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The song of the dunes as a self-synchronized instrument

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Since Marco Polo [1] it has been known that some sand dunes have the peculiar ability of emitting a loud sound with a well-defined frequency, sometimes for several minutes. The origin of this sustained sound has remained mysterious, partly because of its rarity in nature. It has been recognized that the sound is not due to the air flow around the dunes but to the motion of an avalanche, and not to an acoustic excitation of the grains but to their relative motion. By comparing several singing dunes and two controlled experiments, one in the laboratory and one in the field, we finally demonstrate here that the frequency of the sound is the frequency of the relative motion of the sand grains. The sound is produced because some moving grains synchronize their motions. The existence of a velocity threshold in both experiments further shows that this synchronization comes from an acoustic resonance within the flowing layer: if the layer is large enough it creates a resonance cavity in which grains self-synchronize. Sound files are provided as supplementary materials.

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In musical instruments, sustained sound is obtained through the coupling of excitation and resonance. The excitation is a more or less periodic instability, like the rubbing stick-slip instability of the bow of a violin or the Von-Karman whistling instability of a flute. This excitation is coupled with a resonance (the string for the violin, the air volume for the flute). The coupling results in the adaptation of the instability frequency to the one fixed by the resonance. Does the sound emitted by the sand dunes originate from a similar mechanism? It has long been recognized that the song of dunes comes from the flowing motion of sand grains in an avalanche [2, 3, 4, 5, 6, 7]. Direct observations, as we have done in Morocco, Chile, and China, show that this sound does not originate from stick-slip motion of blocks of grain (as the bow of a string instrument), because it is produced only by dry grains flowing freely. Neither does it correspond to a resonance inside the dune (as in a wind instrument), because the same frequency has been measured at different locations on a dune and, also, in the same field in dunes of different sizes.

The first significant observation is that the frequency measured depends only on the size of the grains, each dune field having a characteristic grain size and frequency. Study of the motion of the grains in an avalanche shows how grains have to pass periodically

Location	Grains size (μm)	Predicted frequency (Hz)	Measured frequency (Hz)
Ghord Lahmar (Tarfaya, Morocco)	160	100	105 ± 10
Mar de Dunas (Copiapo, Chile)	210	87	90 ± 10
Cerro Bramador (Copiapo, Chile)	270	77	75 ± 10
Sand Mountain (Nevada, USA)*	340	68	63 ± 5

TABLE I: Sound Frequency of Singing Dunes. Comparison of the frequency predicted from the grains size with the measured frequency. *From [4]; others are from our own measurements [26, 27, 28]. El Cerro Bramador sound properties were first reported by Darwin [2].

over each other, dilating locally, and then hitting lower grains [8]. This particular motion explains that a grain flows with a constant velocity and an avalanche with a linear velocity profile in depth [9]. The corresponding constant velocity gradient is precisely the average shock frequency, f , identical throughout the avalanche depth. Experiments [10] and theory [8] give $f = 0.4\sqrt{g/d}$, proportional to $\sqrt{g/d}$ as first proposed by [11]. This diameter to frequency relation is in accordance with what has been measured (see Table 1) [26, 27, 28]. Even if there is a slight deviation, as noticed by [12], it is

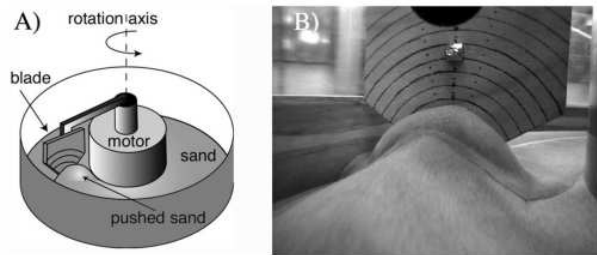


FIG. 1: A: Sketch of laboratory experiment. Channel is of 1 m diameter and 25 cm width. B: Picture of flat pushing blade in channel, taken by camera moving with blade. Black spot on top is microphone (also rotating). Circles on blade, separated by 1 cm, allow direct measurement of height of pushed mass during motion

noticeable that the prediction is within the error bars. In granular avalanches, this frequency is fixed by gravity, but pushing such "musical sand" with the hand, a plate, or the legs can create different notes [13, 14] from 25 to 250 Hz in Morocco [29, 30] (cf. supplementary recordings [26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36, 37] to listen to the sound of dunes). To reproduce this effect in the laboratory, a blade is plugged at different depths into a prepared crest of singing sand (from Ghord Lahmar, Tarfaya, Morocco) and is pushed by a motor at different velocities (see Figure 1). This experiment allows an independent control of both the shearing velocity and the mass of sheared sand, making it possible to obtain sustained sounds of constant and well-defined frequencies [31, 32]. This demonstrates that the booming sound can be reproduced in a controlled way in the laboratory, and consequently that the dune itself is not needed to produce the sound. The results in Figure 2 show that it is neither the velocity nor the mass that controls the frequency, but the shear applied to the grains. This demonstrates the hypothesis of [15], and is conclusive proof that what is being heard is the relative motion of the grains.

Singing dunes usually present well-sorted and rounded grains [4, 16]. This means that they can all share the same average motion in the avalanche. Each grain, passing over lower grains and hitting them, creates a local sound wave with the associated dilatation, compression, and shocks. All these events are desynchronized a priori in the flowing layer. All the pressure fluctuations then mainly cancel out, leading to a light, high-frequency rustling, as is normally heard in sand avalanches [33]. So, how can a low-frequency sound be produced? The only possibility is that a given number of grains start to move coherently. Then the whole flowing layer will move up and down, and its surface will directly emit a pressure wave in the air, like a loudspeaker (or the belly of a violin). The surface motion amplitude is the amplitude of the motion of one grain (between $0.13d$ and $0.03d$)

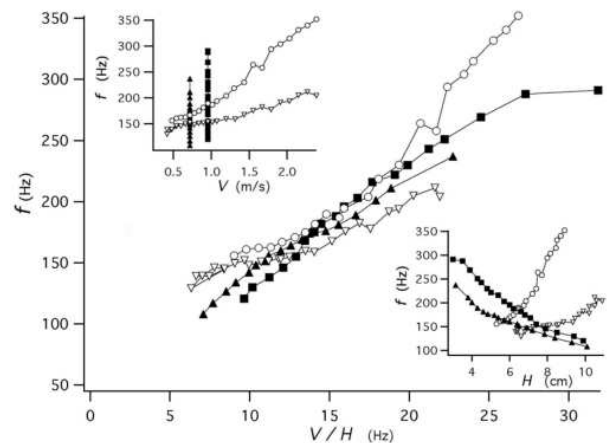


FIG. 2: Frequency emitted by pushed (sheared) sand, measured in laboratory experiment, as a function of two laboratory control parameters, height of mass of sand, H , and velocity of pushing blade, V . Four series of measurement are shown, two at constant pushing velocity (black squares and upward triangles), two at constant plugging depth (gray open circles and downward triangles). Two insets show that frequency depends on both parameters. In upper left, frequency varies with plugging depth, even at fixed velocity, and in lower right, two curves have opposite variations with pushed height (two gray curves are not vertical as pushed height increases with velocity, even at a constant plugging depth). Main plot shows that four curves collapse on a single one when plotted as a function of ratio of velocity with height, which is mean shear rate to which mass of sand is submitted. Frequency observed is ten times mean shear, meaning that height of real shear zone, between pushed mass and fixed bed, is on the order of 10% of pushed sand height.

times the number of coherent grains layers. Surprisingly, it is easy, with only a few synchronized layers of grains, to obtain the high power measured, around 110 dB [17]. The coherence of the shocks also explains the seismic wave emitted in the dune [34], which can be felt with the feet much further away than the acoustical sound transmitted through the air [4]. The essential question is: why would the grains synchronize? It has been proposed recently that the grains excite a coherent wave within the dune, which in turn vibrates the grains coherently [18]. But why would the random collision of the grains create a coherent wave in the first place [33, 34]? We propose here that the synchronization is due to a resonance within the flowing layer, as dunes are not needed for sound production. A moving sand grain emits a sound wave during its up and down motion. If the wave goes to the surface, reflects, and comes back to the grain after exactly one motion period, this sound wave can slightly push the grain, helping the grain to regularize its motion. It can also induce the grains that are close to move coherently, with the same phase.

Considering the boundary conditions (a fixed sand bed below, and a free moving surface above), this resonance condition corresponds to a depth of $\lambda/4$, where λ is the

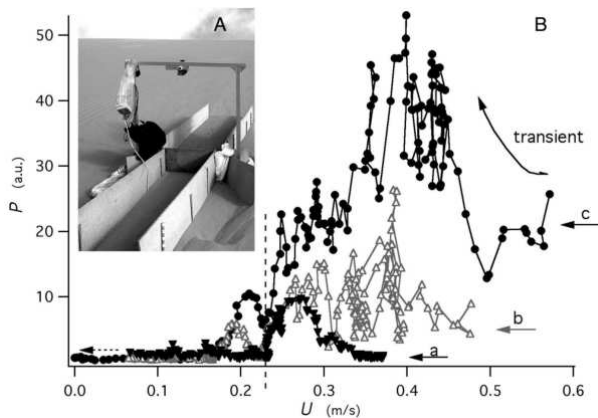


FIG. 3: A: Photo of experiment on dune. A channel, 45 cm wide, 3 m long, was constructed with lateral wood plates, with a gate in middle, on slip face of singing dune. Using spontaneous flow of grains at their critical angle, two slopes of different heights are prepared. Then gate is removed, and controlled avalanche is produced. Sound level is recorded simultaneously with the surface flow. B: Amplitude of sound (pressure level P) as a function of velocity at surface U in middle of channel. Three experiments are shown, starting with different initial height difference: (a) 5 cm, (b) 6.5 cm, (c) 10 cm. As flow starts (a, b, c arrows), sound takes some time to develop (transient arrow). With avalanche, height difference decreases, velocity at surface too, eventually stopping (dashed arrow). Durations of experiments are roughly 15 s. In three experiments, sound stops for a surface velocity below 0.23 m/s. Bump seen below (not seen near threshold, curve a), can be ascribed to a secondary sound emission in lower part of channel.

wavelength (like the resonance of a rod with one end handled and the other one free). For a smaller depth, no resonance can occur. But for any larger depth, the resonance can occur because the synchronized layers will appear at a quarter of a wavelength below the free surface. This reasoning is consistent with our field observation that avalanches that are too thin do not produce any sound, whereas when they become thick enough, even though they may be small in transverse directions, they sing. This height condition, $H \geq \lambda/4$, can be rewritten as a grain velocity condition. Using $\lambda = c/f$, where c is the sound velocity in the sheared layer, it gives $fH \geq c/4$. In the flowing layer, the shock frequency f is also the shear rate (constant in depth), so that the velocity at the surface is $U = fH$. Thus the condition also reads $U \geq c/4$. Controlled experiments have been conducted on the Ghord Lahmar dune near Foug Agoutir, Tarfaya, Morocco, by constructing a channel in which a controlled avalanche is produced (see Figure 3). The results show that there is a threshold surface velocity below which no sound is emitted [35, 36, 37]. This threshold gives the sound speed in the flowing layer, $c = 4U = 0.92$ m/s. The laboratory experiment corroborates the field experiment. Figure 4 shows the threshold curve in the velocity/depth coordinates. The curve indicates that there is a threshold velocity (dashed line), below which no sound can be

made. Taking into account that the sheared layer is now between the pushed pile and the static grain bottom, it then gives a resonance condition $H \geq \lambda/2$ (like a string held at both ends), which translates for the pushing velocity into $V \geq c/2$. This result gives a sound velocity $c = 0.94$ m/s, which compares well with the one measured in the field, for the same sand.

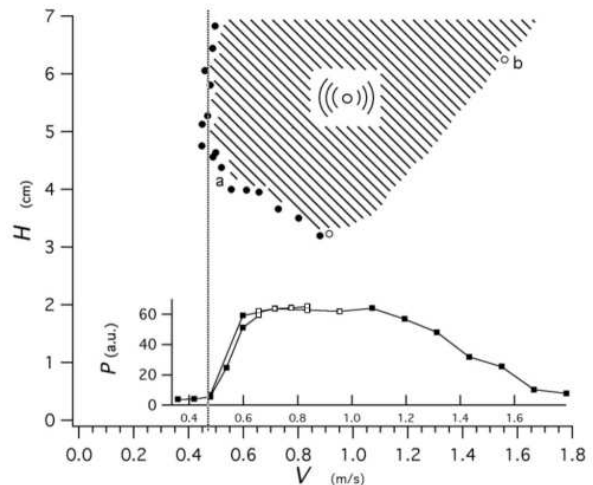


FIG. 4: Parameter range for sound emission (shaded area) in laboratory experiment, depending on velocity of blade V and height of pushed sand H . Right threshold occurs when sand is pushed too quickly, so that it is not sheared but projected away (fluidized). Lower threshold (for $H \sim 3$ cm) could come from fact that number of pushed grains becomes too small to obtain a proper shear in this particular shearing geometry (Figure 1B). Left threshold shows that there is no sound emission below a pushing velocity of 0.47 m/s. Inset: variation of sound amplitude P with increasing velocity, from point a to b. Hollow points correspond to measurements where the microphone saturated.

Surprisingly, 0.9 m/s is also the threshold velocity for producing sounds obtained by [19] when plunging a rod into singing beach sand. Could the sound emission in this case come from the creation of a supersonic shock wave? A resonance at a quarter of the acoustic wavelength is well understood in a vertically vibrated layer of grains [20]. The surprising result, here, is the very low sound velocity: the sound velocity within quartz grains is around 3750 m/s and 330 m/s in air. Considering a mixture of sand and air, a smaller sound velocity of around 10 – 33 m/s can be obtained by an effective medium computation [20], but it is still much larger than what we observed. Such a low sound velocity, which has also been proposed for singing sand recently [21], could come from two factors. First this sound velocity is observed in the sheared layer. As the sound passes in part through the contacts between the grains, the reduced number of contacts in flowing sand makes it more difficult for the pressure wave to propagate. The second reason can be related to the fact that not all sand is musical, and not all well-sorted dunes sing.

The musical property probably comes from a special surface state of the singing sand grains [22]. The ability to sing has previously been ascribed to the presence of a silica gel layer on the grain surface [23], known as desert glaze [7, 24]. The importance of such a layer is shown by the fact that after intensive use the grains lose their sound-emitting properties. The surface state of the grains seems to reduce the sound velocity from its normal value to a much lower one. This could explain why the threshold (in height or velocity) for sound emission is not constant across geographical locations. In China, several people pushing simultaneously as much sand as possible are needed to produce sound. It could also explain why avalanches never produce any sound normally, as it is difficult to produce a flowing layer that would be thick enough. This surprisingly low sound velocity for musical sand, and its sensitivity in other parameters, such as humidity, temperature [3], or dust [25], should now warrant particular attention.

This age-old geological mystery of singing avalanches reveals an original way of producing sound. The sound comes from the synchronized motion of grains, and it is shown here that they synchronize because of a resonance inside the sheared layer. In this way, singing avalanches may be understood as a new type of instrument, as the frequency is not controlled by the resonance, but imposed by the motion of the grains. If a resonance is still needed, it is not to select the frequency, but to produce the necessary self-synchronization of the grains.

Thanks are due to Hervé Belot, who participated in the first experiments on the dunes, Marc Elsen, who was the first to train on the singing sand in the lab, Margherita Peliti, who trained on a first version of the laboratory experiment, Laurent Quartier for constructing the laboratory experiments, Bruno Andreotti for enforcing the idea that the sound could be emitted in the air as a loudspeaker, and Andrés Illane-Campo, for guiding us in Copiapo to the singing dunes. This work was possible only thanks to an Action Concertée Incitative Jeune Chercheur.

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- [26] supplementary audio file 1. From Ghord Lahmar, Foum Agoutir, Tarfaya, Morocco.
- [27] supplementary audio file 2. From el Calleron del medio en la Mar de Dunas, Copiapo.
- [28] supplementary audio file 3. From el Cerro Bramador, Copiapo.
- [29] supplementary audio file 4. Leg pushes.
- [30] supplementary audio file 5. Hands pushes.
- [31] supplementary audio file 6. From one laboratory experiment run.
- [32] supplementary audio file 7. Scale, mix of several laboratory experiments.
- [33] supplementary audio file 8. Stereo recording under an avalanche, with sounds from asynchronous; from Ghord Lahmar , Foum Agoutir, Tarfaya, Morocco.
- [34] supplementary audio file 9. Same as previous, with sounds from synchronous grains.
- [35] supplementary audio file 10. Canal experiment c).
- [36] supplementary audio file 11. Canal experiment b).
- [37] supplementary audio file 12. Canal experiment a).