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Booming avalanches: a linear instability resulting from the coupling between shear bands and surface elastic waves

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Singing dunes, which emit a loud sound as they avalanche, constitute a striking and poorly understood natural phenomenon. We show that the shear zone between the avalanche and the solid part of the dune excite surface elastic waves, whose vibration produces the coherent acoustic emission in the air. Due to the non-linearity of Hertzian contacts, the speed of sound c in granular matter is expected to increase with pressure as $P^{1/6}$. We show theoretically and experimentally that under gravity, there exists a discrete number of modes localized at the free surface that can be related to a wave-guide effect (stratification in P and thus in c). The theoretical dispersion relation is compared to lab experiments as well as field measurements performed on singing dunes. We show that the amplitude of the sound during booming avalanches (105 dB) saturates exactly when the vibration makes the grains take-off the flowing layer. On the other hand, we show that the sound frequency (100 Hz) is controlled by the shear rate at the interface between the sand avalanche and the static zone, which for granular matter is equivalent to the mean rate at which grains make collisions. This proves the existence of a feedback of elastic waves on particle motion, leading to a partial synchronisation of the avalanching sand grains. We finally show how booming avalanches can be interpreted as a phase synchronisation linear instability resulting from the coupling between shear bands and surface elastic waves.