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Ernst Julius Öpik's (1916) note on the theory of explosion cratering on the Moon's surface—The complex case of a long-overlooked benchmark paper

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Abstract–High-velocity impact as a common phenomenon in planetary evolution was ignored until well into the twentieth century, mostly because of inadequate understanding of cratering processes. An eight-page note, published in Russian by the young Ernst Julius Öpik, a great Estonian astronomer, was among the key selenological papers, but due to the language barrier, it was barely known and mostly incorrectly cited. This particular paper is here intended to serve as an explanatory supplement to an English translation of Öpik's article, but also to document an early stage in our understanding of cratering. First, we outline the historical–biographical background of this benchmark paper, and second, a comprehensive discussion of its merits is presented, from past and present perspectives alike. In his theoretical research, Öpik analyzed the explosive formation of craters numerically, albeit in a very simple way. For the first time, he approximated relationships among minimal meteorite size, impact energy, and crater diameter; this scaling focused solely on the gravitational energy of excavating the crater (a "useful" working approach). This initial physical model, with a rational mechanical basis, was developed in a series of papers up to 1961. Öpik should certainly be viewed as the founder of the numerical simulation approach in planetary sciences. In addition, the present note also briefly describes Nikolai A. Morozov as a remarkable man, a forgotten Russian scientist and, surprisingly, the true initiator of Öpik's explosive impact theory. In fact, already between 1909 and 1911, Morozov probably was the first to consider conclusively that explosion craters would be circular, bowl-shaped depressions even when formed under different impact angles.

Nowadays, with the enormous supply of scientific publications, it becomes progressively more difficult to master the entire literature, or even the details of one narrow branch of science. This has led to the ever increasing habit of trusting authority, second- and even thirdhand. Statements are repeated that never would have been made upon critical study of the evidence. Erring may be human, but too much reliance on unchecked authority may lead to unwarranted perpetuation of error… (Öpik, 1971, p. 109)

INTRODUCTION

Only during the later part of the twentieth century have high-velocity impacts of solid bodies and collision events been recognized as one of the most important factors in the evolution of the terrestrial planets. Decisive to the common acceptance of this fundamental concept, in reference to the lunar meteoritic hypothesis, was the seminal book *The Face of the Moon* (1949) by Ralph B. Baldwin (1912–2010) (see e.g., Urey 1956; Lewin 1962; Shoemaker 1962; Baldwin 1963, 1978; McCall 1980; Hoyt 1987; Wilhelms 1993; Schultz 1998; Koeberl 2001). Attempts at clarification, after century-long debates that volcanic activity was not linked to ring structures ("ring mountains," "crater mountains," "cirques"; Fig. 1) in our solar system, had also stimulated the search for scars left by falls of cosmic bodies onto the Earth. In fact, this was a preliminary step in the introduction of new catastrophic hypotheses. Although these were rooted in the late seventeenth century (comet/flood) theories, and had been developed as diverse concepts by German scholars in the early nineteenth century, cosmic collisions and meteorite craters did not become important scientific matter until the 1930s (Ley 1944; Hoyaux 1946; Baldwin 1949; Khabakov 1949; Paluzíe Borrell 1953; Urey 1956; Both 1961; Fielder 1961; Green 1965; Bronshten 1979; McCall 1980; Hoyt 1987; Mark 1995; Schechner 1997; Schultz 1998; Sheehan and Dobbins 2001). Subsequently, it took three more decades for hypervelocity impacts to become accepted as a natural geological factor in space history. This provided the definitive proof of causal links between evolutionary catastrophes and the disastrous effects of bolide impacts on our planet (e.g., Melosh 1989; Wilhelms 1993; Mark 1995; D'Hondt 1998; Palmer 2003; French 2004; Reimold 2007; Nield 2011; Osinski and Pierazzo 2013). Ever since the classic "Alvarez paper" (Alvarez et al. 1980), extraterrestrial hazard themes have been the subject of intense debate in mainstream science.

In the literature, the British astronomer Richard A. Proctor (1837–1888) and the American geologist Grove K. Gilbert (1843–1918) have commonly been regarded as the founders of the current meteoritic impact model of lunar craters (Proctor 1873, 1878; Gilbert 1893). However, an inadequate understanding of the energetics and mechanisms involved in crater formation was the main obstacle to an effective growth of bolide bombardment ideas, as stressed by Gifford (1924, 1930a), Baldwin (1949, 1963, 1978), Melosh (1989), Schultz (1998), Pierazzo and Melosh (2000) and Koeberl (2001), among others. In this context, Baldwin and Wilhelms (1992) cited an early (published in 1916) paper, in Russian, by Ernst Julius Öpik (1893–1985), a great Estonian astronomer, among three "lost" key papers in lunar studies. The main reason for this probably was the language barrier and the fact that it appeared in the poorly known, not widely distributed "Bulletin of the Russian Society of Friends for the Study of the Universe" (*Mirovedenie*).

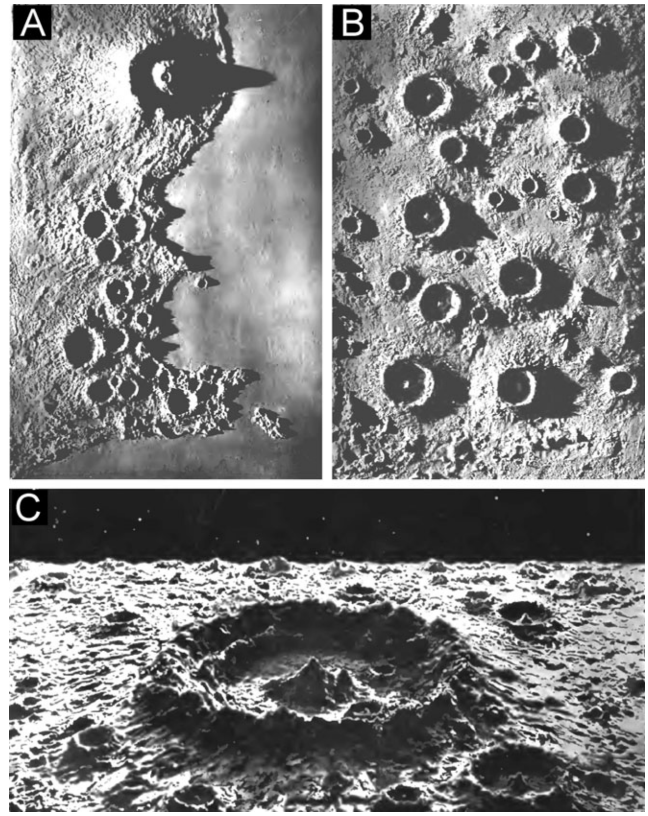

Fig. 1. A popular presentation of the nineteenth century volcanic theory in the book *The Moon: considered as a planet, a world, and a satellite* by Nasmyth and Carpenter, printed in five editions between 1874 and 1916. The influential work was spectacularly illustrated by images of plaster models representing the lunar surface features, illuminated from various angles, more realistic than contemporary telescopic photographs. (A–B) An instructive comparison of two areas, terrestrial (A; the volcanic neighborhood of Naples, Italy) and lunar (B; about Crater Theophilus), of the same size; the Vesuvius region, well-known from ancient times as the Campi Phlegraei (burning fields), was seen as a terrestrial analog to the cratered lunar surface (the Moon as "a grand Phlegreian field"); from the third edition (1885, pls. 6, 7). C) Typical lunar "ring-mountain," with a distinctive central peak, as an extinct volcano, from the fourth edition (1903, pl. 17).

Ever since having been cited by Baldwin (1963), Öpik's (1916) paper has been referred to and fairly widely recognized as the first to document that a hypervelocity impact was similar in fact to an explosion, and, therefore, the resultant structures would be circular irrespective of the angle of incidence (Hoyt 1987, pp. 196–197; Melosh 1989, p. 5; Wilhelms 1993; Pierazzo and Melosh 2000; Koeberl 2001; Masaitis 2006; also in the Russian-language literature, see Bronshten 1979). This novel theoretical approach decisively explained the long-lasting puzzle in lunar studies that had been

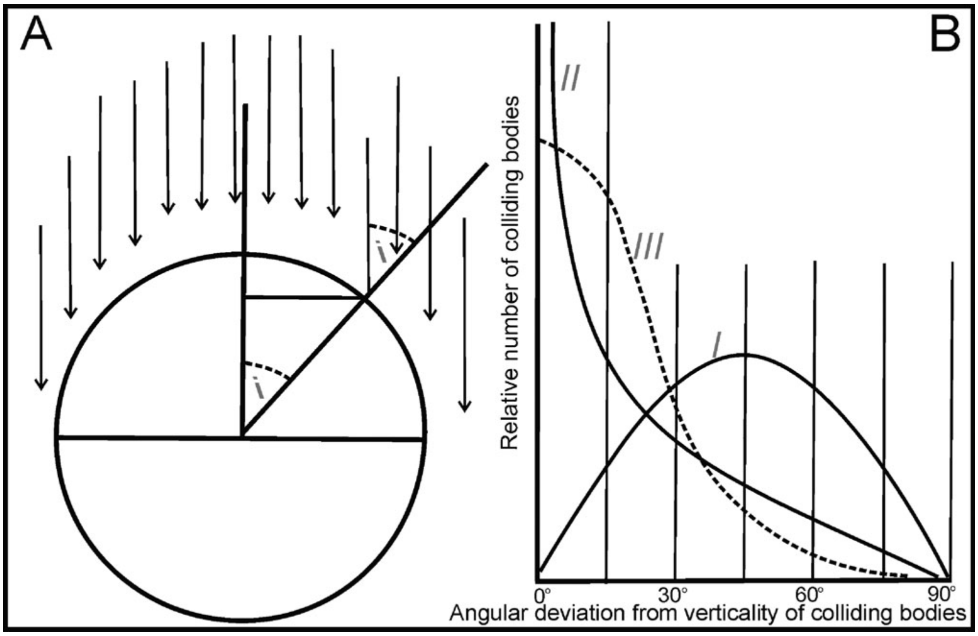

Fig. 2. Diagrammatic illustration of Gilbert's (1893, figs. 11 and 12) theoretical approach to the roundness paradox of lunar impact scars, based on geometric relationships of an incidence angle of Saturnian ring—derived moonlets (A; sin *i* as an expression of the proportionate number of the objects whose incidence angle is less than *i*), and estimated distribution curves (B) for meteors (I) and moonlets (II), and type of curve derived from ellipticity analysis of the Moon's craters (III). Note an overall agreement in a predominant approximation to verticality, predicted from circularity of lunar craters and the law of incidence angle for moonlets (but not for meteors!). This was a starting point for Gilbert's (1893) hypothesis that lunar craters record a final phase of the satellite formation due to collision coalescence of debris derived from the disc-like ring around the Earth.

discussed by Gilbert (1893; see Fig. 2) and Wegener (1921). Of note, in this respect, is the fact that, at the time, the reference terrestrial Meteor Crater in Arizona was essentially interpreted by American scholars as a signature of purely mechanical destruction of the ground by an inert body that struck the Earth (i.e., as impact craters *par excellence*, versus explosive craters, as defined by Krinov 1966). In this particular case, the misunderstood physical process was the prime reason why its impact origin was refuted (Gilbert 1896). In fact, Gilbert (1896) accepted the rival endogenic hypothesis—a volcanogenic steam explosion—because he allowed for only partial melting of the projectile mass and target liquefaction (Gilbert 1893, p. 259).

The present note started out as an explanatory supplement to the English translation, by Tõnu Viik, of Öpik's (1916) article on the origin of lunar craters. It was our wish to make this eight-page paper, originally published in Russian with a summary in French, available in English, and, in addition, to explain a number of misconceptions. In the introductory paragraph, Öpik made it clear that his physical considerations were based on a model of explosion lunar craters proposed earlier by the Russian political revolutionary, physicist, and astronomer, Nikolai Alexandrovich Morozov (1854–1946), who appears to have been unknown in the English-language literature. Öpik's main aim was to capture the cratering process postulated by Morozov numerically. With regard to misunderstandings, Baldwin and Wilhelms (1992, p. 3837) claimed that, "Öpik [1916] erroneously considered that craters called to the transfer of momentum, not energy," which, however, refers to later papers (Öpik 1936a, 1958a, 1961) in which he focused on penetration mechanics of the crater-forming projectile. Additionally, the 1916 note was said to have been published either in Estonian (Baldwin 1963, p. 9) or in Estonia in Russian (Baldwin 1978, p. 367), but it actually appeared in St. Petersburg (Petrograd at the time). It appears that this "exotic" paper has never been studied thoroughly, if at all, by English-speaking readers (and obviously not by French speakers either, although there was at least a French summary).

The present note documents an important episode in the history of meteoritics and attempts to rectify false impressions that have resulted from papers by influential scientists such as Ralph Baldwin. The aims of the present paper are threefold (1) to outline the historical-biographical setting of this milestone research during the First World War (T. Viik); (2) to provide a brief introduction of N. A. Morozov as an unusual man, scientist, and the true initiator of Öpik's concept

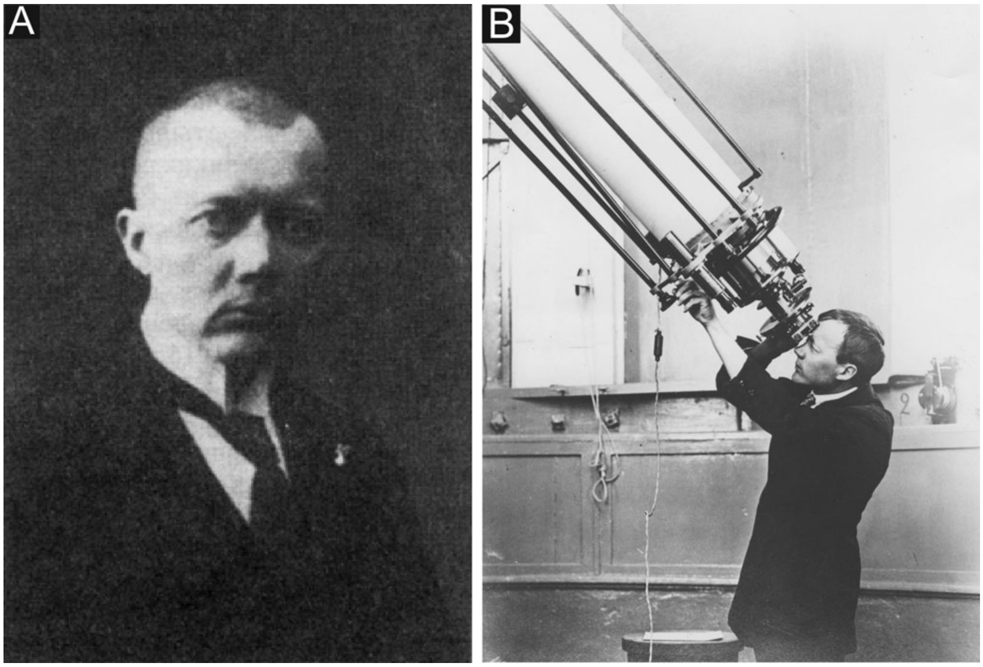

Fig. 3. Ernst Julius Öpik in 1922 (A; from Bronshten and Pustylnik 2002, p. 36), and in 1929 at the Tartu Observatory 20 cm Zeiss telescope (B; courtesy of H. Eelsalu).

of impact (E. Jagt-Yazykova and G. Racki); and (3) to revise the scientific value of this benchmark article from both historical and modern perspectives (G. Racki, C. Koeberl, and J.W.M. Jagt).

ERNST JULIUS ÖPIK: LIFE AND EARLY SCIENTIFIC WORK

Ernst Julius Öpik (Fig. 3) was born in the small township of Kunda (Estonia), in a family of a customs officer, on October 22, 1893 (Bronshten and Pustylnik 2002). As a gymnasium schoolboy in Tallinn, he founded an astronomy club, the members of which made observations using a 3″ telescope bought from their own savings. He graduated from the gymnasium in 1911, winning a gold medal, and went to study physics and mathematics at Moscow University. Already in his student years, he was interested in studying the solar system and, more specifically, meteors. After graduating with honors in 1916, he was employed at the Moscow Observatory and in 1919, left for Central Asia to work at the Turkestan University and the Tashkent Observatory. Traveling via Moscow in 1921, he returned to his native Estonia, which had just won its independence.

In Estonia, Öpik was employed by the University of Tartu at the Observatory as an astronomer–observer. Free of administrative tasks, Öpik devoted his time to research and between 1922 and 1940, he published 65 papers on very broad topics, ranging from statistical studies of double stars to the internal structure of stars. He honed his double-count method of meteors and designed a new device, the rocking-mirror meteor camera. His results did not go unnoticed and in 1930, Harlow Shapley invited him as a visiting professor to Harvard University, where he delivered lectures on astronomical statistics. During one of such visits, Öpik took part in the 2 year Arizona meteor expedition during which 26,000 meteors were registered. One of the main outcomes of this expedition was the finding that sporadic meteors move around the Sun in the same direction as planets do. Until then, it was thought that all directions of meteor movement were equally probable (Öpik 1933).

One of the most important results obtained at Tartu Observatory in 1938 concerned the internal structure of red giants. Contrary to Eddington, Öpik assumed that the chemical composition of these stars was not homogeneous. He solved the respective equations under this assumption, taking into account the most modern results in nuclear reaction rates and found quite realistic models for red giants (Öpik 1938a, 1938b), thus antedating similar results by 10 years (Richardson and Schwarzschild 1948).

His successful studies were interrupted by the Second World War, during which the battlefront swept twice over Estonia. Having experienced Soviet power after 1917, Öpik decided to emigrate in 1944, first to Germany, where he was one of the rectors of the Baltic University during 1945–1947. In 1948, Öpik moved, together with his family, to Armagh in Northern Ireland and continued his astronomical career at Armagh Observatory as a research associate, having been invited by E. M. Lindsay. Öpik worked there for more than 30 years. In view of the fact that he did not like to publish his results in high-ranking journals (for which G. Gamow reproached him, after having seen Öpik's papers on the internal structure of red giants in the *Proceedings of Tartu Observatory*; Öpik 1977), he founded a new journal, the *Irish Astronomical Journal*. Unfortunately, this series has been discontinued. However, it should be noted that his reluctance to publish in international journals was not absolute. Even some of his first works came out in the *Astronomische Nachrichten* (in 1914) and the *Astrophysical Journal* (1916).

Öpik died in Bangor, Northern Ireland, on September 10, 1985.

Below, we discuss Öpik's early papers in more detail, having noted that from the very beginning, he was interested in celestial bodies of the solar system. In 1912, he published his first scientific paper which outlined personal observations of Mars and Venus in the *Bulletin of the Russian Society of Friends of the Study of the Universe—Mirovedenie* (Öpik 1912). The young student demonstrated his talent fully in a paper entitled "The method of counting the number of shooting stars," which appeared in print in the same bulletin as the 1912 paper and which has remained valid to this day (Öpik 1914). He also published an undervalued paper on the meteoritic origin of lunar craters (Öpik 1916; see Fig. 4), which is the main theme of the present note. Of his other works from this period, the one on an original method to determine the distance of the Andromeda galaxy is particularly significant (Öpik 1921).

The impact theory continued to interest Öpik (see below). In 1936, he published a paper on the possible consequences of meteor collisions in space (Öpik 1936b). In all of his works, Öpik demonstrates depth of thinking and an amazing simplicity in tackling even the most complicated problems of physics and astronomy. P. M. Millmann put a name to this quality; it is quantitative common sense. It is this quality that Öpik exploited in full and always without the help of computers (Millmann 1972).

ИЗВѢСТІЯ РУССКАГО ОБЩЕСТВА ЛЮБИТЕЛЕЙ МІРОВѢДѢНІЯ

Томъ V.

1916 г.

№ 19—24.

(310 стр. 94 рис. въ текстѣ и 2 отдѣл. табл.).

ПЕТРОГРАДЪ.

Типографія Редакціи періодическихъ изданій Министерства Финансовъ.

1916.

Fig. 4. Title page of the journal *Bulletin of the Russian Society of Friends of the Study of the Universe—Mirovedenie* of 1916; courtesy of St. Petersburg State University Library.

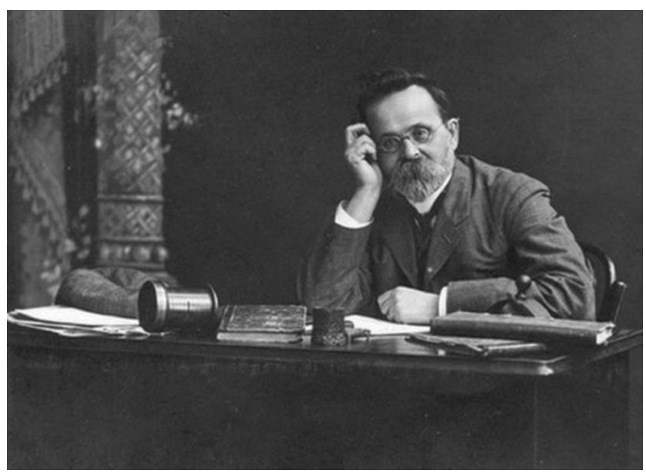

Fig. 5. Nikolai A. Morozov in 1909 (from: http://www.bizslovo.org/content/index.php/ru/istoriya-nikopolya/148-pochat-xx-st/848-bogush-ego-proklyali.html).

NIKOLAI A. MOROZOV AND HIS FORGOTTEN CONTRIBUTIONS TO PLANETARY SCIENCES

In Russia, Nikolai A. Morozov (Fig. 5) is today widely known as a political revolutionary who spent more than 25 years in prison; few people see him as a scientist (see e.g., http://en.wikipedia.org/wiki/Nikolai_Alexandrovich_Morozov). A look at his very unusual life and numerous scientific papers suggests he is best referred to as *an unvalued pioneer scientist who proposed many revolutionary ideas for that time*. To sum up the life of this member of the Russian Academy of Sciences is far from straightforward. He was the director of the Saint-Petersburg Institute of Natural Sciences;

professor *honoris causa* of Saint-Petersburg University; a member of the Russian Astronomical Association, the Société Astronomique de France, and the British Astronomical Association; as well as a revolutionary who met and admired Marx, Lenin, and Stalin; and also wrote a pamphlet, *The Terrorist Struggle*. He was an extremely unusual and extraordinarily talented person.

Morozov was the bastard son of a wealthy landowner, who received a very good education at home, was proficient in Latin and Greek, and successfully finished the 2nd Moscow gymnasium. From an early age, Morozov was particularly interested in natural and earth sciences. In 1870–1871, he was listed as a volunteer student at the Faculty of Natural Sciences (Moscow State University) and took part in paleontological field work in the Moscow area. However, because of his political activities, he was arrested on numerous occasions. During the first few short-term arrests, he began to write science-fiction stories, which he himself referred to as semifantastic (Pervushin 2005). From 1884 onwards, he was imprisoned for life at Shlisselburg fortress, but was granted amnesty in 1905. During his 25 years in prison, he learned 11 foreign languages and wrote numerous works on chemistry, physics, mathematics, astronomy, philosophy, aviation, political economy, antique history, linguistics, even so-called "scientific lyrics," and fairy tales for children.

Some of his papers still are important scientifically. For example, modern physicists have fully confirmed his statement of the complex structure of atoms and interconvertibility of all chemical elements that was presented in one of his monographs in 1906. After prison, Morozov began to publish his works and continued research. One of his monographs compiled numerous detailed and impressive data on geology of the western Caucasus (Morozov 1910b). However, it seems that most of all, he was interested in planetary sciences, as well as in chronology, especially its astronomical aspects. His fundamental work *The history of human culture in science coverage, Christ* (Morozov, 1924–1932) comprises 10 volumes (only 7 of these were published during his lifetime). He perceived biblical texts as encrypted descriptions of astronomical phenomena. In this huge work, Morozov presented many revolutionary hypotheses, e.g., a new concept of astronomical chronology.

All these hypotheses met with severe criticism; in fact, this continued until the end of the twentieth century. His single presentation in the English scientific literature on astronomy was prepared by M.S. Kissell, who presented a summary of Morozov's biography and translated some the most important (in his view) parts of a 300-page book entitled, *The revelation in thunder and storm* (1907), actually combining his methods of considering the biblical texts as encrypted descriptions of astronomical phenomena with some specially worded instances of disagreement (Kissell 1940–1941). It should be noted that almost immediately after this publication, Morozov was depicted rather like a pseudoscientist whose work was fascinating, but did not deserve the slightest credibility (Bobrovnikoff 1941).

Morozov's interests were wide ranging, from chemical elements to the essence of life; from the appearance of stars in an explosion of cosmic bodies to the formation of clouds; from vector calculus to the theory of relativity, the processes occurring in the center of the globe; to aeronautics; from ancient and medieval history to science outcomes at the start of the twentieth century. Today, many of his ideas, including the hypothesis of meteorite catastrophes, have been revived and have received significant support. A crater on the moon has been given his name, and a minor planet (1210) was named Morosovia is his honor.

Morozov's Concept of Meteorite Craters

Essential to the present note is Morozov's hypothesis of meteorite impacts in the geological history of the Earth and Moon, which actually appeared already in some of his early popular-scientific publications (Morozov 1909). However, an early science-fiction story on the lunar subject, written by Morozov during his first imprisonment in 1882 and published in 1910, together with other semi-fictional stories (Morozov 1910a; unavailable to us), became very popular (Pervushin 2005). Interestingly, in 1963, his pioneer paper of 1882 was reprinted (incorrectly announced as published for the first time, from manuscript), albeit in a shortened version in the popular-science journal *Tekhnika Molodezhi*, to which comments by the academic V.G. Fesenkov were added (Fesenkov 1963; Morozov 1963). He underlined, however, the limited applicability of this overall fruitful notion. In this science-fiction publication, Morozov described weightlessness and put forward the hypothesis that lunar craters were not the result of volcanic activity (as then considered), but of the impact of meteorites and comets. He also ascribed this collision origin to lunar grooves, and intuitively predicted a similar origin for terrestrial impact craters (Morozov 1963, p. 30):

> As it would be interesting to investigate the lakes scattered in the Trans-Ural steppes, which on the large maps take completely this form, as if they been engraved by the many fragments of numerous group of bolides! Indeed if they are actually of meteoric origin, and meteors, as usual, include iron, then by

Fig. 6. Title pages of Morozov's article of 1909 on the Moon puzzles in the popular-science journal *Vestnik Znanya* (A; from: http://www.ras.ru//MArchive/pageimages/543/1_036/001.jpg), and his book on a comet collision with Earth from 1910, an "edited" copy of a title page of baroque comet anthology *Theatrum cometicum* by the Polish nobleman and intellectual, Lubieniecki (1668) (B; from: http://www.ozon.ru/context/detail/id/3451436/).

> means of the magnetic needle it will be possible to discover in the depth of soil the presence of this iron, and then everything will be proven!

The next paper, in 1909 (Fig. 6A), appeared in the form of an essay. In fact, it was a scientific description of the Moon's surface (Fig. 7), in which a "revolutionary" meteoritic theory of crater origin was proposed. Öpik (1916, p. 125) summarized this as follows,

> . . . the cosmic mass moving with great velocity strikes the surface of our satellite, is smashed to pieces and buries itself into surface rocks; in consequence of the heat generated by the impact a considerable part of the meteoric mass and the surrounding rocks turns into gas which is very resilient due to its high temperature: an explosion happens that scatters around the rock and makes a crater—a bowl-shaped depression with a rim; the meteoric mass generates the central peak. Absence of analogical formations on the Earth can be explained by the detained influence of our atmosphere which destroys the force of impact.

The key idea that explosion craters would be regularly circular depressions even at different angles of strike on a non-consolidated "dusty" surface, is expressed by Morozov as follows,

> The rarity of such ovals [i.e., oval-shaped craters] indicates apparently that the meteorites at the time of their fall on the Moon exploded from self-heating, and, that is why, discarded the surrounding dust in all directions regardless of their translational motion in the same way as artillery grenades do when falling on the loose earth. (Morozov 1909, p. 7)

A more comprehensive account of Morozov's meteoritic theory was presented in the chapter entitled, "Volcano and its significance in the life of the planet. Terrestrial volcanoes and the lunar cirques," in his overlooked 1911 monograph *Universe* (pp. 733–762; see Fig. 8). Öpik's (1916) note lacks references, but he may have been familiar with this innovative concept through another source, such as a book on comet hazards (Morozov 1910c; unavailable to us; see Fig. 6B), or a lecture he attended. For example, Morozov presented these controversial notions at a meeting of the Russian

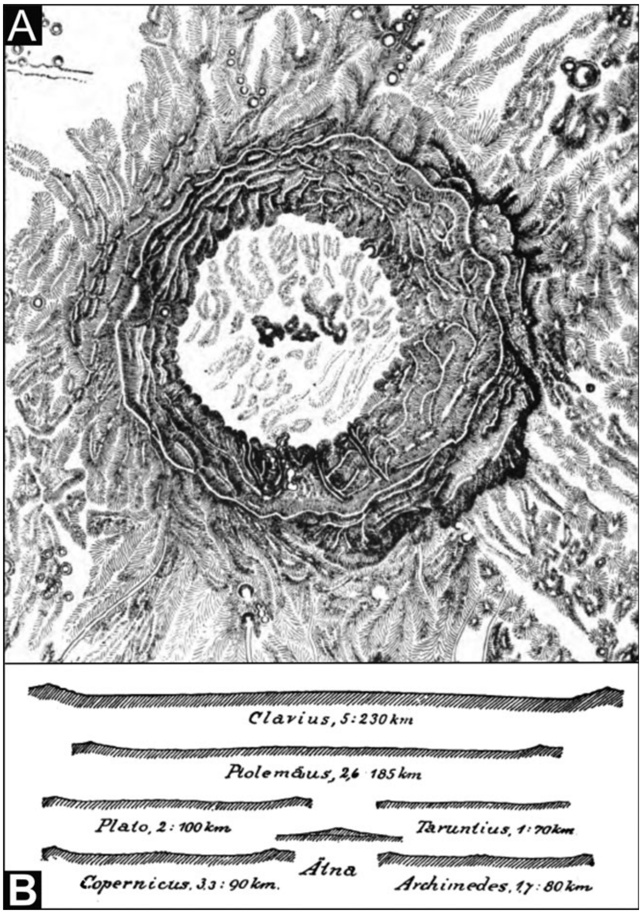

Fig. 7. Map of the ring-mountain Copernicus (93 km in diameter; A) and real profiles of several of the Moon's craters versus Etna (B), according to Fauth (1907, based on his figs. 35 and 17, respectively). This book by the German selenologist, Philip Fauth (1867–1941), was an important source for Morozov, seeing that the crater profiles were copied (without giving credit) in his 1909 essay (see Fig. 6A). Nevertheless, Fauth considered meteoritic bombardment of our satellite to be an inadequate process to produce enormously large ring mountains, exemplified by Copernicus Crater.

Astronomical Society on 20 March 1908 (Muratov 1908). On the other hand, Morozov certainly supported Öpik's early research work, and, as director of the institute, he published his paper on the Perseid meteors in 1920 (see Bronshten and Pustylnik 2002, p. 31).

Later, the idea of meteoritic catastrophes was meaningfully developed by Morozov in the sixth volume of *Christ*. This extraterrestrial motif was discussed in terrestrial (also historical!) and lunar contexts, with a detailed presentation of the Canyon Diablo and Tunguska events, and the interaction between the atmosphere and differently sized meteorite bodies (albeit without reference to Öpik's 1916 note). In addition, he had already envisaged an impact-generated tsunami (Morozov 1930, p. 480):

> Because of the fact that three-fourths of the terrestrial globe is covered with water, it is necessary to assume that three-fourths of meteorites fall on the sea surface and therefore could be the cases, when, after falling not very far from the coast, they produced such wave, which could not be distinguished from the results of an underwater earthquake, and it was therefore attributed to an earthquake.

ÖPIK'S (1916) NOTE IN HISTORICAL AND PRESENT-DAY PERSPECTIVES

In the first decades of the twentieth century, the case of circular depressions on the Moon was seen as controversial and begged many questions, in spite of the discovery in Arizona of a well-preserved meteorite crater and the increased criticism of the predominantly volcanic paradigm (Figs. 9 and 10), as reviewed by Beard (1917), Wegener (1921), Gifford (1924, 1930b), Marshall (1943), Khabakov (1949), Paluzíe Borrell (1953); Bronshten (1979), Hoyt (1987), Wilhelms (1993), Mark (1995), Greene (1998), Schultz (1998), and Koeberl (2001), among others. To the young Öpik, at Moscow University, hypervelocity collisions in space were unquestionable facts in the light of Morozov's inspiring concept, although the key papers by Proctor (1873, 1878) and Gilbert (1893, 1896) probably remained unknown to him. His alleged ignorance of the literature may also have involved the hot debate around the Canyon Diablo impact, which was nearly limited to American periodicals (e.g., Barringer 1905, 1909; Fletcher 1906; Merrill 1908; Pickering 1909; Schwarz 1909; Magie 1910; Thomson 1912; Darton 1916; but see Fig. 10D), and German selenological literature (see Wegener [1921] for a review), which, at least in part, was known to Morozov (e.g., Thiersch and Thiersch 1883; Fauth 1907; see Fig. 7 herein). On the other hand, Öpik (1967a, p. 38) made clear that the theory of sea-covered lunar *maria* (now obsolete) had been taken from an uncited source; this might reflect the way of referencing at the time in Russia.

Later, he participated in polemics with the latest lunar volcanists (including N.A. Kozyrev, a Russian proponent of the "infamous" gaseous eruption from the crater Alphonsus; Öpik 1971), and he argued emphatically (Öpik 1967b, p. 356) that,

> Wishful thinking has always been the stimulus of Western civilization; it led Christopher Columbus westward, and his discoveries are not the less important because he miscalculated the size of the earth and did not reach the lands of Eastern Asia as he intended. A working hypothesis, even an erroneous one, is better than none; it sets goals and leads to

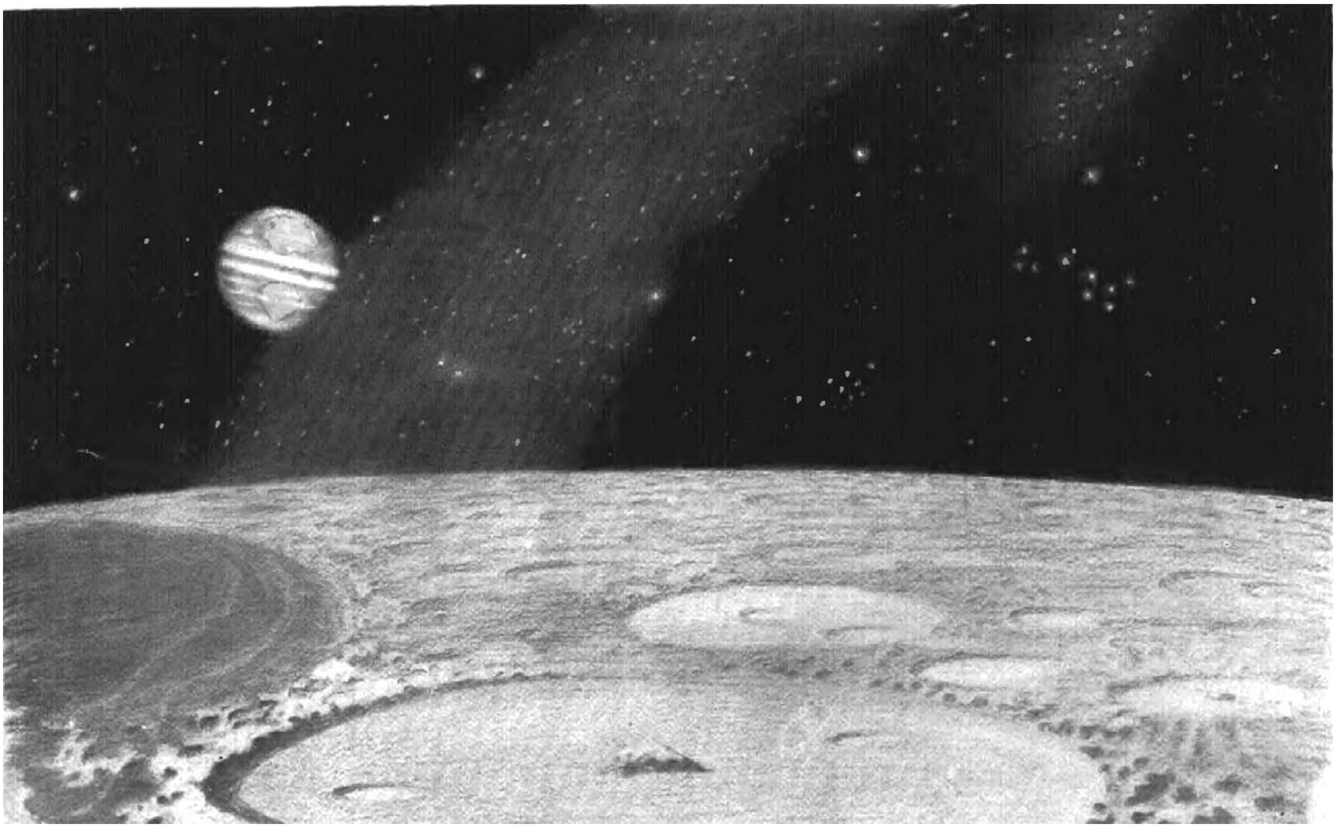

Fig. 8. Landscape of the Moon, based on Morozov's sketch and completed by the artist I. D. Chakhrov, in the book *Universe* (1911, plate between pages 722 and 723) for illustration of his meteoritic theory. A dark-colored mare, bordered by "coastal dunes" (on the left), and flat-bottomed crater group are visible (compare with a traditional reconstruction with extinct volcanic cones in Fig. 9A).

> discoveries which could be missed on a more orthodox course. On the other hand, I for my part prefer a frame which is internally consistent and as free as possible from arbitrary assumptions; in my work, I cannot yet see where the volcanic theory would usefully apply. Our yardsticks of fact and fancy are so different that no useful dialogue can result.

Öpik's Cratering Model versus Contemporary Views—Questions of Priority

According to Baldwin and Wilhelms (1992), Öpik's most important conclusions in 1916 were that, "meteorites possessed such tremendous amounts of kinetic energy that the resulting impact craters would be huge by comparison with the meteorites" and, therefore, "impact craters must be formed by explosions due to the high energies of striking meteorites," as well as that, "such impacts, even at low angles of fall would result in circular craters, thus correcting Gilbert, whom he did not mention." The attribution of merit is at fault, because the hypotheses were essentially credited in the note to Morozov. Therefore, Öpik considered only ideally round impact structures in his estimates, and a doctrinal paradox of lunar crater circularity did not actually exist for him in the light of Morozov's theory, although this "dilemma" persisted until the late 1950s (Gaydon and Learner 1959).

In fact, explosive-volatilization phenomena, resulting from the enormous energies of falling interplanetary projectiles, were suggested, in different forms, in a number of earlier papers. Actually, details of the birth of this thought remain unexploited. For example, Proctor (1878, p. 164; see Fig. 11), in connection with the Earth's "meteoric aggregation" and a crater record of lunar "meteoric artillery," asserted that,

> in reality, some 30 million bodies large and small must actually impinge on the moon's surface each year; and probably some ten or twenty thousand are of the kind we call fire-balls. It is, however, to be noted that almost every mass which thus strikes the moon must be vaporised by the intense heat excited as it impinges on the moon's surface...

As to the fate of the Canyon Diablo meteorite, its partial vaporization was hinted at by Merrill (1908),

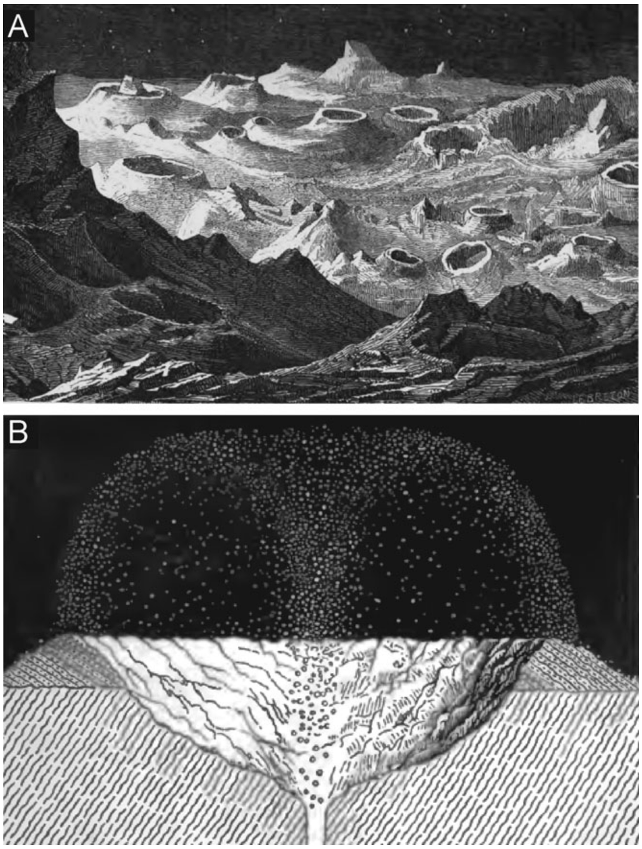

Fig. 9. Landscape of the Moon, as reconstructed in the late nineteenth and early twentieth centuries in accordance with the volcanic theory of crater origin (A, after Flammarion 1867; fig. 47; compare Fig. 8 herein), and a cross section of the Moon's volcano, formed in a fountain-like eruptive action (B, after Nasmyth and Carpenter 1903, fig. 23). Nasmyth and Carpenter accepted only bombardment of our satellite by "dark meteoric particles and masses."

albeit cautiously ("as seems probable," p. 496), and associated with an impact-induced steam explosion (similar explanations survived until the 1930s; see Mark 1995, pp. 54–57). In addition to Morozov (1909, 1911), other forgotten European scientists noted this cratering query connected to "the sudden arrest of a cosmic movement" (Fauth 1907, p. 37), while Meyer (1902, 1906) and Mulder (1911) already made direct references to explosive processes in discussing the formation of the Meteor Crater (for a review, see Hoyt 1987, pp. 191–192). In particular, Marten Edsge Mulder (1847–1928), a professor of ophthalmology at the University of Groningen (the Netherlands, 1897–1913), in his totally overlooked 1911 paper, in Dutch, found fault with Barringer's (1909) account of the formation of that alleged impact crater, did experiments and came to the conclusion that only a single, large meteorite had struck the surface of the Earth at high speed. In his opinion, on its way through the atmosphere, the frontal part of this meteorite must have been hollowed out, but because of sheer size, it had not exploded. Upon slamming into the target rocks (limestones and sandstones), pressure had increased and those rocks had penetrated deeper into the Canyon Diablo meteorite, leading to further compression of gases inside the body and resulting in explosion. Mulder (1911, p. 885) prophetically predicted, "I fear that the Standard Iron Company, which will have bought the crater to extract large treasures from it, will find itself greatly deceived."

In contrast, Steavenson (1937, p. 968), who had underlined the "admirable treatment" of the cratering process by Gifford, noted,

> I am unable to say who it was that first realized that meteoric impacts on the surface of the moon would be of an explosive nature, and would therefore give rise to circular craters; but, so far as I know, this most important consideration was first brought to the public attention of astronomers by the late Prof. A. W. Bickerton, in the course of discussions at meetings of the British Astronomical Association in 1915.

In fact, Bickerton's priority was indicated by Gifford (1930a, 1930b); (see Hoyt 1987, p. 205). Alexander William Bickerton (1842–1929) was a prominent subscriber of the Partial Impact Theory, describing the explosive collision of two stars (e.g., Bickerton 1879). Indeed, he remarked that meteorite strikes could usually "produce an explosive action," but also highlighted the fact that this penetrating bolide "would produce volcanic action," and "consequently oblique impacts would produce roughly circular volcanic rings" (Bickerton 1915, pp. 284, 313). Subsequently, these premature ideas were independently developed by Herbert E. Ives (1882–1953), who compared lunar craters to those formed from explosions of bombs dropped by airplanes (Ives 1919; for similar empirical data from the First World War, see Bosler 1916, 1920), and in particular by Gifford (1924). Recently, Melosh (2013, p. 32) stated that,

> A.C. Gifford [1924, 1930a] first realized that the energy per unit mass of a body travelling at 3 km s^{-1} is comparable to that of TNT. Gifford proposed the "impact-explosion analogy," which draws a close parallel between a high-speed impact and an explosion.

However, it is interesting to note that Ives (1919, p. 249) already anticipated most of this, at least in an experimental and qualitative way, rather than by theoretical deduction:

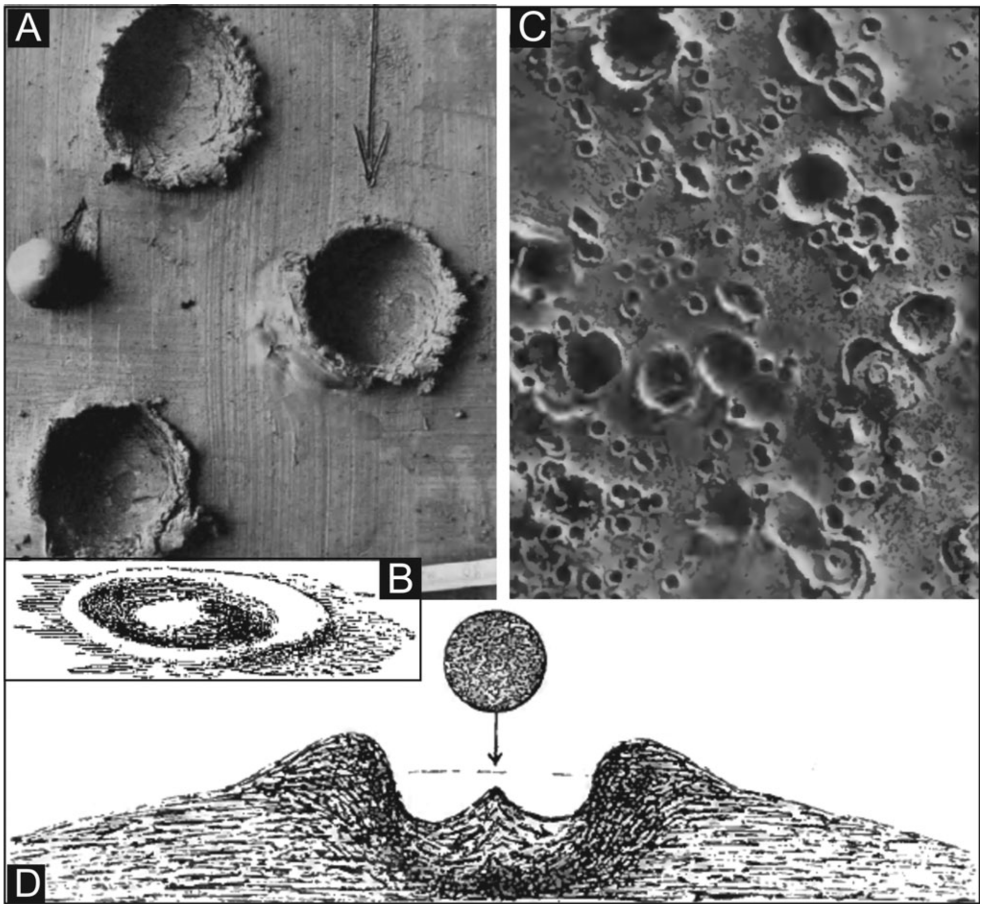

Fig. 10. Experimental results thought of as key supporting arguments for the meteoritic origin of lunar craters in the early twentieth century (A–C; Wegener 1921; Ley 1944), and just then scheme of collision of "satellite," 80 km in diameter, with the lunar surface (D). A) Clay slab pitted by clay balls thrown obliquely against the plastic target (experiments conducted by Gilbert [ca. 1891] and quoted by Gilbert 1893; p. 266, but not illustrated; after El-Baz 1980; fig. 4); the crater ellipticity is found to be "a function not only of angle of incidence, but also of softness of material, and, inversely, of velocity of impact" (compare Proctor 1878, pp. 165–166). B) Central hill formed experimentally within cup-like cirque by gravitational recoil of water drop into a mud. C) Lead target indented by bullets (from See 1910; pl. 12c; a similarly riddled lead plate also in Beard 1917; fig. 3), seen as a model equivalent of scarred lunar surface (compare Fig. 1B). D) According to See (1910, p. 337, pl. 12a), a falling large cosmic body "would sink down into the soft and uncompacted surface," while the central peak would represent remnant fragments of the disintegrated projectile, an idea quoted by Öpik (1916).

> Thus our calculation leads to the conclusion that a meteor striking the moon, with even the lowest velocity at which these are observed, would become a very efficient bomb... Moreover, the available energy is so great that even if the meteor strikes at very great angles to the vertical the result will be an explosion.

And, in particular, in this undervalued paper, Ives (1919, pp. 249–250) noted on the subject of the paucity of meteorite craters in comparison to the Moon that,

> We may note in passing that the Canyon Diablo, the most perfect imitation we have of a lunar crater, bears numerous evidences of having been caused by an explosion of other than subterranean origin. But the most complete answer to this criticism is found by noting; first, that the earth is surrounded by an atmosphere which in previous ages must have been much denser than now and so would dissipate the energy of falling meteors, as indeed we see it doing now; and second, that the earth's surface has been undergoing the processes of upheaval and weathering for perhaps countless ages since the collision with the giant meteor swarms which permanently marked the dead and atmosphereless lunar surface.

Contrary to hypotheses put forward by Morozov-Öpik and Bosler-Yves, "buried" for decades, Gifford's well-reasoned notions, published originally in a New Zealand journal, were widely distributed throughout the community of astronomers as "The New Meteoric

Fig. 11. Richard Anthony Proctor (1837–1888), a British astronomer, known for popular writings about science (from: http://upload.wikimedia.org/wikipedia/commons/2/26/Richard_Anthony_Proctor2.jpg), and title page of an illustrated magazine *Belgravia*, in which he published an essay in 1878, the most far-reaching presentation of meteoric theory in the nineteenth century English literature.

Hypothesis," also in an account in a review journal, *Scientia* (Gifford 1930b), and the Hector Observatory *Bulletin* (Hoyt 1987, p. 208) and a reprint in the *Journal of the Royal Astronomical Society of Canada*. Indeed, A. C. Gifford (Fig. 12) had perfectly shown that "the form produced by an explosion is very different from that made by the fall of an inert mass," although he focused only on projectile velocity (as opposed to Öpik's 1916 scaling of both impactor size and speed; see Table 1). This successful reception in global science is well exemplified by Steavenson's 1937 note, and by a symptomatic summary published 25 years later (Shoemaker 1962, p. 316):

> The concept of explosion of the meteorite or of rock heated by impact goes back at least to Merrill (1908, pp. 494–495) and has been elaborated by Ives (1919), Gifford (1924, 1930) and Moulton (1931)… So widely has his [Gifford's] concept been described that craters of inferred high-velocity impact origin are now commonly referred to as explosion craters.

However, even the priority of this concept was questioned in Soviet literature, as a statement in Stanyukovich and Bronshten (1962, p. 305) clearly exemplifies:

Table 1. Numerical relationships between meteorite size, impact energy and crater diameter, based on the impact energy used for "useful" work in the cratering process (for a density of the meteorite body of 6 kg m^{-3}; Öpik 1916).

Velocity of meteor ($km\ s^{-1}$)	Diameter of crater (km)	Minimum mass of meteor (tonnes)	Minimum impactor diameter (km)
2	2	8.000	0.02
	30	4×10^8	0.6
	60	6×10^9	1.5
30	2	40	0.003
	30	2×10^6	0.1
	60	3×10^7	0.25
60	2	9	0.002
	30	4×10^5	0.06
	60	7×10^6	0.15

> In 1937, K.P. Stanyukovich set up what was apparently the first well-grounded theory of the formation of lunar craters, taking into consideration not the purely mechanical action of the meteorites, but the fact that explosion phenomena take place at large impact velocities.

The problem with this claim, which was also made by e.g., Lewin (1962), Bazilevsky and Ivanov (1977),

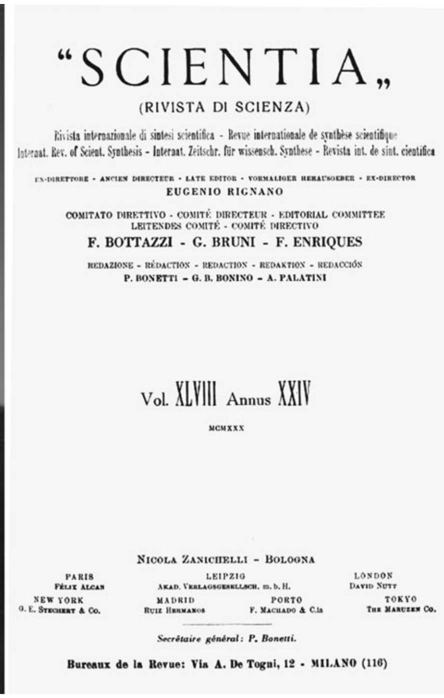

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Fig. 12. Algernon Charles Gifford (1862–1948), a New Zealand astronomer, well known as the father of the explosion impact model of lunar craters (from: http://www.dnzb.govt.nz/en/photograph/195/algernon-charles-gifford), and title page of the Italian international review journal, *Scientia,* in which he issued an extended summary of "The New Meteoric Hypothesis" (Gifford 1930b; included also a French translation). The original importance of this publication was announced in the astronomical column of *Nature* (September 6, 1930; vol. 126).

Fedynskii and Dabizha (1979), Hranina (1987), and Ivanov (2000), is illustrated by the fact that only an outline of this theory had been put before the Second All-Union Conference on Comet and Meteor Astronomy (in Moscow in 1937), as the single-sentence announcement in Astapovich (1937) shows. Of note is that in the first article on the cratering scenario by Stanyukovich and Fedynskiy (1947), and in a review paper by Bronshten (1979), both of Öpik's (1916, 1936a) papers were mentioned within the context of priority. In contrast, the assumed conceptual supremacy of the "well-grounded" theory, developed by Stanyukovich on a coherent mathematical-physical basis, over Gifford's concept (Bronshten 1979, p. 10), remains unnoticed in English-language papers to the present day.

Bronshten and Pustylnik (2002, pp. 100–101) pointed out that this selective credit approach was the result of discrimination against scholars from the so-called Capitalist countries by Soviet scientists during "a war against cosmopolitism," and the ideological stigmatisation conforms to Öpik's professional life. However, the reasons must certainly have been more complex, because the even more far-reaching exclusion concerns also the Academician N. A. Morozov (e.g., in monographs by Khabakov [1949] and Krinov [1966]). For exceptions, reference to Morozov's lunar notions is made by Glazer (1934), Baev and Shishakov (1941), and Bronshten and Pustylnik (2002, p. 14).

Revised Novelty of Öpik's (1916) Note

The heuristic value of the theoretical study in 1916 by the young Öpik may be supplemented by additional lesser known concerns, such as the formation of secondary craters by ejecta of large-scale impacts (a concept immediately criticized by Chizhevsky [1917] from the viewpoint of volcanic theory), and a possible causal connection of meteorites and volcanic hypotheses (see below). In particular, Öpik first scaled the relationships between minimal meteorite size, impact energy, and crater diameter (Table 1). This simplified scaling was based solely on the gravitational energy of excavating the crater (a "useful" work approach; compare also Wilson 1925). In the next paper on the meteoritic crater theory in the Estonian periodical, Öpik (1936a, p. 4) included observations on the newly discovered Kaali crater on Ösel Island (now Saaremaa, Estonia); he noted,

> The mechanical work required to lift up the walls of the crater, throwing out the fragments, and shattering

> and pulverizing the rocks, must represent a very small fraction of the total energy developed by impact. By setting this amount of work equal to the kinetic energy of the meteor, we get a minimum estimate of its mass.

Accordingly, a minute lunar crater with a diameter of 2 km has been predicted to result from the impact of a meteorite with a minimum mass of 8000 tonnes, i.e., with a diameter of 20 m, at a very low velocity of 2 km s^{-1}, but weight and size rapidly decrease for a speedy projectile of 30 km s^{-1} (40 tonnes and 3 m, respectively). Interestingly, a quite similar mechanical approach to crater excavation was also conducted as early as 1910 by the American physician William F. Magie (1858–1943), who estimated the mass of the Canyon Diablo meteorite to have been between 60,000 and 15,000,000 tonnes, noting that, "a mass of 400,000 tons moving with a velocity of from 18 to 20 miles a second would bring in the estimated amount of energy" (Magie 1910, p. 48). The comparable minimum mass calculation by Öpik (1936a) had provided a similar figure (60,000 tonnes for an object of 20 km s^{-1} speed). He preferred, however, far greater mass approximates (from 2 to 5 million tonnes), based on more advanced physical models, from bolide penetration ("like a dum-dum bullet") and crater volume. Recent mass predictions are exactly intermediate, i.e., between 110,000 (see Kring 2007) to 263,000 tonnes for a coherent single cosmic projectile (Artemieva and Pierazzo 2011; Table 1). Thus, the simple, yet novel, calculation by Öpik (1916) provided a lower constraint of lunar impactor size as a reliable starting point for the terrestrial crater estimates published twenty years later (Öpik 1936a; see reviews of Canyon Diablo bolide approximations in Walton 1959; Bronshten and Pustylnik 2002, pp. 101–102; Kring 2007). This yardstick numerical approach was either overlooked or referred to Öpik's 1936 paper.

What is more, Öpik unquestionably proved that bolides measuring some tens of meters in diameter "must reach the earth surface with such a velocity as if there was no atmosphere at all." Previous calculations by Fletcher (1906) had already indicated such great penetrative ability for Earth-striking large meteoritic bodies, but at an abnormally high speed of 80 km/s. However, the long-established belief in the effective atmospheric shield against cosmic bombardment, seen also in ideas expressed by Morozov (1909, 1911) and Gifford (1924, 1930b), persisted until the 1940s (Vand 1945), and it was even used in support of an igneous origin of lunar craters by Marshall (1943). Öpik (1916) also decisively assumed that, at an early stage, our planet "went through the period of crater formation," but rightly, in the same way as Proctor (1878) had done, clarified the absence of recognized terrestrial craters in his days, as follows,

> we must explain the absence of corresponding formations on the Earth not by the hindrance of the flight of a bolide by the atmosphere but by erosional and denudational processes that erode the formations by the effects of precipitation and weathering, constantly smooth the relief of the Earth's surface such that if there were no processes of mountain formation all the mountain ranges existing nowadays would have disappeared in some tens of millions of years. (Öpik 1916, p. 129)

Development of Impact Hypothesis by Öpik, and a Modern Perspective

Already as a renowned researcher, Öpik successfully improved his cratering hypothesis "on a rational mechanical basis" (Öpik 1962, p. 221). He considered a physical model of bolide impact from the viewpoint of numerous lunar and terrestrial aspects, inclusive of a potential cause of mass extinctions (see Öpik 1958b; Racki 2012), combining comprehensive mathematical and physical insight. Nevertheless, only rarely did he highlight the underrated merit of his 1916 paper. In a review paper, on the evolution of the surface of the Moon, he had more widely discussed progress in lunar research (Öpik 1967a, p. 38):

> Half-a-century ago, the author pointed out that, in absence of endogenic activity and without an atmosphere, the major surface features of the moon must have remained essentially unchanged, figuratively speaking since "the day of Creation" (Öpik 1916); meteorite impacts were regarded as the only factor of change, and the important role of secondary craters, produced by ejecta of major events —meteoritic or primitive volcanic—was considered. The conclusions were arrived without knowledge of previous work by G.K. Gilbert (1893) who actually is the father of the modern version of meteoritic theory of lunar craters. The present study leads essentially to the same conclusion, except that primitive plutonic activity seems to have been limited to partial melting caused by impacts, while true volcanic activity or lava effusions due to internal activity never have affected the observable surface of our satellite.

Recently, at least one important modification has been made as the outcome of numerical simulations. Terrestrial craters may be formed by a fall of a tight swarm of impactor relic bodies after major destruction of its mass in the atmosphere (i.e., a clustered event, an impact variety suggested already by Proctor (1878) and Barringer (1905, 1909), while such fragmentation and ablation are absent in lunar cratering on account of a lack of an opposing atmosphere (Artemieva and Pierazzo 2011).

On numerous occasions, Öpik (1961, 1962, 1967a, 1969, 1971, 1977) discussed weaknesses of artificial impact imitations by nuclear explosions at length, as well as an advantage of his momentum rationale in cratering "*a priori* theory" (versus a kinetic energy "dogma"; see Öpik's critics in Baldwin 1963; pp. 123–124, 158–179). H. J. Melosh (personal communication, April 2014) summarized these polemics as follows, "Nor was it strictly wrong. The modern view using Pi-group scaling is neither exactly energy or momentum scaling, but a mixture of both." Bronshten and Pustylnik (2002, p. 72) reached a similar conclusion.

With satisfaction, Öpik noted a marked increase in the number of impact researchers in the 1960s and 1970s, and even went as far as to announce the birth of "craterology," as a "branch of science dealing with the very processes of formation and destruction of solid celestial bodies" (Öpik 1979, p. 98). He rigorously traced also successive discoveries of terrestrial craters (and discussed criteria for their identification; Öpik 1954, 1964), as he had predicted a great number of undiscovered large-sized structures, caused by asteroid falls of the Apollo-Icarus group (Öpik 1954). Nevertheless, it was with some sarcasm that he noted the "temporarily forgotten selenological" paper of Gilbert (Öpik 1962, pp. 220–221):

> Over more than century the meteoritic theory of lunar craters has been proposed and rediscovered independently by different authors in different countries. The lack of intercommunication in this respect was characteristic of the very much neglected branch of selenography, often considered not worthy of the attention of full-fledged astronomers. The proponents of the theory did not always use sound physical arguments... The modern outline of the impact theory has been given by Öpik (1916); he also pointed out that secondary craters can be produced by fragments ejected from major explosions. This contribution remained unnoticed in the west, and the credit for the revival of the impact theory of lunar craters on a rational mechanical basis is given by Baldwin to A. C. Gifford...

A year later, Baldwin (1963, p. 9; repeated in Baldwin 1978, p. 367) already corrected this credit error in modern impact theory. He noted that in the case of Öpik's (1916) paper, "merit was not recognized," but unfortunately, in both of his papers Öpik's and Gifford's pioneering views on explosion cratering were considered largely jointly. As noted above, Baldwin and Wilhelms (1992) later maintained attribution of this credit in an article on three long-overlooked benchmark papers. Those authors posed the elementary rhetorical question (p. 3841), "What progress might have been made if the three papers of Gilbert (1893), Öpik (1916), and Daly (1946) had been well known!"

FINAL REMARKS

In their historical review of the experimental setting of the recent impact theory, Drake and Komar (1984, p. 411) stated that,

> Many ideas held by scientists at various times up to the present can be traced back to the work of Robert Hooke in the seventeenth century... We have shown that many ideas we believe are modern have origins that date far back in time... The study of the development of ideas in our science, besides providing perspective and a sense of continuity, could also reveal concepts applicable to the modern paradigm or the creation of a new one.

The convoluted case of a long-overlooked benchmark article in Russian, published in a local journal during the First World War, by a young astronomer from eastern Europe who had just graduated from Moscow University, is a good illustration of the above. In fact, this was merely a small step toward great scientific success during his later career in Estonia, the USA (University of Maryland), and Northern Ireland (Bronshten and Pustylnik 2002). As a final point, Ernst Julius Öpik is regarded as being "among the very great astronomers of the 20th century" (De Groot 1986, p. 440) who, "was among the first to put forward a number of ideas now regarded as part of mainstream astronomy" (Elliott 2007; see also Lindsay 1972; Wetherill 1986; Bronshten and Pustylnik 2002; Sterken 2011; Racki 2012).

In conclusion, the republication of Öpik's (1916) article in English, together with this explanatory article, is viewed as a kind of scientific vindication and historical atonement, after such a long time during which his (and, of course, Morozov's) creative impact ideas were not more than "a lonely cry in the wilderness" (as poetically expressed by Öpik 1977, p. 17). These two cases also demonstrate how a limited flow of research information, in a world, divided by both language and political barriers, have led to multiple formulations and rejections of the same scientific ideas. Certainly, other forgotten precursors of theories currently held to be conventional, and a diversity of "wild" ideas await to be revived.

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APPENDIX

A Note on the Meteoric Theory of Lunar Craters

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(Originally in *Mirovedenie*, vol. 5, pp 125–134, May 1916)

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Translator's preface

Ernst Julius Öpik wrote this classical paper when he was a student at Moscow University. As it was written in Russian and published in an obscure journal it was almost forgotten or quoted in a wrong context—perhaps only partially helpful was the fact that the summary was in French.

In this paper Öpik advanced the idea of N. A. Morozov about the meteoritic origin of the lunar craters by giving a quantitative aspect to this idea and showing that meteors moving with velocities characteristic of the solar system can give rise to craters observed on the Moon. His approach is based on a simplified model but even so, the results, although approximate, provide a firm understanding of those processes. The significance of this brief 8-page note, published almost 100 years ago, is extensively discussed in the accompanying paper by Racki et al.

The translator tried to preserve Öpik's somewhat antique, concise, and laconic style (and the original French summary and its translated version are added as well). The translator was confused only in some equations, and the problems are noted in three footnotes.

The meteoric theory of formation of lunar craters, presented by N. A. Morozov, consists briefly of the following: the cosmic mass moving with great velocity strikes the surface of our satellite, is smashed to pieces, and buries itself into surface rocks; as a consequence of the heat generated by the impact a considerable part of the meteoric mass and the surrounding rocks turns into gas which is very resilient due to its high temperature: an explosion happens that scatters around the rock and makes a crater—a bowl-shaped depression with a rim; the meteoric mass generates the central peak. The absence of similar formations on Earth can be explained by the detained influence of our atmosphere, which retards the force of impact. This theory has one weak point—namely the quantitative side of it. We try to determine how large must be the mass of this hypothetical material to form a lunar crater as a result of the impact.

We determine the approximate amount of work needed to make a crater. Since for our case we need only the order of magnitude we may deal with a cylindrical ring instead of a rim of a height of h, with the outer diameter of d and the inner diameter of d_1; the volume of which is $\frac{\pi}{4}(d^2 - d_1^2)h$ and the mass $\frac{\pi\delta}{4}(d^2 - d_1^2)h$ where δ is the density of lunar rocks. In Fig. A44 there is the cross-section of the rim and the dashed line depicts our approximated cylindrical ring.

The work of an impact can be expressed by lifting a certain mass—the mass of the lunar crater to some height; the average effective height could be equal to h since half of the particles will rise higher and another half–lower. This means that if the acceleration of gravity is g on the lunar surface the work done by

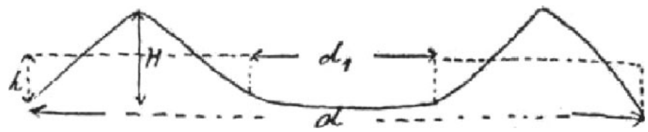

Fig. 44.

lifting the mass is $R = \frac{\pi\delta g}{4}(d^2 - d_1{}^2)h^2$ ergs. If the meteoric mass is x and the velocity of the mass is v, the kinetic energy will be xv^2 ergs but as only a part of the energy is used for making the crater, then obviously

$$\frac{xv^2}{2} > R,$$

hence it follows that

$$x\frac{\pi\delta g(d^2 - d_1{}^2)h^2}{2v^2} \qquad \text{(A1)}$$

The minimal value of the meteoric mass x_0 is equal to the right part of inequality Equation A1.

For instance, let us take $d = 60$ km, $h = 1.8$ km (approximately the Tycho crater where the height of the wall H is $\approx$ 3.5 km, consequently $h \approx 1.8$ km); supposing that the slope is 30° (this is the maximum value) we arrive at $d_1 = 32$ km (because $d - d_1 = 2.3,\ 5.4^*$) and the minimal mass of the meteor is $x_0 = \frac{3 \times 10^{10}}{v^2}$ tons, while v is measured in kilometers per second; for of another crater of similar proportions x_0 is proportional to the diameter to the fourth power and it is easy to obtain the equation

$$x_0 = 2 \times 10^3 \frac{d^4}{v^2} \text{ tons} \qquad \text{(A2)}$$

here d and v are measured in kilometers. (We have omitted all calculations; in calculations with formulae A1 and A2 one has to use d, h and v in centimeters but x_0 we will obtain in grams). The density of lunar rocks is assumed to be 2.5.

If the density of the meteor is 6 it is easy to derive that its diameter will be (in kilometers)

$$a = \frac{1}{100} d^3 \sqrt{\frac{d}{v^2}} \qquad \text{(A3)}$$

In the following Table there are some calculated examples for the minimum mass and dimensions of a hypothetical meteor which is needed to form rims of different dimensions.

Velocity of meteor v in km s^{-1}	Diameter of crater d (km)	x_0—minimum mass of meteor in tonnes	a—minimum diameter in km (δ = 6)
2	2	8.000	0.02
	30	4×10^8	0.6
	60	6×10^9	1.5
30	2	40	0.003
	30	2×10^6	0.1
	60	3×10^7	0.25
60	2	9	0.002
	30	4×10^5	0.06
	60	7×10^6	0.15

We see in the Table that for forming an ordinary lunar crater with a diameter of 30 km we must have a meteor with the mass of 400,000 tonnes, with the diameter 60 m and with the velocity of 60 km s^{-1}; since there is no doubt that only a small part of the impact energy is used for 'useful work', the obtained values are definitely many times less than the real values.

It is obvious that for such huge meteoric masses the retarding effect of the atmosphere must be negligible, as in the first place it must depend on the ratio of the mass of the penetrated air during the flight to the meteoric mass; it is known that the thickness of our atmosphere is equal to a layer of water with thickness of 10 m or to the layer of meteoric matter with the thickness of 1.5 m; in that case a meteor with the minimal diameter of 60 m must be 40 times larger than the column of the atmosphere which resists the meteor; in that case it is obvious that they (meteors) must arrive at the surface of the earth with almost unchanged velocity.

We have the possibility to illustrate the question of the atmospheric resistance to a flight of a meteor from the quantitative side, too; we do not know which laws govern the resistance of the environment at such high velocities; that is to say that we do not know the resistance coefficient since theoretically the resistance at small and large velocities (compared to the velocity of sound) must increase proportionally to the square of the velocity; but at the velocities close to that of sound—faster; therefore, the resistance could be expressed by the equation

*The formula $d - d_1 = 2.3,\ 5.4$ remains inexplicable. Perhaps at first Öpik used some other variables, later changed them and forgot to mention this in the text.

$$p = kv \qquad \text{(A4)**}$$

where k is a variable that changes not much at low and high velocities but which increases when the velocities are close to that of the sound.

In order to find the approximate value for k at high velocities—let us denote it by K—we may use the following consideration; the luminescence of a meteor in our atmosphere is due to the work of friction; if p is the resistance of the environment (in kg by the per square metre), v is the velocity of motion then the work on every square metre per second is $R = pv$; e.g., for a shooting star at the height of 100 km we may estimate the average velocity as v = 50 km s^{-1} (Perseids); on the other hand we may take that this work goes all to radiation into space; if we assume that for our example the average temperature of the radiating surface is equal to the temperature of the Sun—this is suggested by the colour of the meteor—then it is easy to calculate, knowing the solar constant that each square metre will be radiating 13,000 kilocalories per second, so the work of friction R = 13,000,424 or approximately 5,000,000 kgm per second; thus pv = 5,000,000 kg but since v = 50,000 m s^{-1} then p = 500,000,000 kg per square metre. Since the atmospheric pressure at the height of 100 km is approximately five millionth of the normal pressure than in an environment with the normal pressure at the velocity of 50 km s^{-1} the resistance were p = 500,000,000 kg per square metre; if we substitute this value into formula (A4) and take v = 50,000***, we get for K for high velocities 0.2 kg, which is approximately three times larger than for small velocities; however, the accuracy obtained by very coarse calculations of this quantity is not high—it shows only the order of magnitude.

Now we may solve the following problem: to determine approximately the dimensions of the meteor (with a density of 6), which, in moving through the atmosphere, loses only a small part of its velocity, e.g., 10 km s^{-1} of the original velocity of 60 km s^{-1}; in that case we may assume that the velocity at flight is constant and 55 km s^{-1}; this gives us, by using this velocity, the resistance at the atmospheric pressure of 600 million kg per square metre; it is not difficult to show that at the constant velocity the work, spent for overcoming the resistance in penetrating the atmosphere is the same as if the atmosphere had a constant density and lifted to the height of 8 km (in fact the density decreases with the height, so the resistance to the movement decreases; but at the same time the covered distance is larger and the work, as the product of the distance and resistance will remain constant); therefore, the general work spent to overcome the resistance per each square meter of the cross-section of the meteor is 600,000,000 × 8000 = 5 × 10^{12} kgm or about 10^{10} calories. It is not difficult to calculate that if we change the velocity from 60 to 50 km s^{-1} the loss in the energy for each kilogram is 130,000 or roughly 10^5 calories (according to the formula $120(v^2 - v_1{}^2)$ where velocities v and v are expressed in km s^{-1}); therefore for each square meter of the cross-section there must be = 10,000 kg of the meteoric matter which gives 20 m at the density of 6. Therefore it may be seen that bolids with the cross-section of some tens of metres must reach the earth surface with such a velocity as if there was no atmosphere at all; but in that case the absence of a rim on the Earth cannot be explained by the hindering effect of the atmosphere, to say nothing of the fact that if such a huge amount of meteoric matter falls in great quantities, we must find it in the fossil record everywhere.

If we agree with the meteoric hypothesis of the formation of lunar craters, we must explain the absence of corresponding formations on the Earth not by the hindrance of the flight of a bolide by the atmosphere but by erosional and denudational processes that erode the formations by the effects of precipitation and weathering, constantly smooth the relief of the Earth's surface such that if there were no processes of mountain formation all the mountain ranges existing nowadays would have disappeared in some tens of millions of years.

However, by explaining the events in such a manner we have to suppose that during the last geological formations the mechanism that is responsible for the formation of rims stopped to function—since otherwise these rims or at least their weak traces would have been preserved on the Earth up to our time. In this case, would it not be natural to seek for the cause not in cosmic masses but in activities of the Earth or the Moon? Proceeding from this consideration I think that it is possible to give an explanation of the formation of lunar craters and some other formations, which is a connection of the meteor theory with the volcanic theory.

Let Fig. A45 depict the Moon in an early period of its evolution and let its thin crust be breached by an explosion at A; the parts of the crust, volcanic ash etc. are strewn in different directions with different velocities, dispersed in a fan-like manner, which are marked by arrows in Fig. A45; dashed lines represent the trajectories; as a result of the absence of the atmosphere these trajectories depend only on the value of the velocity and its direction but they do not depend

**Proceeding from the logic of Öpik's speculation formula (A4) should be "$p = kv^2$".

***In the original text, v was erroneously substituted by U.

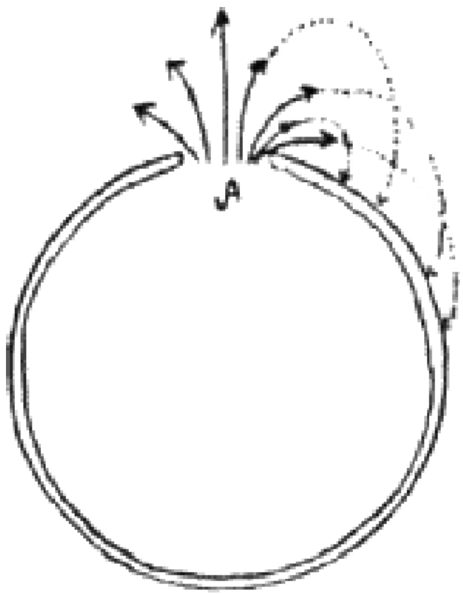

Fig. 45.

on the dimension of particles. Since the gravitational force of the Moon is small, the particles can fly very far from the place of the explosion; at velocities close to the velocity of the free fall from infinity—but this velocity for the Moon is only 2.4 km s^{-1}—the debris of the explosion can fall at arbitrary points of the lunar surface. And so, the fall of large compact masses may form the rims entirely in the same way as the fall of cosmic masses; it is true that as a result of lower velocity (it cannot be larger than 2.4 km s^{-1}—otherwise the body will fly infinitely far), the mass needed to form a lunar crater must be larger. For instance, it can be seen in our Table that for producing a crater similar to that of Tycho the needed mass is 6 billion tonnes with a velocity of 2 km s^{-1}, and if we take the density to be 6 then the diameter of the meteor must be 2 km; this value is of the same order as the central peak in Tycho crater; at the same time assuming the cosmic origin and accordingly, the cosmic velocity of the impacting body, the diameter would be considerably less.

Therefore, at all places of the lunar surface where the less and more massive debris are going to fall—and they have to fall everywhere, provided the strength of an eruption will be the same as in the case of the Earth volcanoes—the large and small rims will be formed; at the same time and at the place of eruption, as a result of particles thrown out vertically or at small angles and falling back, a crater is formed.

Besides of the large parts of debris, the small particles can also be the products of an eruption—volcanic ash; let us imagine a cloud of this material having been thrown out at an arbitrary angle, where different particles will be thrown out with different velocities; in this case the particles will fall at different places around the centre of explosion; the particles with low velocities closer and those with higher velocities further; all of them are situated along a great circle outgoing from the centre of the explosion; moreover, if the thrown-out ash is bright, then we get a bright ray; if the velocities of separate particles are rather close to the escape velocity (2.4 km s^{-1}) then the bright ray could circle the whole Moon. If during the eruption many such ash clouds were thrown out in different directions then we get a system of dispersed bright rays similar to Tycho crater. The length of rays will evidently depend on the strength of eruption and on the depth, i.e., on the ratio of the diameter of the breach in the lunar crust to the thickness of the crust; at larger depth the greater part of particles will be thrown vertically up; at smaller velocities—in different directions; at the same velocities the length of bright rays will be evidently smaller for the first case than for the second case.

Some theories try to explain the referred systems by atmospheric flows which took the volcanic ash everywhere; but it is clear that such regular formations must be due to regular causes and not due to non-constant factor as the atmospheric flows. However, for my explanation of the origin of bright rays there is no need to allow with a certainty that the atmosphere is entirely absent at this stage of the evolution of Moon's life; there could have been a thin atmosphere which together with the products of eruption at the place of explosion were thrown into space where the volcanic ash and the debris moved along their trajectories without any resistance; because the height to which the debris was thrown must have been much larger than the height of the lunar atmosphere. At the same time the atmospheric resistance to huge parts of debris must have been practically zero.

As it is known, many of the lunar craters are brighter than their surroundings so that during the full moon they may be seen as bright white patches.

This circumstance is a superfluous proof in favour of the common character for the formation of rims and bright rays; because the bright volcanic ash thrown out as separate clouds must have accompanied the thrown-out debris on their flight; but during the fall due to its small dimensions it was somewhat delayed by the atmospheric resistance and after that while depositing it had to cover the formed crater and its neighbourhood with white coating.

The fact that in so-called lunar maria there are much fewer rims than in the rest of lunar surface remains to be explained from our viewpoint. The most natural explanation that is most in accordance with the look of the lunar surface could be the following. During the period of formation of craters lunar maria were real seas; the thrown-out debris, not meeting substantial resistance in the atmosphere had, however, to meet the immeasurably larger resistance of water so that the might of the impact decreased to negligible values; beside of that the formation of a crater in the seabed had to be hindered by the fact that the hurled out in every direction particles from the weakened impact had to be stopped by the resistance of water and settled down again as a puddle on the seabed, not considerably changing its relief.

When the Moon was deprived of its seas due to a loss of water into interplanetary space, the volcanic activity significantly decreased so that after that the number of formed rims was small; because of that the lunar maria have few craters.

We may assume that the Earth, too, went through the period of crater formation; however, since that period the smoothing effect of water and air was able to completely change its appearance many times over and from these pristine mountains there is no trace. It could be, too, that during the early stages of its evolution the Earth was completely covered with oceans that hindered the formation of rims. However, the Moon lost its atmosphere early and because of that kept its initial appearance unchanged; she died early but in return she retained the features of her early youth; she is not a decrepit and aged world since the dead do not age; she is like an embalmed mummy and by its appearance we may judge the appearance of the world in the beginning of the Genesis.

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La théorie météorique des cratères lunaires, proposée par N. Morosov, cherche à expliquer ceux-ci par des masses cosmiques qui, tombant sur la surface, se vaporisent subitement et donnent lieu à une explosion comparable à celle des obus qui, tombant obliquement, peuvent néanmoins produire un trou circulaire. Mais il se présente une difficulté d'explication—c'est la masse énorme des météores. L'ordre de grandeur de cette masse peut être évalué par le procédé suivant: la force vive $\frac{mv^2}{2}$ du météore doit être au moins égale au travail R, nécessaire pour transporter les masses constituant le cratère de la hauteur zéro jusqu'à la hauteur qu'elles possèdent; on obtient ainsi $\frac{mv^2}{2} \geq R$ et $m \geq \frac{2R}{v^2}$ (a). Le travail R ne diffère pas sensiblement de la valeur donnée par l'équation (1) δ = densité des matériaux lunaires = 2,5 (d, d_1 et h voir Fig. A44).

Dans le tableau j'ai calculé les masses et diamètres minimum des météores nécessaires pour produire un cratère avec des dimensions proportionnelles à celles de Tycho, pour les valeurs sucessives de v (2–60 km s^{-1}) et de d (2–60 km; Tycho = 60 km, h = 3.5 km), et pour $\delta = 6$ (densité du météore). Il est évident que des météores de telles dimensions doivent passer l'atmosphère terrestre sans résistance sensible.

Pour calculer la résistance de l'air pour les vitesses cosmiques, on peut se servir des considérations suivantes. Admettons que pour les étoiles filantes traversant notre atmosphère la conduction de chaleur est petite par rapport à la radiation (la radiation est proportionnelle à T^4, la conduction à T); s'il en est ainsi, le travail de résistance doit être égal à 424Q, c'est à dire, $pv = 424\ Q$, ou p est la résistance, v—la vitesse, Q—la radiation d'un mètre carré par seconde; pour les Perséides $v = 50$ km s^{-1}, $Q = 13.000$ calories = radiation du soleil (les températures sont probablement égales; [ainsi $p = 100$ kg par m^2 à une hauteur = 100 km, où la pression est $\frac{1}{5.000000}$ atm]; d'ou la résistance au niveau de la mer serait pour $v = 50$ km s^{-1} 5.10^8 kg m^{-2}. Grâce à ce résultat j'ai calculé, qu'une masse de diamètre 15–20 m et de densité 6, ayant une vitesse initiale de 55 km s^{-1} devrait arriver à la surface de la terre avec $v = 45$ km s^{-1}. Voilà pourquoi, si la théorie cosmique des montagnes lunaires était juste on devrait observer sur la terre des cratères semblables.

Je propose ici une modification de la théorie—une théorie, intermédiaire entre la théorie météorique et la théorie volcanique. Supposons que les masses, qui en tombant donnèrent naissance aux cratères, étaient des projectiles lancés par une catastrophe volcanique; la Fig. A45 représente l'éruption hypothétique; les lignes courbes indiquent les trajectoires des projectiles; si la vitesse est voisine de 2,4 km s^{-1}, ils peuvent tomber à une distanse arbitraire, même au point diamétralement opposé à celui de l'éruption; pour donner naissance aux cratères de 2–60 km de diamètre; les diamètres des projectiles (vitesse 2 km s^{-1}) devraient atteindre 30–2.000 m (pic central).

A la place de l'éruption se formera un cratère «principal» (Tycho, Copernic), les projectiles couvriront la surface entière de cratères secondaires. Les raies blanches, qui émanent par exemple de Tycho, sont facilement expliquées, si on suppose que des nuages de matière blanche ont été simultanément émis dans la même direction, mais avec des vitesses différentes.

L'éclat (intense) de la plupart des cratères s'expliquerait par la même matière blanche, qui accompagne les grands projectiles et tombe un peu en retard.

Ces éruptions se passaient probablement quand l'écorce de la Lune était encore très mince. Probablement c'était a l'époque où les mers de la Lune étaient des mers véritables; c'est peut être la raison pour laquelle les cratères sont si rares dans les mers; la résistance énorme de l'eau a diminué la force du choc. On peut supposer, qu'à l'époque primitive des cratères se formèrent aussi sur la Terre; mais l'activité de l'eau et de l'air, qui change le relief de la Terre en quelque millions d'années les a effacés, tandis que sur la Lune l'aspect primitif de la surface s'est conservé grâce à l'absence de l'atmosphère.

E. Öpik

The meteoritic theory of the lunar craters as proposed by N. Morosov tries to explain their origin by cosmic masses, falling to the surface, suddenly evaporating and generating an explosion comparable to bombshells, that falling obliquely may (even so) produce a circular hole. However, something is difficult to explain—it is the enormous mass of the meteors. The magnitude of this mass can be evaluated by the following method: the momentum of the meteor must be equal to the work R, needed to transport the masses forming the crater from the zero (initial) height until the height they have, thus, obtaining $\frac{mv^2}{2} \geq R$ and $m \geq \frac{2R}{v^2}$ (a). The work R does not differ substantially from the value given by Equation (1): δ = density of the lunar materials = 2.5 (d, d_1 and h see Fig. A44).

In the Table, I have calculated the masses and the minimum diameters that are necessary to produce a meteor crater with dimensions proportional to those of Tycho, for successive values of v (2–60 km s^{-1}) and d (2–60 km, Tycho = 60 km, h = 3.5 km), and for $\delta = 6$ (density of the meteor). It is obvious that meteors with such dimensions must pass through the Earth atmosphere without significant disturbance.

To calculate the air resistance for cosmic speeds, we can use the following considerations. We have to suppose that for the shooting stars that across our atmosphere, the heat conduction is small compared to the radiation (the radiation is proportional to T^4, to the conduction T), and if so, the work of resistance must be equal to $424Q$, that is so, $pv = 424Q$, where p is the resistance, v the speed, Q the radiation of a square meter per second; for the Perseids $v = 50$ km s^{-1}, Q = 13,000 calories = the solar radiation (the temperatures are probably equal; [thus, p = 100 kg per m^2 for a height = 100 km where the pressure is $\frac{1}{5{,}000{,}000}$ atm]; thus, the resistance to the sea level would be for $v = 50$ km s^{-1} of 5.10^8 kg m^{-2}. With this result I have calculated that a mass of 15–20 m in diameter and with a density of 6, with an initial speed of 55 km s^{-1} should arrive at the surface of the Earth with $v = 45$ km s^{-1}. This is why, if the cosmic theory of lunar mountains was correct, one should observe similar craters on the Earth.

Here I suggest a modification of the theory—an intermediate theory between the meteoritic theory and the volcanic theory. If we suppose that the masses, who form craters when they fall, were projectiles launched by a volcanic catastrophe, the Fig. A45 shows the hypothetical eruption; the curved lines indicating the trajectories of the projectiles; if the speed is around 2.4 km s^{-1}, they can fall at an arbitrary distance, even to the point diametrically opposite to the point of the eruption; to form craters with diameters of 2–60 km; the diameters of the projectiles (speed 2 km s^{-1}) should reach 30–2000 m (central peak).

A main crater will be formed where the eruption take place (Tycho, Copernicus), the projectiles will cover the entire surface of secondary craters. White stripes, which emanate for example from Tycho, are easily explained if we assume that clouds of white matter were simultaneously released in the same direction, but with different speeds. The brightness (intense) of most of the craters can be explained by the white matter, which come with the big projectiles and fell somewhat afterward.

These eruptions probably occurred when the crust of the Moon was still very thin. It was likely at the time when the seas of the Moon were real seas; perhaps this is the reason why so few craters occur in the seas: the huge resistance of the water having decreased the intensity of the impact. We can suppose that, at the early stage, craters were also formed on Earth; but that the activity of the water and of the air, that affect the topography of the Earth in a few millions years, have deleted them, while on the Moon the primary appearance of the surface was preserved due to the absence of an atmosphere.

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