DEFORMATION AND SPALLATION MECHANISMS IN TEKTITES.

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Introduction: Primary tektite morphologies are derived through rotation. This was recognized as early as 1934 [1]. Historically, primary forms are spheres, variably prolate spheroids, spheroidal dumbbells and spheroidal apioids. Almost all tektites demonstrate a 'flattening' of spheroidal morphologies to ellipsoidal. In the proximal setting, e.g. indochinites, the trend continues to biconvex, plano-convex, concavo-convex and biconcave discs to tori (as fragments). It is suggested by [2] & [3] that centrifugal forces in a rolling motion trend a sphere to an oblate (discoidal) form. As the rolling becomes a tumbling motion, discs irreversibly evolve to prolate forms (including dumbbells). No atmospheric interaction is implied and therefore all morphologies are considered primary.

A discoidal form may, however, also evolve due to aerodynamic forces. Shear forces set up internal vortices in the molten tektite body (Fig. 1). The same process is at work in raindrops and smoke rings. As atmospheric interaction is involved, the resulting shapes must be considered secondary.

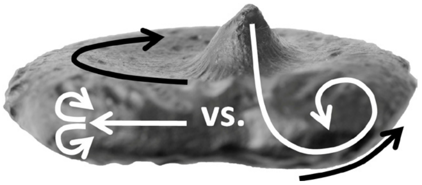

Fig. 1: An Indochinese biconcave discoidal teardrop. Arrows show centrifugal (left) vs. aerodynamic shear forces inducing internal vortices (right).

When variably cooled tektites re-enter the atmosphere they are re-heated, cooled and spalled. A mechanism is proposed for creation of spallation scars.

Atmospheric exit: *Observations:* Tektite bubble pressures, broadly corresponding to formation / solidification height, indicate medial and distal tektites formed at heights of 40 km plus [4] [5] [6] with medial forms up to 70 km [7]. Proximal splashforms formed at lower altitudes of 12 and 22 km [8].

Proximal tektites (e.g. indochinites, moldavites, georgiaites, ivorites) display a continuous morphological sequence from spheroidal, ellipsoidal, biconvex, plano-convex, concavo-convex and biconcave disc to tori (as fragments). In raindrops and various other fluid - fluid interactions these morphologies have been demonstrated to be produced by aerodynamic forces [9] [10] [11]. The vast majority of medial tektites (e.g. philippinites, billitonites, bediasites) and probably all distal tektites (e.g. javaites, australites) are variably 'flattened' and display a sequence from spheroidal to ellipsoidal to occasionally biconvex discs prior to re-entry modification [12]. Oriented medial and distal tektites were not spherical at the point of re-entry [13]. Solid, homogenous, spherical bodies do not orient.

Biconcave discs are not found in a medial or distal setting, with the exception of one tori [14], which is probably not of primary origin. Teardrop and dumbbell morphologies in a given geographic locality have equivalent 'flattening' compared to originally spherical forms. Most discs have only one, or one prominent, concavity which is normally anterial and slightly off-center, i.e. discs lack precise symmetry. The 'flattened' morphologies clearly evolved in flight and not on the ground as spallation surfaces occur on the rapidly cooled 'flight exposed' anterior surface only.

Discussion: The molten tektite morphology is, or is potentially, influenced by the following factors / forces acting upon the body: Cohesive forces give rise to surface tension and capillary action; centrifugal; aerodynamic (shear creating internal vortices); deceleration; hydrostatic; viscosity (resisting deformation with cooling), angle and velocity of ejection [2] [3] [10] [15].

Tektites formed at altitude in rarefied atmosphere, but at hypervelocity tektites would still suffer aerodynamic drag, being deformed if viscosity permitted. Note that the most 'flattened' bodies, e.g. indochinites, formed at the lowest altitudes (highest air density).

If discoidal tektites were formed by centrifugal forces in the rolling mechanism one would expect a spheroidal, ellipsoidal, biconvex, biconcave disc to tori sequence. No, or very rare, plano-convex and concavo-convex specimens, which lack perfect symmetry, should be observed. Symmetrical biconcave discs with two even, centrally placed, concavities should be the norm, which is not the case. Furthermore, there is no mechanism for the production of flattened teardrops (e.g. Fig. 1). These would require a teardrop to go from a tumbling to a rolling motion, which is very problematic, and then for the more rapidly cooled tail to be unaffected by the centrifugal forces pushing the molten mass to the margins. The 'primary' shapes should be found in assemblages at all distances, albeit in different ratios. Whilst flattened morphologies are found in all assemblages, the most flattened discoidal forms are never truly found in medial or distal settings. This suggests that discoidal forms are not primary or somehow form exclusively from higher viscosity proximal melts. If prolate forms developed from ‘flattened’ discoidal forms then where are these intermediate forms in the medial and distal settings?

Conclusions: The spheroidal primary morphologies constitute the more stable forms produced by tumbling rotation [2]. The fluid tektites (spherical and spheroidal prolate, dumbbell and apioid forms) then interact with the rarefied atmosphere at high velocity, deforming from a spheroidal section to ellipsoidal, biconvex, plano-convex, concavo-convex, biconcave and tori (which fragment due to inherent instabilities). Medial tektites (which traverse the atmosphere the fastest due to optimal ejection angle / velocity) and distal tektites (lower, sub-optimal ejection angle / higher velocity), form at higher atmospheric levels, incur less atmospheric interaction and hence less deformation.

The principal forces involved would be aerodynamic forces with high pressures at the stagnation point causing a punt (anterior concavity) and shear forces creating internal vortices trending the shape towards biconcave / tori; deceleration forces, resulting in flattening; surface tension resisting deformation; viscosity, as the tektite cools increasingly resisting deformation and locking in non-equilibrium forms. Variations in these forces, caused by ejection angle and velocity, melt composition and temperature account for all known tektite morphologies. Atmospheric and gravitational effects will differ for other planets.

Atmospheric re-entry: *Observations:* Medial and distal tektites usually display spallation surfaces with navels (etched circular cracks), whereas proximal tektites display smooth spallation surfaces (bald spots).

Spallation mechanism: During re-entry all tektites are initially heated, but only the distal, highest velocity, forms ablate. Once the bulk of the inherited cosmic velocity is lost the anterior surface is rapidly cooled in the frigid upper atmosphere. This results in spallation, which is believed to occur due to cooling and not due to re-entry heating (although heating is a prerequisite).

Where spallation takes place under high deceleration pressures a two-phase fracture is formed (idea from [16]). Due to cooling contraction, it is interpreted that triangular / polygonal cracks perpendicular to the surface plus surface parallel cracks form, driven by mode I opening (tensile) stresses [17]. As the surface parallel crack moves towards the centre of the triangular to polygonal spallation shell the deceleration pressure of the body is focused on an ever smaller attached area. Resultant point pressure induces a Hertzian cone (recognized by [18]) beneath the shell fragment. The shell fragment may remain attached to the top of the Hertzian cone and, if 'etched', form a mushroom-like protrusion. Similar fracture was reproduced experimentally (Fig. 2) by striking a glass sphere to form a Hertzian cone and then heating the surface (not cooling in this case) until spallation occurred.

If the pressure under which the mode I opening (tensile) crack forms, due to thermal contraction, is lower (i.e. lower re-entry velocity or stationary) then the point pressure is insufficient to induce a Hertzian cone. A smooth spallation surface, termed a bald spot in indochinites, is formed. Large oriented philippinites (i.e. bifurcated cores) were too large to cool sufficiently prior to re-entry. This inhibited crack formation, resulting in a later stage, lower pressure, spallation with no Hertzian cone formation. Hertzian cones in tektites are, for the most part, not collision impact derived as they are less common in proximal tektites (where chances of impact are greater) and the arrangement in medial and distal tektites is not random.

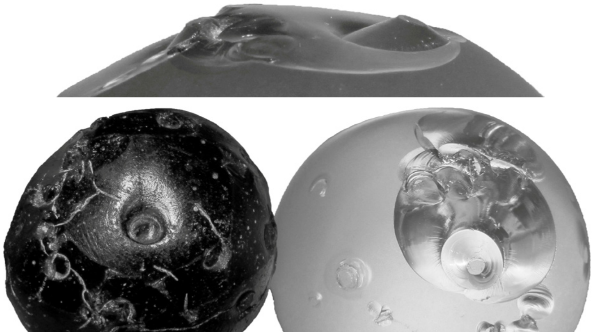

Fig. 2: A glass sphere hammered to produce Hertzian cones, then heated to induce spallation. Compared to the anterior surface of a well preserved, minimally etched, philippinite from Sipalay (bottom left).

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