Reports

Lunar Glass: Interferometric Evidence for Low-Temperature Shock

Abstract. *Glass objects in the fines from the Apollo 11 and Apollo 12 missions are shown, by two-beam reflection interferometry, to have been subject to shock at temperatures below the melting or softening point of the glass. Possible causes for the glass fragmentation are discussed.*

Several of the investigators who have studied lunar samples have drawn attention to evidence for shock effects in both lunar crystalline minerals and lunar glass (*1*). Evidence that crystalline minerals have been subject to shock is derived from a wide variety of microscopically visible shock effects, which include microfracture, mechanical twinning, the appearance of deformation lamellae, the development of kink bands, birefringence, alternations of refractivity, and also phase conversions. Evidence that glasses have been subject to shock is more difficult to obtain, and especially uncertain is the possibility of separating mechanical shock from thermal shock. The observations described here are representative of those I have made on glass objects extracted from Apollo 11 and Apollo 12 fines. Apart from extraction with tweezers, the objects have been untouched. Results from two-beam optical interferometry fully demonstrate that the glass has been subject to relatively mild, but certain shock.

The fines contain two distinct kinds of glass, namely, (i) very large numbers of small fragmented angular pieces and (ii) the now familiar melt forms including spherules, cylinders, pear shapes, and so forth, covering a wide range of sizes from 1 mm downward to the limit of microscopic observation. In general, if glass is subject to shocks of progressively increased severity, then, provided the effective shock temperature does not reach the softening point (say, of the order of 700°C), one could expect to observe a sequence of events such as (i) the formation of a single crack, then (ii) the development of multiple cracks, and then (iii) complete fragmentation. A still more energetic shock, with consequent higher temperature, would induce melting of fragments into spherules and other melt forms.

The evidence already adduced for shock in lunar glass by earlier investigators includes the appearance of both flow and recrystallization effects in glassy spherules. Such effects are essentially thermal and need by no means imply that mechanical shock has occurred. I have interferometrically examined a large number of untouched lunar glassy objects, using reflection fringes at magnifications ranging from $\times 20$ to $\times 1000$. The fringe patterns reveal with clarity the surface microtopographies of the objects, and in some objects they show that the body has experienced a shock. Furthermore, the shock has been of relatively low energy in that it has been insufficient to induce a melt. It is thus possible to record and evaluate shock effects that do not reach the energies required to induce those flow and remelt situations upon which the earlier investigators depended as indicators.

All the interferograms were taken on an optical system of my design, with 5460-Å mercury light, the object being matched against a specially chosen smooth reference surface of glass. Figure 1A shows a typical interferogram

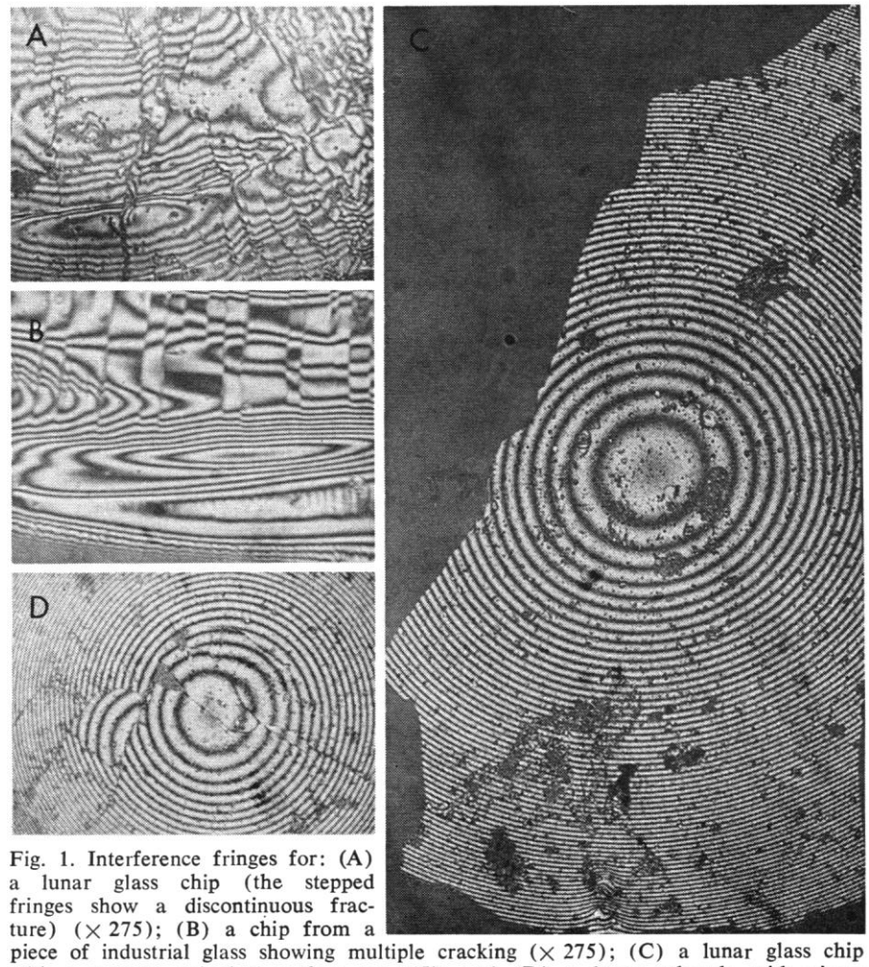

Fig. 1. Interference fringes for: (A) a lunar glass chip (the stepped fringes show a discontinuous fracture) ($\times 275$); (B) a chip from a piece of industrial glass showing multiple cracking ($\times 275$); (C) a lunar glass chip with a concave spherical surface ($\times 165$); and (D) a lunar spherule with pieces chipped off ($\times 220$).

for a local region on the surface of a typical 1-mm fairly flattish glass fragment (there are large numbers like this in the sample). The interferogram is a surface contour map, with height changes of half a light wave from fringe to fringe. A characteristic feature shown by this and numerous other samples is the existence of the discontinuous fracture, indicated by the stepped fringes. Such stepped fractures are quite characteristically produced by mechanical impacts on glasses at temperatures well below the softening point. Thus for comparison there is in Fig. 1B a typical interferogram shown by a randomly selected 1-mm fragment of glass produced in the laboratory by pulverizing a small piece of industrial glass rod with a hammer at room temperature. It is evident from the similarity, despite random selection, that not only has the lunar glass been fractured by shock, but also clearly the shock event took place well below the softening point. The appearance corresponds to phase (ii) above, that is, multiple cracking with stepped displacements.

A gentler shatter effect appears to be associated with the lunar glass chip which gives the quite remarkable fringe pattern shown in Fig. 1C. These are monochromatic fringes in reflection, and with the aid of supplementary white-light fringes it has been unambiguously established that this near-spherical surface is not convex, but concave. Indeed it has an almost perfectly spherical concave surface, and the fringes give the radius of curvature as close to 0.5 cm. The smooth specular character of the surface as indicated by the fringe quality is notable.

A reasonable explanation for the origin of this unusual object is to assume that a larger block of glass had within it an almost perfectly spherical vacuole with a diameter close to 1 cm. This glass block then shattered, and this chip is a piece which formed the surface of the vacuole. This surface would not only be concave, it would be nearly spherical and would also be highly specular; all of these properties characterize this object precisely. That the breakup of the original block was not too violent is established by the fact that even at this magnification there is no evidence of any other single or multiple cracking steps.

Such a fragment as this could have been created by a minor impact breaking the parent block, or alternatively through simple cooling shatter of the parent, probably in a state of strain because of the vacuole. The latter explanation is more likely, for the glass chip under discussion shows birefringent strain when examined in transmission between crossed polars. One thing is certain—the block was well below the softening point when it broke up. It is equally certain that it is inconceivable to visualize creation of a concave surface by any subsequent remelting mechanism after fracture.

Different kinds of crack effects caused by low-temperature shock are shown by many glassy spherules. A high proportion of the spherules give high-quality, almost circular Newton's rings, which establish their almost perfect sphericity. Yet about one-third of the 200 such objects I have studied show crack effects which (along with other evidence) imply that the spherules have been splash projectiles, originating perhaps from an energetic meteoric collision, and ultimately acquiring cracks through impact on landing. Splash droplets can be expected to take on a nearly spherical shape in flight. Figure 1D shows the interference fringe pattern given by a nearly spherical object. It is quite clear that the sphere on landing has chipped and cracked in several places. In order for this to have happened, the impact must have taken place when the object was frozen hard, that is, well below the softening point. This would imply adequate time in flight, hence its range must have been considerable; thus an energetic explosive event must have initiated the formation of the spherule.

Although it is notoriously difficult to estimate shock temperatures in shocked minerals, with glasses, on the contrary, the very existence of sharply defined discontinuous steps proves in such cases that the temperature has not approached the softening point. The great numbers of small angular shock-formed glass fragments in lunar soil and the huge numbers of tiny glassy microspherules require explanation. From repeated counts I have made on smears from five different samples (two from the Apollo 11 landing site, and three from different areas around the Apollo 12 landing site—one sample from near the module, one about 80 m away, and one about 120 m away), using a good microscope objective at × 1000, I find that there is something in the neighborhood of 300 million microspherules and cylinders per kilogram of lunar soil, and doubtless there are many more below the limit of optical resolution. The quantities from the two sites, although far apart, are similar within the limits of sampling.

A reasonable hypothesis on their origin is as follows. One can conjecture that an initial violent meteoric impact on lunar rock leads to the formation of splashed glass. The small droplets will freeze solid before landing. The larger lumps will probably resplash on landing. If this same region is then resubjected to frequent successive meteoric impact, which may or may not create glass, but which will certainly send shock waves through the surrounding surface, very frequent repeated shock waves can conceivably fragment the glass lying around into numerous particles, and this process may continue until there is massive fragmentation. When, occasionally, a more violent impact takes place, sufficiently violent to produce a shock wave hot enough to melt many of the tiny fragments of glass already created by the earlier numerous but less violent impacts, this process can readily produce the vast numbers of fractured and remelt objects. There is no necessity to invoke the idea of unusual hot solar flares to produce the temperatures needed to melt the observed microspherules; shock waves are adequate for the purpose.

There remains to be considered the possibility that shock of the kind shown in Fig. 1A is purely thermal, and not mechanical. The monthly temperature cycling on the lunar surface over a range of some 300°C in the change from lunar day to lunar night, repeated for possibly billions of times, could possibly lead to a thermal fatigue fracture effect, which could cause the observed fractures. However, in view of the small size of the objects, it is clear that the rate of temperature change is relatively slow. Nevertheless, if thermal cycling is indeed the cause of the fracturing, then the intriguing possibility arises that the smaller fragments are those that have been longer exposed to cycling. On this basis, the smaller the fragments, the older they would be. However, quite a large fraction of the glass objects (both fragments and spherules) do not show fracture cracks. Because the specimens are all quite small it is reasonable to argue that all of the material has had a reasonably similar thermal history.

It is clear from the interferograms (and in this report I have chosen only four out of some hundreds taken) that it is certainly worth while to extend interferometric studies to larger pieces

of lunar material. Not only glasses, but objects such as crystals and other smooth surfaces of sufficient specular character are worthy of study. In particular, light could be thrown on erosion processes.

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Genetic Polymorphism of Basic Proteins from Parotid Saliva

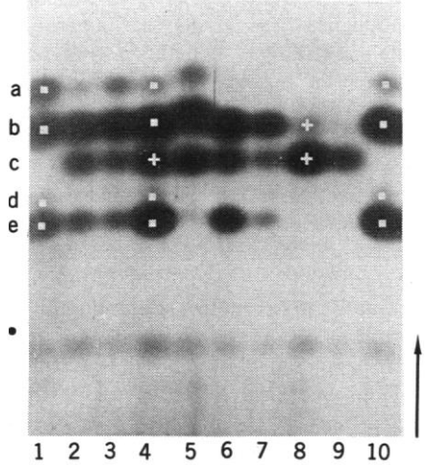
Abstract. *In a study of 90 randomly chosen parotid salivas from Blacks three phenotypes were observed during acid-urea starch-gel electrophoresis. Inheritance was controlled by two codominant alleles at an autosomal locus. Of 101 Caucasians, one had a heterozygous phenotype indistinguishable electrophoretically from that in Blacks. Gene frequencies were: for Blacks, parotid basic protein* $(Pb^1) = 0.84$, $(Pb^2) = 0.16$; *for Caucasians,* $(Pb^1) \sim 0.995$, $(Pb^2) \sim 0.005$.

The proteins of human serum and red cells have been extensively studied by electrophoretic and immunological methods, and many genetic polymorphisms have been identified (*1*). Since parotid fluid is easy to obtain (*2*) and is known to be a rich mixture of proteins, especially basic components (*3*), I examined it for the presence of new genetic polymorphisms. Genetic variation of salivary amylase has been described (*4*), and much is known about the relations between secretor, Lewis, ABO, and H genetic systems to factors in the saliva (*5*). Electrophoresis of parotid proteins in alkaline systems has been studied (*3*), but there have been only a few reports of electrophoresis on acid gels (*6*). Therefore, I studied basic parotid fluid proteins, using starch-gel electrophoresis in acid-urea buffers and a sensitive stain for arginine-rich basic proteins (*7*). I now report that there is genetic polymorphism in the fastest migrating basic components of the parotid saliva of Blacks, and that a parotid basic protein variant, electrophoretically indistinguishable from that in Blacks, was found in one Caucasian family.

Electrophoresis of concentrated parotid fluid (*8*) yielded at least 20 bands that stained for protein. However, genetic polymorphism was observed only in the fastest migrating basic components, and in these the mobility was greater than that of lysozyme (Fig. 1). Relatively stable band patterns of the fastest migrating polymorphic basic proteins were obtained from samples of normals and variants regardless of the time of day (or proximity to meal) that the sample was collected. The locations of bands representing proteins [including amylase, immunoglobulin A (IgA), lysozyme, and albumin] known to occur in parotid fluid were identified in the electrophoretic pattern (*9*) and did not correspond to the fastest migrating basic proteins that showed polymorphism.

Samples of parotid fluid from different adult populations were collected. Among 90 samples from Blacks, three patterns were observed. The most common was a four-band pattern labeled bands a, b, d, and e (Fig. 1, channels 1 and 10). This pattern is postulated to represent the common homozygous type (1-1) determined by an allele at an autosomal locus for these parotid basic proteins that I have designated Pb^1 (parotid basic protein). The next most common type was a five-band pattern with an additional band c, along with bands a, b, d, and e. The darkness of band d appears to vary directly with that of band e, and if band e was not very heavy, band d was usually not visible. There is some variation between samples of this type (Fig. 1, channels 2 to 7). In particular, bands a and e sometimes were so faint in relation to bands b and c that further concentration of the samples was needed to see them. This second general pattern is postulated to be the heterozygous phenotype (1-2) determined by the two alleles Pb^1 and Pb^2. The third and least common pattern showed predominance of band c, some protein at position b with a trace of protein just behind position a in concentrated samples, and no bands at positions a, d, and e (Fig. 1, channels 8 and 9). This pattern may represent the homozygous type (2-2) for the variant allele.

Some variation in relative intensities and mobilities of the bands in the common homozygous and heterozygous phenotype has been observed. Tests by incubation of samples with and without inhibitors of proteolysis suggest that the observed phenotypes are partly determined by enzymatic changes oc-



Channel	Phenotype	
1 and 10	1-1, Black	
2	1-2, Black	
3	1-2, Caucasian	
4	1-2, Son	Black
5	1-2, Father	Black
6	1-2, Son	Black
7	1-2, Son	Black
8	2-2, Father	Black
9	2-2, Black	
10	1-1, Black	

Fig. 1. Photograph of part of a gel (10 to 22 cm from sample slots) used for electrophoresis of parotid basic protein variants. This acid-urea starch-gel was stained for arginine-rich proteins and the most rapidly migrating basic proteins are shown. More slowly migrating proteins (amylase, albumin, and IgA) are not shown. Each channel contains a different sample. White squares and white crosses indicate the proteins determined by Pb^1 and Pb^2, respectively, in band patterns from representative samples of the three phenotypes observed (1-1, 1-2, and 2-2). For ease of photography, parotid proteins were concentrated only 1.6 times, and some bands shown by squares or crosses in representative samples were either faint or absent in other samples on this gel. However, they were seen in more concentrated specimens, except occasionally for band d, which varied directly with the heavier band e, and thus was absent when band e was weak. The position of lysozyme is indicated by a black spot and appeared as a zone of negative staining in more concentrated specimens.