Song of the Dunes as a Self-Synchronized Instrument

S. Douady,[1] A. Manning,[1] P. Hersen,[1,2] H. Elbelrhiti,[3,4] S. Protière,[1] A. Daerr,[3] and B. Kabbachi[4]
[1]*Matière et Systèmes Complexes, CNRS & Université Paris 7, CC7057, Jussieu, 75005 Paris, France*
[2]*Bauer Center for Genomics Research, Harvard University, 7 Divinity Avenue, Cambridge Massachusetts, USA*
[3]*Physique & Mécanique des Milieux Hétérogènes, E.S.P.C.I.& CNRS, 4 rue Vauquelin, 75005 Paris, France*
[4]*GEOenvironement des Milieux ARIDes, Geology Department, Université Ibn Zohr, BP 28/5, Cité Dakhla, 80000 Agadir, Morocco*
(Received 23 October 2005; published 7 July 2006)

Since Marco Polo it has been known that some sand dunes have the peculiar ability to emit 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 singing dunes around the world and two controlled experiments, in the laboratory and the field, we prove that the frequency of the sound is the frequency of the relative motion of the sand grains. Sound is produced because moving grains synchronize their motions. The laboratory experiment shows that the dune is not needed for sound emission. A velocity threshold for sound emission is found in both experiments, and an interpretation is proposed.

DOI: 10.1103/PhysRevLett.97.018002 PACS numbers: 45.70.Ht, 05.45.Xt, 43.75.+a, 91.60.Lj

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 Kármán 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 [1]? It has long been recognized that the song of dunes originates in the flowing motion of grains in a sand avalanche [2–7]. Direct observations, as we have made in Morocco, Chile, China, and Oman, show that this sound does not come from the 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 can be measured at different locations on a sand dune and, also, in dunes of different sizes in the same dune field. The first significant observation is that the sound frequency depends only on the size of the grains, each dune field having a characteristic grain size and frequency. The study of the motion of the grains in an avalanche shows how grains have to pass periodically over each other and then hit lower grains [8]. The loss of impulsion at each shock explains that a grain flows with a constant velocity. The grains inside the avalanche remain in contact with each other, giving a roughly 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 Bagnold [11]. This diameter to frequency relation is in accordance with what has been measured (see Table I) [12(a)–12(c)] (cf. supplementary recordings [12(a)–12(l)] to listen to the sound of dunes). It is noticeable that the prediction is within the error bars—even if there is a slight deviation.

In granular avalanches, this shock 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 [12(d),12(e)]. We reproduce for the first time 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 rotated by a motor at different velocities (see Fig. 1). This experiment allows independent control of both the shearing velocity and the mass of sheared sand. With this original setup, sustained sounds of constant and well-defined frequencies are obtained in a wide frequency range [12(f),12(g)]. This demonstrates that the booming sound can be produced in a controlled laboratory experiment, and that the dune itself is not needed as a resonator to produce the sound. The wide continuous range of frequencies show that it is not a resonance within the experimental set-up. Lower frequencies could not be produced because the finite width of the channel limits the maximum amount of sheared sand. However, in the field, frequencies as low as 25 Hz were obtained [12(d)]. The experiments show that it is neither the velocity nor the pushed mass that controls the sound frequency, as one frequency can be obtained with various velocity/height situations (see insets of Fig. 2). More importantly, they show that the frequency is only controlled by the mean shear applied to the grains (see Figure 2). This result, together with the result that the frequency of the spontaneous avalanches is the internal velocity gradient, demonstrates finally the hypothesis of Poynting and Thomson [15], that the sound is produced by the relative motion of the moving grains.

The laboratory experiment not only produces controlled sounds of various frequencies but also shows that not all

TABLE I. Sound frequency of singing dunes. Comparison of the frequency predicted from the grains' size with the measured frequency.

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)[a]	340	68	63 ± 5

[a]From [4]; others are from our own measurements [12(a)–12(c)]. El Cerro Bramador sound properties were first reported by Darwin [2].

shearing of sand creates a sound (see Fig. 3). There is a minimum velocity, around $c_e = 0.47\ \mathrm{m \cdot s^{-1}}$, under which no sound is produced. At this threshold, both the frequency of the emitted sound and the height of the pushed mass of sand varies (from 100 to 350 Hz and 10 to 3 cm, respectively). At the same time, their product, that is to say the mean shearing velocity, following the scaling of Fig. 2, remains constant. This sets an important condition for any physical interpretation that would claim to explain this threshold.

One can ask if there is a similar threshold for the avalanches. To check this we experimented directly on the singing dune of Ghord Lahmar, near Foum Agoutir, Tarfaya, Morocco. By constructing a channel with an intermediate gate, which can be released suddenly, controlled avalanches were produced (see Fig. 4). The results indeed show a threshold surface velocity, $c_d = 0.23$ m/s [12(j)–12(l)]. A low velocity threshold, 0.9 m/s, is also found for producing sounds obtained when plunging a rod into singing beach sand [16].

Singing dunes usually present well-sorted and rounded grains [4,17]. This means that they can all share the same motion in the avalanche, with each grain passing over lower grains and hitting them. These motions are not synchronized *a priori* in the flowing layer, leading to a light high-frequency rustling, as is heard in normal sand avalanches, or below the threshold [12(h)]. The only way to produce a low-frequency sound [12(i)] is that a given number of grains move in synchrony. Then, the flowing layer moves up and down, its surface emitting 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 0.13 d and 0.03 d) times the number of synchronized grains layers. Surprisingly, it is easy, with only a few synchronized grain layers, to obtain the high power measured, around 110 dB [18]. The synchronization of the shocks also explains the seismic wave emitted in the dune [12(i)], which can be felt with the feet much further away than the acoustical sound transmitted

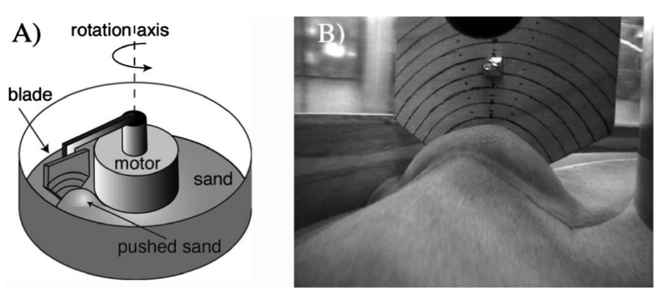

FIG. 1. (a) Sketch of the laboratory experiment. Channel is of 1 m diameter and 25 cm wide. (b) Picture of the flat pushing blade in channel, taken by camera moving with blade. Black spot on top is a microphone (also rotating). Circles on blade, separated by 1 cm, allow direct measurement of height of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

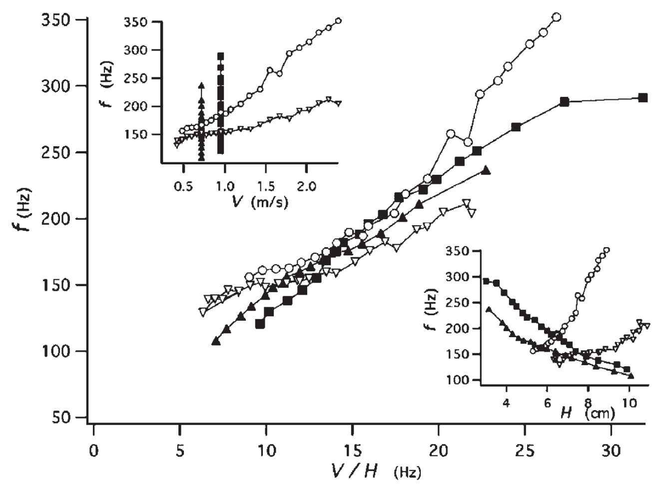

FIG. 2. Frequency emitted by pushed (sheared) sand, measured in laboratory experiments, as a function of two laboratory control parameters: the height of sand, H, and the velocity of the pushing blade, V. Four series of measurement are shown; two at constant pushing velocity (black squares and upward triangles), two at constant plugging depth (gray open circles and downward triangles). Two insets show that frequency depends on both parameters. In the upper left, frequency varies with plugging depth, even at fixed velocity, and in the 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 the four curves collapse on a single one when plotted as a function of the ratio of the velocity with the height, which is the mean shear rate to which the mass of sand is submitted. The observed frequency is roughly 10 times the mean shear. A simple interpretation is that the height of the real shear zone, h, between the pushed mass and the fixed bed, is on the order of 10% of the pushed sand height.

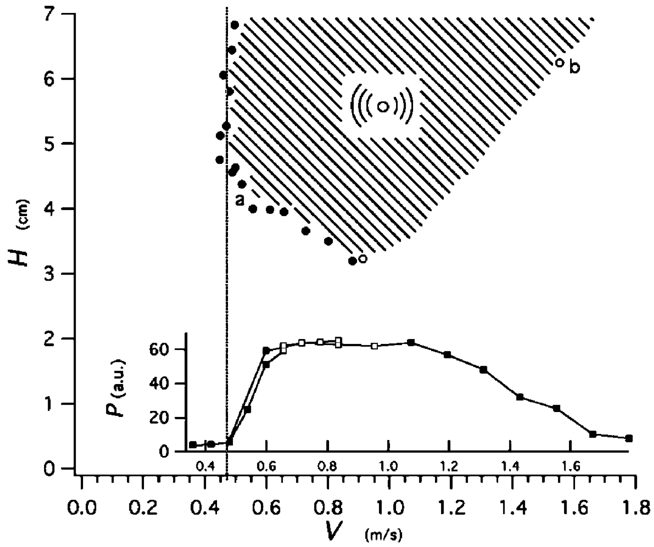

FIG. 3. Parameter range for sound emission (shaded area) in laboratory experiment, depending on the velocity of the blade, V, and the height of pushed sand H. Right threshold occurs when sand is pushed too quickly, so that it is not sheared but projected away (fluidized). Lower threshold (for $H \sim 3$ cm) could come from the fact that the number of pushed grains becomes too small to obtain a proper shear in this particular shearing geometry [Fig. 1(b)]. 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 point b. Hollow points correspond to measurements where the microphone saturated.

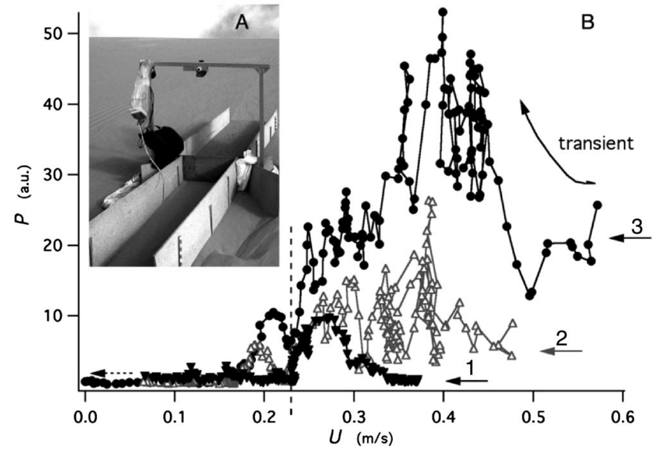

FIG. 4. (a): Field experiments. A channel with a gate 45 cm wide and 3 m long, was constructed on the slip face of a singing dune with lateral wood plates. Using spontaneous flow of grains at their critical angle, two slopes of different heights were prepared. Then the gate was removed, and controlled avalanches were produced. The sound level was recorded simultaneously with the surface flow. (b): Amplitude of sound (pressure level P) as a function of velocity at surface U in the middle of the channel. Three experiments are shown, starting with different initial height difference: (1) 5, (2) 6.5, (3) 10 cm. As flow starts (1, 2, 3 arrows), the sound takes some time to develop (transient arrow). During the avalanche, the height difference decreases, the velocity at surface decreases too and eventually the avalanche stops (dashed arrow). Durations of experiments are roughly 15 s. In the three experiments, the sound stops for a surface velocity below 0.23 m/s. The bump seen below (not seen near threshold, curve 1), can be ascribed to a secondary sound emission in the lower part of the channel.

through the air [4]. The essential question remains: why would the grains synchronize above a given threshold?

It has been proposed recently that the grains excite a coherent wave within the dune, which, in turn, vibrates the grains coherently [19]. But why would the random collision of the grains create a coherent wave [12(h)]? We have seen from the laboratory experiment that dunes are not needed for sound production. Furthermore, following Bolton, we have found that sound can be produced simply by holding the musical grains in a bag and shearing them [13].

A valid explanation of the synchronization has to explain the velocity threshold found both in the controlled avalanche experiment and the laboratory experiment. We are not only looking for a physical phenomena with a characteristic velocity, but also for a mechanism for the grains to synchronize. It is thus natural to suppose that there is a coupling between each layer of flowing grains, pushing them to move simultaneously, and that this coupling propagates through the avalanche depth with a characteristic velocity. This interpretation is reminiscent of the propagation of a shear wave, here in the particular case of grains already flowing (sheared) in the same direction.

The propagation of a coupling wave with a characteristic velocity c, explains that, at the velocity threshold, both the frequency, f, and the sheared height, h, are related. This is the dispersion relation of linear waves: $h = c/f$. The threshold could be interpreted as a cutoff if the propagation duration of the coupling wave across the sheared height is shorter than the characteristic grain motion duration. The different boundary conditions for the avalanche (a free upper surface) and for the experiment (a sheared layer between a static and a pushed pile), explains the difference in the threshold in the two cases: at a free end, a wave is reflected but with a phase shift of $\lambda/4$. Thus the propagation duration is the same with half a length in the case of a free end. This translates into a half threshold velocity, which is exactly what is observed ($c_e = 0.23$ m/s and $c_d = 0.47$ m/s, respectively).

The interpretation, that the grains synchronize their motion through a coupling wave propagating through the sheared layer, explains that the sound could be emitted by shearing the grains independently of any support. For different singing sands of different origins, the first experiments show different threshold velocities, the lower the threshold the more "sonorous" the sand. This difference in sonorous quality could be simply ascribed to a difference in characteristic coupling velocity, and thus threshold. To check this interpretation experiments should be conducted to study directly the existence and characteristic propagation velocity of these coupling (shear?) waves within the flowing layer of the various musical sands.

Mechanical contact between the grains is essential for their synchronization as is revealed by the fact that the sound emission is very sensitive to the grains surface state and contact conditions. Not only are all sands musical, but the musical property requires a special surface state for the singing sand grains [20]; they also need to be free of dust and humidity [21]. The ability to sing has previously been ascribed to the presence of a silica gel layer on the grain surface [22], known as desert glaze [7,23]. The mechanical importance of such a layer is shown by our preliminary observations that after intensive use the grains lose this layer, and simultaneously their sound-emitting properties.

This age-old mystery of singing avalanches reveals an original way of producing sound. The sound comes from the synchronized motion of grains. It is proposed here that grains synchronize because of a coupling 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 a resonance, but imposed by the motion of the grains. If a coupling 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, Phillipe Walter for helping us to observe our grains surface layer, and Simon Dagois-Bohy and Sylvain Courrech du Pont for fruitful discussion. This work was possible only thanks to an Action Concertée Incitative Jeune Chercheur.

[1] Marco Polo, in *The Description of the World* edited by A.C. Moule and Paul Pelliot (G. Routledge, London, 1938), Chap. LVII.

[2] C.R. Darwin, *The Voyage of the Beagle* (John Murray, London, 1890), 11th ed., Chap. XV, p. 359.

[3] G.N. Curzon, *Tales of Travel* (Hodder and Stoughton, London, 1923), p. 261 (reprinted: Century, London, 1988).

[4] J.F. Lindsay, D.R. Criswell, T.L. Criswell, and B.S. Criswell, Geol. Soc. Am. Bull. **87**, 463 (1976).

[5] F. Nori, P. Sholtz, and M. Bretz, Sci. Am. **277**, 64 (1997).

[6] P. Sholtz, M. Bretz, and F. Nori, Contemp. Phys. **38**, 329 (1997).

[7] R. Cooke, A. Warren, and A. Goudie, *Desert Geomorphology* (University College London, London, 1993), p. 313.

[8] L. Quartier, B. Andreotti, S. Douady, and A. Daerr Phys. Rev. E **62**, 8299 (2000).

[9] J. Rajchenbach, Phys. Rev. Lett. **90**, 144302 (2003).

[10] G.D.R. Midi, Eur. Phys. J. E **14**, 341 (2004).

[11] R.A. Bagnold, Proc. R. Soc. A **295**, 219 (1966).

[12] (a) See EPAPS Document No. E-PRLTAO-97-051628 for audio file 1 (from Ghord Lahmar, Foum Agoutir, Tarfaya, Morocco); (b) for audio file 2 (from el Calleron del medio en la Mar de Dunas, Copiapo); (c) for audio file 3 (from el Cerro Bramador, Copiapo); (d) for audio file 4 (leg pushes); (e) for audio file 5 (hand pushes); (f) for audio file 6 (from one laboratory experiment run); (g) for audio file 7 (scale, mix of several laboratory experiments); (h) for audio file 8 (stereo recording under an avalanche, with sounds from asynchronous grains; from Ghord Lahmar, Foum Agoutir, Tarfaya, Morocco); (i) for audio file 9 (same as [12(h)], with sounds from synchronous grains); (j) for audio file 10 [canal experiment (3)]; (k) for audio file 11 [canal experiment (2)]; (l) for audio file 12 [canal experiment (1)]. For more information on EPAPS, see http://www.aip.org/pubservs/epaps.html.

[13] H.C. Bolton and A.A. Julien, Proc. Am. Assoc. Advance. Sci. **33**, 408 (1885).

[14] A.D. Lewis, South African Geographical Society **19**, 33 (1936).

[15] J.H. Poynting and J.J. Thomson, *Textbook of Physics: Sound* (Charles Griffin, London, 1922).

[16] R.A. Bagnold, *The Physics of Blown Sand and Desert Dunes* (Chapman, New York, 1954), 2nd ed., p. 248.

[17] T.H. van Rooyen and E. Verster, J. Arid Environ. **6**, 215 (1983).

[18] P. Hersen, Ph.D. thesis, Université Paris 7, 2004.

[19] B. Andreotti, Phys. Rev. Lett. **93**, 238001 (2004).

[20] J.J. Qu, Y.P. Wang, W.M. Zhang, F.N. Dai, G.R. Dong, Sun Bo, and S.X. Jiang, Chinese Science Bulletin **43**, 2105 (1998).

[21] P.K. Haff, Am. Sci. **74**, 376 (1986).

[22] D. Goldsack, M. Leach, and C. Kilkeny, Nature (London) 386, 29 (1997).

[23] K. Pye and H. Tsoar, *Aeolian Sands and Sand Dunes* (Unwin Hayma, London, 1990), p. 261.