CONSTRAINTS ON THE NEO IMPACT FREQUENCY FROM ANALYSIS AND MODELING OF APOLLO IMPACT EVENTS. Philippe Lognonné[1], Mathieu Le Feuvre[1], Catherine Johnson[2] (1) Equipe Géophysique Spatiale et Planétaire Institut de Physique du Globe de Paris, Université Paris Diderot, UMR7154 CNRS, France, email : lognonne@ipgp.jussieu.fr, (2) University of British Colombia, Vancouver, Canada

Introduction: The frequency/size law of meteoroids impacting the Moon and the associated probability of NEO impacts are still not known precisely. Uncertainties as large as a factor of 3-5 remain, especially for the moderate-sized impacts which are not observed on the Earth, due to the shielding by the atmosphere. Impact frequencies of these objects are made from the observation of larger impacts by the US DSP satellites [1], recording of luminous flashes [2] or extrapolation of cratering frequencies [3]. We provide here an estimate of the impact frequency, by analysing events recorded during the Apollo Passive Seismic Experiment in a statistical way. Our method is summarized as follows. We used artificial impacts performed during the Apollo program to build a method able to compute the seismic waveform generated by an impact at any epicentral distance and with a given mass and impactor velocity. We then use meteoroid mass/frequency laws to generate, with a random simulator, a history of impacts on the Moon during a given period. We compute the seismic signals generated by succession of seismic sources and estimate the frequency/amplitude relationship of such seismic signals.

Our results also provide an estimate for the meteoritic seismic background on the Moon. This background noise was not recorded by the Apollo seismic experiment due insufficient resolution. Such an estimate can be used in designing a new generation of lunar seismometers, for estimating the probability of detecting proposed impacts due to nuggets of strange quark matter [4], and to inform future lunar based experiments, which require very stable ground, such as optical interferometry moon-based telescopes or gravity waves detectors [5].

Empirical impact Greens functions: In order to assess the amplitude of signals generated by impacts, we use the artificial impacts performed during the Apollo program with the Saturn IV upper stage and Lunar Ascent Vehicle LEM. We assume that the signals generated by these impacts are those of a point force, with known mass and impact velocity, and that they can be used to determine empirical Greens functions. We model the geometrical and attenuation amplitude variations of the artificial impacts, using least squares fitting, in order to be able to simulate impacts at any epicentral distance. Simulated impacts are then modeled simply by taking the two nearest artificial impacts, performing a time shift based on travel times arrivals, and a rescaling for amplitude, and finally averaging these records to compute a synthetic seismogram at the simulated impact's epicentral distance. An example is shown in Figure 1.

Impactor modeling: We assume, following [6], that the NEO population is in a steady-state, being continuously replenished by the influx of material coming from source regions associated with the main asteroid belt or the trans-neptunian disk. We assume that densities, velocity distributions and relative impact rate do not depend on the projectile's mass. Following [7], we calculate for each cell of the NEO model the impact probability with the Earth and Moon, and the corresponding impact velocity, semi-major axis, eccentricity and inclination of the object, respectively, as well as its impact location on the Moon. We have done these simulations for three impact/frequency models: Brown, Ivanov and Ortiz, following the associated references [1,3,2]. The Ivanov model suggests that about 6000 objects of more than 1kg impact the Moon per year, a rate comparable to that of small impacts, but smaller by at least a factor of 2 than that predicted by the Brown model.

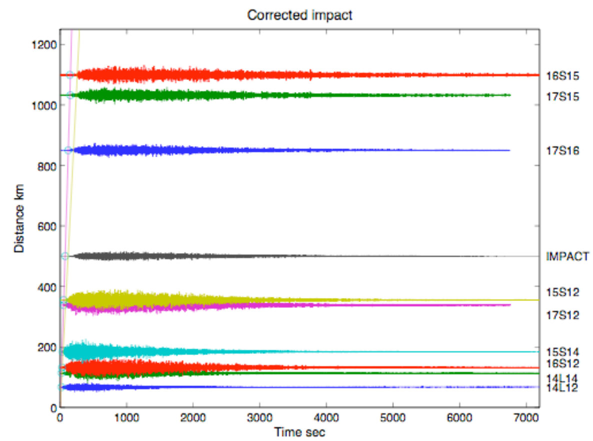

Figure 1: Simulated impact (black, labeled IMPACT), as compared to the artificial ones (other colors). Amplitudes are corrected for geometrical spreading and attenuation

Results: Using the method described above, we obtain a time series of impacts, with the position and time of impact, the vector velocity and the mass of the impactor. Each of these impacts generates a seismic signal, which can then be modeled by our Greens function approach, and added to the simulated time series recorded at a given location. We choose here the Apollo 12 landing site, but our results are not sensitive to the seismic station location.

To compare these models to observations, we use the most recent LP catalogue of events, available on line at the University of Texas [8]. About 12,500 seismic catalogued signals have been identified between July 1969 and September 1977, 1700 of them as meteoroid impacts. For each of these impacts, the compressed scale envelope amplitude was recorded. Figure 2 gives the statistics of these observations, in terms of numbers of event per year, down to the detection threshold (about 0.1 mm in compressed-scale amplitude). Impacts simulated with the Brown model overlap fairly well with the observations and are extended toward much smaller amplitudes with the same logarithmic slope. Impacts simulated with the Ivanov model are typically about a factor of 3 too large, in terms of frequency for a given mass (or about the same factor, in term of amplitude). We note that many of the impacts in our simulation, are on the farside of the Moon while limited seismic observations of impacts have been made at large epicentral distance, with very few at more than 120° epicentral distance [9,10]. We explore reducing the amplitudes of impacts at large epicentral distances, by decreasing the quality coefficient associated with attenuation for epicentral distances greater than 1500 km. Such a larger attenuation in the lunar deep interior has been suggested in several studies [11]. We find that a Q smaller by a factor of 2 provides a reasonable match to the observations for the Ivanov and Ortiz models (Figure 2), while the Brown model with a reduced Q predicts amplitudes that are too low for a given impact frequency. Even though models for the attenuation of the Moon's deep interior are far from definitive, we consider that the frequencies of impactors proposed by Ivanov and Ortiz provide a better match with the lunar seismic observations than those of Brown. More detailed analysis requires an updated model of the lunar attenuation.

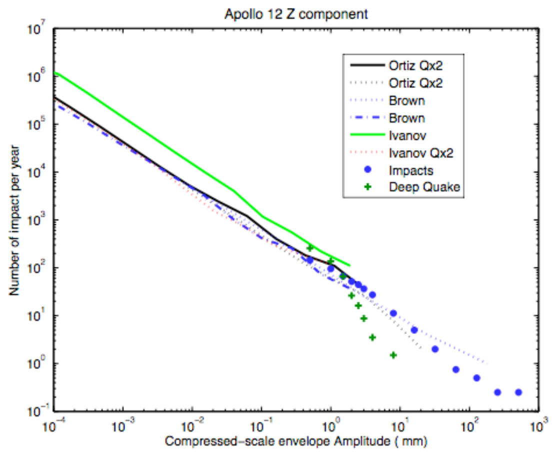

Figure 2: Impact statistics: For the Apollo data, amplitudes are the compressed-scale envelope amplitudes for meteoroids (blue stars) and deep moonquakes (green plus signs). For our simulated seismic records, we compute amplitudes as follows: The absolute value of the difference between consecutive data points is summed over 40 points for the long period data (320 points for the short period data), and this value is plotted yielding one value for each 6 seconds of data at a scale of 157 digital units/cm.

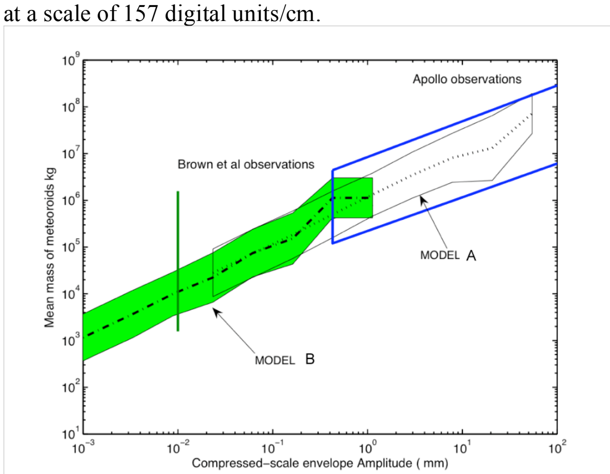

Figure 3: Impactor mass statistics. Model A was derived by matching the Apollo observations to the synthetics, while Model B was derived from for our simulated lunar background seismic noise. The Brown et al. and Apollo observations are shown in green and blue respectively.

Implication for the lunar background seismic noise: We estimate the background seismic noise associated with the small meteoroid impacts, by assuming that the observations, achieved down to about 0.1 mm in compressed scale, can be extrapolated to lower amplitudes. We find a noise level of 0.05-0.1 DU might be considered a detection threshold for single impact events in a future lunar seismic experiment (Figure 4). An rms noise level of 0.05 DU corresponds to 0.25×10^{-10} ms^{-2} in acceleration at 2 sec. The signal below this threshold is associated with impact generated signals, from masses ranging (at 1σ for a log-normal distribution) from 300 kg to 3000 kg (Figure 3). The mass of the Lunar module was about 2300 kg but was detected a a few hundred km only. We can expect therefore a lunar seismic noise level about 400 times lower than on Earth at 2 seconds. Extrapolation to longer periods, if the noise is mainly related to impacts, suggests that at 20s periods (corresponding to long period body waves or crustal surface waves) we can expect a noise one thousand times smaller, while a decrease of only one hundred is obtained on the Earth, leading to a noise level less than 10^{-3} of that on Earth.

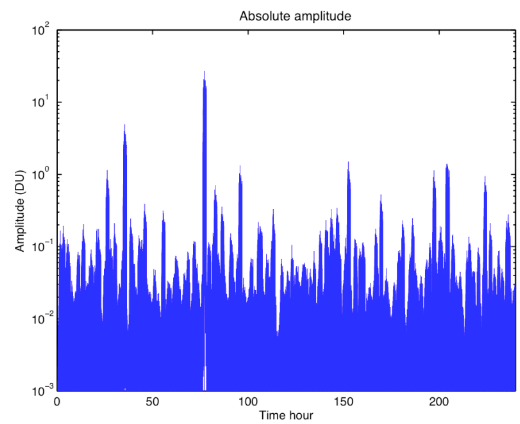

Figure 4: Absolute value (in Apollo DU) of the simulated background Moon seismic noise during a period of 10 days.

References: [1] Brown et al (2002), Nature , 420, 294-296. [2] Ortiz et al (2006) , Icarus, 184, 319-326 [3] Ivanov et al (2003) Asteroids III. Univ. of Arizona Press [4] Banerdt et al (2006) Adv. Space. Res., 37, 1889-1893. [5] Swing, J.P., Astronomy from the Moon, 23rd meeting of the IAU, Joint Discussion 22, 27 August 1997, Kyoto, Japan [6] Bottke et al (2002). Icarus , 156, 399-433. [7] Opik (1951), Proc. R. Irish Acad. Sect. A, vol. 54, p. 165-199 [8] Nakamura, ftp://ig.utexas.edu/pub/PSE/catsrepts [9] Lognonné, P, (2005), Annual Review in Earth Planet. Sci., 33 :19.1-19.34 [10] Lognonné and Johnson, (2007), Treatise in Geophysics, vol. 10, ch. 4 [11] Nakamura, Y., 2005. J. Geophys. Res., 110, E01001