ACOUSTIC FLUIDIZATION AND THE EXTRAORDINARY MOBILITY OF STURZSTROMS.

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Introduction: Sturzstroms are a rare category of rock avalanche that travel vast horizontal distances with only a comparatively small vertical drop in height. Their extraordinary mobility appears to be a consequence of sustained fluid-like behavior during motion, which persists even for driving stresses well below those normally associated with granular flows. One mechanism with the potential for explaining this temporary increase in the mobility of rock debris is acoustic fluidization; where transient, high-frequency pressure fluctuations, generated during the initial collapse and subsequent flow of a mass of rock debris, may locally relieve overburden stresses in the rock mass and thus reduce the frictional resistance to slip between fragments. In this paper we develop the acoustic fluidization model for the mechanics of sturzstroms, and discuss the conditions under which this process may facilitate self-sustaining fluid-like flow of large rock avalanches at low driving stresses.

Background: Sturzstroms are large (volume > 10^6 cubic metres) mass-movements of dry rock debris. They are unusually mobile: the ratio of their fall height *H* to run out length *L* is less than the typical value for small dry rock avalanches (~0.6). *H/L*, which is an approximate measure of the coefficient of friction of the rock avalanche, decreases with increasing avalanche volume [1,2]; in other words, the mobility of sturzstroms increases with avalanche volume. Large dry rock avalanches have been observed on many Solar System bodies. Furthermore, observations suggest sturzstroms "flow" like a fluid [3] (sturzstrom means "fall", or "collapse stream"). There is some geologic evidence for preservation of gross stratigraphy during motion [4]. It would appear that avalanches of a given volume on Mars have shorter relative runout (higher effective coefficient of friction) than Earth [5].

Numerous mechanisms have been proposed to explain the low strength and fluidity of sturzstroms, for example: water or air lubrication [4]; local steam generation [9]; melt generation [10]; grain sorting [11]; dispersive grain flow [12,13]; granular temperature generation [14,15]; acoustic fluidization [16,17]. However, the discovery of sturzstroms on the moon [6], Mars [7,8], Venus [18], Io [19], Callisto [20], and Phobos [21], appears to rule out the fundamental involvement of volatiles or atmospheric gases in the flow mechanism. Furthermore, shear melting is not a ubiquitous feature of large dry rock avalanche deposits and therefore cannot explain the universal trend of high avalanche mobility. The observation of stratigraphy-preservation further rules out any mechanism relying on the preferential sorting of grains.

Melosh [17] persuasively argues that the only mechanism uniquely capable of explaining all the characteristics of sturzstroms is acoustic fluidization.

Acoustic Fluidization: The premise of the acoustic fluidization model for the high mobility of sturzstroms is that large, high-frequency pressure fluctuations, generated during the initial collapse and subsequent flow of a mass of rock debris, may locally relieve overburden stresses in the rock mass and thus sustain rapid fluid-like flow of the debris, even in the absence of large driving stresses. The random nature of the pressure vibrations means that within a small volume of the debris mass (a region smaller than the acoustic wavelength, but larger than a rock fragment) the local pressure will oscillate between less-than-ambient and more-than-ambient overburden pressures. Thus, during periods when the local pressure is low enough to permit slippage, movement of the debris will occur within this small volume. At all other times the debris within the small volume will remain stationary. The time- and space-averaged effect of these frequent failure events results in a creep-like process throughout the acoustically fluidized mass of rock debris. Hence, macroscopically, the debris mass appears to flow; the rapidity of which is a function of the frequency and amplitude of the failure events.

We have developed a mathematical rationale for describing the space- and time-dependent behavior of acoustic energy within a moving dry rock avalanche. Assuming that the propagation of high-frequency vibrations within a mass of rock debris is dominated by scattering, temporal and spatial changes in the acoustic energy field are a result of three processes: (1) Scattering of acoustic energy from regions of high energy to regions of low energy; (2) Dissipation of acoustic energy to thermal energy; and (3) Regeneration of acoustic energy as a result of shear within the avalanche.

For acoustic fluidization to be a viable model for explaining the mobility of sturzstroms, there must be an achievable balance between the first two processes and the last. That is, regeneration of acoustic energy during flow must be sufficient to balance the losses due to dissipation and scattering.

To investigate the conditions for which acoustic fluidization may facilitate self-sustaining fluid-like motion of a dry rock avalanche, we have:

1. Sought steady-state solutions to the acoustic fluidization equation for a dry rock avalanche using a Runge-Kutta integrator coupled to a bisectional shooting method. For this we assume that the dry rock ava-

lanche is a constant thickness and that it flows over a stationary substrate into which acoustic energy may propagate, but in which no strain may accumulate.

2. Modeled the time-dependent behavior of an infinitely long and wide rock avalanche using the SALES 2 hydrocode. This model allows us to test the stability of the steady-state solutions and investigate the effect of initial conditions.

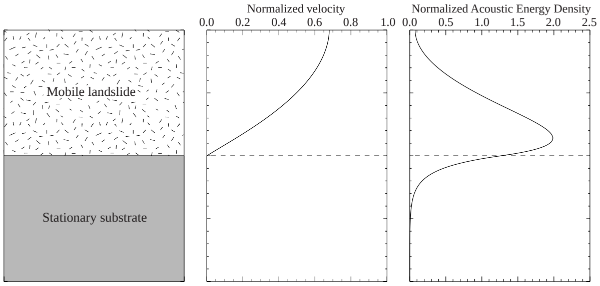

Figure 1: A typical steady-state solution to the acoustic fluidization equations for a dry rock avalanche. The left panel depicts the modeled situation of a mobile rock avalanche moving over a stationary substrate. The center panel illustrates the velocity profile through the flowing avalanche. The right panel shows that the acoustic energy is concentrated near the base of the avalanche.

Results: An example of a typical steady-state solution to the acoustic fluidization equation for a dry rock avalanche is shown in Figure 1. The figure illustrates that the velocity profile through the flowing avalanche is approximately parabolic, implying that the avalanche flows with an almost constant viscosity. The acoustic energy is concentrated near the base of the flowing avalanche, where the shear stresses are greater, and drops to zero at the top of the avalanche and within the stationary ground below the avalanche.

Steady-state solutions to the acoustic fluidization equations for a dry rock avalanche do not exist for all combinations of the model parameters. Whether or not solutions exist depends most sensitively on the regeneration parameter r, which represents the efficiency with which kinetic energy is converted to acoustic energy; the greater r is, the more acoustic energy is regenerated during flow of the avalanche. For stable, steady-state solutions to exist, the regeneration parameter ($r = 2eQ \sin^2\theta$) must be >~1. For a dissipation quality factor $Q \sim 100$ (comparable to the seismic Q in the upper crust) and a slope angle $\theta = 10°$, the required efficiency for converting elastic strain energy into elastic-wave energy, e, is about 0.2, which is well below typical estimates of around 0.5 [22]. Hence, our modeling suggests that acoustic fluidization can facilitate self-sustaining motion of a dry rock avalanche.

The hydrocode simulation results are in remarkable agreement with the results from our steady-state analysis. Our hydrocode simulations begin with either an initial avalanche velocity or an initial acoustic energy field within the avalanche. We find that the simulated rock avalanche achieves the same stable state, provided that the initial acoustic energy available is a very small fraction of the kinetic energy of the rock fall, or the avalanche has a modest initial velocity. For a 10-m thick avalanche traveling down slope of 10°, the required initial velocity is only ~1 m/s.

Conclusions:

- Acoustic fluidization can increase the mobility of a dry rock avalanche.
- For realistic avalanche conditions, acoustic fluidization can facilitate self-sustaining motion of a dry rock avalanche.
- Acoustic fluidization predicts that the avalanche will "flow" with an approximately constant effective viscosity.
- The steady-state solution for an acoustically fluidized rock avalanche may be obtained during simulations of the initiation of a rock avalanche, provided that a small fraction of the kinetic energy of the rock fall is transferred to internal acoustic vibrational energy, or the avalanche has a modest initial velocity.
- Hence, acoustic fluidization can explain the extraordinary mobility of sturzstroms.

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