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A Possible Scattering Mechanism for Lunar Seismic Waves

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Summary: The peculiar character of lunar impact seismograms is explained by a very efficient scattering process in a high Q outer shell of the moon. Ultrasonic model experiments in a steel plate with a random distribution of slits produce records strikingly similar to lunar seismograms. As a first approximation to the theoretical interpretation scattering is treated as a two-dimensional "random walk" process which in its limit is identical with energy diffusion. Arguments are put forward that scattering is caused primarily by a system of deep reaching, steeply dipping open fissures in the moon's uppermost 10—20 km. From the statistical treatment a typical block dimension of the order 1—2 km is suggested. Differences in rock composition are thought to be of minor importance.

Zusammenfassung: Der eigenartige Charakter künstlicher Mondseismogramme wird durch Vielfachstreuung in einer schwach absorbierenden äußersten Schale des Mondes erklärt. Ultraschall-Modellversuche in einer Stahlplatte mit statistisch verteilten Schlitzen führen zu Registrierungen, die Mondseismogrammen erstaunlich ähnlich sind. Als 1. Näherung für eine theoretische Interpretation wird der Streuprozeß als zweidimensionale „Irrfahrt" behandelt, was im Grenzfall identisch ist mit Energiediffusion. Als Ursache für die Streuung wird ein System tiefreichender, steil einfallender, offener Spalten in den oberen 10—20 km des Mondes postuliert und begründet. Eine typische Blockdimension von 1—2 km läßt sich aus der statistischen Betrachtung ableiten. Es wird angenommen, daß Unterschiede in der Gesteinszusammensetzung für den Streuprozeß von geringerer Bedeutung sind.

1. Introduction

First results of the lunar seismic experiment have recently been published in a special volume of Science [LATHAM, EWING, PRESS, SUTTON, DORMAN, NAKAMURA, TOKSÖZ, WIGGINS, DEER and DUENNEBIER 1970]. Among the different signals recorded at the surface of the moon only those of type L seem to be of significance for studies of the moon's near surface structure. The impact of the Apollo 12 Landing Missile ascent stage recorded on November 20, 1969 at a distance of 76 km by the Apollo 12 seismographs was the most important event of this type because in this case the seismic source was known.

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The record shown in Figure 1 differs completely from terrestrical seismograms in several respect:

1. No distinct first or later onsets are found. Instead, the amplitude of ground motion grows almost continuously from zero to its maximum value during the first five minutes of the record.
2. The duration of the ground motion is extremely long. After 30 minutes the amplitude is still $^1/_4$ of the maximum value.
3. The ground motion is irregular in a statistical sense and confined to a frequency band around 1 cps throughout the seismogram.

These facts have to be explained.

It seems highly improbable that source effects (landslide or spray of rocks) offer a satisfactory explanation. If instrumental effects can be excluded an unusual wave propagation process must be responsible. A pure waveguide phenomenon like the terrestrical T-Phase at an oceanic path which is somewaht similar in appearance is improbable for the following reason: The main part of the seismogram corresponds to group velocity values 0.4 to 0.05 km/sec. Since the v_P-velocity for lunar rocks in some depth must be of the order of 4 to 7 km/sec the ratio of acoustical impedances inside and outside the assumed waveguide had to be almost infinity for unattenuated mode propagation. The very thin porous surface layer hardly can account for this process. Therefore a random scattering process in a very high Q surface shell is considered.

2. Model Seismic Experiments

In order to gain at least a qualitative impression of such a process several two-dimensional models for ultrasonic studies have been designed. The most reasonable one which anticipates already the structure proposed in chapter 4 of this paper is shown in Figure 2. A steel plate $600 \times 1000 \times 2$ mm was perforated with slits 30×3 mm in almost random distribution with a density of 400 slits per m^2. In the unperforated plate v_P was 5.5 km/sec and the frequency of the generated seismic pulses in the range of 300—500 kcps. This corresponds to a wavelength of 1.1 to 1.8 cm or about half the length of a slit. The position of the piezoelectric source and receiver is seen in Figure 2.

The result obtained is shown in Figure 3a—3d where only the time scale has been varied. The similarity with the lunar seismogram (Figure 1) is striking. Although at high magnification a first arrival can be detected its amplitude is only $^1/_{50}$ of the maximum amplitude which is built up by superposition of multiple scattered waves about 700 μsec or 250 oscillations after the first motion. Also the slow amplitude decay and the statistical character of the motion is very similar to the lunar seismogram.

If, however, the plate is taken as an analogue to the surface shell of the moon two important differences have to be kept in mind. First, the plate has finite extensions

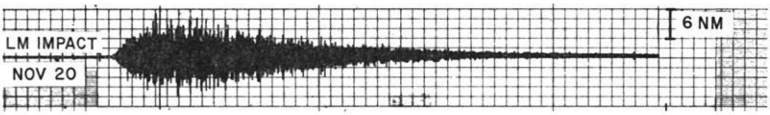

Fig. 1: Apollo 12, LM impact seismogram. $\Delta = 76$ km.
[LATHAM et al. 1970].

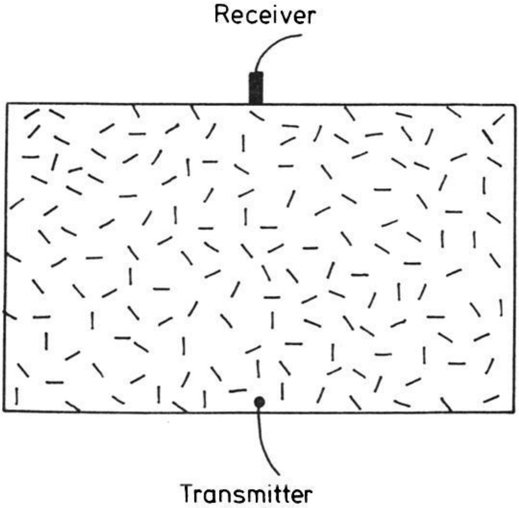

Fig. 2: Ultrasonic model for two-dimensional wave scatter.
(Steel plate 600 × 1000 × 2 mm with slits 30 × 3 mm.)

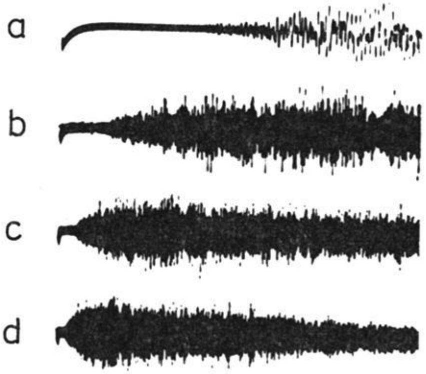

Fig. 3: Ultrasonic seismogram from model Figure 2.

a 75 µsec/cm	c 0.75 msec/cm
b 0.3 msec/cm	d 1.5 msec/cm

and second, the plate was acoustically isolated from its surrounding. Therefore the whole ultrasonic energy is confined to the volume of the plate. The amplitude decay is entirely depending on the internal absorption or the Q value of the plate. Nevertheless, this result was very encouraging.

3. Statistical Consideration

The mathematical treatment of a scattering process as simulated by the model experiment in terms of elastic wave theory would be a formidable task. In a rather crude approximation, however, it can be reduced to a classical problem of statistics, the two-dimensional "random walk" (Irrfahrt) which had been solved already by Lord Rayleigh. It is summarized in a paper by Bartels [1959].

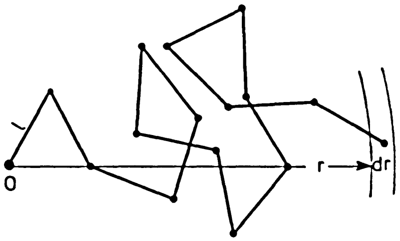

Fig. 4: Random walk, $n = 15$.

Let us assume an acoustcial energy element (phonon) generated at $r = 0$, $t = 0$. It travels a distance l with the velocity v in the horizontal plane until it gets deflected at an arbitrary angle and this repeates n times (Figure 4). In the limit for $n = t \cdot v / l \to \infty$ the probability w to find the phonon after a time t between a distance r and $r + dr$ from the origin is given by

$$w(r,t)=\frac{2\cdot r}{l\cdot v\cdot t}\exp(-r^2/l\cdot v\cdot t). \tag{1}$$

If N_0 is the number of phonons released by the source

$$N(r,t)=\frac{N_0}{\pi\cdot l\cdot v\cdot t}\exp(-r^2/l\cdot v\cdot t) \tag{2}$$

phonons are expected to be found in a unit area at r, t.

$$N(r,t)/N_0=E(r,t) \tag{3}$$

defines the acoustical energy density at r, t for a point source of unit energy. E reaches its maximum value at the time $t_m = r^2/2 \cdot l \cdot v$.

Equation (2) is identical with the fundamental solution [Sommerfeld 1948] of the two-dimensional equation of diffusion

$$\nabla^2 E=\frac{1}{K}\frac{\partial E}{\partial t}$$

where

$$K=\frac{1}{2}l\cdot v$$

the diffusion coefficient. The equation of diffusion has also been applied to lunar seismograms by Latham et al. [1970].

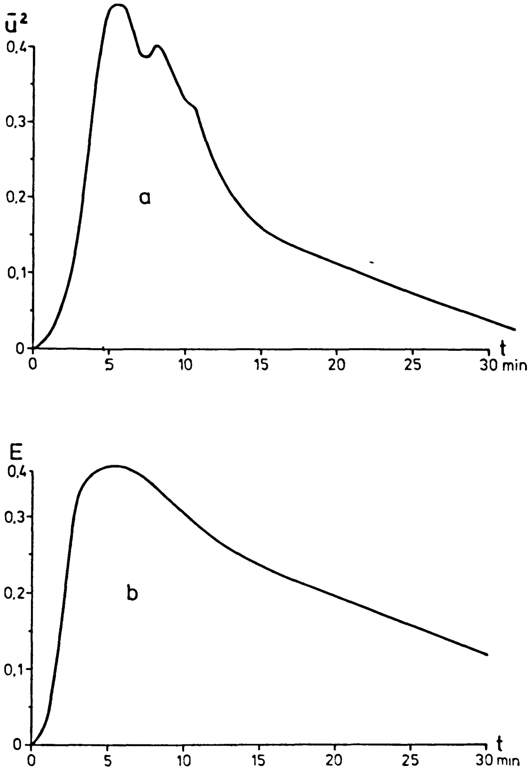

Fig. 5: Energy density a) for LM impact lunrr seismogram, b) for the scattering function ($r = 76$ km, $t_m = 300$ sec).

Figure 5b shows $E(t)$ according to (2) and (3) for $r = 76$ km, $t_m = 300$ sec and therefore $l \cdot v = 9.5$ km²/sec. For comparison the time average $u^2(t)$ of the seismogram trace amplitude $u(t)$ is plotted in Figure 5a. Since the frequency content seems to be roughly the same throughout the seismogram $\bar{u}^2$ is a measure for the kinetic energy density $E(t)$ at the site of the seismometer. The similarity in character of 5a and 5b is evident and justifies in general the consideration made above. It should be remembered that (2) was derived for unattenuated or very high Q propagation. If v_P for lunar rock is of the order of 6 km/sec a typical value for the distance l between consecutive scattering processes is of the order of 1—2 km.

Of course this is a very simplified treatment of the actual problem. The analysis of data as well as the scattering theory could be refined considerably. Nevertheless comparison of the lunar seismogram with model experiment and statistical theory strongly suggests that a multiple scattering process in a high Q outer shell of the moon is mainly responsible for the appearance of lunar seismograms. To confine the seismic energy to a near surface shell a positive velocity-depth gradient is required.

4. A Possible Cause for Scattering

This last chapter deals with some speculations on a possible scattering mechanism. The obvious differences in lunar and terrestrical seismograms must be the result of differences in the physical structure of moon and earth.

If the moon has grown by aggregation of cold interplanetary rock pieces of different size and composition elastic heterogeneity would be the result. For two reasons this is not very likely to account primarily for the seismic observations:

1. The chemical composition of lunar rocks seems not to differ enough to produce scattering of the observed intensity.
2. If rocks were captured by the moon's gravity field and crushed on the surface I would expect higher absorption or a lower Q.

An alternative idea is proposed here which is based on the following facts or postulates:

1. The moon's outer shell consists of magmatic rock, lateral petrographical differences are of second order importance (seismometer site and impact position were positioned in the same mare-landscape).
2. Temperature below the moon surface is low, perhaps —50 °C and slowly increasing with depth.
3. Gravity is 1/6 of g.
4. Circulating water is absent.

Because of item 1 and 2 the material is expected to be extremely hard and brittle and therefore of a very high Q. Thermal contraction, tides, and meteorite impacts caused stress and as a consequence a complex pattern of fracture fissures. On earth, cracks can stay open down to a depth of perhaps 2—3 km, where they become closed by the pressure of the overburden. Since gravity on the moon is only 1/6 of g, open cracks might be present down to 10 or 20 km. On earth tectonic fissures are "healed" by aqueous mineral solutions. This is not possible on the moon. Therefore any fissure will remain open almost indefinitely. Because gravity tends to close cracks with small dip angle essentially vertically dipping fissures will exist. Gaps of one tenth of a millimeter between adjacent blocks are sufficient for total reflexion of seismic waves. Since the moon's surface is covered with a layer of dust these fissures can hardly be seen. Wave transmission from block to block is possible only at spots where they are pressed together firmly. The result of chapter 3 indicates that a typical block size would be of the order of 1—2 km.

This model of lunar tectonics is sketched in Figure 6. It is evident that at a source distance of only 76 km no distinct first arrival can reach the seismograph unless a very good reflecting interface exists in some greater depth. According to this model

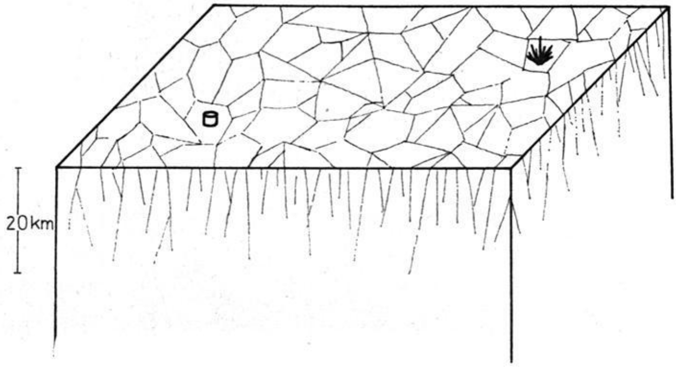

Fig. 6: Block model of the postulated fissure zone.

distinct arrivals of *P*- and *S*-phases can only be expected for epicentral distances of the order of thousand kilometers or for a source located on the same block as the seismometer.

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