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CONCEPTS

Surviving Atmospheric Spacecraft Breakup

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Spacecraft travel higher and faster than aircraft, making breakup potentially less survivable. As with aircraft breakup, the dissipation of lethal forces via spacecraft breakup around an organism is likely to greatly increase the odds of survival. By employing a knowledge of space and aviation physiology, comparative physiology, and search-and-rescue techniques, we were able to correctly predict and execute the recovery of live animals following the breakup of the space shuttle *Columbia.* In this study, we make what is, to our knowledge, the first report of an animal, *Caenorhabditis elegans*, surviving the atmospheric breakup of the spacecraft that was supporting it and discuss both the lethal events these animals had to escape and the implications for search and rescue following spacecraft breakup.

Key words: Caenorhabditis elegans, rescue work, disasters, life-support systems, astronauts, space flight

Introduction

On February 1, 2003, the space shuttle *Columbia* broke up while reentering the Earth's atmosphere. *Columbia* was in the mesosphere approximately 61 km above the Earth's surface while traveling at approximately Mach 19 at the time of the main body breakup.[1] On the shuttle middeck was a passive *Caenorhabditis elegans* life-support experiment, namely the Biological Research in Canisters (BRIC-14)/*C elegans*, which was stowed in the BRIC accessories (ACC) half locker.[2] The loss of spacecraft structural integrity during the breakup exposed all animals onboard to potentially lethal factors, including shear forces, heat, shock wave(s), freezing, explosive decompression, anoxia, cosmic radiation, impact with the Earth, starvation, and environmental toxicity.[3] Despite these factors, *C elegans* survived the atmospheric breakup of *Columbia.*

Containing reproductive, nervous, muscular, and digestive systems,[4] the soil nematode *C elegans* is considered a model system for biomedical research.[5] The experiment onboard Space Transportation System Flight No. 107 (STS-107), *Columbia,* was designed to validate the on-orbit growth of *C elegans* on a media that permitted the automation of experimentation.[6] This experiment was considered an important step in establishing *C elegans* as a model system for space life science research, because the automation of such experimentation is desirable for space life science experiments.[7] Full details of the experiment, its packaging, and the hardware recovery and analysis will be presented elsewhere.

Tragically, *Columbia*'s breakup was not an event that could be survived by her crew.[8] The discussion of rescue practices and the observation of postbreakup video aired by the media led us to suspect that *C elegans* had survived. Survival required escape of lethal events associated with any catastrophic forces associated with breakup, exposure to the atmosphere, and impact with the Earth's surface. Additionally, if *C elegans* had survived, they would need to survive until we or others recovered them and ensured that they were alive. In this study, we discuss the lethal events these animals had to escape, our reasons for believing they had, and the implications for future search and rescue.

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Surviving breakup and exposure to the atmosphere

Under normal operating conditions, spacecraft and life-support systems are designed to protect occupants from lethal events associated with exposure to the atmosphere and the lack thereof.[9] Travel away from the Earth's surface results in a progressive loss of atmospheric pressure, an increased potential for exposure to ionizing ra-

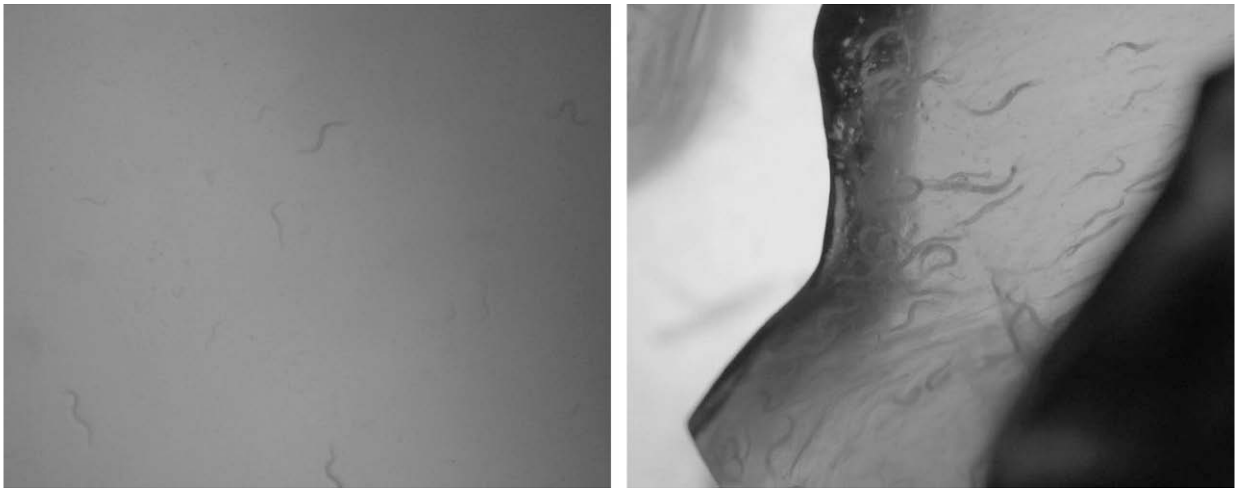
Time line of events

Date	*Event*
January 15, 2003	Animals loaded into canisters
January 16, 2003	*Columbia* launch
January 26, 2003	Canisters observed in on-orbit video of another experiment
February 1, 2003	Breakup of *Columbia*
	Video of intact flight hardware other than the canisters
February 7, 2003	Canister 2 recovered
February 10, 2003	Canister 3 recovered
February 14, 2003	Canister 4 recovered
February 17, 2003	Canister 5 recovered
March 21, 2003	Canister 1 recovered
April 24, 2003	Canister access granted by Columbia Accident Investigation Board
April 28, 2003	Canisters opened and live *Caenorhabditis elegans* observed

diation, and a temperature cycling as crews travel through the troposphere, stratosphere, mesosphere, thermosphere, and exosphere.[10] Spacecraft have carried crews to a number of operational distances from the Earth's surface, thereby exposing crews to different potential stressors.[3,11] During these travels, life-support systems were required to maintain appropriate atmospheric gas pressure and composition, humidity, and temperature; additionally, in many cases, life-support systems were required to maintain water supply and to manage waste.[12] Because of the essential nature of life-support systems, redundancies and backup systems exist, as do rescue systems, which are designed to be used in the event of certain foreseeable emergencies.[12–15] While traveling away from or returning to the Earth's surface, crews are also subjected to acceleration and deceleration forces.[3,11] These forces vary with spacecraft and mission and are of concern when designing spacecraft, life-support systems, and rescue systems.[11,16] Lastly, during reentry, frictional heating is a concern as spacecraft return to denser atmospheres.[11]

It would seem that the longer the spacecraft and life-support systems survive a breakup, the more likely it is that the breakup will be survivable. Following *Columbia*'s breakup, video aired by the media showed that large, recognizable debris had survived the breakup and suggested the likelihood that intact or reasonably intact canisters containing live *C elegans* would be recovered. Experienced aircraft rescue workers know that intact debris is suggestive of a greater likelihood of survival, and we suggest the same is true for spacecraft. We suspected the spacecraft survived long enough to protect its *C elegans* occupants from some of the aerodynamic shear forces, frictional heat, shock waves associated with deceleration and decompression of the cabin, and freezing temperatures of the upper atmosphere. Work performed by the Columbia Accident Investigation Board suggests this is at least partially true. Reconstruction suggests that the canisters housing *C elegans* exited the *Columbia* at 660 to 1050 $km \cdot h^{-1}$, 42 to 32 km above Earth,[8] as opposed to the speed and altitude of the main body breakup, which was Mach 19 and 61 km, respectively.

Soyuz 11 tragically demonstrated that cabin decompression can result in anoxia and crew death.[3,14] Despite this tragedy, not all spacecraft designs proposed since *Soyuz 11* have called for the use of spacesuits while traveling through the atmosphere.[13] Spacesuits are protective, and rescuers should expect a greater potential for successful crew rescue following atmospheric breakup when suits are worn. Unlike humans, *C elegans* can withstand up to a day of anoxia.[17] Therefore, the loss of atmosphere due to decompression was not a concern for the recovery of live worms. Although it has now been shown that the explosive failure of the *Columbia* crew module did not occur,[8] we felt that if the animals were to have survived, the canisters would have had to protect them from such a hazard. The flight hardware was designed to withstand a maximum decompression rate of 62.1 $kPa \cdot min^{-1}$ before exhibiting structural damage. Thus, the video showing the intact flight hardware from the middeck and the later reported identification of intact canisters bolstered our efforts to recover live *C elegans* (Table). Although the canisters housing the animals were not specifically designed to protect them from aerodynamic shear forces and frictional heat, analysis of the recovered canisters, which we will report elsewhere, and the Columbia Accident Investigation Board's reconstruction work[8] suggest that they did protect them. We suggest that the future use of spacesuits designed to withstand reentry independently,[18] encapsulating escape systems,[13,19] or techniques that prevent the structural failure of spacecraft crew compartments in response to thermal



Caenorhabditis elegans survived the atmospheric breakup of the space shuttle Columbia. Recovered animals grown on nematode growth medium are shown on the left and are arrested at the dauer or L1 stage. Recovered animals grown on *C elegans* maintenance medium are shown on the right and are reproductive. The damage to the agar in the right panel is presumably due to forces associated with impacting the Earth's surface. The animals shown are from flight canister 1 and were deposited with the *C elegans* stock center. Photographs were taken approximately 3 hours after opening recovered flight hardware, which was approximately 3 months after the breakup of Columbia.

degradation[8] indicates greater potential for successful crew rescue.

Many animals, including humans and *C elegans*,[20] have survived spaceflight with minimal-to-moderate radiation protection. Given the short duration of return to the Earth's surface following atmospheric breakup, exposure to cosmic radiation should not be an immediate concern for search-and-rescue operations. Although the data we will present elsewhere suggest that radiation exposure did not have long-term effects on at least some of the *C elegans* that survived the breakup, the inclusion of radiation protection in spacesuits worn by crews while traveling through the atmosphere seems prudent.

Surviving impact with the Earth's surface

Even though surface impact is likely the proximate cause of death in both the *Soyuz 1* and STS-51L (*Challenger*) tragedies,[3,14] we were not concerned that *C elegans* would be killed on impact, as they can withstand brief exposure to 100 000 gravities (L. Avery, unpublished data, 1987). With respect to the rescue of future spacecrews, we suggest, as is already known for aircraft crash rescue, that surface impact need not be a lethal event. Although in-flight crew egress from a breaking-up or crashing spacecraft is likely to indicate an increased probability of survival, the lack of signs of egress should not be assumed to indicate the lack of crew survival. Similarly, although future spacecraft designs should continue to consider egress systems for both structurally intact and damaged spacecraft, 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 in their design should be considered to have a higher probability of survival.

Surviving until recovery

As with the survival of aircraft breakups and crashes, spacecrews must survive not only the immediate event but also the interim until search-and-rescue crews arrive. *C elegans* can survive 6 months in the absence of food by entering a "dormant"[6] dauer state.[21] Starvation was not a concern, provided we recovered the animals within 6 months, as was the case (Table). As shown in the left panel of the Figure, animals grown on nematode growth media (NGM)[22] were indeed dauer. Some were also growth arrested in the first larval stage, as is seen in response to starvation. As shown in the right panel of the Figure, animals grown on *C elegans* maintenance media (CeMM)[23] were actively reproducing, which indicates that these animals had not yet exhausted the food source. Presumably, the animals grown on NGM were born in orbit and entered the dauer state as the result of an expected exhaustion of food during the spaceflight, whereas the animals grown on CeMM were several generations removed from those born in orbit. An exact analysis of the number of generations that the CeMM-grown animals were removed from the breakup of the shuttle is complicated by a number of factors, including the invasion of the flight hardware that contained the organisms by an airborne imperfect mold capable of killing *C elegans*. As previously stated, additional details of the experiment, its packaging, and the hardware recovery and analysis will be presented elsewhere. What is remarkable and relevant to this report is that these animals survived despite both the factors previously discussed and the wide postimpact temperature variation. *C elegans* is typically grown on NGM at 16°C to 25°C, where a linear relationship between temperature and life span exists, whereas at 6°C, animals fail to reach reproductive maturity.[24] Temperatures recorded inside the recovered canisters, by autonomous data loggers, indicate average daily temperatures of 4.1°C to 19.7°C prior to recovery.

The US and Russian manned space programs are aware of the survival concerns that exist following spacecraft touchdown and in-flight egress, if not also breakup. Both provide crews with survival training and gear. We suspect the same is true of the Chinese manned space program but not true of all of the X Prize competitors. The recent return of the Expedition 6 crew members via a Soyuz spacecraft highlights the fact that the arrival of search-and-rescue teams may be delayed, even for spacecraft that do not break up and crews that are not in immediate danger. The survival training of crews and the inclusion of survival kits should be considered to increase the probability of survival. As is true for aircraft ejection, survival gear physically stored with a crew member is more likely to be accessible following breakup than is gear stored elsewhere in the spacecraft. Furthermore, gear protected by encapsulation or by being within a spacesuit is more likely to survive a breakup. Analysis of crew training, survival gear, physical proximity of gear to crew, and location of spacecraft breakup should give rescuers an idea of how long the crew is likely to be able to survive in the absence of immediately life-threatening injuries.

We propose that for spacecraft breakup, as is standard with all search-and-rescue missions, elapsed time is a factor in determining the survivability of life-threatening injuries. Therefore, the use of measures to increase the efficiency of locating surviving crew members, such as individual emergency locator transmitters and differential global positioning systems, can be critical. Specifically, the use of active signals from such devices is often associated with the increased survivability of life-threatening injuries following spacecraft breakup. In the absence of active signals from such devices, we propose that standard aircraft search-and-rescue techniques will prove useful, as was the case for *C elegans*.[25] To aid in searches for spacecrews, teams should be familiar with spacecraft design or be supplemented with individuals knowledgeable about the spacecraft. Such knowledge is essential for focusing search efforts on regions that are associated with a higher likelihood for successful rescue. For incidents occurring in areas where the media are likely to be active, such as was the case with *Columbia,* the use of spacecraft knowledge while media broadcasts are being monitored should also aid in the partitioning of search-and-rescue resources. The discovery of live biological payloads following breakup may signal an increased probability of crew survival. However, unless individuals who are knowledgeable about the biological payloads are in close proximity to search efforts, the analysis of biological payloads is more likely to be productive in reconstruction than in search efforts.

Conclusion

To our knowledge, we report the first survival of an animal following the atmospheric breakup of the spacecraft that was supporting it. Its survival clearly demonstrates that atmospheric spacecraft breakup is an event that can be survived. Animals differ in size and have different physiologic systems, requirements, and tolerances. As a result, animals have different potentials for surviving an atmospheric spacecraft breakup. Reconstructive work on other biological payloads onboard *Columbia* has not been published, making it inappropriate for us to comment on their fate. When space travel was first attempted, animals were used to probe the human physiologic ability to survive spaceflight.[11] We hope that the survival of *C elegans* during breakup will be viewed in a similar fashion. We agree with the suggestion[8] that spacecrews could survive atmospheric spacecraft breakup given appropriate levels of protection. Our observations highlight the need to carefully evaluate existing search-and-rescue procedures as well as crew survival systems for inadequacies that may have arisen because of the belief that spacecraft breakup is not survivable. "These things we do, that others may live"—US Air Force Rescue Coordination Center.

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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