Title and Running title: Surviving atmospheric spacecraft breakup

Nathaniel J. Szewczyk, EMT-P, PhD[1,2], Catharine A. Conley, PhD[1]

[1]Space Life Research, NASA Ames Research Center, Moffett Field, CA
[2]Disaster Assistance and Rescue Team, NASA Ames Research Center, Moffett Field, CA

Corresponding author (also for offprints):

Dr. Nate Szewczyk
NASA Ames Research Center
M/S 239-11
Moffett Field, CA 94035-1000

nate@alumni.cmu.edu

cell: 408-242-0743
lab: 650-604-3628
fax: 650-604-3954

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Abstract

In essence, to survival a spacecraft breakup an animal must not experience a lethal event. Much as with surviving aircraft breakup, dissipation of lethal forces via breakup of the craft around the organism is likely to greatly increase the odds of survival. As spacecraft can travel higher and faster than aircraft, it is often assumed that spacecraft breakup is not a survivable event. Similarly, the belief that aircraft breakup or crashes are not survivable events is still prevalent in the general population. As those of us involved in search and rescue know, it is possible to survive both aircraft breakup and crashes. Here we make the first report of an animal, *C. elegans*, surviving atmospheric breakup of the spacecraft supporting it and discuss both the lethal events these animals had to escape and the implications implied for search and rescue following spacecraft breakup.

Key words

C. elegans, search and rescue, atmospheric rentry, astrobiology, planetary protection, life support systems, astronaut

STS-107 (Columbia) broke up while re-entering the Earth's atmosphere. Columbia was in the mesosphere approximately 62 km above the Earth's surface while traveling at Mach 18. Onboard was a passive *C. elegans* life support experiment, the full details of which will be reported elsewhere. Loss of spacecraft structural integrity during the breakup exposed all animals onboard to potentially lethal factors including shear forces, heat, shockwave(s), freezing, explosive decompression, anoxia, cosmic radiation, impact with the Earth, starvation, and environmental toxicity **(1)**). Despite these factors, *C. elegans* survived the atmospheric breakup of Columbia as shown in Figure 1.

Under normal operating conditions the spacecraft and life support systems are designed to protect animals from lethal events **(2)**. Thus, the longer the spacecraft and life support systems survive breakup the more likely it is that breakup is survivable. Following Columbia's breakup, video images aired by the mass media clearly indicated that large recognizable debris survived breakup. This suggests that the spacecraft survived long enough to protect occupants from aerodynamic shear forces, frictional heat, shockwaves associated with deceleration and decompression of the cabin, and the freezing temperatures of the upper atmosphere. These broadcasts also suggested the likelihood that intact or reasonably intact containers containing live *C. elegans* could be recovered. As is standard practice with rescue associated with aviation incidents, such debris should signal rescuers of the possibility of crew survival. The absence of such debris is should be taken as an indicator of decreased, but not impossible, survivability. The images aired by the mass media also highlight the importance of partitioning some search and rescue resources to monitoring of mass media and ground interrogation in locating potential sites of interest that may be spread over a much larger area than for aircraft incidents.

In the case of *C. elegans*, the spacecraft and/or the flight hardware had to protect the animals from explosive decompression. The flight hardware was designed to withstand a maximum decompression rate of 62.1 kPa/min before exhibiting structural damage (D. Reed, personal communication). Thus, the reported identification and recovery of intact flight hardware suggested the possibility of recovering live animals as the flight hardware should have protected the animals from decompression. Unlike humans, *C. elegans* can withstand up to a day of anoxia **(3)**. Therefore, loss of atmosphere due to decompression was not a concern for recovery of live worms. This is in stark contrast to the Soyuz 11 incident in which anoxia secondary to decompression is believed to be the cause of crew death **(1)**). However, the findings with *C. elegans* reported here are in line with the suggestions made to increase crew survival following Soyuz 11. Specifically, spacecraft crews should wear suits that provide protection against atmospheric decompression while traveling through the atmosphere. Use of such suits provides an additional likelihood of survival and their presence and use or absence thereof should be considered when partitioning search and rescue resources. Additionally, incorporation of emergency locator transmitters into such suits should greatly assist in rescue of crew members who are alive but otherwise unable to communicate with rescue crews.

Given the short duration involved in return to the Earth's surface following atmospheric breakup, it is unlikely that cosmic radiation will kill an animal. Many animals including humans, rodents **(4)**, and *C. elegans* **(5)** have previously flown in space and been exposed to cosmic radiation, with minimal to moderate protection, and have survived. Therefore, brief duration exposure to cosmic radiation should not be an immediate concern for search and rescue operations. However, with longer term health in mind, inclusion of radiation protection into life support suits worn by crews while traveling through the atmosphere seems prudent.

Impact with the Earth's surface is by far the most obvious lethal event cited by the general public in relation to lack of ability to survive an airplane breakup or crash. Unlike humans, *C. elegans* can withstand brief exposure to 100,000 x G (L. Avery, personal communication) making surface impact less of a lethal force consideration for this animal. With respect to humans, surface impact is likely the proximate cause of death in both the Soyuz 1 and STS-51L (Challenger) incidents **(1)**). However, as indicated by *C. elegans* survival and as the first author has personaly observed on a plane crash rescue mission, surface impact need not be a lethal event. In flight crew egress from a breaking up or crashing spacecraft is likely to indicate an increased probability of survival. However, lack of signs of egress should not be assumed to indicate lack of crew survival. Future spacecraft designs should continue to consider egress systems for both structural intact and damaged spacecraft but the lack of such systems in a spacecraft should not be taken as an indication that spacecraft breakup or ground impact is not survivable. Additionally, as is the case with automobiles, occupants of spacecraft that have incorporated impact force countermeasures into their design should be considered to have a higher probability of survival.

As with survival of aircraft breakups and crashes flight crews must survive not only the immediate event but also the interim until search and rescue crews arrive. In the case of *C. elegans,* starvation was not a concern as animals were recovered within the period that animals can survive in the absence of food. As shown in the left panel of Figure 1, animals grown on Nematode Growth Media **(6)** are in a dormant dauer state **(7)**, presumably from the expected exhaustion of food during the spaceflight. Animals can remain viable in this state for up to six months. As shown in the right panel of Figure 1, animals grown on *C. elegans* Maintenance Medium **(8)** were actively reproducing indicating that these animals had not yet exhausted food stores. Remarkably, these animals survived despite wide temperature variation (average daily temperatures of 4.1 to 19.7°C prior to recovery), and the invasion of the flight hardware by an airborne mold capable of killing *C. elegans* (not shown). In the case of flight crews, similar survival concerns exist. As recently highlighted by the return of Expedition 6 via a Soyuz spacecraft, arrival of search and rescue teams may be delayed. Measures to increase the efficiency of locating surviving crew members, such as individual emergency locator transmitters, should be evaluated. Similarly, continued survival training of crews is recommended as is inclusion of short duration survival kits to aid crew members in surviving until search and rescue arrives.

Here we report the first survival of any animal following atmospheric breakup of the spacecraft supporting it. While *C. elegans* is three orders of magnitude smaller than humans and can withstand considerably larger G forces, its survival clearly demonstrates that atmospheric spacecraft breakup is survivable. This demonstration highlights the need to carefully evaluate existing search and rescue procedures as well as crew survival systems for inadequacies that may have arisen due to the belief that spacecraft breakup is not survivable. "These things we do that others may live"

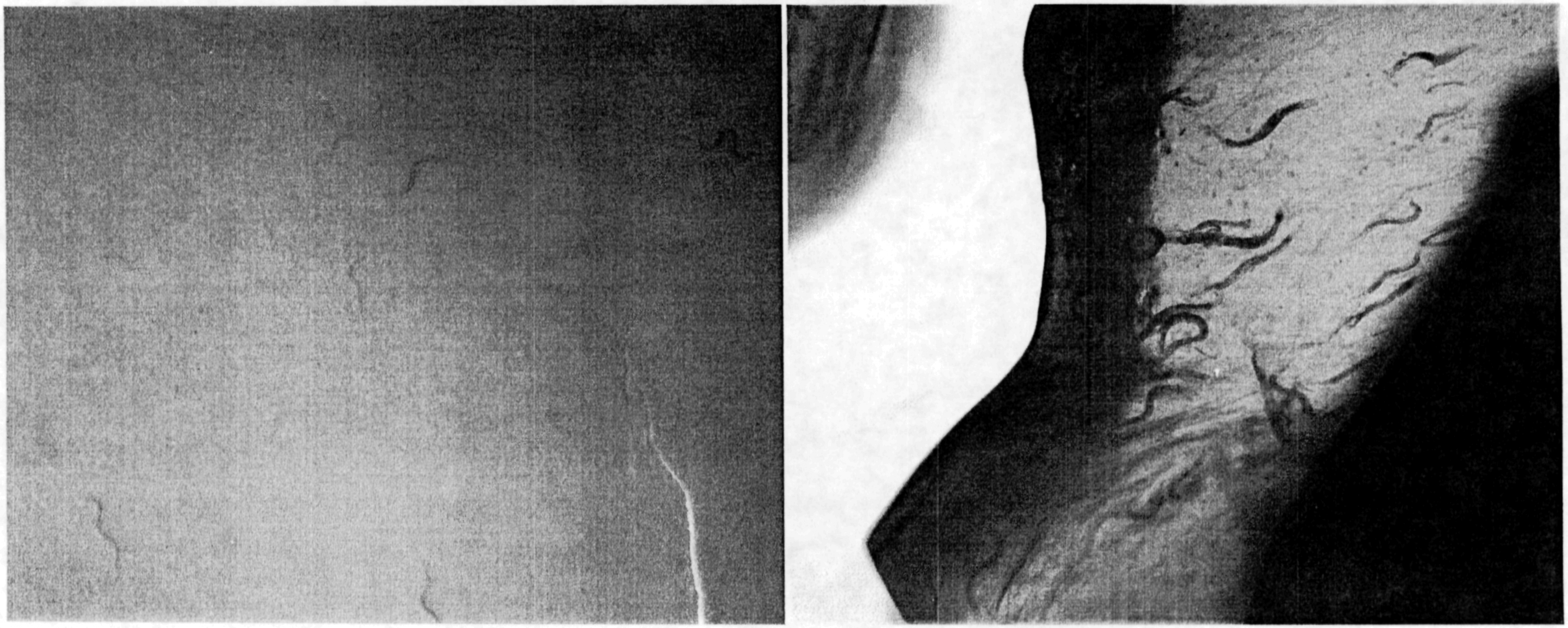

Figure 1: *C. elegans* survived the atmospheric breakup of the Space Shuttle Columbia. Dauer animals that had been grown on Nematode Growth Medium are shown on the left. Reproductive animals that had been grown on *C. elegans* Maintenance Medium are shown on the right. The damage to the agar in the right panel is presumably due to forces associated with impacting the Earth's surface. Photographs were taken one hour after opening recovered flight hardware, which was approximately three months after the breakup of Columbia.

In Memoriam

STS-107
R. Husband, W. McCool, D. Brown, L. Clark, I. Ramon, M. Anderson, K. Chawala

STS-51L
F. Scobee, M. Smith, E. Onizuka, J. Resnik, R. McNair, G. Jarvis, C. McAuliffe

Soyuz 11
G. Dobrovolsky, V. Patsayev, V. Volkov

Soyuz 1
V. Komarov

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