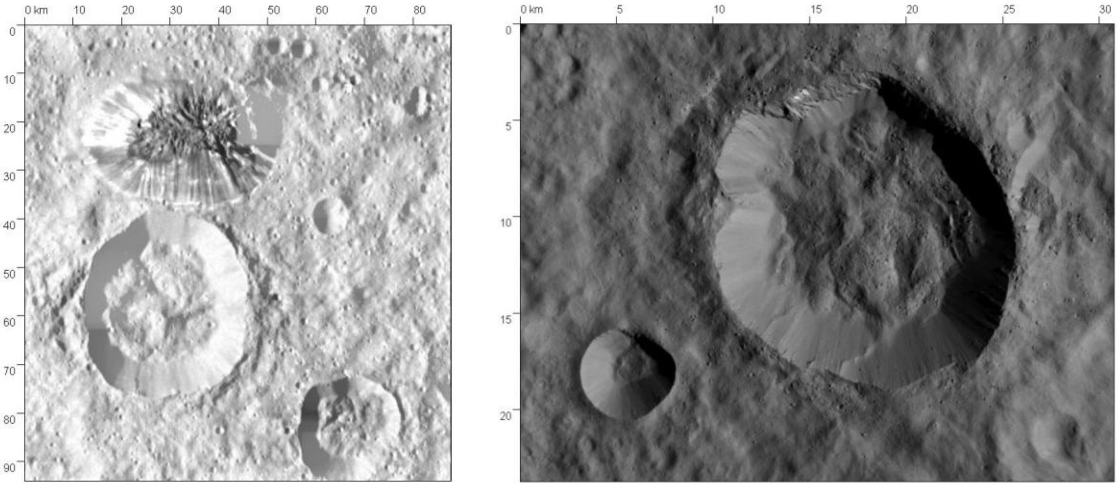

Fig.2. Images of Ceres' ejected mountains and associated craters. Both are crops from the original NASA's views and were contrasted. Left: A view of Ahuna region. A crater (up) and two big table mountains (down and down right), which are separated parts of casted out of the crater conical truncated mountain, are shown. The view also depicts several kilometers wide conical mountain (62,40). Right: A view of Ceres' region at approximately 23° south latitude, 279° east longitude with big table mountain and small mountains (down left and right). To see relief details readers are recommended to invert image colors.
(www.photojournal.jpl.nasa.gov./catalog/pia19631)
(www.photojournal.jpl.nasa.gov./catalog/pia20310)

The necessary condition of ejective orogenesis is the evolvement of faults and crustal cracks due to tensions and shears. In this situation crust becomes an active geologic media with mechanical energy stored and is prone to instabilities of different kinds, one of them being ejective orogenesis. As a rule, mechanical stresses are locally concentrated near crustal discontinuities due to the enhancement of larger scale stresses and are locally alleviated because of deformation stimulated diffusion of different substances and inclusions. The large scale stresses in turn are hierarchically connected to the global body's stress fields. According fracture mechanics stress concentrators are the vicinities of horizontal crustal layer borders, cracks of different directions, contact surfaces, inclusions of different kinds, and other crustal disjunctions. As the mechanics proves the stress energy around crack's tip line transforms into formation of new crack's surfaces for brittle fractures around it or into more energy consuming plastic deformations for ductile fractures.

Before mountain ejection plastic deformations are concentrated in the region of future crater. They lead to vast explosion all over conical crater surface, severe shock substance modifications of it and inside a mountain thrown out. Shock pressures inside it may result in final layered cone in cone inner symmetry the way shock twinning in crystals does. There are also, so to say, singular areas of highly plastically modified materials in ejected mountains. For instance, distinguish beak shaped upper part of the largest table mountain in fig.2 (left) or curved upper part of the down left mountain in fig.2 (right).

The explosion is mediated by dykes' formation along separating surfaces and their curved movement inside crust in the direction of cone geometrical apex. Hence igneous minerals are to be formed. In case of fig.2 dyke's leftovers look like streaks of brighter substances synthesized on crater surfaces and, to lesser extent, on mountains' slopes. In the figure the latter ones are less modified and less contrasted. For Ceres the whiter materials of crater dykes are mechanically stronger than darker materials around them.

Tensile crustal stress is responsible for plastic elongation of local region of future ejection. In fig.2 (left) one can see horizontally elongated crater. Plastic modifications also predetermine crater/mountain size disparities. For instance, the crater and the largest vertically (to page frames) elongated mountain near it are around ten percents different in size due to different plastic rebounds after ejection. The reason is irregular plastic off-set strain. Shear stress ultimately leads to starting rotation of an ejected object and its spiral-like relief features. The examples are curved lines on the slopes of small cones (fig.2, centered [62, 40], [4, 18]). The curvatures are the results of plastic rotations at the start.

Landed objects cohere later to crustal surfaces to become parts of crust and acquire its stresses. Those surfaces may also become stress concentrators under the influence of outer stresses. Plastically modified ejected bodies are genetically connected to the places of their origin. Initial crustal discontinuities leave their heritable marks inside and on outer surfaces of a thrown out object, the simplest ones being fault lines dividing a mountain ca. by half. Therefore features of ejected bodies are predetermined to some extent. Later destruction and slides of ejected bodies continue around inherited stress concentrators, e.g. notice the curved line dividing the upper part of the largest mountain in ca. vertical direction (fig.2 left). The line branches near the center of the table.

Inclinations of crater/mountain slopes determine flight trajectory of an ejected object by means of vector sum of detonation forces exerted on them. It is obvious that maximal vertical velocity is achieved if all slopes are equally inclined, given horizontal force compensation. On the other hand, the formation of faceted pyramid or cone shaped mountains with 45° slopes is the result of tensions along crustal surface which in perpendicular plane produce primary shears 45° to them. This way explosive ejection provides max vertical start velocities to a rotating axially symmetric body with ca. 45° slopes.

The phenomenon of ejective orogenesis is able to proceed with initial formation of curved elevations in flat regions. If the phenomenon advances as/in a volcanic edifice it is caldera formation regime. In this case the shape of ejected mountain is the counterpart of the caldera's one. If the evolving ejective orogenesis stops at its initial stages it may produce separated, chained, or lined rounded positive relief features resulted from the interplay of local plastic deformations and crustal substances' diffusion. Those features sometimes mark fracture lines and their endings on the surfaces of celestial bodies.

3 Standard understanding of Steins

The asteroid resembles a top of cone shape. Its geometry is that of ideally reflecting brilliant cut diamond due to approx. 90° summit angle. Steins rotates ca. around its symmetry axis (z-axis). During the encounter Rosetta mostly observed negative x-axis side of the celestial body [2]. The dimensions along the principal axes of inertia are 6.83x5.70x4.42km. There is a bit of 20% elongation in x-axis direction compared to y one.

Several dozens of Stein's craters are shallow and degraded (figs.3-5), except for Diamond, the largest of craters (1.8x2.1x0.3km), situated near the southern pole. An odd dichotomy in crater densities and cumulative distributions distinguishes surface areas of (-x, -y) and (-x, y) quadrants. More concentrated are craters in the former case, on the asteroid's eastern part, which Rosetta encountered first (e.g. see fig.1, fig.3 left). Authors of article [4] counted 31 and 12 craters, respectively, Obsidian being common for both counts (figs.4,5). The dichotomy is also revealed by very different power exponents of the crater size distribution functions (-3.3 and -1.5, respectively).

A chain of craters or catena (Lapis, Peridot to Agate) goes from Diamond to the northern pole summit approx. in y-z plane (figs.3,5). The same does the elongated groove opposite to the catena (figs.3,4). The bulged equatorial perimeter is marked by big craters (e.g. Chrysoberyl, Topaz). The biggest of them is ca. round depression, compared to Diamond in size, with Jade, Zircon, Garnet, Opal inside (fig.3 right arrow). The depression is divided by the catena.

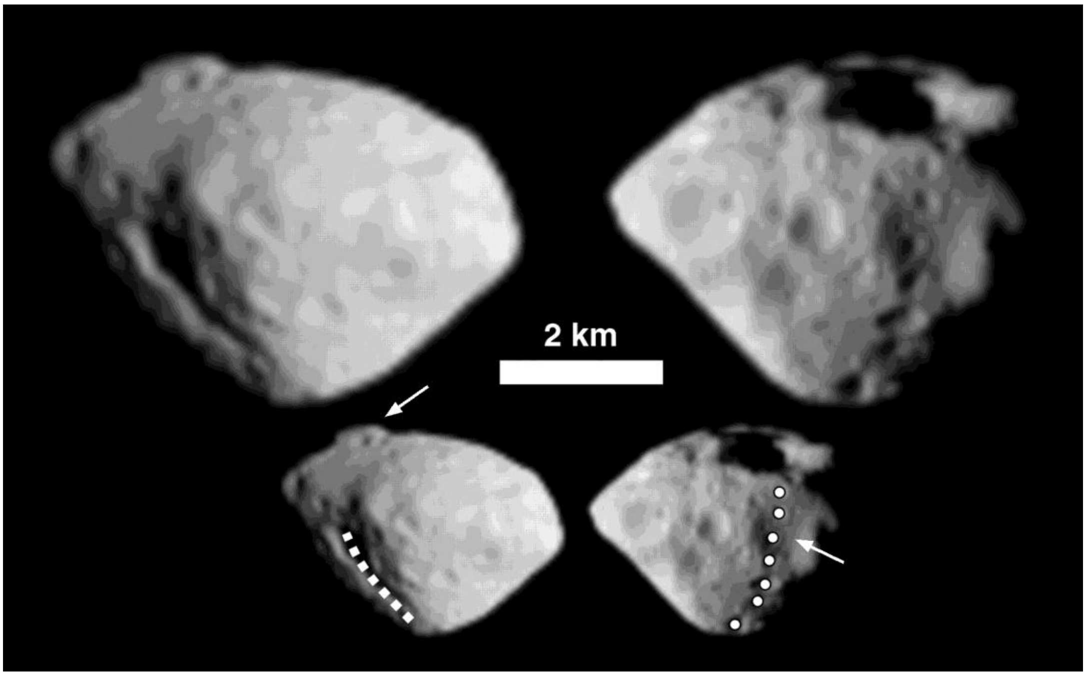

Fig.3. ESA's photography description (with some shortages) states: "The difference in viewing angle between the images is 91°, so they show opposite sides of the body. The positions of the catena with the seven pits (bottom right image) and of the large fault on the opposite side (bottom left image) are indicated". We added two arrows depicting small hill with Turquoise crater on its side and the biggest crater of the equatorial bulge. Scale line is related to the upper row. The catena and the large fault lie approx. in the same y-z plane. (http://sci.esa.int/rosetta/46256-asteroid-2867-steins-rosetta-osiris-images/)

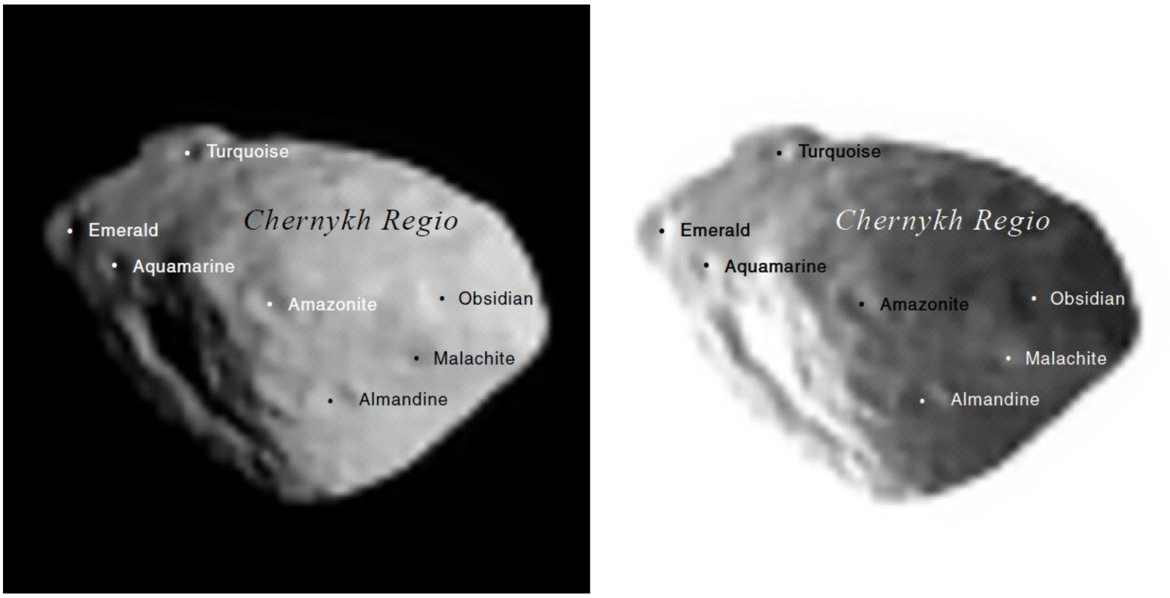

Fig.4.First crop from the original map of Steins' features named after precious stones. *Right view is the negative of the left one.*
(http://sci.esa.int/rosetta/54380-gemstones-on-diamond-like-steins/)

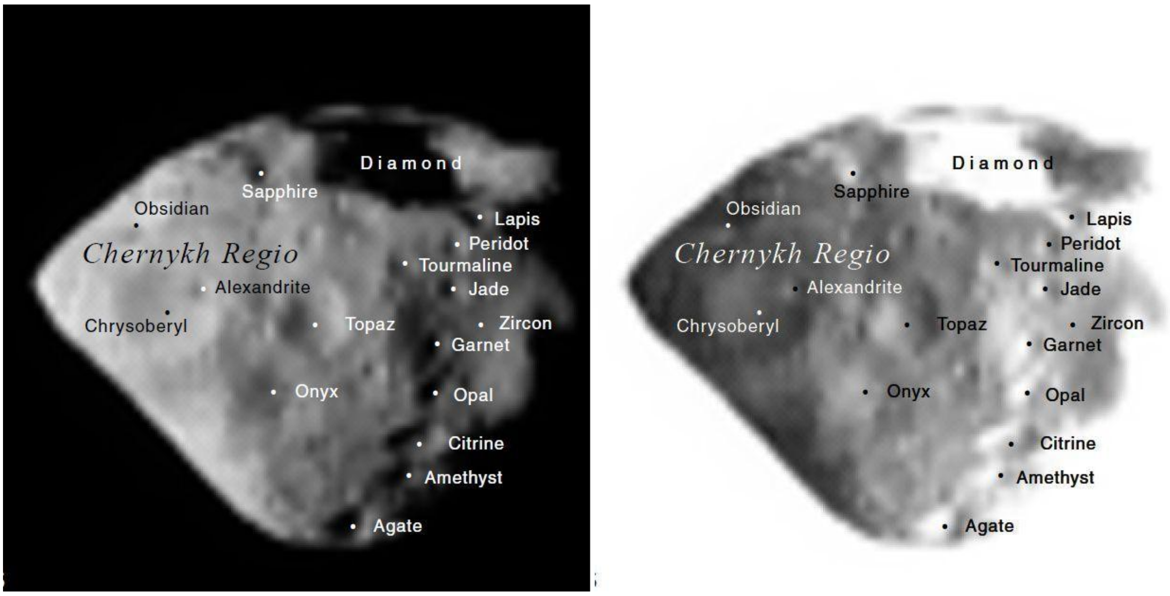

Fig.5. Second crop from the original map of Steins' features named after precious stones. *Right view is the negative of the left one.*
(http://sci.esa.int/rosetta/54380-gemstones-on-diamond-like-steins/)

It is widely agreed that Steins appeared due to impact destruction of a bigger celestial body. Its intriguing relief features are usually explained on the basis of Yarkovsky–O'Keefe–Radzievskii–Paddack (YORP) effect [5]. The effect is thought to happen when solar photons absorbed by a small body are reradiated in infrared and take out its angular momentum, this way changing rotation rate. YORP induced spin-up possibly led to Steins' reshaping and landslides, which diminish crater depths, being the reason of deficit of small (<500m) craters. YORP effect could also have caused materials to migrate to the equator to form the cone shape with equatorial ridge. Case of Steins is the first time that the effect has been seen in a main-belt asteroid.

4 Steins' ejective appearance

Alternatively, we explain the surprising Steins' appearance by its casting out of a parent body in the course of ejective orogenesis and subsequent plastic deformations interspersed by crater formations due to the same ejective orogenesis on smaller scales. The conical celestial body plastically expands mainly in x-axis direction with the simultaneous morphological and material changes. That is why the whole relief look is leaky and not freshly faceted. Steins is obviously at initial evolution stages.

Our rationalization closes the problem of Steins' ideal geometry. The asteroid is in fact flying rock of cone shape. As we discussed in Section 2, 90° summit angle and rotation around the axis of symmetry are natural effects of ejective orogenesis. Further we show that amendments to the ideal geometry are also clarified by the phenomenon.

Several big craters separated by elevations of comparable sizes are regularly located along Steins' equatorial bulge (figs.1,3-5). Those perimeter relief features are obvious remains of regular dyke-type streaks which sculpted the cone surface. Their locations are stress concentrating regions prone to destructions. Departures of dyke remnants' positions from exact regularity appear to result from plastic evolution of the asteroid, which leads to minute x-directional elongation and fracture opening. As it was noticed above the biggest equatorial bulge crater (fig.3 right arrow) is located above the main Steins' fault, punctuated by the catena, in so called singular area of maximal plastic modification of an ejected body.

Crater Diamond is commonly thought of as the result of southern pole impact, which the asteroid amazingly outlived. This approach to the origin of Diamond, which diameter is about half of the average radius of Steins, makes survival of the asteroid problematic. Disrupting impact was to fracture it and produce a rubble pile expected to fall apart. The crater is deep and some of its slopes are inclined >30°, which is the repose angle of regolith particles. In article [6] the slopes are found to be bluer due to the materials different from those regular to Steins' surfaces. Other researchers [7] insist on lack of color variation and surface inhomogeneities larger than 4% (95% confidence level) around the linear depression (dotted in down left view of fig.3) and close to the rim of Diamond.

The hill with Turquoise crater on its side is located near Diamond (fig.3 left arrow). The hill is about of the crater's size and elongated in y-axis direction (reconstructed polar view of Steins is shown in fig.3 of article [5]). It is commonly believed to be excavated by the outer impact. To our opinion, the same main fault, which brought about Steins and was inherited by it, gave birth to Diamond and the hill as its counterpart. Thus ejective explanation states that the hill was thrown out of Diamond, flipped, and dropped down nearby.

This approach directly explains the slope related observations [6]. As is the case for craters of e.g. minor planet Ceres, Diamond's slopes are to be fresher, stronger, and whiter than other surface and slope areas of Steins. Plasticity and space weathering did not manage to destroy them yet. Turquoise crater was formed later on the contact surface between the hill and the crust of Steins, which played the role of stress concentrating discontinuity during subsequent Steins' plastic reshaping [3].

Our scenario means that the asteroid is partly structured. The tendency of some Steins' relief features to be aligned in axial direction or 45° to them (fig.6) is consistent with bulk cone in cone structure [3] and stressed surfaces of the asteroid. Observe diagonally crossing contrast undulations (fig.7) inside the largest bulge crater (region of Jade, Zircon, Garnet craters). X-axis tensions appear to produce shears 45° to them.

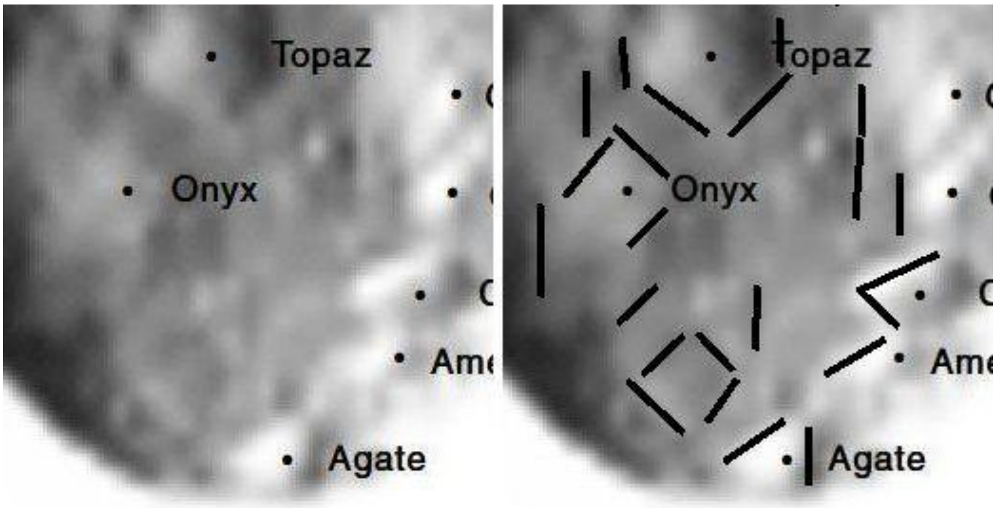

Fig.6. Left: a crop from fig.5 (right). Right: the same crop with regular elevations marked by black lines.

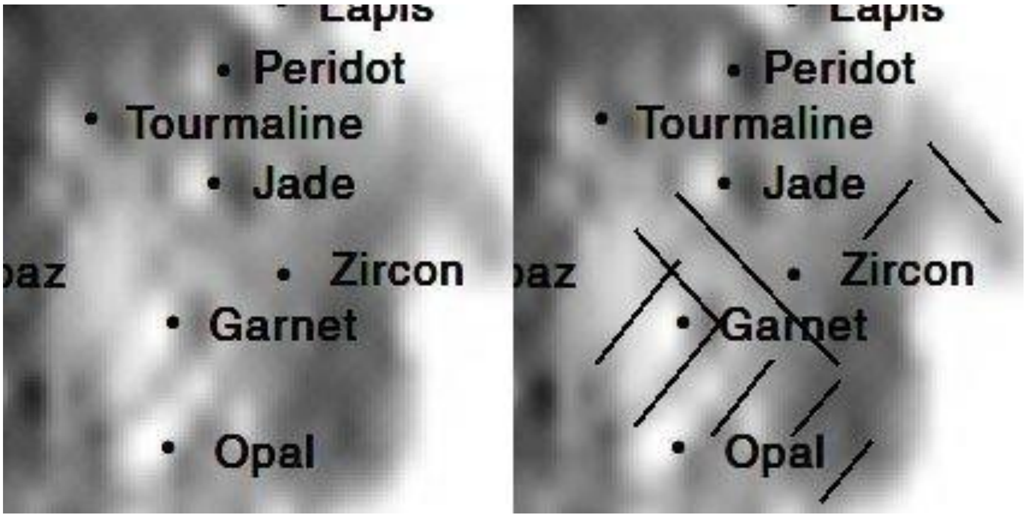

Fig.7 .Left: another crop from fig.5 (right). Right: the same crop with regular elevations marked by black lines.

The expansion of the main fault and a handful of ejections along it are also the reasons of existence of two opposite grooves marked by dotted lines in fig.3. Elongated in x-axis direction northern pole summit is crossed by the fault. The catena's grove looks somewhat wider than the opposite one. Hence, discussed above crater dichotomy [4] appears to result from tensional difference between Steins' sides. Ejective orogenesis is a solid state phenomenon and the increase of tensile stresses stimulates it. Intersections of parent crustal layers inherited by the asteroid with the fault are the places of stress concentration. Those are the plausible positions of separated craters in the catena.

Steins' x-axis extension due to still acting stress mechanisms is also proved by the lined chain of 7 or 8 craters and nearby rhomb like relief features (fig.8). Other evidences are zigzag borders of both grooves and rhomb like shapes of Opal Citrine, Amethyst, Agate, as well as bigger Onyx and Topaz craters (figs.5-8). Larger craters look more rounded possibly due the influence of overall Steins' plasticity. At the same time the plastic reshaping of Steins as a whole is to decay its global shears and diminish crater sizes and depths. Henceforth, ejective orogenesis is to be mostly active in subsurface layers.

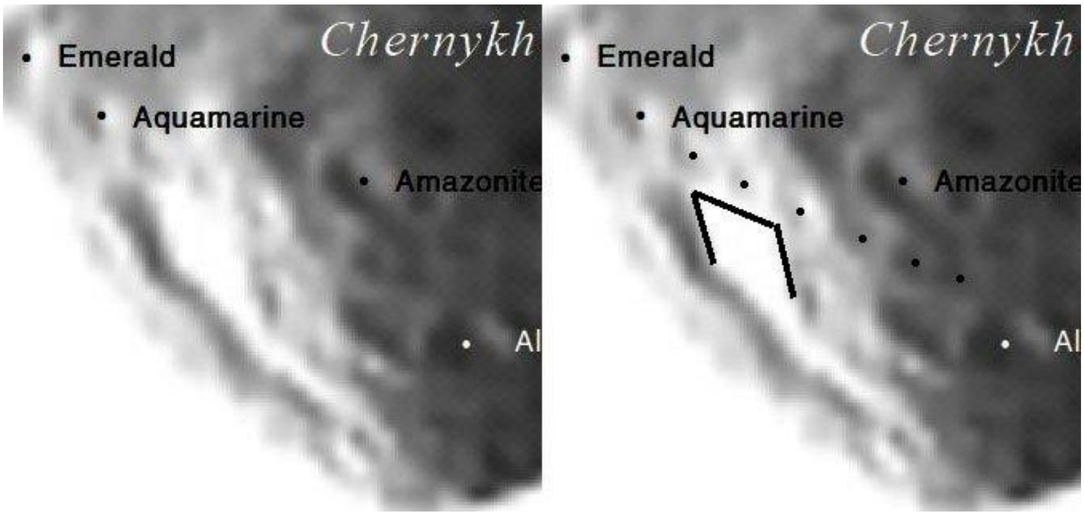

Fig.8 Left: a crop from fig.4 (right). Right: the same crop with one of rhombic relief features and dotted crater chain.

Analysis of multi-spectral optical images indicates that the surface of Steins is highly porous (84%). The result is that the asteroid may in fact exhibit a fractal surface with high roughness present within a large range of scales, from micrometers to centimeters [8]. Rosetta's millimeter/submillimeter radiometer and spectrometer evaluated high thermal power inertia of the surface, which is characteristic of rock dominated regolith. The area-averaged dielectric constant of the surface material ranges 4–20. These values are rock-like, and powdered Moon-like regolith is ruled out [9].

Steins is the first of rare E-type asteroids encountered by a cosmic probe. Ground-based spectral data and those of Rosetta prove that Steins belongs to E[II] subtype which surface is composed of igneous rocks, formed above 1000°C [5]. This is not surprising in the light of our explosive dyke related ejective approach.

E-type asteroids are known for high polarization anomalies of radio waves. To our opinion the reason could be the formation of multiple reflecting structures on fractal surfaces and inside asteroids due to surface or inner structural and/or material regularities, which are natural for ejective orogenesis [3].

5 Discussion

Now we consider Steins characteristics in the context of other asteroids and satellites. Observational data on diameters of the largest craters of small bodies with sizes up to hundreds of kilometers are examined in articles [10,11] . The ratio of Diamond's diameter to mean Steins' diameter is calculated about 0.4 there. Analysis of two dozens satellites and asteroids of different shapes showed that the width of Steins' crater Diamond is not unusual among the largest craters of similar sized bodies. The data also prove approx. equality of largest crater diameters to the radii of their parent bodies. That is crater width to body's size ratio tends to be close to one half (figs.2 in articles [10,11]). That trend directly follows from our cooperative approach to ejective orogenesis, which results from hierarchical fracturing due to instability of active geologic media and nonlinear interaction of its seismic modes. The ratio means prevalent energy canalizing into the first mode (half of body's size wavelength).

Steins is not the only diamond in the sky. For instance, asteroid Annefrank is similar in size (6.6x5.0x3.4km) and partly in geometry. In 2002 NASA Stardust probe flew past the asteroid at a distance of thousands of kilometers. The dozens of images covering large part of the surface showed the object resembling triangular prism with several craters and small rounded bodies on the surface. It is said in article [12], that "Annefrank is highly angular, with flat appearing surfaces, possibly planes formed when it was fractured off of a larger parent". Main belt asteroids are generally faceted in shapes, which are usually extracted from the integration of light curves, giving faceting, not dimensions. According to our approach faceting is the result of fracture planes' crossings inside parent rigid bodies of asteroids.

Majority of asteroids are grouped in families according to their proper orbital elements such as major axes, eccentricities, and inclinations. It is common knowledge that new family members have been forming due to random outer impacts into their parent bodies. Numeric integration of asteroid trajectories allows restore time evolution and history of families. There are lots of articles devoted to the problem and some of simulations are inconsistent with chaotic impact implications. For example, the authors of article [13] discussed serious and puzzling physical problems for collisional processes originating the asteroid dynamical families. They pointed out that recent hydrocode simulations do not reproduce observational high ejection velocities of asteroid fragments.

For Koronis family weird is the surprising result concerning spin vectors of asteroids [14]. First, the rotational axes of its members are not random as they should be. Second, the angular velocities correlate to two separate spin directions found. Another interesting result concerning Koronis family is that the simulated ejection velocity is inversely proportional to the size of an asteroid [15].

Our approach explains this functional dependency. The momentum gaining by an ejected rocky body due to pyramid-like or cone-like underground explosion is proportional to its buried surface area, if detonation conditions are approx. equal. For a cone the buried area is proportional to squared radius of its base. At the same time the momentum is the product of escape velocity and mass, the latter being approximately proportional to volume, i.e. the body's size in third power. Therefore, the velocities of different ejected objects trend to change inversely with their average linear dimensions.

There are also radar observations of Near-Earth asteroids of top shapes. For instance, the asteroid 2008 EV5 0.4km in diameter has equatorial ridge with 0.15km wide depression on it. According to article [16] this concavity was dug out by outer impact or formed because few large blocks left the gap after ridge formation. The shape of the asteroid resembles both larger table mountains shown in fig.2. The northern polar view of the asteroid proves somewhat elongation of it, while the southern view looks almost circular. The southern apex is separated into two parts. Its view proves the existence of saddle-like relief feature near the southern pole of asteroid 2008 EV5 (fig.8 of article [16]).

Other example of top shaped Near-Earth asteroid is 1.5km wide asteroid 1999 KW4 with a pit on its equatorial bulge [17]. The asteroid has an elongated satellite approximately 0.5km in size and tens percents denser than the primary. The moon is on circular 2.5km orbit with synchronous rotation. It is said in the article [17] that such “exotic physical and dynamical properties may be common among near-Earth binaries”.

In works [16,17] the shapes of Near-Earth asteroids 2008 EV5 and 1999 KW4 are explained by YORP effect. Opposite, even the above brief description of them confirms that our rationale is able to give even details of their appearances. Scale independence of our ejective approach allows effective astrophysical analysis of the moon of asteroid 1999 KW4 as well.

Examination of Steins and preliminary study of other space objects lead us to the conclusion, that topological changes due to plasticity may drastically modify initial offspring appearances. But expansion/ejection morphogenesis is not homogenous and proceeds locally, in special directions and in special regions. So it is sometimes possible to find perspectives from which an object looks almost as a newborn or retains its birth look in the main. Those angles of view allow effectively analyze changes in shape (e.g. upper left view in fig 1). That is of great help in deciphering histories of cosmic objects.

Now we formulate one of our universal results with the introductive words of article [4], but adding “not” to them: “Asteroids are not primitive bodies that have been geologically inactive since their formation”. Not only impacts and space-weathering change their forms. From ejective point of view asteroids are members of broad celestial community of layered rock bodies which also includes comets, and satellites. All they are in the process of permanent geologic changes, sometimes catastrophic. The differences between them are those in histories, sizes, space trajectories, and evolution rates.

Literature search shows that the ejective approach has its predecessors. Among them are famous nineteenth century polymath J.L. Lagrange, who in 1812 proposed eruptive volcanic hypothesis of comet originations, his successors R.A. Proctor, A.C. Crommelin, S.K. Vsekhsviatsky, and others. Our main inspiration was the judgment of twentieth century astrophysicist V.A. Ambartsumian about the prevalence of separations in space. He put forward and widely discussed those ideas for stars and large stellar associations discovered by him. We tried to realize his ideas on much smaller scales.

Summary and conclusion

Our sustainable consideration of Steins' properties proved that some larger primary body gave explosive birth to the asteroid. We proposed and confirmed the idea of its rotational throwing out of parent body's crust into space. This fact is demonstrated to be the result of explosive ejective orogenesis. That ubiquitous among solid celestial bodies phenomenon, which was earlier described on example of asteroid Ceres [3], was also briefly reviewed in this paper.

The value of our approach is evidenced by the comparison of Steins' properties with the universal genetic features of ejected mountains and smaller rocks. Our analyses of Steins' ideal symmetrical shape, rotational axis, morphologies of regularly bulged equator, characteristics of the largest crater and nearby hill, opposing grooves, chains of craters, and others showed that all those counted are the features identical to the ones of rocks explosively ejected by layered crusts of rigid bodies.

The general implications of our explosive ejective approach were also discussed for Near-Earth, Main Belt asteroids, and their families. Its qualitative dependencies were demonstrated to be consistent with a number of observational characteristics of asteroids and satellites.

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