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AN INTACT ITEM OF SPACE DEBRIS WITH AN EXPOSURE AGE OF ABOUT 10 YEARS

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We document an artifact found on an Australian beach that appears to be a gas tank from a Soviet spacecraft. Comparison of its microcrater size distribution with those from surfaces on the Long Duration Exposure Facility (LDEF) suggests the object spent around a decade in space, consistent with lifetimes of Molniya satellites that entered around 1990, although this is not an ironclad identification of the source spacecraft type. Entry simulations of objects with similarly low mass/area ratio indicates that temperatures of no more than 1800K are likely: the Titanium alloy from which the object is made would have undergone minimal melting, consistent with the slight fusion observed.

1. INTRODUCTION : ARTIFACT CHARACTERISTICS

The artifact, a hollow sphere, was sent to one of us (WZ), a meteorite dealer and collector, by friends in Australia [1]. It was recovered from a junk yard, where it had sat for almost eight years after it was discovered on a beach near Albany in South Australia (35.0°S, 118.0°E).

The object (fig.1) carries no identifying markings. It is 90 cm in circumference, with a thickened polar cap on one side, and a screw fitting with a metric thread on the other. The threaded section is 42 mm in diameter, and bears a hole 8mm in diameter. The whole thing weighs 6 kg.

The sphere is somewhat corroded, as might be expected from its immersion. Its weight and size are consistent with an average wall thickness of only one or two millimetres. Tapping the object makes a noise of higher pitch than a bell or gong, suggesting a stiff material.

Around the apex (i.e. opposite the threaded fitting) there is some evidence of melting, with blobs of melt creeping away from the apex (fig. 2). Additionally, there are several small craters visible, see fig. 3a and 3b.

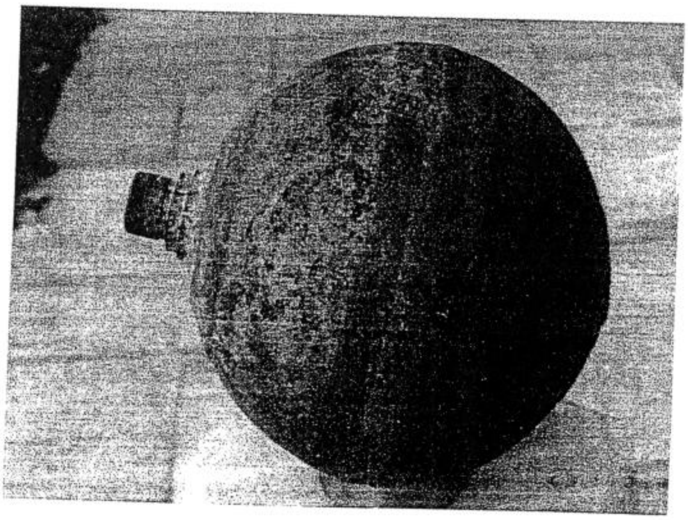

Fig. 1 Picture of sphere.

(A11)

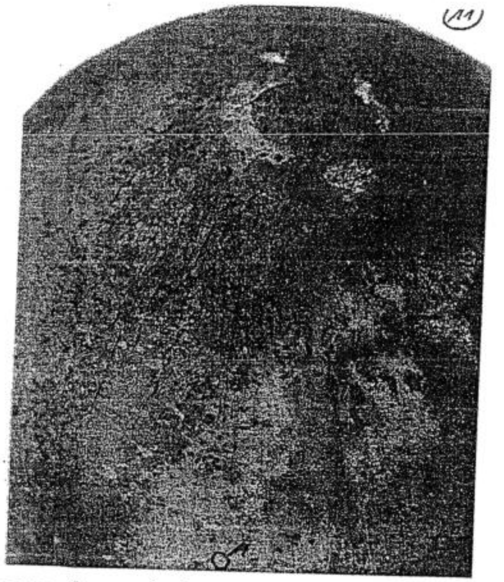

Fig. 2 Close-up of apex of sphere, showing melting and migration of melt away from apex - consistent with the object entering apex-first.

An early suggestion, largely on the basis of the metric thread [1] was that the sphere is a gas tank from a Russian/ Soviet spacecraft, possibly a Molniya satellite (fig. 4). In this paper, we present a more detailed analysis of the crater population and composition, which appear to corroborate this suggestion. We furthermore conduct numerical simulations to establish the likely thermal conditions during entry.

2. COMPOSITION

A small sample of the fused area near the apex was analyzed in an electron microprobe using energy-dispersive X-ray spectroscopy. The count rates (Table 1) suggest an elemental composition typical of modern titanium alloys, e.g. Ti-6Al-4V.

This composition is consistent with the stiff material as indicated acoustically by the structure's impulse response. It

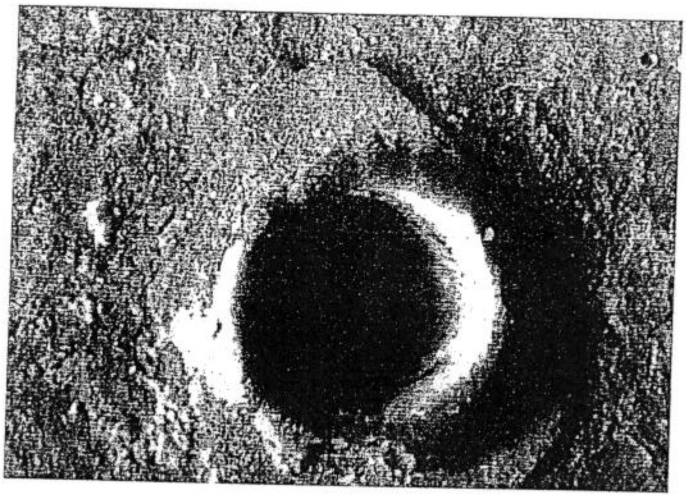

Fig. 3a Typical crater: the flattened bowl shape and the raised lip are characteristic of hypervelocity impact craters.

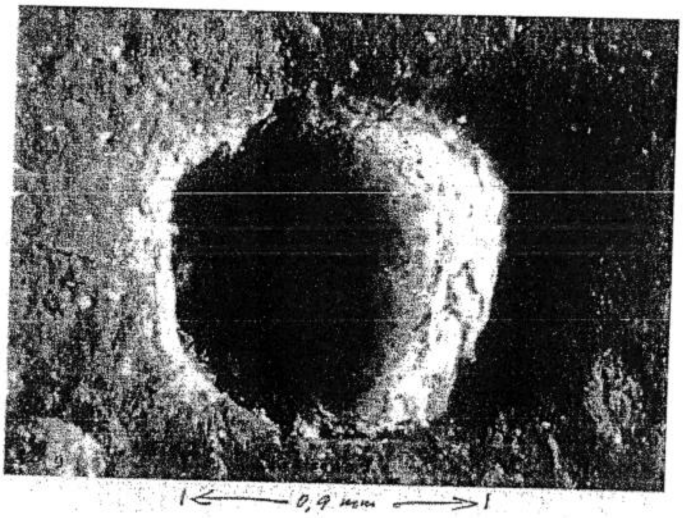

Fig. 3b The largest crater, 0.9 mm in diameter. The slightly noncircular shape may be indictive of an irregular impactor, or a shallow impact angle.

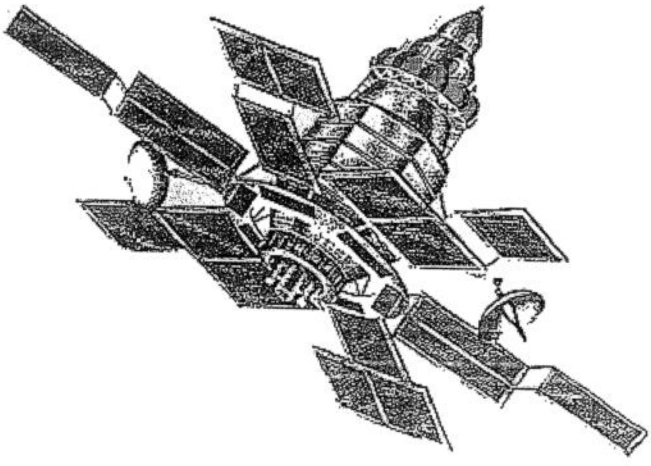

Fig. 4. Sketch of Molniya satellite: the height is around 3.5m - the ring of a dozen 0.3m diameter gas tanks can be seen near the nose (from [1]).

TABLE 1: *K-line Counts of Two Spots Studied with X-ray Microprobe Analysis. Figures in Parentheses are the Percentage of Total Counts.*

Element	Spot 1		Spot 2	
C	215		233	
N	201		259	
Al	3649	(8%)	5696	(11%)
Ti	42225	(88%)	44075	(86%)
V	1602	(3%)	952	(2 %)
O	34		94	
Si	349		650	
Fe	19		62	
Ca	85		103	
Mg	65		777	
Cu	-		102	

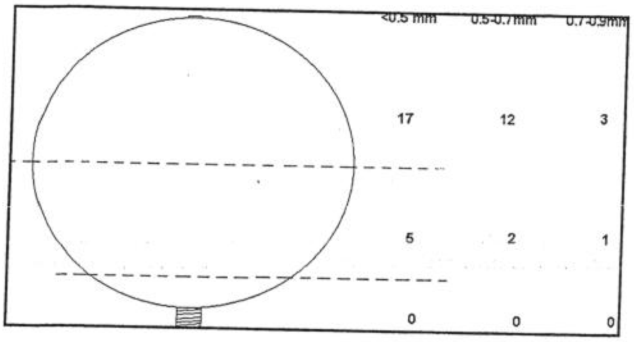

Fig 5. Schematic of crater distribution: even though there is some melting on the upper hemisphere, there are far more craters there, consistent with shielding by the spacecraft of the threaded hemisphere.

is furthermore consistent with the putative Soviet origin, since titanium is a much more widely-used material in the Soviet aerospace industry than in the West.

It may be noted that not only are titanium alloys rather stronger and stiffer than aluminium alloys, while being less dense than steels, but they also have relatively high melting points, a point that may well have contributed to the object's survival.

3. IMPACT CRATER DISTRIBUTION

The observable impact craters were counted by eye and the crude geographical distribution of the craters was also noted and is summarized in fig. 5. The region near the apex where melting is most pronounced does not appear to be significantly depleted of craters. The antapex (threaded pipe) side is somewhat depleted, consistent with this side being largely shielded by the body of the satellite. Satellites designed and built in the West tend to have prepellant tanks on the interior - the exposure of this artifact to space points to a Soviet origin.

The report of a 9 mm diameter crater [1] was in fact erroneous - 0.9 mm was the largest crater measured (fig. 3b).

4. INFERRED AGE FROM CRATER POPULATION

Counts of small craters on recovered spacecraft surfaces are typically performed to determine the population of meteoroids and space debris. Here, we apply the converse of assuming a typical population and infer the exposure age of the artifact, just as counts of (usually kilometer-scale) planetary surfaces are often used to estimate their age.

Of course, comparisons of this sort are fraught with uncertainties. In a highly elliptical orbit, the impactor flux would be somewhat different from an object in LEO. First, since most of the time is spent at high altitudes, the debris flux is lower, since catalogued objects of space debris at least have a maxiumum density below 1000 km altitude. Furthermore, the meteoritic flux would be slightly reduced (since gravitational focussing is lower at high altitude), although this effect is offset by the lower Earth shielding.

During perigee passes, the object would encounter higher debris fluxes than in LEO, since the relative velocity is much higher. However, this period is only a small fraction of each orbit. Another issue to bear in mind for serious quantitative assessment is that a substantial secondary crater population may exist, created by the impacts of ejecta from impacts elsewhere on the satellite.

It would be possible in principle to compute these various factors using sophisticated debris models. However, given the additional uncertainties of crater obliteration by melting and corrosion which are not well-constrained, it is probably not worthwhile to do so.

Accordingly we compare with the observed crater population on surfaces of the LDEF (Long Duration Exposure Facility). This large passive satellite was left in LEO for 6.2 years and then recovered. Higher fluxes were observed on the leading faces of the satellite (the attitude was maintained by the different moments of inertia, producing gravity-gradient stabilization). Accordingly, we compare (fig.6) the crater count determined for the sphere with the 4π average LDEF crater count [3], taken as 2.4 times smaller than that for the most heavily-impacted (ram) direction

Broadly speaking, the counts are similar, suggesting a broadly similar age. In fact, for most of the size range, there are about 20% more craters on the sphere than on LDEF. Furthermore, the LDEF craters were formed in aluminium: a given impactor will produce a smaller crater in denser, harder titanium. Typically, a $(\text{density})^{0.5}$ dependence is observed, so the material effects introduce a 20% or so bias against the sphere. Thus the crater count, and hence the age, is in round numbers about 50% higher than for LDEF, suggesting the object was in space for about a decade.

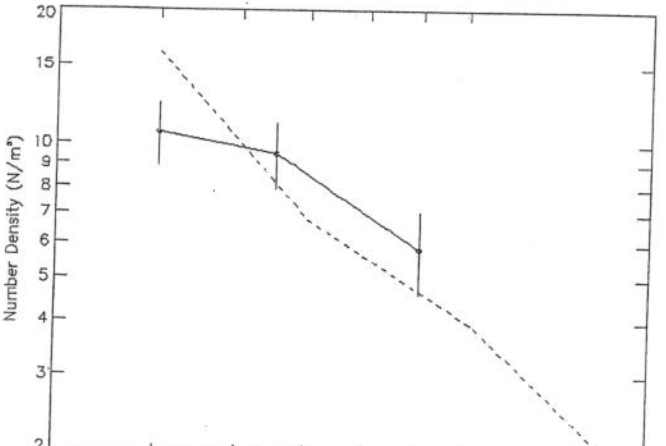

Fig. 6. Microcrater size-frequency distribution on the sphere (solid line) with 1-σ counting uncertainties shown as error bars, compared with LDEF spherical average (dashed lines).

Note that the count for the smallest craters on the sphere is actually lower than that for the LDEF surfaces: this is consistent with the smallest craters being most easily obliterated by fusion and corrosion.

5. A MOLNIYA ORIGIN ?

As suggested in [1], the sphere may belong to a Molniya-class communications satellite: these relatively numerous satellites carry spherical gas tanks apparently similar to that described here. Although many other Soviet satellite types use these tanks, most, like the Progress space station resupply craft and Vostok-derived photoreconnaissance vehicles, are in orbit for only a few months. According to King-Hele *et al.* [3], there were 132 Molniya satellites launched in the 1965-1990 period. Of these 132, the median orbital lifetime was 9 years.

In fig. 7, we plot the lifetime of Molniya satellites against their re-entry date (as computed from the observations and/or predictions in [3]). It is seen that several Molniya satellites re-entered in the years prior to 1991, and they all had orbital lifetimes of 9-14 years.

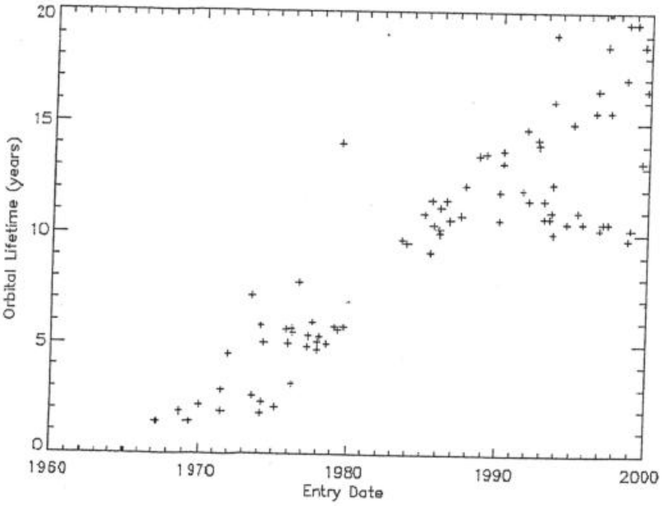

Fig. 7. Orbital lifetime (crosses) of Molniya satellites as a function of estimated entry date : typical lifetime for those satellites entering around 1990 is about 10 years.

While not proof, these data are consistent with the inferred crater age. Zeitschel [1] suggests that the sphere may have been released in a launch accident. An interesting discussion of Soviet launch debris is found in Clark [4]: generally launch debris has a far shorter lifetime than that determined here. Furthermore, the depletion of craters on the lower (thread) half of the sphere suggests that the sphere was attached to the spacecraft for most, if not all, of its space exposure.

The location of the find, at 35°S is certainly consistent with a satellite in a high inclination orbit (as the Molniya satellites), but since ocean currents would allow the artifact to be washed up there having reached anywhere in the eastern Indian ocean, a low-inclination orbit cannot be ruled out.

6. RE-ENTRY SIMULATION

It is perhaps surprising that a small object should survive the formidable mechanical and thermal stresses of re-entry without being expressly designed to do so. Known debris from re-entries is generally confined to large vehicles, notably Skylab. In fact, survival of smaller items is in general to be expected, since (assuming a constant density) the mass per unit area decreases as size decreases. This scaling gives rise to the generally unmelted appearance of interplanetary dust particles (IDPs) below around 150 μm in diameter, while larger particles are in general at least partly melted.

The object at hand, a hollow sphere, is structurally strong and unlikely to be deformed by the loads applied during re-entry. Its hollowness gives it a low ballistic coefficient: this means that relative to a denser object it decelerates harder and higher, but with a lower peak heating rate.

A trajectory simulator, devised for entry analyses of the ESA Huygens probe, was run to determine the deceleration and heating loads that might be encountered by the sphere for various re-entry conditions. The simulator integrates the equations of motion using a 4th order Runge-Kutta integrator. The CIRA 72 atmosphere is used. A drag coefficient of 2 is assumed. Furthermore, it is assumed for simplicity that the heat flux on the leading face of the sphere is equal to the product of the atmospheric density and the cube of the relative velocity. In fact this - pessimistic - assumption is reasonably accurate for the high-altitude free-molecular flow regime.

It is possible, of course, that the object was still attached to its parent satellite on entry. Detailed modelling of this scenario, in the absence of any observational constraints, is beyond the scope of this study, however. In such a case, the tank may have been exposed to higher heating rates, since the heavy satellite will drag the sphere deeper into the atmosphere at high speed, but may also have shielded the sphere somewhat. Molniya satellites have a typical launch mass of around 1500 kg, and a projected area of 2-5 square meters (assuming the solar arrays are ripped off by dynamic pressure early in the entry event) – and so would have an area:mass ratio around 4 times smaller than the sphere itself.

The peak deceleration in gravities, and the peak heating rate (expressed as an equivalent black-body radiance temperature) are shown in fig. 8 for the sphere for two entry angles, and for an entire Molniya satellite. Although these crude calculations are only a guide, they do show the relatively mild environment encountered by the sphere.

7. CONCLUSIONS

We have described an artifact which appears to be a component of a Russian satellite. It has a microcrater population consistent with a space exposure of about ten years. Electron microprobe analysis indicates a composition consistent with typical titanium alloys.

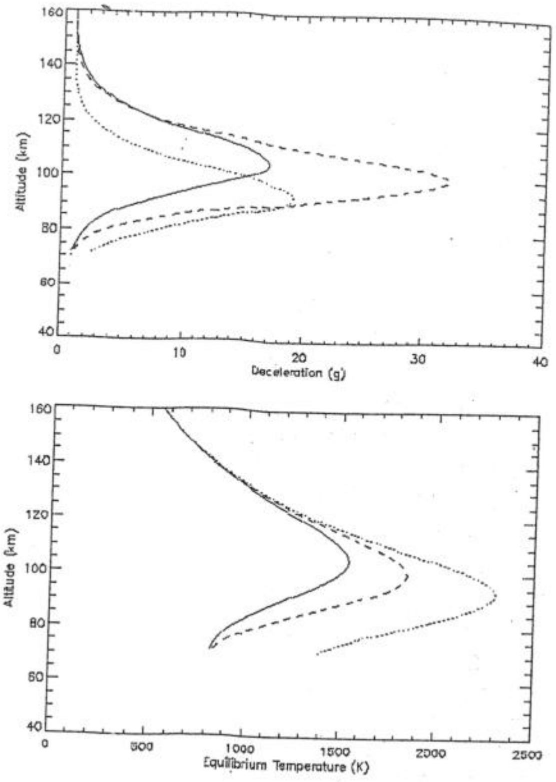

Fig. 8. Entry simulations : objects are released with an entry angle γ (defined at 200 km altitude) and an entry speed of 7000 m/s. The solid (γ=-10^0) and dashed (γ=-20^0) curves show the sphere (area/mass=0.01m^2/kg) while the dotted curve shows an entire satellite (area/mass=0.0025m^2/kg). Although peak g-loads are similar, the sphere encounters temperatures low enough for Titanium to survive, while in the case of the entire satellite, it would melt.

It is remarkably intact given the rigors of entry, for which it was not (presumably) designed - its survival is understandable given the very low mass/area ratio of a thin-walled hollow sphere, combined with manufacture from a high melting point strong material like titanium. While similarly-dimensioned objects of steel, beryllium might survive, it is unlikely that such objects made from aluminium alloys would do so. All the facts at hand are consistent with an origin from a Molniya satellite, although other spacecraft may also be consistent.

It seems likely that other such objects wait to be found, not least the other tanks from the same spacecraft.

8. ACKNOWLEDGEMENTS

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