THE ORIGIN OF THE SHAPES OF LUNAR GLOBULES

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Abstract. This paper considers three hypotheses for the origin of the shapes of the regular elongated prolate and dumbbell-shaped lunar glass globules. These are the break-up of a jet, the vibration-freezing hypothesis and the rotational hypothesis. It is concluded that there are many results favouring the latter hypothesis so that its validity now appears conclusive. Applications of the hypothesis as a tool in lunar science are briefly discussed.

Soon after the return of lunar rock, it was suggested that the shapes of the regular dumbbell and oblate glassy objects and lunar rock were a consequence of the angular momentum they possess whilst cooling in free flight above the lunar surface (Bastin and French, 1970). Subsequent papers, Pugh (1972), Bastin and Volborth (1974), Cloud *et al.* (1970), Fulchignoni *et al.* (1971), gave evidence in favour of this view. An alternative proposal imagined that the regular elongated shapes result from the partial breakup of a jet of liquid glass (Tolanksy, 1971; Isard, 1971; Scarlett and Buxton, 1974). More recently Chernyak and Nussinov (1976) proposed that the shapes were caused by the sudden freezing of a vibrating droplet.

I believe there are many reasons for supposing the rotational hypothesis to be the only tenable one. Several of these reasons have not before been published and the subject has not been reviewed. The discussion is of some importance since, if the rotational hypothesis were proven, it would provide a valuable means of investigating the details of meteorite impact explosions. Furthermore, the equilibrium shape attained by a liquid mass under the action of rotation and surface tension alone is in itself an interesting problem in classical physics. The shape acquired by a rotating mass under self-gravitation has been examined extensively. The corresponding case in which surface tension dominates and is applicable to systems of a much smaller scale, has not yet been analyzed.

Although there have been suggestions that some globules, in particular the orange spherules, were formed by endogenic processes, most investigators agree that the globules are the result of molten rock fragments produced by meteoritic impact. Proponents of all the above hypotheses also agree that the particles will in general cool and become solid in free flight in the vacuum above the Moon's surface. They agree that surface tension is important in determining the shape of globules and that the cooling time increases with globule size so that some of the more massive globules may return to the lunar surface and splash as liquids; they also agree that the larger globules which do solidify in flight are likely to be shattered on impact with the lunar surface, and that many of the globules may subsequently be pitted or broken by meteoritic impact.

I do not know of any argument which substantially favours the jet- or the

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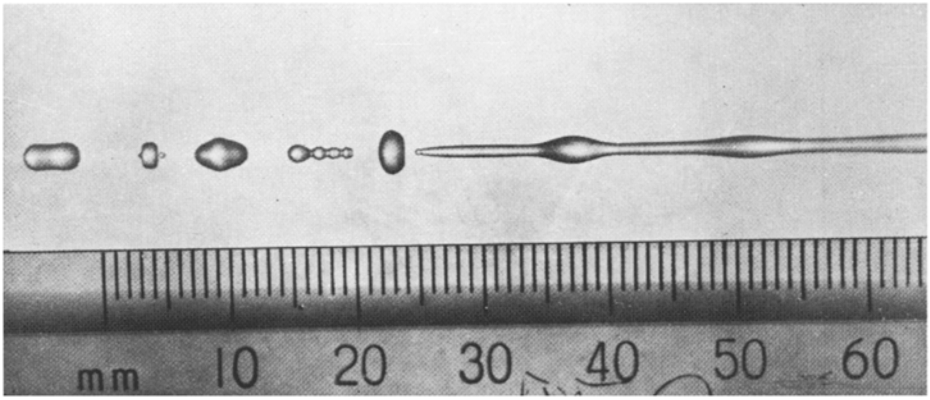

Fig. 1. The break-up of a water jet. Photograph C. S. Parkin (1973).

vibrating-droplet hypothesis for globule formation, but I now list arguments which argue strongly either against these hypotheses or in favour of the rotational hypothesis.

(1) The suggestion by Chernyak and Nussinov that dumbbells are formed by the sudden freezing in a particular position of a vibrating droplet does not bear quantitative analysis. The period of oscillation of a particle of linear dimensions 100 μm is about 10^{-4} s. During the whole of an oscillation it will only cool by between 10^{-2} K and 10^{-4} K. Although the viscosity of glasses vary rapidly with temperature (three orders of magnitude for 100 K) it is quite impossible that there can be any appreciable change in viscosity throughout a complete vibrational period, let alone during a small fraction of the period. Calculations for droplets throughout the micron to millimetre scale of size show similar results.

The criticism by Chernyak and Nussinov that rotating particles must show evidence of Coriolis forces is false. Those particles formed with a low maximum temperature doubtless do show these effects. However, if the temperature is sufficiently high for the internal motions to damp out, the particle will, before solidification, rotate as a rigid body and Coriolis force will have no effect.

(2) The shapes of globules are not consistent with the jet model. Figure 1 shows that, in the case of dumbbell-shaped drops formed in a liquid jet, the curvature at the ends of the dumbbell (i.e., the extremities of the long axis) is low, whereas, in the actual lunar globules (see Figure 2), the curvature at these extremities is clearly larger than that elsewhere on the globule surface.

(3) There seems little or no evidence for supposing that immediately after the explosion the liquified rock emanates in jets, i.e., in cylinders whose axis is parallel to the direction of motion. There is considerable literature on the subject of jetting in hypervelocity explosions (Walsh *et al.*, 1953; Guest and Greeley, 1977). The error made by the proponents of the jet hypothesis for dumbbell formation seems semantically based. It hinges on the use of the word 'jet'. In studies of hypervelocity explosions it is clear that

Fig. 2. Photographs of two dumbbell globules, (a) courtesy of the Max-Planck-Institute für Kernphysik, (b) courtesy of the Dept. of Chemical Engineering, Loughborough University of Technology.

the word is used to represent a group of high velocity particles, ejected at about the same time from about the same point, whose initial motions occupy a small localized region in velocity space. Jet advocates for dumbbell formation assume a jet to be a cylinder of circular cross-section whose length is long compared with its diameter, but there is no reason to suppose that such cylinders are produced by hypervelocity impact. The heating process which is essentially a degradation of acoustic into thermal energy would not be expected to give rise to such a cylindrical jet. Random variations in the strength and composition of the rock should produce a random distribution of melted material with the void – ratios and particle separation rapidly increasing during the explosion.

(4) The rotational hypothesis allows the curvature to be predicted as a function of the distance from the mass centre of the dumbbell. Pugh (1972), for example, shows that, if G is the total curvature and the surface tension is S, then

$$GS = p_0 + \tfrac{1}{2}\rho\omega^2 x^2,$$

where x is the distance from the rotational axis, ρ the density, ω the angular velocity of the globule, and p_0 a constant having dimensions of pressure. Pugh's analysis of a particularly fine sample (Figure 2(a)) showed good agreement with this relation – as may be seen in Figure 3.

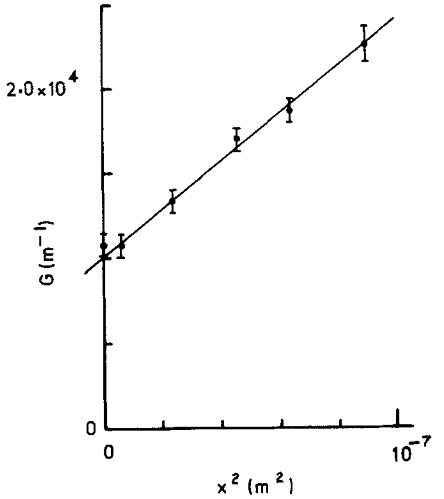

Fig. 3. Results of an analysis by Pugh (1972) of the two-dimensional curvature (G) as a function of the square of the distance (x^2) from the minor axis of the dumbbell. The scales refer to the actual distance for the globule deduced from measurements of the photograph and the known value of photographic magnification.

(5) The rotation hypothesis accounts for the prolate spheroids as well as dumbbell-shaped globules. Prolate spheroids would occur if the angular velocity of the droplets were lower than in the case of dumbbells. Objects of negligible rotation would be expected to solidify as spheres. If the rotational rate is too large, the dumbbell breaks into two parts and so never exists in a stable form.

(6) Whereas in the jet-model and vibrating droplet model dumbbells are transitory features, they represent stationary states in the rotational hypothesis. Immediately after the explosion a globule should consist of material whose velocity varies in a random but continuous way from point to point. Relative shear motions within the fluid will dissipate viscously, but the angular momentum of the object as a whole remains fixed. The viscous damping will cause all elements of the globule to come to rest with respect to each other in a rotation frame of reference: the globule then rotates as a rigid body. Bastin and

French (1970) carried out an analysis of the time taken for the internal motions to damp out, and concluded that in many cases this time was less than the cooling time. We should thus expect many globules to attain equilibrium states before they solidify. For this to happen it is necessary for the globule to have an initial temperature well above the melting point.

(7) The relaxation time τ for internal motions of high viscosity to die away (see, for example, Bastin and French, 1970) is approximately given by

$$\tau \approx \frac{\eta d}{T}, \tag{2}$$

where d is some linear dimension of the globule, T the surface tension, and η the coefficient of viscosity. If the globule has a maximum temperature during its formation only marginally above the melting point, the globule will always be very viscous, and τ will exceed the cooling time. The globule thus solidifies in a non-equilibrium state, and this will correspond to an irregular, albeit smooth, shape which will mirror the original configuration of the liquid mass. Many examples of such globules are found amongst the fine lunar soil particles. They represent a subset of those particles which we should expect on the rotation hypothesis but additional explanations must be invoked for the jet hypothesis to be adopted.

(8) At the very early stages of the explosion the expanding material has a macroscopically high density which should correspond to a value not appreciable lower than that of the liquid. However, there will be large differences in velocity of the various regions of material in the explosion. Even if we imagine a perfectly uniform surface for the meteorite impact, there will be large velocity gradients in the material immediately after impact. For example, a velocity of 10^3 ms^{-1} for the ejected particles at the centre of the explosion implies, for a crater of a metre diameter, a linear velocity gradient of at least 2×10^3 s^{-1} since at the edge of the crater the ejected particles have negligible velocity. Because of the random nature of the structure of the surface, there will be localised changes in velocity which could cause much greater velocity gradients. Any asymmetry in momenta about any plane containing the mass centre of the particle and the direction of motion will, in general however, cause the particle to spin. We thus see a ready cause for the rotational motion. Indeed, the calculation given above in this paragraph is in fair agreement with the value of the velocity gradient deduced by Pugh (1972) from measurements on a single dumbbell. Had a crater of smaller dimensions been chosen, exact agreement could be found between the predicted velocity gradient and that deduced by Pugh. If very high gradients exist, any liquified mass of material will be torn apart until a group of droplets is produced in which the surface tension will prevent any further centrifugal disintegration. Attempts at further precision in the analysis may be difficult to realise. However, the discussion may imply that the oblate globules come mostly from smaller meteorite impacts where, during the explosion, velocity gradients are much greater.

(9) Perhaps the most conclusive evidence favouring the rotational hypothesis relates to inclusions of heavier particles and bubbles within the dumbbells. The particles are

found to migrate towards the extremities of the dumbbell whereas the bubbles move towards the dumbbell centre. This is exactly what would be expected on the basis of the rotational hypothesis. A detailed theory of the process has been given by Bastin and Volborth (1974), and accounts exactly for the observed distribution.

In the case of dark included particles it is generally agreed that they consist of material probably of higher melting point, and certainly of higher density, than the basic globule substrate. Gold (1975) has made measurements of the densities of sections of the dumbbells, and concludes that the extremities have the highest densities. The largest bubbles and particles almost all seem to have arrived at or close to their equilibrium position. However, the expected rate of movement increases rapidly with particle size (Bastin and Volborth, 1974). This is exactly consistent with observation, there being numerous examples of dumbbell globules with a variety of sizes of bubbles, only the largest of which have attained the central equilibrium position. If it is assumed that the included bubbles have originally a random spatial distribution, it is possible to estimate statistically (with an accuracy which increases with the number of bubbles) the highest temperature the droplet attained during the meteoritic explosion that formed it. Bastin and Volborth (1974) deduced maximum temperatures of 1860 and 2000 K for two such globules.

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