SNOWBALL EARTH AND ASTEROID SHOWERS: A BRIEF REVIEW. Christian Koeberl[1] and Boris A. Ivanov[2], [1]Department of Lithospheric Research, University of Vienna, Althanstrasse 14, A-1090 Vienna, Austria (christian.koeberl@univie.ac.at); [2]Institute for Dynamics of Geospheres, Russian Academy of Sciences, 119334 Moscow, Russia (baivanov@idg.chph.ras.ru).

Introduction: The idea about "catastrophic" asteroid and comet impacts having severe effects on Earth has evolved from an unusual and remarkable idea [1] to some kind of mainstream direction of thinking about Earth's history as having been under a permanent meteoroid and cratering bombardment [2]. In many aspects the investigation of "impulsive" impact effects depends on the "memory" effects of the Earth as the lithosphere/hydrosphere/atmosphere system. The problem could be conditionally separated into a set of problems such as (1) how large should be an impact to have a prolonged effect, (2) could there be "unstable" periods in Earth's history when a single impact is a trigger for global changes, (3) could the repetitive impacts (an "impact shower") enhance the bombardment efficiency. The separated problem is the intensity of the proposed "showers". Here we present a brief review of some recent developments and publications.

Variable bombardment rate: Over the past several years, a lot of new data have been obtained from imaging of the Moon and Mars. The special case of small craters allows us estimate the present-day bombardment flux of bodies smaller than ~1 m in diameter [3, 4] and compare this with same-size terrestrial bolide data [5]. First observations [3] on the Moon do not reveal any dramatic deviation from the standard "Neukum chronology" for ~10 m lunar craters, derived earlier for a ~100 Myr interval [6].

Attempts to find sufficient variations in the production rate for larger craters on the Moon (and Earth) with new remote sensing data started with Galileo images [7] with the cautious suggestion that that the cratering rate has increased by 2x during the past ~300 Myr. New experimental techniques, based on thermal lunar data (with some model assumptions), have been used to propose that the impact rate increased within the last ∼500 million years [8] - see also comments [9] and the reply [10] in a short discussion.

Techniques to estimate the lunar crater age counting small overlapping craters encounter a problem when the variable bombardment rate is analyzed. The key question is – does the bombardment rate change correspondingly in all crater size ranges? Some studies try to vary both large crater formation rate and the production rate used for dating small craters, resulting in "new" crater retention ages [11]. Another point of view is that the asteroid collisions produce more large fragments and less small fragments (in comparison with the "background" bombardment flux) and try to merge "old" crater retention ages with a variable rate of large crater formation [12].

The opposite direction of thinking is the modeling of collisional dynamics of asteroids and injection of fragments into "fast delivery" routes to planetary crossing orbits. Bottke et al. [13] proposed the bombardment rate in the Earth/Moon system due to "favorable" formation of the Baptistina asteroid family. In the "favorable" orbital configuration many fragments of the assumed parent ~170-km-diameter body would be injected into planetary-crossing orbits, increasing the bombardment flux on Earth and the Moon by a factor of 2–3 for ~10-km-sized projectiles (it is interesting to note that on Venus such a "shower" should be twice as intense). For the Baptistina case the period of an enhanced bombardment is on the order of 100 to 150 Myr. Recently the number of suspicious asteroid's families able to produce Earth-crosser's "shower" was expanded [11, 12], and more analytic work is demanded to make a qualitative prediction of the large crater formation rate variations in the Earth/Moon system. We repeat that special attention should be devoted to the size-frequency distribution (SFD) in recent families and the following collision SFD evolution to update the standard lunar crater retention age technique..

Impacts and the Earth's environment: In some respects, the bombardment history on Earth is a more complicated problem than the cratering history on the Moon. To make an impression about corresponding lunar and terrestrial data we plot in Fig. 1 the general chronology of Snowball glacial intervals from [14]. The current understanding of the geological history of the Earth, based on direct observations, proposes that the Precambrian Earth episodically has been globally covered by ice. Two known so-called Snowball episodes lasted about 660-710 Ma and 645-655 Ma (besides an earlier phase, the Huronian glaciation at around 2.4-2.1 Ga). The general impression from Fig. 1 is that largest preserved impact structures are not connected with any of the known global glaciation periods. A proposed connection between asteroid showers and glaciations, as discussed in [11], is still questionable: the "new" chronology puts the "shower" ~50 to 70 Ma ahead of the anticipated Sturtian glaciation. The "old" chronology in [11] spreads the possible "shower" craters over a large part of the terrestrial glaciation history.

The comparison of a single "critical" impact with a multiple "shower" bombardment is an open field of investigations. It is necessary to study could the consequences of a single impact event to decay slowly enough to be enhanced with the subsequent "shower" event. The more simple case of a repetitive impact heating of the lithosphere on the early Earth could be definitely solved by comparison between the impact rate and the conductive lithosphere cooling [15]. The more complicated hydrosphere/atmosphere response to large scale impacts is still to be studied.

An instructive example of the problem with respect to multi-disciplinary investigations can be found in the study of the impact and volcanism across the Cretaceous-Paleogene boundary [16], where the most probable scenario is that the impact created the initial opportunity for extinction and the rise new Cenozoic species and communities, but volcanism might have contributed to the extinction as well. By analogy one could suggest that asteroid impact/impacts could play a role in the global glaciation/deglaciation (e.g., [21]), but in an environment shaped by non-impact processes.

References: [1] Alvarez L.W. et al. (1980) *Science, 208*, 1095-1108. [2] Marchi S. et al. (2021) *Nature Geoscience, 14(11)*, 827-831. [3] Speyerer E.J. et al. (2016) *Nature, 538(7624)*, 215-218. [4] Daubar I.J. et al. (2013) *Icarus, 225*, 506-516. [5] Brown P. et al. (2016) *Icarus, 266*, 96-111. [6] Ivanov B.A. (2006) *Icarus, 183*, 504-507. [7] McEwen A.S. et al. (1997) *JGR-Planets, 102(E4)*, 9231-9242. [8] Mazrouei S. et al. (2019) *Science, 363*, 253-257. [9] Hergarten S. et al. (2019) *Science 365*, eaaw7471. [10] Mazrouei S. et al. (2019) *Science, 365*, eaaw9895. [11] Terada K. et al. (2020) *Nature Communications, 11(1)*, 3453. [12] Kirchoff M.R. et al. (2021) *Icarus, 355*, 114110. [13] Bottke W.F. et al. (2007) *Nature, 449*, 48-53. [14] Hoffman P.F. et al. (2017) *Science Advances, 3(11)*, doi 10.1126/sciadv.1600983. [15] Ivanov B.A. (2004) *Solar System Research, 38*, 266-279. [16] Hull P.M. et al. (2020) *Science, 367*, 266-272. [17] Erickson T.M. et al. (2020) *Nature Communications, 11*, doi 10.1038/s41467-019-13985-7. [18] Kamo S.L. et al. (1996) *Earth and Planetary Science Letters, 144*, 369-387. [19] Davis D.W. (2008) *Geology, 36*, 383-386. [20] Swisher C.C. et al. (1992) *Science, 257*, 954-958. [21] Koeberl C. and Ivanov B.A. (2019) *Meteoritics Planet Sci., 54*, 2273–2285.

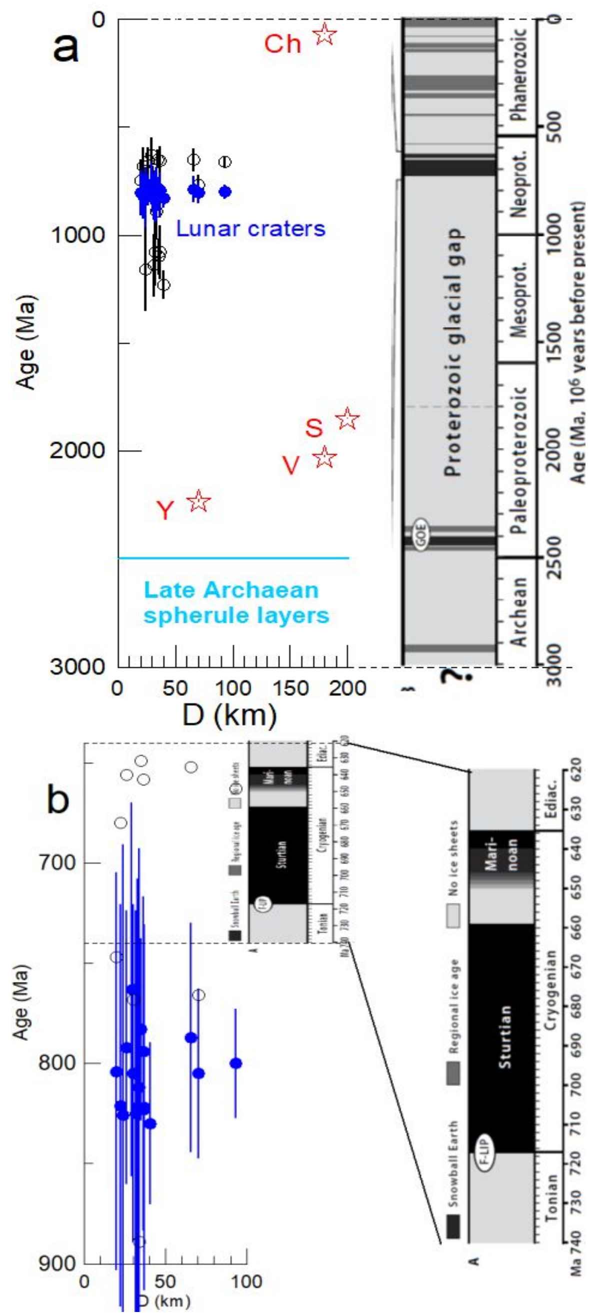

Figure 1. General chronology of Snowball glacial intervals from [14]; **a** – the whole post-Archean period, blue line at 2500 Ma corresponds to the effective end of the early bombardment [2], red stars: selected large impact craters: Yarrabubba [17], Vredefort [18], Sudbury [19], Chicxulub [20]; blue and open circles are for "new" and "old" chronology of lunar D>20 km craters [11]; **b** – enlargement of left panel for 620 to 900 Ma period with same lunar data from [11]. One could see the ~50 Ma gap from the "asteroid shower" proposed by [11] and the Sturtian glaciation period, while the "old" chronology is a better fit to the Marinoan glaciation.