Origins: From the Protosun to the First Steps of Life
Proceedings IAU Symposium No. 345, 2018
B. G. Elmegreen, L. Viktor Tóth & M. Güdel, eds.

doi:10.1017/S1743921319001467

Near-Earth object population and formation of lunar craters during the last billion of years

Sergei I. Ipatov[1], **Ekaterina A. Feoktistova**[2] **and Vladimir V. Svetsov**[3]

[1]Vernadsky Institute of Geochemistry and Analytical Chemistry of RAS, 119991, 19 Kosygin st., Moscow, Russia
email: siipatov@hotmail.com

[2]P.K. Sternberg Astronomical Institute, M.V. Lomonosov Moscow State University, 119899, 13 Universitetsky Pr., Moscow, Russia

[3]Institute of Dynamics of Geospheres of RAS, 119334, 38 Leninskii pr., Moscow, Russia

Abstract. We compared the number of lunar craters with diameters greater than 15 km with age less than 1.1 Gyr in the region of the Oceanus Procellarum with the estimates of the number of craters made based on the number of near-Earth objects and on the characteristic times elapsed before collisions of near-Earth objects with the Moon. Our estimates allow the increase of the number of near-Earth objects after a recent catastrophic disruption of a large main-belt asteroid. However, destruction of some old craters and variations in orbital distribution of near-Earth objects with time could allow that the mean number of near-Earth objects during the last billion years could be close to the present value.

Keywords. methods: n-body simulations, Moon, solar system: formation

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We analyzed diameters of lunar craters with age less than T_{OP}=1.1 Gyr in the region of the Oceanus Procellarum. Data on the craters were taken from the database of the lunar craters of the P.K. Sternberg Astronomical Institute. The ratio r_{OP} of the area of the considered region to the full surface of the Moon is 0.176. In the above region, the number N_{obs} of the craters with a diameter $D > 15$ km (the same number is with $D \geqslant 16$ km) is 52. Results of our analysis of the number of craters of different sizes in the above region are in accordance with the earlier conclusion (Hazards 2010) that the number of impactors with a diameter $d > d_p$ is proportional to $d_p^{-2/3}$. The mean lunar impact velocity of asteroids was calculated to be 18.3 km/s by Minton, Richardson & Fassett (2015) and 19.7 km/s by Stuart & Binzel (2004). Werner & Ivanov (2015) concluded that the final rim crater diameter, D_v (in km), for a vertical impact is

$$D_v = 4(d_p \cdot U^{0.58})^{0.91}, \tag{1}$$

where d_p is the diameter of the impactor, and U is the impact velocity in km/s. The formula (1) was obtained for complex craters with a diameter $D > 15$ km. The size of a crater depends also on the impact angle θ approximately as $(\sin\theta)^{1/3}$ (Melosh H. J. 1989). Taking into account that the impact probability density is equal to $\sin 2\theta$, for the mean (over angles) value of the diameter of the crater, the coefficient 4 in (1) should be changed for 3.3. Based on the formula (1) with the coefficient 3.3, we obtain that the average diameter D_v of the crater that is produced by impactors with a diameter $d_p = 1$ km is 15.3 km and 15.7 km, for U equal to 18.3 km/s and 19.7 km/s, respectively.

The total number N_{1km} of NEOs (near-Earth objects) with diameter $d > 1$ km is estimated to be about 920. The ratio k_{ECO} of the number of NEOs to the number of

ECOs (Earth-crossing objects) was estimated by Ipatov & Mather (2004) to be about 1300/756≈1.72. The similar ratio (6718/3906≈1.72) was considered for the objects discovered before June 1, 2010 (Hazards 2010). Characteristic times T_E elapsed before collisions of an Apollo object and of an Aten object with the Earth were estimated in Ipatov & Mather (2004) to be about 164 and 15 Myr, respectively. T_{Eecos}, which is the value of T_E for all ECOs, equaled to 67 Myr. Before 2004 the obtained values of T_{Eecos} were greater. For example, T_{Eecos}=100 Myr in Ipatov (2001). The smaller than in previous papers values of T_{Eecos} in Ipatov & Mather (2004) were due to several Atens with small inclinations discovered at the beginning of 2000th. For the increase of the inclination of the Aten object 2000 SG344 from its present value equaled 0.1° to 1°, the values of T_{Eecos} were obtained to be equal to 97 Myr for all ECOs. Such difference in the values of T_{Eecos} illustrates the contribution to the mean value of T_{Eecos} of rare objects with high probabilities of collisions with the Earth. Studies of dynamics of initially Jupiter-crossing objects showed (Ipatov & Mather 2004) that the probability of a collision of one object with the Earth can be greater than the sum for thousands of other objects in similar initial orbits. The ratio p_{EM} of probabilities of collisions of NEOs with the Earth to that with the Moon is considered to be about 22 (Leuvre & Wieczorek 2011).

The number of impacts of NEOs with a diameter $d > 1$ km onto the considered lunar region during time T_{OP} can be estimated to be

$$N_{est} = N_{1km} \cdot r_{OP} \cdot T_{OP} / (T_{Eecos} \cdot k_{ECO} \cdot p_{EM}). \tag{2}$$

At N_{1km}=920, $k_{ECO} = 1.72$, $r_{OP} = 0.176$, $T_{OP} = 1100$ Myr, $T_{Eecos} = 100$ Myr, $p_{EM} = 22$, we have $N_{est} \approx 47$. For N_{obs}=52 the ratio N_{obs}/N_{est} is close to 1.1. Bottke, Vokrouhlicky & Nesvorny (2007) suggested that a recent catastrophic disruption of a large main-belt asteroid 160 Myr ago could increase the present value of N_{1km} compared to its mean value for a whole 1 Gyr interval. For such disruption, the mean value of N_{1km} should be smaller than 920, and the number N_{est} of craters with $D > 15$ km should be smaller than 52. As we noted above, Ipatov & Mather (2004) obtained $T_{Eecos} = 67$ Myr. Some ECOs earlier also could have small inclinations. In Ipatov & Mather (2004) 110 Atens were considered. If inclinations are randomly distributed in the range from 0 to 22°, one of them would have inclination between 0 and 0.2°, i.e. 0.1° on average. If we consider $T_{Eecos} = 67$ Myr for $T_{OP} = 1.1$ Gyr and $N_{1km} = 920$, then $N_{est} \approx 70$ and in order to have $N_{est} = N_{obs} = 52$ in the formula (2), we need to consider the mean value of N_{1km} during T_{OP} to be smaller than 920 by a factor of $70/52 \approx 1.35$, that is in accordance with the asteroid breakup considered in Bottke, Vokrouhlicky & Nesvorny (2007). Not all craters with a large age could survive. So the actual value of N_{obs} could be greater than its present value. For greater values of $N_{est} = N_{obs}$, in the formula (2) we need to consider greater values of N_{1km} or smaller values of $T_{Eecos} \cdot k_{ECO}$. In principle, our estimates can also allow that the mean number of NEOs during the last billion years was about the same as that in the present time.

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https://doi.org/10.1017/S1743921319001467 Published online by Cambridge University Press