Research Paper
Lichens Survive in Space: Results from the 2005 LICHENS Experiment

LEOPOLDO G. SANCHO,1 ROSA DE LA TORRE,2 GERDA HORNECK,3 CARMEN ASCASO,4 ASUNCIÓN DE LOS RIOS,4 ANA PINTADO,1 J. WIERZCHOS,5 and M. SCHUSTER6

ABSTRACT
This experiment was aimed at establishing, for the first time, the survival capability of lichens exposed to space conditions. In particular, the damaging effect of various wavelengths of extraterrestrial solar UV radiation was studied. The lichens used were the bipolar species Rhi- 
zocarpon geographicum and Xanthoria elegans, which were collected above 2000 m in the mountains of central Spain and as endolithic communities inhabiting granites in the Antarctic Dry Valleys. Lichens were exposed to space in the BIOPAN-5 facility of the European Space Agency; BIOPAN-5 is located on the outer shell of the Earth-orbiting FOTON-M2 Russian satellite. The lichen samples were launched from Baikonur by a Soyuz rocket on May 31, 2005, and were returned to Earth after 16 days in space, at which time they were tested for survival. Chlorophyll fluorescence was used for the measurement of photosynthetic parameters. Scanning electron microscopy in back-scattered mode, low temperature scanning electron microscopy, and transmission electron microscopy were used to study the organization and composition of both symbionts. Confocal laser scanning microscopy, in combination with the use of specific fluorescent probes, allowed for the assessment of the physiological state of the cells. All exposed lichens, regardless of the optical filters used, showed nearly the same photosynthetic activity after the flight as measured before the flight. Likewise, the multimicroscopy approach revealed no detectable ultrastructural changes in most of the algal and fun- 
gal cells of the lichen thalli, though a greater proportion of cells in the flight samples had compromised membranes, as revealed by the LIVE/DEAD BacLight Bacterial Viability Kit. These findings indicate that most lichenized fungal and algal cells can survive in space after full exposure to massive UV and cosmic radiation, conditions proven to be lethal to bacteria and other microorganisms. The lichen upper cortex seems to provide adequate protection

1Departamento de Biología Vegetal II, Universidad Complutense, Madrid, Spain.
2Instituto Nacional de Técnica Aeroespacial, Torrejón, Madrid, Spain.
3Institute of Aerospace Medicine, German Aerospace Center DLR, Köln, Germany.
4Centro de Ciencias Medioambientales, CSIC, Madrid, Spain.
5Servei de Microscopia Electrónica, Universitat de Lleida, Spain.
6Universität Erlangen-Nürnberg, Ökophysiologie der Pflanzen, Erlangen, Germany.
**INTRODUCTION**

Exobiology experiments are directed toward the possibility of the presence or survival of life beyond the confines of Earth. Interplanetary space is especially interesting because of the potential for testing Panspermia. The Panspermia theory holds that reproductive bodies of living organisms can exist throughout the universe and develop wherever the environment is favorable (Richter, 1865; Arrhenius, 1903). In recent years, the Panspermia theory has been reformulated in terms of the Lithopanspermia hypothesis, which postulates that microorganisms that reside within impact ejecta could be transported between planets (Fajardo-Cavalzos et al., 2005). Spores of *Bacillus subtilis* can survive years of exposure to space in low-Earth orbit (Horneck, 1993; Horneck et al., 2001; Rettberg et al., 2002), shock and heat of simulated impact (Horneck et al., 2001; Burchell et al., 2004), and hypervelocity atmospheric entry (Fajardo-Cavalzos et al., 2005). However, a major criticism of interplanetary transfer of life is that the extremely harsh conditions of interplanetary space, mainly massive UV and cosmic radiation, are lethal to all forms of life. Experiments led by the European Space Agency (ESA), however, have shown that some terrestrial organisms can survive this highly extreme environment if there is sufficient shielding from UV radiation (Horneck et al., 1984; Mancinelli et al., 1998; Mancinelli and Klovstad, 2000). In a study by Rothschild and Mancinelli (2001), however, only 25%–40% of halophilic Archaea and cyanobacteria survived after two weeks of exposure to the Sun in outer space, and Bertolani et al. (2001) found that multicellular eukaryotic organisms like nematodes perish when directly exposed to the Sun.

Many lichen species are regarded as extremophiles in terms of their tolerance to temperature, radiation, and desiccation. In high mountains and polar regions, lichens are well adapted to long-term desiccation, temperatures between −40 °C and 60 °C, and high radiation, including UV (Green et al., 1999; de la Torre et al., 2002; Heber et al., 2006). Dry lichens can recover after 10 years of inactivity and are able to survive against solar radiation. Moreover, after extreme dehydration induced by high vacuum, the lichens proved to be able to recover, in full, their metabolic activity within 24 hours. Key Words: Lithopanspermia—Exobiology—Lichens—BIOPAN experiment. Astrobiology 7, 443–454.

**MATERIALS AND METHODS**

Thalli of *Rhizocarpon geographicum* on natural rock were collected in the mountains of central Spain (La Plataforma, Sierra de Gredos, Avila, Spain; 2020 m above sea level, 40°16’ N, 5°14’19” W), and thalli of *Xanthoria elegans* were collected from their rock habitat in the Sierra Nevada Mountains of southern Spain (Peñones de San Francisco, Sierra Nevada, Granada, Spain; 2400 m above sea level, 37°06’ N, 03°23’ W). Pieces of granite rock that contained endolithic lichens were collected in continental Antarctica (Granite Harbour, Ross Sea Coast, Antarctica; 150 m above sea level, 77°00’ S, 162°34’ E). Cylindrical rock samples (10 mm in diameter and 6.9 mm in
height) that contained epilithic or endolithic lichens were cut out of larger rocks with a diamond point saw continuously cooled with running water. Only those areas of the rock that showed a rich population of lichens were selected for the LICHENS experiment. The diameter of these samples was chosen so that they coincided with the diameter of the optic fiber of the fluorometer system, which would allow for homogeneous measurements of the whole thallus during successive experiments.

Experimental design

As part of the FOTON-M2 mission, launched from Baikonur on May 31, 2005, on board a Soyuz rocket, material for the LICHENS experiment was included in the ESA facility BIOPAN. BIOPAN is a multi-user exposure facility, designed for exobiology, radiation biology, radiation dosimetry, and material science investigations in space (Fig. 1). BIOPAN is installed on the external surface of the FOTON descent capsule that protrudes from...
the thermal blanket that covers the satellite. The mission profile of the facility, described in Demets et al. (2005) and Baglioni et al. (2007), includes late installation at the launch site and early retrieval after landing. BIOPAN is equipped with a motor-driven hinged lid that, during nominal operations, opens 180° in orbit to expose the samples within to the harsh space environment. In BIOPAN, the test samples are exposed to a basic menu of microgravity and cosmic radiation, with exposure to space vacuum and/or solar UV radiation as optional additions.

The hardware to which lichens were fixed was designed and constructed by INTA (Spanish Aerospace Establishment, Madrid, Spain). The sample carrier consisted of two sample plates (78 × 50 × 23 mm) for the accommodation of lichen samples (nos. 2 and 3 in Fig. 2) and a cover plate (80 × 50 × 3 mm), which gave support to screw heads and the optical filters below its circular holes (no. 1 in Fig. 2). Each sample plate was comprised of 12 cells that housed the lichen samples; vent holes made for a direct interaction with the space vacuum. Ventilation holes passed through all three plates and were left open during the entire space flight. The top layer (no. 2 in Fig. 2) allowed for exposure of the lichen samples to the full space environment, which included selected wavelength ranges of extraterrestrial solar UV and VIS radiation. To expose the samples to a discrete number of wavelengths, each sample cell was covered with an optical filter (13 mm diameter and 2 mm thick). Assembly was as follows: 3 cells with a Suprasil SQ0 quartz window allowed transmission of wavelengths at λ > 170 nm; 3 cells with a long pass filter allowed transmission of UV at λ > 280 nm; 3 cells with a long pass filter allowed transmission of UV at λ > 320 nm; and 3 cells exposed the samples to VIS (λ > 400 nm). The bottom layer (no. 3 in Fig. 2) accommodated an identical set of lichen samples, which experienced the same space exposure conditions as those in layer 2 except for exposure to solar UV and VIS radiation. They served as in-flight dark controls. For thermal control, the cover plate (plate no. 1 in Fig. 2) was painted white (SG-121 FD®) to reflect radiation. We used standard space materials, ISO AlMgSi, an aluminum alloy, for fabrication of the hardware, which had a final area of 78 × 50 mm and a total mass of 250 g.

Cylindrical biological membranes of polysulfon (Berghof und Anlagetechnik GmbH), with a pore size of 100,000 daltons, were positioned inside the sample cells to avoid contamination between the experiments integrated in BIOPAN. For fixation of the lichen samples in the hardware cells, we used Scotchweld® and Silicone RTV566® glue mixed with Primer SS41565® (General Electric Silicones Europe).

The lichens were exposed to the space environment for two weeks while in Earth orbit aboard the BIOPAN facility. An identical set of hardware with lichens was produced and kept for the same period in the laboratory at ambient conditions (air, 20 °C) and in darkness to serve as laboratory ground control (Earth control). During the mission all samples were in an anabiosis state caused by natural dehydration.

**Fluorescence analysis**

On June 16, immediately after landing in the region of Kostanay (Kazakhstan), the BIOPAN was detached from the FOTON capsule and sent to the European Space Research and Technology Centre (Nordwijk, the Netherlands). The BIOPAN was opened on June 19 in the ESTEC clean room, and the experiments were returned to the corresponding researchers. The following day, we started the rehydration and revitalization process under controlled conditions in our laboratory facilities in Madrid. These consisted of maintaining probes in a climatic chamber at a temperature of 10 °C and a 12 h dark / 12 h light cycle treatment for 72 h. This photosynthetically active light (400–700 nm) was obtained from a mercury lamp that reached the probes at around 100 μmol m⁻² s⁻¹ photosynthetic photon flux density (PPFD). The sample chambers were sprayed with 25 ml of deionized water twice a day. Fluorescence measurements were carried out two or three hours after spraying the lichens with water.

Survivability was determined first by measuring the quantum yield activity of photosystem II, assessed by fluorescence measurements of chlorophyll a, using a MiniPAM (Walz, GmbH, FRG) (Maxwell and Johnson, 2000). The measuring and saturation light passed through a fiber optic cable held at an angle of 60° to the lichen surface. The cable had nearly the same diameter as the lichen sample (10 mm) to allow better replicates of the same measurements. Potential maximal photosystem II (PSII) quantum yield (Fv/Fm = variable fluorescence / maximal fluorescence)—for nomenclature see van Kooten and...
Snel (1990)—was measured after the samples had been kept for 20 min in darkness, so that all reaction centers were open (Schreiber et al., 1994). Due to physical constraints, fluorescence cannot be obtained from the rock samples that contained the endolithic algae. Fluorescence and electron microscopy techniques allowed us to evaluate the integrity of the algae and fungi of both endolithic and epilithic lichens.

Microscopy analysis

Confocal scanning laser microscopy. Samples were analyzed with a Zeiss LSM 310 confocal microscope. Fluorescence assays and determination of the proportion of living and dead cells were performed on fragments of lichen thalli immediately after the photosynthetic experiments were finished according to the protocol described in de los Ríos et al. (2004). The LIVE/DEAD BacLight Bacterial Viability Kit L-13152 (Molecular Probes) was used to distinguish living cells from cells with compromised cell membranes, the latter interpreted as dead mycobiont and photobiont cells. This kit contains two proprietary nucleic acid stains that differ in their ability to penetrate bacterial cell membranes. The green fluorescence nucleic acid stain, SYTO 9, labels all cells, and the red fluorescence nucleic acid stain, propidium iodide, only penetrates cells with damaged membranes and quenches the green SYTO 9 stain. As noted, we interpreted cells that were fluorescing green as viable, and those that were fluorescing red as dead, though the test only gives an indication of the integrity of the cell membrane. The fluorescence intensity of living and dead microorganisms was determined by CSLM double-channel or three-channel scanning. An argon laser was used to generate an excitation wavelength of 488 nm, whereas the resultant emission of living microorganisms (SYTO 9) was filtered through a 515–545 nm band pass filter and that of dead ones (propidium iodide) through a 575–640 nm band pass filter. On occasion, the signal of algal autofluorescence was also collected by filtration with a >570 nm long pass filter. Each channel was displayed in a single color (green, red, and blue, respectively).

Low-temperature scanning electron microscopy. Untreated lichens were examined using the low-temperature scanning electron microscope (LTSEM). Small lichen fragments were mechanically fixed onto the specimen holder of the cryo-transfer system (Oxford CT1500), plunged into sub-cooled liquid nitrogen, and then transferred to the preparation unit via an airlock transfer device. The frozen specimens were cryo-fractured and transferred directly via a second air lock to the microscope cold stage, where they were etched for 2 min at −90 °C. After ice sublimation, the etched surfaces were gold-sputter coated in the preparation unit. Samples were subsequently transferred onto the cold stage of the SEM chamber. Fractured surfaces were observed using a Zeiss DSM960 SEM microscope operating at −135 °C with 15 kV acceleration potential, 10 mm working distance, and 5–10 nA probe current.

Transmission electron microscopy. Small lichen fragments were fixed in glutaraldehyde and post-fixed in osmium tetroxide solution, dehydrated in a graded ethanol series, and embedded in Spurr’s resin following the protocol described in de los Ríos and Ascaso (2002). Ultrathin sections were post-stained with lead citrate (Reynolds, 1963) and observed in a Zeiss EM910 scanning transmission electron microscope (STEM) operating in transmission electron microscope mode at 100 kV.

Table 1. Flight and Environment Data of the Lichens Experiment During the ESA BIOPAN-5 Mission Lasting 14.8 Days on the Russian Satellite Foton-M2

<table>
<thead>
<tr>
<th>Temperature range (°C)</th>
<th>Solar constant hours</th>
<th>Solar PAR&lt;sup&gt;a&lt;/sup&gt; (kJ m&lt;sup&gt;2&lt;/sup&gt;)</th>
<th>Solar PAR&lt;sup&gt;b&lt;/sup&gt; (kJ m&lt;sup&gt;2&lt;/sup&gt;)</th>
<th>Solar UV&lt;sup&gt;c&lt;/sup&gt; (kJ m&lt;sup&gt;2&lt;/sup&gt;)</th>
<th>Solar UV&lt;sup&gt;d&lt;/sup&gt; (kJ m&lt;sup&gt;2&lt;/sup&gt;)</th>
<th>Solar UV&lt;sup&gt;e&lt;/sup&gt; (kJ m&lt;sup&gt;2&lt;/sup&gt;)</th>
<th>Ionization radiation (µGy/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>−21.7 to +21.8</td>
<td>58.78</td>
<td>133,144</td>
<td>22,473</td>
<td>18,893</td>
<td>2,908</td>
<td>671</td>
<td>213.36</td>
</tr>
</tbody>
</table>

<sup>a</sup>Photosynthetically active radiation
<sup>b</sup>UV-A: 315–400 nm
<sup>c</sup>UV-B: 280–315 nm
<sup>d</sup>UV-C: 200–280 nm
RESULTS

During the two-week BIOPAN flight, lichens were exposed to the space conditions listed in Table 1. Along with the vacuum of space, they received different ranges of the spectrum of extraterrestrial solar electromagnetic radiation, which included the highly energetic vacuum-UV (>170 nm) at a total amount of about 22 MJ m\(^{-2}\), which is equivalent to 44 h insolation at the distance of the Earth (Fig. 3). They were also exposed to cosmic radiation with a total dose of about 3 mGy. The satellite orbited the Earth every 90 min, which resulted in exposure to the Sun for approximately 60 min and the protection of Earth’s shadow for 30 min. These orbit characteristics made for a temperature fluctuation of about 10 °C per orbit (Fig. 4). The maximum oscillation of the temperature from launch to landing was nearly 42 °C (−21° to +21 °C). These extreme temperatures, though dramatic, are in fact rather moderate in comparison to the natural Earth-bound conditions experienced by the selected lichens.

Potential PSII activity recovered rapidly after wetting the desiccated thalli. The dehydrated thalli reached 90% of final maximum activity after a short recovery phase of 3 h. All exposed lichens, regardless of the optical filters used, showed nearly the same photosynthetic activity after the flight as was measured before the flight (Fig. 5). The photosynthetic activity of the lichens exposed to solar UV and VIS radiation was also similar to that shown by the in-flight dark controls as well as that of the Earth control. Flight samples as well as Earth controls of the studied species, *Rhizocarpon geographicum* and *Xanthoria elegans*, largely recovered their photosynthetic activity 3 h after spraying with water. After 24 h under revitalization conditions, all samples fully recovered their photosynthetic activity comparable to that measured before flight (Fig. 5, Table 2).

A multimicroscopy approach has revealed that most of the different lichenized algal and fungal cells, which form the lichen thalli of both species, survived exposure to space conditions (Figs. 6–11). These lichen thalli after the flight were made up of living and dead symbiont cells as shown by confocal scanning laser microscopy of the LIVÉ/DEAD BacLight kit stained samples (Figs. 6–7). The staining revealed that a significant proportion of the algal symbiont cells (83% of photobiont cells in *Xanthoria* thalli and 71% in *Rhizocarpon* geographicum thalli) survived the space mission.
LICHENS SURVIVE IN SPACE

FIG. 4. Temperature profile of the LICHENS experiment during the BIOPAN-5 mission.

FIG. 5. Maximal quantum yield of photosystem II, before and after the flight, of *Rhizocarpon geographicum* (a) and *Xanthoria elegans* (b). After the flight, lichens were reactivated under controlled conditions as described in the text, and their yield was measured after 3 h and 24 h. White and gray bars represent Earth controls and in-flight dark controls, respectively. Samples exposed to extraterrestrial solar electromagnetic radiation are listed under “exposed.” The patterns indicate the different wavelength ranges.
**Rhizocarpon** did not show damage in the membrane after 2 weeks of exposure to space conditions (Fig. 6). Approximately 60% of the mycobiont cells of both species showed intact membranes, which we interpret to mean that the cells were viable (Fig. 7). In addition, there was no evidence of striking ultrastructural changes in the algal and fungal cells in the different layers of these lichen thalli when imaged with the LTSEM (Figs. 8–9) and TEM (Figs. 10–11): cellular integrity had not been lost nor had severe plasmolysis occurred. It is especially interesting that cells of the outer layers of the lichen, which were exposed more directly to space conditions, and the fungal cells, which formed the upper cortex of the lichen thalli, showed the same cellular integrity and ultrastructure as those in the Earth control (Figs. 9–11). It is likely that the cortex provided a protective “blanket” for the cells.

**DISCUSSION**

Living cells in an interplanetary journey are subjected to the damaging effects of extreme vacuum, extraterrestrial solar UV radiation, cosmic ionizing radiation, and a wide range of temperatures (Nicholson *et al.*, 2000; Nicholson *et al.*, 2005). Since high-vacuum conditions produce an extreme dehydrating effect, they have been considered to be one of the most lethal factors of the space environment. However, different living forms seem to be well adapted to survive long periods of desiccation in space. For example, most of the exposed spores of *Bacillus subtilis* survived after a short exposure (10 days) to space vacuum (Horneck, 1993), and 70% of these spores survived after nearly 6 years of exposure (Horneck *et al.*, 1994). Survival of space vacuum has also been reported with regard to the cyanobacterium *Synechococcus* and the extreme halophile *Sancho* *et al.*

### Table 2. Quantum Yield Activity of Photosystem II of Lichens on Natural Rock Substrates Measured Before and After the BIOPAN-5 Mission

<table>
<thead>
<tr>
<th>Lichen species</th>
<th>Earth control (before)</th>
<th>Earth control (after)</th>
<th>In-flight dark control (before)</th>
<th>In-flight dark control (after)</th>
<th>Flight sample exposed to λ &gt; 170 nm (before)</th>
<th>Flight sample exposed to λ &gt; 170 nm (after)</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Rhizocarpon geographicum</em></td>
<td>668.5 ± 20.0</td>
<td>671.5 ± 26.9</td>
<td>657.5 ± 40.7</td>
<td>674 ± 22.1</td>
<td>684</td>
<td>690</td>
</tr>
<tr>
<td><em>Xanthoria elegans</em></td>
<td>695.7 ± 26.1</td>
<td>688.7 ± 49.7</td>
<td>659.2 ± 22.8</td>
<td>663.5 ± 23.9</td>
<td>739</td>
<td>738</td>
</tr>
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*Measurements after the flight were taken after 24 h of revitalization process.*

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**FIG. 6.** Confocal scanning laser microscope image of the algal layer of *Xanthoria elegans* thalli after the flight, exposed to solar UV and VIS radiation of wavelengths λ > 280 nm stained using the LIVE/DEAD BacLight kit. The nuclei of algae with compromised cell membranes, interpreted as dead cells, appeared red with the propidium iodide stain. Live cells were identified by green nuclei stained with SYTO 9 and by the bright blue signal of autofluorescence. A, algal cells; F, fungal cells; Ap, apothecium. Red arrows indicate dead cells.

**FIG. 7.** Confocal scanning laser microscope image of a group of hyphae from *Xanthoria elegans* thalli after the flight exposed to solar UV and VIS radiation of wavelengths λ > 170 nm stained using the LIVE/DEAD BacLight kit. Dead hyphae appear red from the propidium iodide stain whereas live cells were labelled green with the SYTO 9 stain. A, algal cells; F, fungal cells. Red arrows indicate dead cells.

**FIG. 8.** Low-temperature scanning electron microscope image of the algal layer from *Xanthoria elegans* thallus after the flight exposed to solar UV and VIS radiation of wavelengths λ > 170 nm showing cellular integrity in both the algal cells and cells of the fungal partner. A, algal cells; F, fungal cells.

**FIG. 9.** Low-temperature scanning electron microscope image of the upper cortex from *Xanthoria elegans* thallus after the flight exposed to solar UV and VIS radiation of wavelengths λ > 280 nm. Cells retained their cellular membrane integrity (visualized in non-fractured cells, black arrows) and lacked signs of plasmolysis (visualized in fractured cells, black arrowheads).

**FIGS. 10–11.** Transmission electron microscope images of *Rhizocarpon geographicum* thallus after the flight, exposed to solar UV and VIS radiation of wavelengths λ > 170 nm. Such analysis did not reveal any detectable ultrastructural damage in fungal and algal cells of the algal layer (Fig. 10) or in fungal cells of the upper cortex (Fig. 11). F, fungal cells.
FIGS. 6–11.
Haloarcula (Mancinelli et al., 1998). Pluricellular organisms such as nematodes have also been shown to be desiccation resistant in exobiology experiments (Bertolani et al., 2001). This ability to survive desiccation may be related to the presence of sugars and polyalcohols, which stabilize the cellular macromolecules during extreme dehydration processes (Crowe and Crowe, 1992). Lichens are rich in sugar alcohols, which are assumed to be the basis of their remarkable desiccation tolerance (Kappen and Valladares, 1999). In endolithic Antarctic biofilms, extracellular polymeric substances (EPS) contribute significantly to the intercellular structure and have been proposed as a strategy to avoid desiccation stress (de los Ríos et al., 2001). This ability to survive in space for several hundred thousand years (Horneck et al., 2001).

Ultraviolet radiation has been considered the most damaging factor for living organisms in outer space. The highly desiccation-tolerant spores of Bacillus subtilis are rapidly killed when exposed to the full spectrum of extraterrestrial UV radiation (Horneck et al., 1984; Horneck et al., 2001; Nicholson et al., 2005). Similar results have been obtained for other organisms tested in exobiology experiments, including viruses, bacteria, fungi, and nematodes (Nicholson et al., 2000; Rothschild and Mancinelli, 2001). The green algae Chlamydomonas reinhardtii tested in BIOPAN showed a very low tolerance to UV radiation. All the wild types in that experiment died, even behind a 5% transmission filter. Only when the solar UV was blocked or the total transmission was reduced to not more than 1% were survivors found (René Demets, personal communication). Therefore, the observed full recovery of the photosynthetic activity of the lichenized green algae, even in those exposed to 99% of the extraterrestrial sunlight, was unexpected. The recovery of photosynthetic activity can be partially explained by the combined effects of a thick and dense upper cortex and a high concentration of lichen substances, which also efficiently screened the harmful radiation. A direct relationship between pigment production and light intensity has been well established for alpine and polar lichens (Ahmadjian and Jacobs, 1987; Kappen, 1993). The bright colors of the studied species Rhizocarpon geographicum and Xanthoria elegans are due to rhizocarpic and parietin phenolic acids that accumulate in the upper cortex and may be important in filtering UV radiation (Solhaug et al., 2003; Gaussa and Solhaug, 2004). The high tolerance of some lichens to UV exposure in a desiccated state has been recently attributed to an efficient thermal dissipation mechanism of light energy (Heber et al., 2006).

Cosmic radiation, mainly the heavy ions of high charge Z and high-energy particles (HZE), could easily penetrate even the thick lichen cortex and damage or kill cells (Nicholson et al., 2000). However, due to their low fluence, their deleterious effect strongly depends on exposure time. It has been calculated that, with regard to cosmic radiation, spores of Bacillus subtilis could survive in space for several hundred thousand years (Horneck et al., 2001).

The temperature range of the BIOPAN during the flight fluctuated from $-20$ to $+20$ °C. Since polar-alpine lichens are tolerant of a much wider natural temperature range (Kappen, 1993), no deleterious effect of temperature was expected. These findings suggest that some lichen species may be pre-adapted to cope with the extreme conditions of outer space. Lichen chemistry and thallus structure seem to provide an adequate shield to the effects of both UV radiation and high vacuum. Even though membranes were damaged in some cells, as determined by LIVE/DEAD staining, the rest of the cells remained capable of maintaining the photosynthetic productivity of the lichen. Moreover, after extreme dehydration induced by high vacuum, lichens proved to be able to recover, in full, their metabolic activity in a remarkably short time (24 h). It is difficult, however, to extrapolate these short-term experimental results to a long-term scenario of thousands or millions of years. Accumulated galactic cosmic radiation effects in a dose of 10–50 kGy have been postulated as sufficient to completely sterilize the surface of a meteor (Clark, 2001). The value of this calculation based on laboratory measurements in a long-term space scenario is equivocal (Horneck et al., 2001).

Since we did not detect any clear physiological or structural degradation in the lichens after the two-week exposure to space conditions, we are not able to give any estimate about the half-life of these lichen species in space. Our findings indicate, therefore, that these types of lichens have the capability to survive an ephemeral ejection into space. How long they will retain their viability in the interplanetary environment remains a challenge for future experiments.
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Address reprint requests to:

L.G. Sancho
Departamento de Biología Vegetal II
Facultad de Farmacia
Universidad Complutense
Plaza Ramón y Cajal s/n
28040 Madrid, Spain

E-mail: sancholg@farm.ucm.es