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Impact cutoff frequency – momentum scaling law inverted from Apollo seismic data

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ABSTRACT

We perform the analysis of both long and short period data for 40 large meteoroid impacts event gathered by the Apollo lunar seismic network. We extract the linear momentum released by the impact and the cutoff frequency of the recorded seismic spectrum, related to the radiation process of the shock wave generated by the impact. By using a proxy to the local porosity, based on the density of surface craters and well correlated to the most recent GRAIL observations, we demonstrate that the seismic cutoff frequencies for 40 selected impacts correlate with this proxy and therefore likely with the porosity at the impacted areas. Our finding shows that lunar seismic records of meteoroid impacts represent unique geophysical data documenting medium to high-energy (0.1–1 kt TNT yield) impact processes, including the interaction of shock waves with porous media. This work can be applied to the analysis of the seismic data to be obtained by the InSight mission in 2016 and the investigation of the lateral variations in the Martian regolith.

1. Introduction

The seismic detection of impacts on the airless Moon was quite common during the operation of the lunar seismic network with 1753 impact detections reported (Nakamura, 2008). The impact rate depends on the size of the impactors, and was first studied extensively by Oberst and Nakamura (1987, 1991) who proposed an annual rate of impacts given by the relation:

$$\log_{10} N = -0.99 \log_{10} E + 11.4, \qquad (1)$$

where N is the number of events per year, and E is the kinetic energy in J. Assuming an impact velocity of 14 km/s and a seismic coupling efficiency of 10^{-6} (Oberst and Nakamura, 1987, 1991), the energy of the largest yearly impact is $10^{11.5}$ J, equivalent to a mass of about 3500 kg.

This is a unique data set, on Earth only a few impacts have generated well-detected P and S waves related to the impact surface (Edwards et al., 2008). The impactors detected by the Apollo long-period (LP) stations have a mass between fractions of a kilogram to several tons. For impacts at an average speed of 20 km/s (a value more relevant than the one taken by Oberst and Nakamura (1987, 1991) and proposed by Le Feuvre and Wieczorek (2008) from a statistical analysis of the impactors trajectories), the energy released per kg is equivalent to about 48 kg of TNT (1 TNT is equivalent to 4.184 GJ). A number of impacts were detected by at least 3 of the 4 stations, enabling the location of the impact. Much smaller mass impactors (on the order of a fraction of a gram) were detected with the short-period (SP) instruments at only one station (Duennebier and Sutton, 1974). When integrated on a global scale, this continuous flux of small impactors has been proposed as the primary source of a continuous micro-seismic noise of the Moon (Lognonné et al., 2009).

Source spectra are typically characterized by a plateau at low frequencies and a roll-off slope for high frequency. For quakes, the low-frequency level is proportional to the seismic moment, while it is proportional to the impactor momentum on the lunar Apollo seismic records (Lognonné et al., 2009; Gudkova et al., 2011). The high-frequency asymptote is related to the elastic source displacement time history and the form of the radial stress drop field (Denny and Johnson, 1991). The frequency corresponding to the intersection of the horizontal low-frequency asymptote and the sloping high-frequency asymptote is called the corner frequency (or cutoff frequency). The cutoff frequency is determined by the source size and material properties of the impacted medium (e.g.,

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Table 1
Location and seismic parameters of the meteoroid impacts analyzed in this study.

Impact	Date (year, month, day, hour, min)	Lat	Long	mv (kg m/s)	τ (s)
1	1971/05/12, 09:34	−18.9	−5.9	8.18E+06	0.50
2	1971/05/23, 22:09	1.7	−16.6	2.48E+07	0.45
3	1971/06/27, 18:44	57.0	129.4	7.11E+07	0.70
4	1971/07/27, 11:34	7.8	−21.9	3.49E+06	0.60
5	1971/10/20, 17:57	36.1	−36.9	3.89E+07	0.70
6	1972/01/04, 06:24	74.1	2.5	1.38E+07	0.70
7	1972/05/13, 08:35	1.5	−17.1	8.22E+07	0.80
8	1972/07/17, 21:45	32.8	137.6	1.89E+08	1.55
9	1972/07/31, 17:57	34.5	4.8	1.76E+07	0.60
10	1972/08/29, 22:48	15.8	22.9	6.87E+06	0.50
11	1972/09/21, 00:37	−4.1	4.5	2.19E+06	0.50
12	1972/11/14, 19:14	3.9	−19.5	2.28E+06	0.60
13	1972/11/19, 18:13	55.4	−61.3	1.69E+07	0.60
14	1972/12/02, 07:47	65.1	−75.7	9.50E+06	0.70
15	1973/04/23, 13:45	−34.1	113.0	7.39E+07	1.10
16	1973/07/04, 02:35	4.9	83.0	9.03E+06	0.80
17	1973/08/01, 10:51	16.6	−52.1	5.03E+06	0.75
18	1973/09/26, 20:37	28.7	41.1	8.49E+06	0.65
19	1973/10/21, 05:21	−33.9	9.1	3.74E+06	0.60
20	1973/12/24, 09:54	−24.8	−25.1	4.11E+06	0.55
21	1974/04/19, 18:23	7.4	−33.6	4.41E+06	0.50
22	1974/06/30, 17:34	9.5	43.3	7.51E+06	0.65
23	1974/07/06, 14:03	19.5	12.8	4.53E+06	0.60
24	1974/07/17, 11:54	20.3	6.5	4.24E+06	0.75
25	1974/09/23, 11:42	−2.9	−24.0	9.83E+05	0.60
26	1974/11/21, 13:05	−7.3	19.9	1.20E+07	0.55
27	1974/12/09, 09:19	−14.1	11.0	3.40E+06	0.50
28	1974/12/15, 08:57	1.6	−8.2	6.75E+06	0.55
29	1975/03/01, 04:07	15.8	−27.2	7.92E+06	0.65
30	1975/03/05, 21:41	−52.4	4.2	2.16E+07	0.85
31	1975/04/12, 04:10	2.0	43.2	7.87E+07	0.65
32	1975/05/04, 09:55	−36.4	−121.3	3.02E+08	1.25
33	1975/10/06, 12:47	−23.9	29.8	6.31E+06	0.60
34	1976/01/13, 07:05	−39.4	62.8	7.10E+07	0.70
35	1976/01/25, 15:59	−5.6	−71.5	9.93E+07	0.80
36	1976/05/16, 12:37	−10.4	15.3	9.48E+06	0.65
37	1976/05/28, 05:52	−16.8	−10.0	5.58E+06	0.55
38	1976/11/14, 23:05	23.8	−73.9	1.14E+08	1.00
39	1977/04/17, 23:26	−20.5	−63.8	4.77E+07	0.80
40	1977/06/28, 22:14	−13.5	−75.3	2.89E+07	1.30

porosity). This is valid also for nuclear explosions, where the cutoff frequency depends on the geological materials (e.g., Xu et al., 2014).

The largest meteoroid impacts that correspond to impactors with kinetic energies in the range of 0.5–1.5 (kt) kiloton (units of TNT mass–energy equivalent) have been recently studied by Gudkova et al. (2011) and they are characterized by the cutoff frequencies ranging from 1 to 1.5 Hz, typically twice lower than those expected for nuclear or chemical explosions with comparable yields (Xu et al., 2014). Logically, this lower cutoff frequency seems to be related to the much lower seismic velocities and densities of the lunar regolith, compared to the bedrock where nuclear or large chemical explosions occur, but the systematic and complete analysis of the relation between the seismic impulse (or moment) and cutoff frequency of the Apollo seismic observations has never been performed.

In this paper, we report for the first time the observational constraints on the cutoff frequency-momentum scaling law, which will be crucial for estimating the size of impactors for future seismic monitoring on the Moon, Mars and other planetary bodies with thin or no atmosphere. This study is based on the Apollo seismic data and the crater density on the lunar surface. In addition to the first theoretical analysis of the observed dependence of the cutoff frequency, we also provide observational evidence on the sensitivity of the cutoff frequency to the regolith porosity.

2. Analysis of meteoroid impacts recorded by the Apollo seismometers

We have performed the analysis of 40 large meteoroid impacts located in different regions (Table 1 and Fig. 1) and recorded by the Apollo network during the 1970s on both LP and SP vertical components of the seismic instruments from up to three stations. The four Apollo seismometers operating as a network were extremely sensitive, capable of detecting displacements of 3×10^{-10} m at frequencies between 0.1 and 1 Hz on the LP instrument in flat response mode, 0.5×10^{-10} m at 0.45 Hz for the LP instrument in peaked response mode, as well as 0.5×10^{-10} m at 8 Hz for the SP instrument (Lammlein et al., 1974). In addition to the very low environmental noise and low attenuation, the Apollo seismic network acted as an efficient impact detector (e.g. McGarr et al., 1969; Oberst and Nakamura, 1987; Lognonné et al., 2009; Kawamura et al., 2011; Yamada et al., 2011). An example of waveforms for a natural impact is shown in Fig. 2.

When a meteoroid impacts the Moon, its linear momentum is transferred into the target and its kinetic energy is distributed between heating and fracturing of the target with a small fraction of energy (of the order of 10^{-4}–10^{-6}) being transferred into shock and seismic waves. The seismic efficiency of an impact, defined as the ratio of seismic energy over the impactor kinetic energy, depends on meteoroid characteristics such as mass, composition, velocity and impact angle, as well as on the properties of the target