Table 2 Unity check errors for damaged structure

Node	Direction	Measured modes used: Four	Eight
1	X	0.00	0.03
	Y	0.01	0.00
2	X	0.01	0.02
	Y	0.01	0.00
3	X	0.01	0.02
	Y	0.01	0.03
4	X	0.02	0.05
	Y	0.01	0.04
5	X	0.01	0.03
	Y	0.03	0.08
6	X[a]	1.52	1.42
	Y[a]	0.76	0.93
7	X[a]	1.44	1.39
	Y[a]	0.75	0.93
8	X[a]	2.20	2.13
	Y	0.02	0.06
9	X[a]	2.08	2.10
	Y	0.03	0.03
10	X	0.01	0.03
	Y	0.03	0.04
11	X	0.01	0.02
	Y	0.03	0.02
12	X	0.01	0.03
	Y	0.03	0.01

[a]Indicates a significantly affected degree of freedom.

Table 3 Percent stiffness reductions for damaged structure

Member	Exact reduction	Measured modes used: Four	Eight
f	80	77.2	80.9
g	40	39.7	40.3
h	30	29.6	30.1
i	0	0.0	−0.9
j	0	1.2	−0.7

modes. Members requiring many modes to be sufficiently exercised, such as those near the free end, will probably require many measured modes to detect their damage.

The simulated measured modes used in the example are perfectly orthogonal and free of error, but real measured modes are neither. The experimental errors will introduce additional unity check errors. The effectiveness of the proposed method in real application, wherein actual test data are used, is still an open question. Furthermore, the proposed method requires that the analytical model of the original structure should have been verified by a mode survey test. How well the model should correlate with the test data, for the proposed method to work, has not yet been established.

Conclusions

Using a test-verified analytical model of the original undamaged structure and measured normal modes obtained after damage has occurred, the proposed unity check method appears to be able to locate the damaged structural members and to determine their stiffness reductions. The effectiveness of the method has been demonstrated with a numerically simulated and idealized example. Applicability of the method to real structures using actual test data is yet to be explored.

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Solar Array Degradation by Dust Impacts During Cometary Encounters

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Introduction

THE effect of hypervelocity impact on spacecraft materials and structures is a subject that has received extensive attention in the context of space debris in Earth orbit. Motivated by forthcoming missions to small bodies and recent results on hypervelocity impacts on solar panels returned to Earth from the Hubble Space Telescope, I consider the damage to spacecraft solar arrays during the spacecraft flybys of comet Halley in 1986 and show that the performance loss seems to be related to the fluence of the smallest impactors and is around three orders of magnitude higher than would be expected from crater-area considerations. The nonlinearity and the magnitude of the solar array degradation with dust fluence are consistent with open-circuit failures of solar cell strings, possibly by impacts on or near cell interconnects.

Spacecraft Results

It is well known that solar array performance degrades in space, such that arrays need to be sized for their end-of-life performance. For example, in low Earth orbit (LEO) silicon solar arrays degrade by up to 3.75% per year, of which 2.5% is attributed to radiation damage.[1] The rest of the damage is attributed to other mechanisms such as thermal cycling, uv degradation, and micrometeoroid and debris strikes. How much damage is due to the latter effects is difficult to determine. However, the handful of cometary encounters to date allows the determination of array damage due to dust impact: the large dust fluence causes significant, and therefore measurable, array performance loss, there are simultaneous dust flux measurements, and the short duration of the degradation event eliminates most alternative damage mechanisms.

The two Russian Vega spacecraft were the first spacecraft[2] at comet Halley in 1986, and each had large, unprotected planar solar arrays and an instrument pointing platform. Although they came no closer than 8000 km to the nucleus, they both suffered severe dust damage due to the large dust fluence and the high impact velocity (78 $\mathrm{kms^{-1}}$). Vega 1 lost its high- and low-frequency plasma wave analyzer, and Vega 2 lost the low-frequency plasma wave analyzer and its three-axis magnetometer. Also, they lost about 50% of their solar array generation capacity (Fig. 1).

The Giotto spacecraft[3] made a very close encounter[4] (~600 km at 69 $\mathrm{kms^{-1}}$) with Halley soon thereafter. It had a cylindrical solar array behind a Whipple bumper shield. A large impact near closest approach generated a nutation, which may have exposed the array to dust impacts thereafter. The array may have also suffered some

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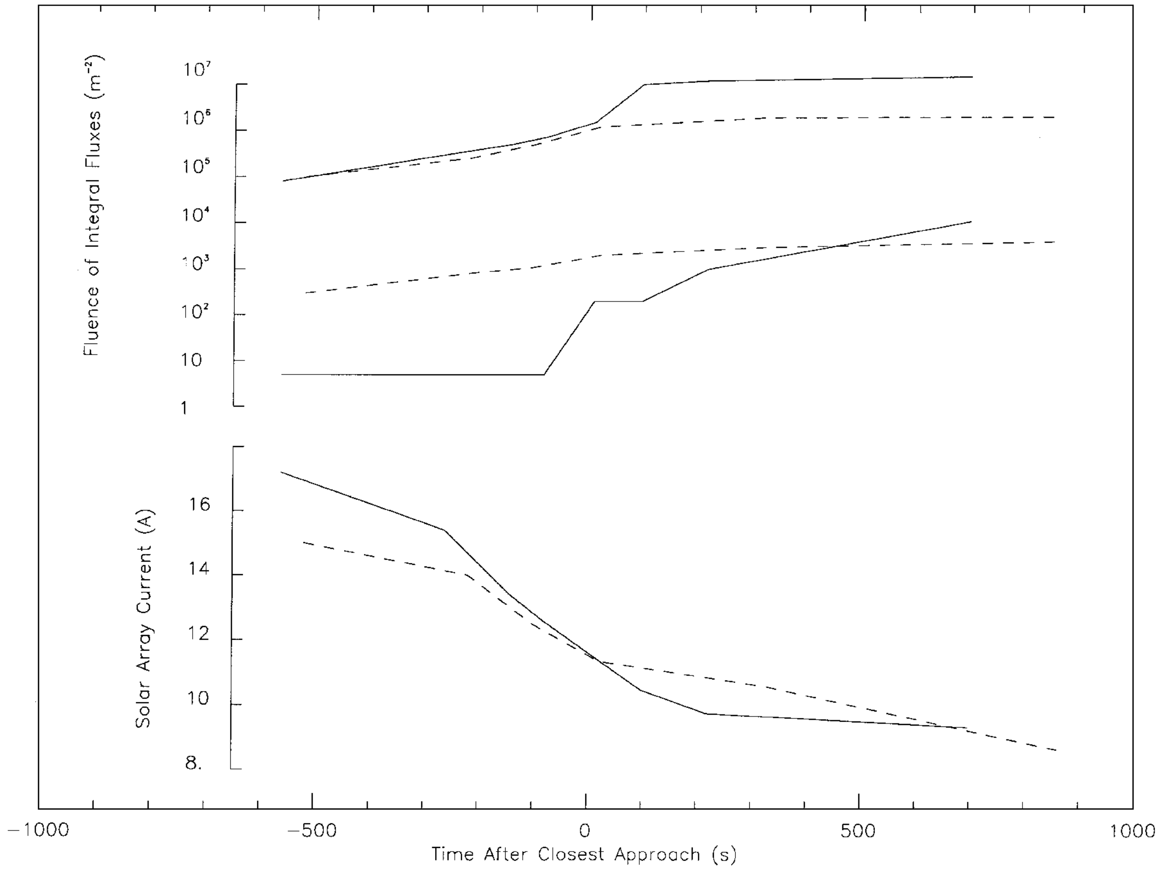

Fig. 1 Cumulative dust fluence on Vega 1 (——) and Vega 2 (- - -) during their comet Halley encounters for particle masses >1.5 × 10^{-16} kg (upper curve) and >9 × 10^{-14} kg particles (lower curves) from Ref. 6. Solar array current as a function of time is also shown for the two spacecraft.

secondary impacts from, for example, the camera, which was not protected by the bumper shield and was destroyed during the encounter. Several other instruments were damaged, thermal coatings were degraded,[5] and the solar array power dropped from 196 to 191 W (Ref. 4). Giotto went on to explore comet Grigg–Skjellerup, but there the dust fluence was extremely small—indeed only four impacts in total were detected—and no degradation was noticed.

All three spacecraft at Halley were equipped with various dust counters.[6,7] Because the solar array current of the Vegas was recorded as a function of time during the encounter, the array degradation may be correlated with the dust fluence recorded by these dust counters (Fig. 1). It may be seen that degradation occurs throughout the encounter, before any significant number of large particles have impacted the spacecraft. Further, the number of large impacts jumps sharply at closest approach, whereas the array current does not drop as suddenly. Thus, perhaps unexpectedly, larger impacts are not the principal source of array degradation. The history of small impacts seems much more consistent with the solar array damage.

Analysis

Figure 2 plots the damage against the cumulative fluence of small particles, i.e., the area density of impacts throughout the encounter above a mass threshold of 1.5 × 10^{-16} kg. Damage is defined as $[I_0 - I(t)]/I_0$, with I_0 the initial undegraded array current and $I(t)$ the solar array current recorded at time t during the encounter. The data for the two spacecraft are broadly self-consistent (on a similar plot for large particles, the data are not self-consistent), although note that Vega 1 received almost an order of magnitude higher fluence as it encountered a dust jet[6] shortly after closest approach. The fluence was taken from the dust counter data in Ref. 6, scaled by 0.61 to reflect the orientation[2] of the panels to the velocity vector.

The Giotto data point is generated by taking the dust fluence from Ref. 7 for the same mass threshold as before and dividing by 2π sin(1 deg) as the array was exposed for only half the encounter, is cylindrical (and so the fluence is shared around the array's circumference), and was inclined to the fluence by 1 or 2 deg. Because of the bumper shield geometry and the uncertainties in the spacecraft's attitude around and after closest approach,[8] this number is very uncertain and is an upper limit but seems comparable to the Vega data.

The choice of 1.5 × 10^{-16} kg is somewhat arbitrary, although the particle mass distribution function is shallow for lower masses, and particles much smaller than this would cause craters smaller than the wavelength of light. Because the mass distribution function above this threshold is steep, the crater area produced is dominated by this size impactor; i.e., though larger particles cause more damage, there are so few of them.

If the damage were due to the coverglass of the cells becoming opaque due to cracking and spalling, the loss might be expected to be equal to the area fraction of the cell covered by impacts. However, this corresponds, using empirical relations[9] for crater spall area for brittle targets (which varies as the impact energy to the power 0.75), to a spall diameter of a few micrometers for the threshold mass used. Thus the ~10^7-m^{-2} fluence experienced by Vega 1 would lead to an area fraction of about 0.03%. Further, until large (>50%) area fractions are reached, the degradation of the array current would be expected to be fairly linear with the fluence. Thus a damage model assuming a crater area effect[10] (whether opaque or not, and the spall zone is not typically completely opaque[11,12]) is not consistent with the data and would seriously underestimate the damage. In passing, the experiments of Fager[13] may be noted, in which laboratory impacts onto solar cells produce opaque spall craters amounting to about 2% of the cell area, but the loss in cell current is typically nearer 10%, again suggesting a direct proportionality is inappropriate (although these data are for single cells rather than arrays, and some of the loss is due to carbon deposited on the cell by the gun used to generate the impacts).

However, cells are not used in isolation, and one open-circuit failure in a string of cells can effectively remove the entire string's contribution to the array current. A model of array performance, following that in Ref. 14, seems to reproduce the shape of the spacecraft

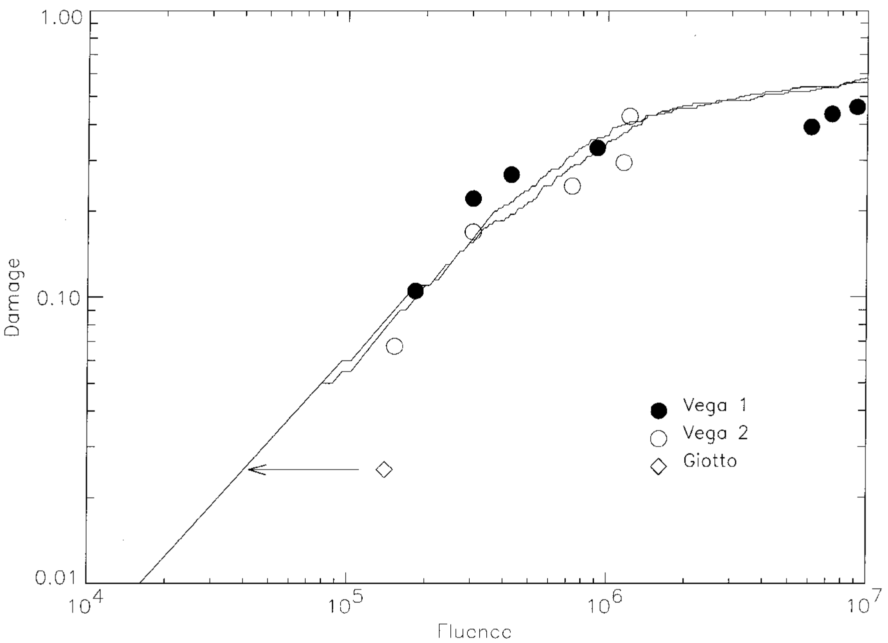

Fig. 2 Damage, i.e., fractional loss in solar array current, against the 1.5×10^{-16} kg dust fluence for the Vegas and Giotto. The solid lines are two runs of the model described in the text.

results (Fig. 2). The array is assumed to be made of 100 parallel strings of 200 submodules in series, each of two cells in parallel. (Other sets of parameters produce similar curves.) One cell is chosen at random and assumed to fail open circuit and drops the current from that string by one-half: If the other cell in that submodule has already failed, then the entire current from that string is lost. One cell is chosen for every 8000 impacts per square meter. Because already damaged cells can be chosen, as well as cells in strings that are already damaged, the damage curve turns over once the damage becomes significant (~50%).

For typical coverglass thicknesses of ~100 μm, impactors of the threshold size considered here would not crater down to the cell itself, and so damage to the cell or conductors on it seems unlikely. However, the onset of damage at a fluence of $\sim 10^4$ m^{-2} is consistent with open-circuit failures of array components with an area of about 100 mm^2; impacts on or near cell interconnects are an obvious possibility, and these are clearly vulnerable to being broken off the cell, although any failure with a similar probability and series-parallel behavior would reproduce the curve in Fig. 2.

Viewed in this context, the Giotto loss of 2.5% of array power may be considered as the loss of two array strings [each comprising 74 cells (Ref. 3) of a total of 5000 of which only half are illuminated at one time]. Note that, although this model assumes open-circuit failures, short-circuit failures are also possible with impacts on solar arrays.[15]

Applicability and Conclusions

The study presented here is largely irrelevant to typical spacecraft missions in LEO and geosynchronous Earth orbit (GEO) because the impact rates on spacecraft in these orbits are very small. With a typical flux of 10^3 impacts/m^2/year for $\sim 10^{-15}$-kg (~1-μm-diam) particles,[16] it would take an average GEO satellite around 10^4 years to accumulate the fluence experienced by Vega 1. Further, typical collision velocities (~7 kms^{-1}) mean each such impact has 100 times less energy than those during the Halley flyby. Thus the solar array damage for Earth orbiters attributable to micrometeoroids and debris is very small compared with that due to radiation and other mechanisms.

The study is, however, important for several new missions to comets. The Stardust mission is due for launch in 1999 and will fly through the coma of comet P/Wild-2 to collect a sample of cometary dust captured in aerogel. The recently selected Contour mission plans a flyby of at least three comets, namely, Encke in 2003, Schwassmann–Wachmann-3 in 2006, and d'Arrest in 2008. Performance in the later encounters clearly requires that the degradation in the earlier encounters is small.

The New Millenium DS-1 mission, due for launch in July 1998, is a technology demonstration mission carrying an ion propulsion system and a concentrator-array solar generator. After flyby of an asteroid and Mars, the spacecraft will make a flyby of a comet. The concentrator-array generator may have damage mechanisms substantially different from those of conventional arrays, however.

The European Space Agency's Rosetta mission plans a rendezvous with comet Wirtanen, depositing a lander, and the DS-4/Champollion mission intends a landing and sample return. In these two cases, the relative velocities are low, and so although cometary dust may hit the solar arrays, the impacts are not at hypervelocity and the degradation investigated in this Note is probably not applicable.

The analysis of the Vega data seems consistent with open-circuit failures, rather than optical degradation of the cells themselves, estimates of which seriously underestimate the array degradation. Further, these failures appear correlated with surprisingly small impactors, although this may be due in part to the extremely high flyby velocities at Halley, which are rather higher than typical flybys of a few kilometers per second. Careful attention to array design, e.g., short strings, and good power margins should make a mission robust to large impact fluences.

A better-documented laboratory study of solar array performance before and after bombardment by a measured dust fluence would be useful to confirm the indications given in this Note. The performance of a set of cells in series parallel and the robustness of interconnects to impact damage should be investigated. Given the uncertainty of the Giotto result and the similar geometry for the Stardust and Contour missions (at least) investigation of the effect of very shallow impact angles and/or ejecta impingement and secondary impacts should be considered.

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