# Fluidization on the Moon ( ?)

The appearances of a number of features on the lunar surface are strongly suggestive of flow patterns while certain spatially variable properties, such as albedo, suggest the possibility that dust has been transported over the lunar surface.[1,2] The nature of the fluid that could have flowed remains in doubt, and in particular, controversy turns about Gold's[3] suggestion that dust has been transported over large distances on the lunar surface with the aid of electrostatic forces. The question of dust flows presents a difficult problem in the theory of granular media and it is not surprising that the matter is difficult to settle. However, an alternative suggestion about how lunar dust (or ash) could be given mobility has been offered by O'Keefe and Cameron[4] who propose that the lunar dust has been fluidized by outgassing, and their suggestion presents a number of interesting possibilities for the evolution of certain lunar features.

Fluidization[5] occurs when gas or liquid flows up through a bed of particles rapidly enough so that the viscous drag on the particles can support their weight. When this occurs the medium takes on many aspects of a liquid that is an excellent conductor of heat and mass. As the mean upward flow of the fluidizing agent is increased from zero, a critical velocity is reached at which the bed expands slightly and incipient fluidization occurs. With increasing velocity, the fluidized medium becomes more agitated and, in gas-fluidized beds, bubbles form (generally) at the bottom of the bed. These bubbles, or voids of particles, are unlike bubbles in liquids in that gas circulates through them,[6] but, like ordinary bubbles, they rise upward and agitate the surface of the bed. The bubbles appear to be the result of instabilities of internal waves in the fluidized bed.[6] As the flow rate is increased still further, particles from the top of the bed are carried off; this is called pneumatic transport. A familiar natural manifestation of fluidization by liquids occurs when water welling up from an underground stream fluidizes the overlying sand and produces a bed of quicksand.

The suggestion of O'Keefe and Cameron has geological precedents, particularly in the *nuée ardente*,[7] "an extremely hot, opaque, billowing cloud"[8] which flows from volcanoes in violent eruptions. The *nuée ardente* can spread thick layers of ash miles from its source. The Katnai eruption in Alaska filled a valley of over 53 square miles 100 ft deep in ash while the *nuée ardente* that rolled down the side of Mount Pelé in the Caribbean in 1902 destroyed the town of Ste. Pierre. The mobility of the *nuées ardentes* can be understood if they are fluidized,[9], though some discussion has centered on the source of the fluidizing gas. The most natural source seems to be outgassing from the particles themselves, but other possibilities have been debated. (Incidentally, in connection with Gold's ideas, it is interesting to note McTaggart's suggestion that electrostatic forces may play a "minor role in . . . increasing the mobility of . . . a *nuée ardente*".[8]) The mechanism of outgassing from the fluidized particles themselves is adopted by O'Keefe and Cameron and in a rediscussion of the lunar case, O'Keefe and Adams[12] conclude that because of the low lunar gravity and the absence of an atmosphere, fluidization on the Moon could result in even more extensive ash flows than on Earth. In this connection, O'Keefe has discussed the possibility that the flow of fluidized material might account for the observation of Shoemaker[13] that the number of craters of diameter less than 500 meters is less than would be expected for impacts over the estimated life of the Moon. He also proposes the fluidized flow as an explanation of the observed softening of the rims of craters of diameters of several hundred meters.

In addition to the possibilities involved in dust transport by fluidization are some recent suggestions that fluidization may have played an important role in the evolution of the lunar morphology. Perhaps the most striking of the suggested possible results of lunar fluidization is seen in the Mare Orientale, which shows a series of concentric rings, similar to, but more extensive than the ring systems about other maria. Baldwin[14] has interpreted such rings as "tremendous ripples" produced by impacts. In particular Van Dorn[15] has shown that the rings of the Orientale complex are spaced as if the individual rings represented the crests of a Tsunami—"the gravity wave system formed in the sea following any large-scale short-duration disturbance of the free surface".[16] The Orientale complex qualitatively resembles a Tsunami in that the crest separation increases outward from the source, which is a natural outcome of dispersion. In Van Dorn's view an energetic impact generated a Tsunami in the lunar surface, which responded like a fluid. In some way the fluid motion was abruptly arrested, freezing-in the instantaneous wave pattern. The best fit, which is remarkably good, is obtained if the "fluid" were 50 km deep and the freezing time was about $\frac{1}{2}$ hr after impact.

Van Dorn has proposed that his results can be explained if the impact succeeds in producing transient melting beneath a 50-km layer of unconsolidated material. The lava can then fluidize the overlying rubble bed, and this fluidized bed transmits the waves.[17] It might seem remarkable that this model works so well since Van Dorn has used inviscid theory, however, he points out that for viscosities below 7 × $10^5$ centipoises the dispersion relations are not significantly altered. The typical values of viscosities encountered in fluidized media are well below this value ($\sim$10 poise) but it might nevertheless be worthwhile to carry out the calculation for a fluidized medium. However, the conditions contemplated by Van Dorn represent a sort of limiting case of fluidization theory, since the lava density is probably close to that of the rubble and one has almost to deal with a suspension. What remains unclear in the picture is the manner in which the fluidized properties can be lost over a large area virtually simultaneously; indeed this problem probably exists for any medium which is only temporarily a fluid.

In Van Dorn's picture the fluidization is secondary to the main idea that the rings around craters are wave crests. For not only does he fit the Orientale rings to the Tsunami model, but also, using his 50-km depth, he has obtained an excellent fit to the ring spacings around other maria. This success lends considerable support to the idea that the maria are the aftermaths of violent impacts. It is interesting in this connection that the near side of the Moon is qualitatively richer in filled maria than the far side, since this points to a greater frequency of such impacts on the near side, which may have resulted from gravitational focussing by the Earth. In any event, the work of Van Dorn is in line with the impact theory, and leads to quantitative information about the impacts.

Fluidization has also been invoked, this time as a principal agent in crater formation, by Mills,[18] and his suggestion lends great astronomical interest to the physics of fluidization. Mills has performed experiments in gas-fluidized beds in which he cuts off the gas supply gradually. On doing this he finds that the surface of the bed of particles is left pocked with numerous craters in a remarkable likeness of portions of the lunar landscape. In such experiments the largest craters would not be expected to have diameters exceeding the bed depth. However, Mills found that if the bed has a large but shallow surface depression before fluidization, after fluidization an equally large crater with a pronounced rim is left on the site of the original depression; this large crater has very few smaller craters in its interior and numerous small craters on its rim. In his experiments, Mills finds structures resembling other lunar surface features such as rilles, dimples, domes, double craters, and interlocking and parasitic cones.

The essential feature of Mills' experiments is that the source of gas not be cut off abruptly, else the surface of the bed is left flat. But once this aspect is introduced, it is not difficult to set up the experiment and obtain craters, though we recommend that the apparatus should not be left on the floor, else a zealous janitor may dispose of it. Indeed, with our second apparatus, we readily produced cratered "landscapes", though it is clear that complete success of such experiments depends on a variety of parameters. For example, in our admittedly brief fling in the laboratory, we did not produce the large craters which resulted from initial surface depressions in Mills' work.

One tricky aspect of setting up fluidization experiments is the difficulty of getting a truly uniform gas input from below. If the input is not uniform, one often gets channeling, a situation in which only local regions are fluidized. These, however, can become cratered and perhaps one is seeing here a process like that which makes the lunar craters which have been interpreted as "blow holes".[1] Though channeling is not a good thing for industrial fluidization it may be relevant to the suggested lunar fluidization. Thus, by intentionally setting up a channeling experiment with large areas of the bed cut off from the direct flow, we were able to raise pronounced rims. If channeling is acceptable, then a very simple experiment which causes fluidization is possible: simply put a dab of petroleum jelly on the bottom of a tin can, cover with a layer of sand, and heat over a Bunsen burner. When the jelly volatilizes a fluidized column forms and produces a nice crater. (If sufficient heat is not provided, the volatilized jelly may be trapped in the overlying sand, and instead of fluidization you get a solidified, crumbly, black surface on the bed.)

An apparently related set of experiments has also been reported by Kaarsberg.[19] In an abstract he reports having subjected a visco-elastic bed to gaseous eruptions from below. The results are surface features "which bear a close resemblance to such lunar features as domes, symmetrical and polygonal craters, and the peaks and vents found in central regions of some crater floors". There is a similarity here to the results reported by Mills, but it is not clear whether fluidization is involved, since the medium is visco-elastic. Probably, what occurs is something like channeling, but the theory of the process involved in Kaarsberg's experiments will probably be nastier in some respects than the case of strict fluidization.

The production of lunar-like features on fluidized beds is very impressive but before accepting the mechanism as a real possibility for the Moon we must enquire whether fluidization could have occurred extensively on the Moon. Let us then try to estimate the velocity of the emitted gas which is needed to fluidize the surface dust on the Moon. To do this, we assume that the outgassing takes place below the dust layer, rather than from the particles themselves as in the discussion of O'Keefe and Adams. This simplifies the calculation slightly and is more in keeping with the Mills experiment.

The mean gas velocity needed to maintain fluidization is obtained by equating the reduced gravitational force on a particle to the drag exerted on it. The drag force is

$$F_D = 6\pi\alpha a\eta v,$$

where $a$ is the particle radius, $\eta$ is the gas viscosity, $v$ is the mean gas velocity, and $\alpha$ is the correction factor to the Stokes drag required because a particle in an assemblage feels a different force than an isolated particle. At incipient fluidization $\alpha$ is found experimentally to be 68.5 for both spherical particles and irregular particles of comparable sizes.[20,21] If $\rho_s$ is the density of an individual particle, $\rho$ is the gas density, and $g$ is the acceleration of gravity, the reduced gravitational force is $\frac{4}{3}\pi a^3(\rho_s - \rho)g$. On equating these forces we find that for incipient fluidization

$$v = v_0 \sim 3 \times 10^{-3} \frac{ga^2(\rho_s - \rho)}{\eta}.$$

If, as is true for gas fluidization, $\rho \ll \rho_s$, the value of $v_0$ for particles of size[22] $\sim 50\,\mu$ fluidized on the Moon by steam ($\eta \sim 10^{-4}$) is $\sim\frac{1}{2}$ cm/sec.

Now suppose that the layer which was fluidized had a depth $h_0$ before fluidization and that $\rho_s = 3$ g/cm$^3$ (basalt). The weight of a column of unit area is $(1 - \epsilon_0)g\rho h_0$, where $\epsilon_0$ is the value of the voidage, $\epsilon$, if there is no fluidization. (The voidage is the fractional volume not occupied by solid matter.) If the gas pressure at the surface is zero, the pressure at the base must be able to support this weight, hence

$$p \sim 10^4 h_0$$

for $\epsilon_0 \sim 0.8$ and $h_0$ in cm. If we now estimate the gas density using the perfect-gas law, we have for the typical value

$$\rho \sim \frac{1}{2}\left(\frac{\mu m_{\mathrm{H}} p}{kT}\right) \sim 10^{-8} h_0 \text{ g/cm}^3$$

for $T \sim 800$ °K and $\mu$ (the mean molecular weight) $\sim 20$. We thus obtain a gas flux, assuming the outgassing to be uniform over the Moon,

$$J \sim 2 \times 10^9 h_0 \text{ g/sec.}$$

To find out how long the fluidization can be maintained at this outgassing rate, we must know the total amount of gas released. In the case of the Earth, it appears that the bulk of the outgassed matter is contained in the oceans. If the Moon has outgassed the same quantity per unit mass, the total outgassed $\sim 10^{22}$ g, and the above flux density could have been maintained uniformly over the Moon for a time

$$\tau \sim \frac{10^5}{h_0\,(\mathrm{cm})}\ \mathrm{yr}.$$

If fluidization is to be responsible for reasonably large craters ($\sim$tens of km) we would expect $h_0 \sim 1$ km, even allowing for Mills' trick for making large craters. If we then suppose that such an $h_0$ is a possible value for the depth of the dust layer, we see that $\tau \sim 1$ yr. Of course, the fluidization does not have to occur everywhere at once, so that the process can well have happened at different epochs at different times. Nevertheless, one year is not a comfortably long time, and with the uncertainty in the various estimates (especially in view of our possibly generous estimate of the amount of outgassing), the case for making large craters by fluidization does not seem overwhelmingly strong. On the other hand with rather shallower depths, such as contemplated by O'Keefe and Adams, a reasonably extensive fluidized activity seems admissible. Certainly, local fluidization seems not unlikely, especially in the bottoms of impact craters or in caldera, tension fractures, or other weak spots in the lunar crust. Thus it seems entirely plausible that small irregularities, such as "sand castles", might be caused by fluidization, while it seems that the possibility that larger craters are formed in this way is not definitely excluded.

Naturally, there are a variety of possible complications that might beset fluidization on the Moon, and we cannot go into these here. Also, of interest in their own right, are the experimental results of Mills. Clearly a considerable amount of explanation is demanded by them, especially of the remarkable "memory" of initial conditions which is carried through the fluidized state. Some qualitative rationalizations seem possible but quantitative justifications promise to be difficult.

Finally, there is the question of possible direct tests of the fluidization hypothesis. One possibility, of course, would be to actually find fluidization on the Moon. Kosyrev's[23] observations of gas emission from Alphonsus raise the possibility that small beds of lunar "quicksand" may now exist in the interior of some lunar craters. But such dramatic confirmation is perhaps too much to hope for; indeed, Kopal[24] rejects the outgassing interpretation of Kosyrev's observations. A more tangible, though less conclusive, confirmation is possible in the determination of the variation of particle size with depth. If, as Mills suggests, and as seems quite likely, the lunar fluidization is turned off gradually, then, in the last phases, after the agitation by bubbles has ceased, a settling of heavier particles toward the bottom should occur and the depth dependence should be noticeable. As far as we are aware, no detailed calculations exist on which to base a quantitative prediction, and this is just one of the many challenges to both theoreticians and experimentalists presented by the possibility of fluidization on the Moon.

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**References**

1. R. B. Baldwin, Ann. Rev. Astron. Astrophys. **2,** 73 (1964).
2. J. A. O'Keefe, in *Proceedings of the 1965 IAU-NASA Symposium* (Johns Hopkins Press, Baltimore, 1966), p. 259.
3. T. Gold, Monthly Notices Roy. Astron. Soc. **115,** 585 (1962).
4. J. A. O'Keefe and W. S. Cameron, Icarus **1,** 271 (1962).
5. J. F. Davidson and D. Harrison, *Fluidized Particles* (Cambridge University Press, 1963).
6. J. D. Murray, J. Fluid Mech. **21,** 337 (1965); **22,** 52 (1965); **28,** 417 (1967).
7. L. D. Leet and S. Judson, *Physical Geology* (Prentice-Hall, 1965), 3rd ed.
8. K. C. McTaggart, Am. J. Sci. **258,** 369 (1960).
9. D. L. Reynolds, Am. J. Sci. **252,** 577 (1954).
10. M. C. Brown, Am. J. Sci. **260,** 467 (1962).
11. K. C., McTaggart, Am. J. Sci. **260,** 470 (1962).
12. J. A. O'Keefe and E. W. Adams, J. Geophys. Res. **70,** 3819 (1965).
13. Shoemaker, in "Surveyor V, A Preliminary Report" (Scient. and Tech. Div. NASA SP-166, 1967).
14. R. B. Baldwin, in *The Face of the Moon* (Univ. of Chicago Press, 1949).
15. W. G. Van Dorn, Nature **220,** 1102 (1968).
16. W. G. Van Dorn, Contemp. Phys. **9,** 145 (1968).
17. W. G. Van Dorn, Science (in press).
18. A. A. Mills, *Abstracts of Papers, Fluid Mechanics in Relation to Natural Phenomena* (University of Newcastle-upon-Tyne, 1969).
19. E. A. Kaarsberg, Trans. Am. Geophys. Union **50,** 228 (1969).
20. P. N. Rowe, Trans. Inst. Chem. Eng. (London) **39,** 43 (1961).
21. B. A. Partridge and E. Lyall, U.K. Atomic Energy Authority AERE-M2152, 1969.
22. L. D. Jaffe, Science **164,** 775 (1969).
23. N. A. Kozyrev, Sky and Telescope **18,** 184 (1959).
24. Z. Kopal, *An Introduction to the Study of the Moon* (Reidel, 1966).