A Cruise-Phase Microbial Survival Model for Calculating Bioburden Reductions on Past or Future Spacecraft Throughout Their Missions with Application to Europa Clipper

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Abstract

During transit between the Earth and planetary destinations, spacecraft encounter conditions that are deleterious to the survival of terrestrial microorganisms. To model the resulting bioburden reduction, a Cruise-Phase Microbial Survival (CPMS) model was prepared based upon the Lunar Microbial Survival model, which considers the effects of temperature, vacuum, ultraviolet (UV), and ionizing radiation found in the space environment. As an example, the CPMS was used to determine the expected bioburden reductions on the Europa Clipper spacecraft upon arrival at Jupiter under two different transit scenarios. Under a direct trajectory scenario, exterior surfaces are rapidly sterilized with tens of thousands of lethal doses (LDs) absorbed to the spacecraft exterior and at least one LD to all interior spaces of the spacecraft heated to at least 240 K. Under a Venus-Earth-Earth gravity assist (VEEGA) trajectory, we find substantially higher bioburden reductions resulting from the spacecraft spending much more time near the Sun and more time in transit overall. With VEEGA, the exterior absorbs hundreds of thousands of LDs and interior surfaces heated above 230 K would absorb at least one LD. From these simulations, we are able to generalize about bioburden reduction in transit on spacecraft in general, finding that all spacecraft surfaces would sustain at least one LD in ≤38.5 years even if completely unheated. Temperature and vacuum synergy dominates surface reductions out to at most 3.3 AU (for gold multilayer insulation), UV irradiation and temperature between 3.3 and 600 AU, and past 600 AU the effect of vacuum acting alone is the primary factor for all exterior and interior surfaces. Even under the most conservative estimates, if the average interior temperature of the Cassini spacecraft exceeded 218 K, or the Galileo spacecraft interior exceeded 222 K, neither spacecraft would have likely had any viable bioburdens onboard at disposal. Key Words: Forward contamination—Planetary protection—Europa Clipper—Bioburden reductions. Astrobiology 20, 1450–1464.

1. Introduction

All planetary exploration spacecraft will, in the course of their missions, pass close to, land upon, or traverse the atmospheres of solar system bodies. For a significant number of these targets, those ranked by the Committee on Space Research (COSPAR) as category III or greater (Kminek et al., 2010, 2017; Frick et al., 2014), forward contamination by terrestrial microorganisms is undesirable. As such, under present planetary protection protocols, steps must be taken to partially clean and sanitize spacecraft that are intended to visit such targets, or whose trajectories bring them sufficiently close to such targets that a loss of spacecraft control could result in an inadvertent crash on those bodies.

Such cleaning and sanitizing protocols are costly and significantly affect the planning and execution of spacecraft missions. Notably, among landed spacecraft, the landing site selection process for the 2020 Exo-Mars rover (Vago et al., 2015) and some aspects of traverse planning for the Mars Science Laboratory (MSL) rover (Witze, 2016) were chosen expressly to avoid special regions (i.e., regions that have a potential to support Earth microbial life, or in which an extant Mars microbiota might reside; Rummel et al., 2014). Furthermore, decontamination procedures can involve techniques, such as extended periods of heating and hydrogen peroxide vapor (Frick et al., 2014; Jones et al., 2016), which may have deleterious effects on spacecraft components and can drive the selection of components.
toward those that can withstand such treatments rather than those components that can deliver the best science with minimal spacecraft resource usage.

The desire to minimize forward contamination is also a significant concern for orbiters. Both the Galileo and Cassini spacecraft were intentionally deorbited into the atmospheres of Jupiter and Saturn (Edgington and Spilker, 2016), respectively, to avoid any chance that the spacecraft might impact any of each planet’s icy moons. The justifiable requirement to dispose of the spacecraft while their instruments still functioned and propellant remained in their tanks nevertheless reduced the length and therefore the science return of both missions.

However, at the time of disposal, did any viable microorganisms remain on either spacecraft? The environmental conditions of deep space are known to be deleterious to microorganisms (Nicholson et al., 2000; Horneck et al., 2010), and it would be expected that the bioburden on spacecraft at launch would be progressively reduced over the course of each mission. To determine how much sanitization of spacecraft is required before launch, and whether proactive disposal is required near the end of life for each mission, it is important to quantify how the bioburden on spacecraft change over the course of their planetary missions. Biocidal action on a spacecraft’s bioburden will be affected by the following: (1) the overall time spent in space, (2) a function of where each spacecraft spends specific time periods (i.e., inner vs. outer solar system residence times), and (3) the extent that exterior surfaces of the spacecraft shield internal bioburden from the biocidal space environment.

Recently, Schuerger et al. (2019) developed a Lunar Microbial Survival (LMS) model to quantify the forward contamination of the Moon resulting from spacecraft that have landed and impacted there. This model included the deleterious effects of the lunar environment on both exterior and interior surfaces, taking into account interior spacecraft shielding. As the lunar and deep space environments share many similarities and all of the deleterious factors, the LMS model formed an ideal basis from which to develop a Cruise-Phase Microbial Survival (CPMS) model for predicting forward contamination of planetary bodies by past or future spacecraft. As such, this article describes the necessary modifications of the LMS to arrive at a general CPMS model. As an example of the utility of the CPMS model, bioburden reductions for the upcoming Europa Clipper (EC) mission were calculated. By design, biocidal activity for microorganism on or within the EC spacecraft after arrival in the intense jovian radiation fields is ignored in the CPMS model.

Note that both the LMS and CPMS should be considered “1st-order models” in that they are based upon a synthesis of a large amount of laboratory data from different studies. As should be expected with a synthesis of this type, some parts of the parameter space have been well explored by multiple groups, while the data in other locations are somewhat sparse. This necessitates interpolation and extrapolation to provide the reader with the best possible complete picture of inactivation due to the interactions of as large a variety of factors as possible, given the currently available work. Furthermore, to simplify the equations, we have limited ourselves to consider only a single species: Bacillus subtilis.

Although additional work is desired with other species to gauge how the interplanetary environment affects microbial survival in a more generalized way, it becomes very difficult to incorporate survival data on multiple species under diverse conditions into a single microbial survival model. Using only data on *B. subtilis* remains valid because most other nonspore-forming species are considered to be significantly more sensitive to the biocidal conditions in space compared with *B. subtilis* (see reviews by Nicholson et al., 2000; Horneck et al., 2010). It is generally assumed that if conditions inactivate populations of spore-forming species such as *B. subtilis*, then most (if not all) other nonspore-forming species found on spacecraft are also likely to be inactivated. In every empirical article that we have considered for this study, plus several review articles on the topic, this assumption is validated. As such, future work will endeavor to validate the CPMS and LMS models in a broader range of conditions and will extend the work to a broader range of species.

## 2. The CPMS Model

### 2.1. Model elements

Schuerger et al. (2019) identified and quantified five groups of factors extant in the lunar space environment (table 2) that are deleterious to microorganisms, including (1) high vacuum, (2) temperature extremes, (3) ultraviolet (UV) radiation, (4) interactions with solar wind particles (SWPs) and occasional solar particle events (SPEs), and (5) galactic cosmic rays (GCRs), including high-mass and high-energy particles (HZEs). Several of these factors can combine together to act synergistically to kill microbial cells or spores. Most notably, the rate of deactivation from synergistic and simultaneous exposure to vacuum (<10⁻⁴ Pa) and high temperature (100°C) was captured in the LMS (Schuerger et al., 2019).

Of the five factors modeled, two were especially significant: UV irradiation, although restricted only to external surfaces, was found to be the most significant biocidal factor in inactivating spores of the bacterium, *B. subtilis*, reaching a lethal dose (*LD*; defined as a −10 log [i.e., 10⁻¹⁰] reduction in viable population; see Schuerger et al., 2019) in as little as 36 min. Temperature and vacuum working together and affecting both external and shallow internal surfaces (defined as those parts of the spacecraft in thermal contact with the spacecraft surface) could produce a *LD* within 8 h. Among the other factors, SPEs, GCRs, and HZEs were not significant for lunar spacecraft missions of typical length (20 years or less), resulting in approximately −1 log of reduction, or less. However, for SWPs, a rate of −3 logs per lunation (29.53 days) on external surfaces only could be expected over the course of each mission. As such, the CPMS will focus on vacuum, heat, UV radiation, and SWPs.

To adapt the LMS into a CPMS model, it is important to examine how the environment experienced by spacecraft in cruise will differ from the environment on the surface of the Moon. There are three key differences. First, spacecraft traveling within interplanetary space will not be partially shielded by the bulk of the Moon and will be directly exposed to SWPs, UV radiation, and solar heating at all times, although only for surfaces aimed toward the Sun. While the exposures to all penetrating ionizing radiation, such as the
GCRs and HZE, are necessarily doubled by this adaptation, these factors still remain relatively small and are ignored in the current CPMS model.

Second, and most importantly, the distance from the Sun over the mission of any particular spacecraft will vary considerably. As such, spacecraft with a trajectory that takes them closer to the Sun than the orbit of Earth (<1 AU) will see external and shallow internal surfaces receive increased rates of solar heating (both surfaces), UV radiation (external surfaces only), and SWPs (external surfaces only). spacecraft traveling away from the Sun will see a corresponding decrease in these radiation and heating effects. It is for this reason that the specific trajectory, and therefore the time spent at each distance from the Sun for any individual spacecraft, is important to model the total LDs from the combined effects of biocidal space conditions.

Finally, in the LMS model, spacecraft were typically treated as passive space vehicles that had ceased functioning and for which there were no active controls exerted over internal temperatures or the spacecraft orientations to the Sun. This situation is not true for spacecraft in a cruise trajectory to a planetary body, in which mission control will actively control internal temperatures and will actively orient the spacecraft, using the Sun as a reference, to achieve mission goals and carry out science operations.

As with the LMS model, this study defines a LD as a reduction in the viable population of microorganisms by a factor of ~10 logs (10^{-10}) (see Schuerger et al., 2019 for a more expansive discussion of the term). Furthermore, this study divides spacecraft into three zones: (1) external surfaces that are directly exposed to the solar and space environments, (2) shallow internal surfaces that are in thermal contact with the exterior of the spacecraft but are shielded from direct exposure to UV radiation or SWPs, and (3) deep internal surfaces whose temperatures are controlled by the spacecraft systems and their allowable flight temperatures.

### 2.2. Model equations

The equations used to construct the CPMS model follow an identical derivation compared with the LMS model (Schuerger et al., 2019). The first calculation deals with the intensity in W per m^2 of UV radiation on any external surface element of a spacecraft in cruise, X, which is a function of the orientation/attitude of that surface element, θ, with respect to the solar vector, s, as well as the mission (i.e., spacecraft clock or SClock) time, t, and thereby the corresponding distance of the spacecraft from the Sun at that time, r(t), compared with the distance of Earth, r_EARTH, from the Sun.

\[
S(s, θ, t) = 26.8 \text{ W m}^{-2} \sin \left( \frac{r_{\text{EARTH}}}{r(t)} \right)^2 \tag{1}
\]

It is the inverse square of the distance from the Sun that modifies this equation from that of Schuerger et al. (2019), which had been based on the works of Schuerger et al. (2003; 2006). Next, Eq. 1 can be used to determine the fractional reduction in bioburden, \( \Delta N_{\text{UV}} \), beginning at time \( t \) occurring over a set amount of time, \( Δt \), due to UV falling on an exterior surface by making use of the biphasic curves for the UV inactivation of *B. subtilis* spores (Schuerger et al., 2019) in an identical manner to Eq. 2 of the LMS model:

\[
\Delta N_{\text{UV}}(t) = \frac{N_{\text{UV}}(t + \Delta t)}{N_0(t)} = 10^{-3.374 \times S_{\text{UV}}/9500 \text{m}^{-2}} \tag{2.a}
\]

\[
\Delta N_{\text{UV}}(t) = \frac{N_{\text{UV}}(t + \Delta t)}{N_0(t)} = 10^{-0.062 \times S_{\text{UV}}/9500 \text{m}^{-2}} \tag{2.b}
\]

Here Eq. 2.a is the primary response and 2.b is the secondary response. As in the LMS model, the CPMS switches between the primary and secondary phases once a fractional reduction in the population of 6.37 \times 10^{-5} (~4.196 logs) is achieved, based on the biphasic responses observed by Schuerger et al. (2003; 2006).

While Schuerger et al. (2019) considered the effects of temperature acting alone, as well as synergistically with vacuum, it is unusual to have pressurized areas in spacecraft while in cruise. As such, the CPMS uses only the equations for vacuum and temperature acting together:

\[
\Delta N_{T + V}(t) = \frac{N_{T + V}(t + \Delta t)}{N_0(t)} = \exp(-\lambda \Delta t) \tag{4.a}
\]

\[
\lambda(T) = 308 s^{-1} \cdot \exp \left( -\frac{498.8}{T} \right) \tag{4.b}
\]

These equations were derived by Schuerger et al. (2019) by analogy to the inactivation behaviors of *B. subtilis* spores to varying temperatures, which follow an Arrhenius process with a coefficient of determination of over 0.999. This suggests strongly that an underlying temperature-dependent physical or chemical process is operational, which causes the deactivation. Since vacuum is no stronger or less strong at any particular temperature, it follows that the synergistic effects of temperature and vacuum should also have an Arrhenius dependence. However, the Arrhenius exponent for the synergistic process could be different for temperature acting alone, as there are examples of physical processes that are enhanced in vacuum; for example, desiccation. As such, Schuerger et al. (2019) derived Eq. 4.a and 4.b by fitting Arrhenius curves to data at 25°C and 100°C.

The temperatures of spacecraft components are estimated by complex calculations and depend on the active heating and cooling cycles used to maintain the interiors of spacecraft, how thermally isolated components are from one another, and what materials are used on outside surfaces as part of the thermal insulation system. For simplicity, the basic version of the CPMS model will assume that spacecraft are covered by gold multilayer insulation (MLI), which has typical emissivity, \( ε \), of 0.03 (Gilmore, 2002) and albedo, \( A \), of 0.72 (Finckenor and Dooling, 1999), making this material attractive for rejecting solar heating while allowing internally generated heat to be retained.

For a surface that does not change its attitude angle toward the Sun, the surface temperature of the exterior surface of the MLI can then be calculated according to an energy balance between the incoming solar radiation that is absorbed on a unit area of surface and the outgoing thermal emission from that unit area of surface. The absorbed radiation is equal to the solar flux, represented by the luminosity of the Sun, \( L_\odot \), or 3.828 \times 10^{26} \text{ W} \) divided by the area through which this energy passes, a sphere with the radius of the distance from...
the Sun of interest. \( r(t) \). This flux is multiplied by the fraction absorbed \((1 - A)\) and the dot product between the surface outward normal and the solar incidence vector, which represents the degree to which the surface is pointed toward the Sun, referred to as attitude angle. The emitted radiation follows the Stefan–Boltzmann law and is equal to the emissivity of the surface multiplied by \( \sigma \), the Stefan–Boltzmann constant equal to \( 5.67 \times 10^{-8} \) W m\(^{-2}\) K\(^{-4}\) multiplied by the temperature of the surface area element to the fourth power:

\[
\frac{L_0(1 - A) \hat{\mathbf{s}} \cdot \hat{n}}{4\pi r(t)^2} = \varepsilon \sigma [T(\hat{\mathbf{s}}, \hat{n}, t)]^{1/4} \tag{5.a}
\]

Rearranging Eq. 5.a yields the following:

\[
T(\hat{\mathbf{s}}, \hat{n}, t) = \left[ \frac{L_0(1 - A) \hat{\mathbf{s}} \cdot \hat{n}}{4\pi r(t)^2 \varepsilon \sigma} \right]^{1/4} \tag{5}
\]

Furthermore, note that since MLI produces a large temperature drop between the exposed side of the thermal insulation and the spacecraft-facing side, thermal losses to the interior of the spacecraft are minimal, and thus, there is negligible inward propagating thermal radiation from the MLI blanket compared with the energy exchanged at the sunward side. Heat transfer can take place along each layer through conduction, but the amount of heat transferred in this way depends on the specific geometry of the spacecraft and is neglected in this study.

Below \( \sim 210 \) K, henceforth referred to as the “Vacuum Limit,” temperature ceases to have a synergistic effect on microbial inactivation, and the rate of reduction due to vacuum alone becomes the dominant factor, with a biphasic response that mirrors reductions from UV radiation:

\[
\Delta N_V(t) = \frac{N_V(t + \Delta t)}{N_0(t)} = \exp(-1.15 \times 10^{-7} s^{-1} \Delta t) \tag{6.a}
\]

\[
\Delta N_V(t) = \frac{N_V(t + \Delta t)}{N_0(t)} = \exp(-1.82 \times 10^{-8} s^{-1} \Delta t) \tag{6.b}
\]

Schuerger et al. (2019) derived these general relations, and noted the change from the first phase to the second at 94 days of exposure, based on extensive literature on microbial reductions in vacuum (e.g., Morelli et al., 1962; Lorenz et al., 1968; Hagen et al., 1971; Bäcker et al., 1974; Hornbeck et al., 1984, 1994, 1995; Koike and Oshima 1993; Dose and Klein, 1996).

For completeness, the model also considers the effects of the SWPs, although this is considerably less significant than the other factors (see Schuerger et al., 2019, based on the works of Smithers et al., 2007 and Moeller et al., 2010):

\[
\Delta N_{SW}(t) = \frac{N_{SW}(t + \Delta t)}{N_0(t)} = \exp(-2.67 \times 10^{-6} \text{m}^2 \text{s}^{-1} \Delta t / (r(t)^2)) \tag{7}
\]

Note that Kayser et al. (1984) confirmed model predictions that the solar wind density and kinetic energy flux follow an inverse square dependence out to beyond 20 AUs, indicating that the velocity of the solar wind remains constant, but the density falls off. Furthermore, the LMS made the simplification that the solar wind vector and the solar vector were oriented in the same direction because the effects of both were integrated over an entire lunation over which both vectors would rotate through 360°. Such a simplification is also reasonable to make in the CPMS because azimuthal and out-of-plane velocities of the solar wind are at most \( \sim 10 \) km s\(^{-1}\), comparable with typical spacecraft velocities and much lower than the radial component of the solar wind of \( 450 \) km s\(^{-1}\) as measured by examining cometary tails (Brandt et al., 1972) and by \textit{in situ} measurements from spacecraft (Kayser et al., 1984), resulting in azimuthal angles of a few degrees or less. This difference is sufficiently small as to be ignored in the CPMS model. As a result, the deleterious effects of SWPs will be combined with the effects of UV radiation, which also falls off as the inverse square of distance, as described in Eq. 1.

3. Results: Simulation of the Cruise Phase of the EC Spacecraft

3.1. Overview of the EC mission

The EC spacecraft is an orbiter platform that will fly high-inclination orbits around Europa to provide low-altitude flybys as part of a mapping mission to study the ice shell/ocean composition and geology, and map the surface in preparation for a Europa lander sometime in the 2030s (Clark et al., 2011; Buffington, 2014; Bayer et al., 2015). The EC spacecraft will be solar powered (50 m\(^2\) of solar cells), contain nine instruments, stand \( \sim 6.4 \) m tall (prelaunch), and contain a heated internal \textit{Vault} heavily shielded against ionizing radiation expected in the equatorial plane of Jupiter (Fig. 1). The internal \textit{Vault} bioburden reduction estimates are discussed below.

The CPMS model developed in Section 2 may be applied to any space vehicle transiting through the solar system, but the results will depend primarily on the specific trajectory that the vehicle takes to its destination. As such, to demonstrate the capabilities of the model and how the model may be applied to a particular case, this section discusses specific results for two published potential trajectories (Buffington, 2014; M. Dinicola (JPL), personal communications, 2019) for the upcoming EC mission. In both cases, the shapes of the trajectories uniquely describe the positions of the spacecraft as a function of time via the orbital mechanics (e.g., Curtis, 2009), and from the published trajectory shapes (Buffington, 2014), the positions as functions of time were reconstructed. Describing both trajectories will further facilitate comparisons between different types of scenarios applicable to different missions. Additional discussions and other broad results from the model are discussed further in Section 4.

3.2. Direct trajectory

Buffington (2014) describes a direct \textit{Hohmann} trajectory for the EC spacecraft to Jupiter launching June 14, 2022 and arriving March 05, 2025, which has since been updated to a potential launch on July 4, 2023, and corresponding arrival at Jupiter on December 3, 2025 (M. DiNicola (JPL), personal communication, 2019), as shown in Fig. 2A. Orbital reconstruction provides the spacecraft distance from the Sun as a function of time and is shown in Fig. 2B. As of this
FIG. 1. The EC spacecraft in its cruise-phase configuration (A) with the solar panels aimed back toward the Sun. The shielded Vault (red arrow) is located on the top of the main body of the spacecraft and is shielded from the intense ionizing radiation expected in Jovian space. A close-up of the folded EC spacecraft before launch (B) shows the external back-side of the vehicle that will be pointed primarily away from the Sun during cruise (images courtesy of NASA/JPL-Caltech). EC, Europa Clipper. Color images are available online.

FIG. 2. Heliocentric distance for a direct (i.e., “Baseline”) trajectory of the EC mission. At left (A), a top-down diagram of the trajectory of the spacecraft (blue) compared with the orbits of Earth and Jupiter (red) is shown. At right (B), a plot of heliocentric distance versus time that shows how the spacecraft recedes from the Sun (partially adapted from Buffington, 2014 with updated timing from M. DiNicola (JPL), personal communications, 2019). BPM, broken-plane maneuver; JOI, Jupiter Orbit Insertion maneuver. Color images are available online.
writing (fall 2019), all launch dates and arrival dates are tentative, and based on published literature and communications with the EC team.

By using the resulting heliocentric distance and Eq. 1, the solar UV flux on the spacecraft can be calculated as a function of the angle between the solar vector and the surface orientation to the Sun, as shown in Fig. 3A. An angle of zero degrees indicates an element on the spacecraft surface that is pointed directly at the Sun, whereas an angle of 90° indicates an element on the spacecraft surface that is perpendicular to the Sun. By inserting the result into Eq. 2, the reduction as a function of time and angle can be calculated (Fig. 3B).

For a surface pointed directly at the Sun, the equivalent of nearly 3530 LDs (i.e., −3.53 × 10⁴ log reductions) can be received over the course of the trajectory from UV irradiation alone. In fact, to receive less than a single LD by UV irradiation, a surface element would need to be within 0.017° of being perpendicular to the solar vector over the course of the entire direct trajectory. As such, if sterilizing the exterior of the spacecraft were desired, there would be sufficient time to rotate the spacecraft and expose every surface to the Sun for long enough to accumulate >>1 LD over the course of the direct trajectory. The earlier in the trajectory of the mission that rotation relative to the solar vector is completed, the faster would be the bioburden reduction, given that the spacecraft recedes from the Sun relatively quickly along the direct trajectory.

In a similar manner to how UV irradiation was considered, the synergistic interaction between temperature (T) and vacuum (Vac) can also be quantified. First, the temperature of the exterior of the spacecraft can be calculated according to Eq. 5, as a function of the angle between the solar vector and a vector drawn normal to an element on the spacecraft surface, as shown in Fig. 4A. Taking this result and inserting it into Eq. 4 provides the reduction as a function of time and is shown as Fig. 4B.

As with the LMS (Schuerger et al., 2019), synergism between T + Vac accounts for more LDs over the course of the transit to Jupiter than results from UV alone. Here, ~55,000 LDs (−5.5 × 10⁵ logs of reduction) are accumulated versus only 3530 LDs (i.e., −3.53 × 10⁴ log reductions) for UV alone. As such, viable microorganisms cannot be preserved on the external surfaces of the EC spacecraft, or on internal surfaces that are in thermal contact with the surface, unless they are fully shielded from solar heating and UV irradiation. In fact, a half-hour of direct exposure to solar heating (Heat) and Vac at 1 AU is sufficient for sterilization.

For deep interior surfaces (i.e., surfaces considered to be sufficiently deep within the vehicle that conditions are controlled or solar heating excluded), it is only the

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**FIG. 3.** UV irradiation of external surfaces only of the EC spacecraft (A) and the resulting reduction in the viable bioburden as measured in log₁₀ (B) for the direct trajectory. An LD is represented as a −10 log reduction from initial values, something that is achieved very quickly for all surfaces exposed even at glancing angles to the Sun near 90°. Note that the top panel describes the instantaneous flux, whereas the bottom panel describes the effect of the accumulated dose. All surfaces oriented closer to the Sun than 89.983° receive at least one LD during a direct cruise to the jovian system. LD, lethal dose; UV, ultraviolet. Color images are available online.
combination of $T + \text{Vac}$ that matters for the deactivation of the microbial load. Rather than prescribing a single temperature, the CPMS was used to produce linear models for deactivation by different values of the internal temperature of the EC spacecraft (Fig. 5). The plots in Fig. 5 are direct extrapolations of the Arrhenius kinetics described for $T + \text{Vac}$ on bioburden reductions on lunar spacecraft for the LMS model (Schuerger et al., 2019).

If the EC spacecraft interior is maintained at a temperature of 210 K or less, Vac alone (Eq. 6, red line in Fig. 5) will be the greatest contributor with approximately $-1 \log$ of bioburden reduction over the course of a direct transit to Jupiter. Higher temperatures reduce the microbial bioburdens more quickly and for temperatures $>240$ K, an LD or greater is accumulated during the 2.4-year transit. Note that Vac working alone has a biphasic response, and so, there is an elbow in the vacuum limit calculation (see Schuerger et al., 2019 and Eq. 6 in the present article).

3.3. Venus-Earth-Earth gravity assist trajectory

The Venus-Earth-Earth gravity assist (VEEGA) trajectory (Buffington, 2014; M. DiNicola JPL, personal communications, 2019) provides for a significantly longer transit time to Jupiter and takes the spacecraft much closer to the Sun than does the direct trajectory discussed in Section 3.2. As a result, the reductions encountered are larger in the VEEGA trajectory. The VEEGA trajectory (Fig. 6A) and distances from the Sun versus time (Fig. 6B) are shown in Fig. 6. Note that in the VEEGA trajectory there are two times when the spacecraft would be closer to the Sun than Earth’s orbit and also three excursions further out than 1 AU.

FIG. 4. Temperature of external surfaces (MLI modeled here) and shallow internal surfaces of the EC spacecraft (A) and the resulting reduction in the viable bioburden as measured in log10 reductions (B) for the direct trajectory. An LD is represented as a $-10 \log$ reduction from initial values, something that is achieved very quickly for all surfaces exposed even at glancing angles to the Sun. MLI, multilayer insulation. Color images are available online.

FIG. 5. Reducions in microbial bioburdenes are due to the synergistic effects of temperature and vacuum conditions at various temperatures for the direct trajectory. The reduction from vacuum alone for temperatures below 210 K (Section 2.2) is shown in red, with different color contours indicating the reductions from temperature and vacuum working synergistically. Above $\sim 240$ K at least a single LD (i.e., $1, -10 \log$ reduction) would be accumulated. Color images are available online.
Furthermore, the VEEGA trajectory requires substantially more time, in excess of 6 years, from May 24, 2023, through January 15, 2030, to arrive at Jupiter (DiNicola, JPL, personal communication). As of this writing, all launch dates and arrival dates are tentative.

As in Section 3.1, Fig. 7 shows the UV flux at the spacecraft (Fig. 7A) and resulting reduction in microbial bioburden over time (Fig. 7B), and Fig. 8 shows the temperature (Fig. 8A) and synergistic \( T + \text{Vac} \) reductions (Fig. 8B) over time.

As expected, the reductions are significantly greater for the VEEGA trajectory at \( 24,900 \text{ LDs} \) (i.e., \(-2.49 \times 10^5 \) logs of reduction) from UV and \( 746,000 \text{ LDs} \) (\(-7.46 \times 10^6 \) logs) from the synergistic effects of \( T + \text{Vac} \). These inactivation rates represent greater than a sevenfold increase in UV-based reductions and nearly a 14-fold increase in reductions due to \( T + \text{Vac} \) interactions. In fact, even neglecting the substantially greater time spent close to the Sun in the VEEGA trajectory, the substantially larger amount of time spent in transit increases bioburden reductions in every part of the spacecraft. Total inactivation is increased even in the deep interiors where temperatures required to achieve at least one \( LD \) are reduced to \( \geq 230 \text{ K} \) (Fig. 9), and even vacuum alone achieves double the reduction compared with the direct trajectory (Fig. 4) due to the increased transit time.

4. Discussion

4.1. Europa Clipper

4.1.1. Bioburden reduction strategies and structures. The EC spacecraft will be launched as a Category III mission (Frick et al., 2014) with special care given to reducing the bioburden at launch by approximately \(-3 \) logs due to the very low probability of an unintended impact with Europa during the 45 flybys preplanned for the mission (Buffington, 2014; Bayer et al., 2015). Given that the dry mass for the EC spacecraft is expected to be \( \sim 2200 \text{ kg} \) (Bayer et al., 2015), we estimate that the probable bioburden at launch (without prelaunch bioburden reduction protocols) will be \( \sim 1 \times 10^{10} \) spores/cells (i.e., based on 2200 kg multiplied by \( 3.89 \times 10^6 \) spores/cells per kg from the LMS model in Schuerger et al., 2019). However, if prelaunch cleaning and sterilization protocols can achieve a bioburden reduction of \(-3 \) logs, the estimated bioburden for the EC spacecraft might be as low as \( 1 \times 10^7 \) spores/cells at launch. For external surfaces, given the results of Section 3, this means that sterilization to \(<1 \) spore/cell on external surfaces will proceed quickly especially if care is taken to rotate the spacecraft early in its mission to ensure all external surfaces receive a few hours of direct sunlight.

The survival of spores/cells in the interior will depend on the temperature that is maintained within the interior of the spacecraft. The EC has a shielded compartment called the Vault that is intended to house most of the payload and spacecraft electronics, data recorders, and control computers (Bayer et al., 2015). Current estimates suggest that EC will have a mission exposure of \( \sim 2.7 \text{ Mrad} \), primarily from electrons in the Jovian radiation belts (Bayer et al., 2105). The Vault will have \( 3/8'' \) thick aluminum walls to decrease the ionizing radiation dose to \( \sim 150 \text{ krad} \) within the Vault. For our discussion here, we estimate the potential bioburden reductions within the Vault during the cruise phase only and disregard the low ionizing radiation expected during the
cruise phase. If the Vault (vented to interplanetary space is assumed) is maintained with an internal temperature of 240 K, then a single LD might be expected between 2 and 2.5 years in transit, even if the higher bioburden number at launch is used (i.e., $1 \times 10^{10}$ spores/cells). This LD number drops to 1 year for 250 K, 0.5 years for 260 K, and 0.2 years for 270 K. Thus, if the internal Vault temperature can be raised a few tens of K above an uncontrolled thermal profile, it is possible that between 1 and 12 LDs from a $T+Vac$ effect might be achieved during the cruise phase to Jupiter.

4.1.2. Comparison between EC trajectories. Trajectories such as the VEEGA are often preferred over direct trajectories as they allow the use of a less energetic rocket at launch or an increase in the total payload of the spacecraft, which, in turn, increases the science return of the mission. As shown in Section 3, the resulting increase in transit time has the additional benefit of reducing viable bioburdens on the spacecraft once it arrives at its destination. For interior surfaces, this increase in bioburden reductions would be due completely to the increased time required for the spacecraft to complete flying the extended VEEGA trajectory. Thus, a spacecraft spending twice as long in space would see twice as much reduction on interior surfaces due to vacuum-only effects.

By contrast, for external surfaces, it is the increase in time spent closer to the Sun, particularly inside the orbit of Earth, which provides significant additional reductions. For the example presented in Section 3, the doubling of the time spent in space between the direct and VEEGA trajectories results in a factor of $7 \times$ increase in UV inactivation along with a factor of $14 \times$ increase in synergistic effects by $T+Vac$ deactivation. The larger increase for external surfaces occurs because of the nonlinearity of the flux of UV and the heating flux, both of which decrease as the inverse square of distance from the Sun. Furthermore, the increase in the inactivation is larger for $T+Vac$ synergistic effects since the temperature has an additional $T^4$ dependence on heating flux.

4.2. Rates of reduction in different parts of the Solar System

4.2.1. External surfaces. While the total reductions in bioburdens on spacecraft are direct functions of the spacecraft trajectory and history, important general conclusions can be drawn by examining the rates of reductions in different parts of the solar system. The bioburden reduction rates described herein can be applied to any spacecraft and are not unique to any one mission. To examine the differing effects, the numbers of logs of reduction for external
surfaces per hour oriented toward the Sun were calculated (Fig. 10). The figure describes distances from 0.1 AU, well within the orbit of Mercury, out to 100 AU, more than twice the mean orbital distance of Pluto.

Near the Sun, the synergistic $T + \text{Vac}$ effects produce greater reductions than any other single or combination of factors, rising to 5000 LDs (i.e., $-50,000$ logs) per hour at 0.1 AU (Fig. 10) for spacecraft covered with gold MLI. As the distance from the Sun increases, $T + \text{Vac}$ falls off more quickly than other factors due to the Arrhenius dependence of inactivation on temperature in Eq. 4 (temperature itself falls as $1/r$ as spacecraft recede from the Sun, as per Eq. 5). Eventually, UV becomes a more important sterilizing factor between 3 and 4 AU from the Sun. However, for most reasonable trajectories, when using current propulsion technologies, all spacecraft outer surfaces will be completely sterilized before they reach this distance. Primary-phase UV is important mainly for smaller spacecraft, such as planetary CubeSats, which may have been shielded during transit and are deployed only upon arrival at their destinations. For these spacecraft, the primary phase UV can dominate from just past 0.7 AU out to several hundred AU, but once the first $-4$ logs of reduction are complete, spacecraft will experience additional

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**FIG. 8.** Temperatures of external surfaces (MLI modeled here) and shallow internal surfaces of the EC spacecraft (A) and the resulting reduction in microbial bioburden as measured in base-10 logs (B) for the VEEGA trajectory. An LD is represented as a $-10$ log reduction from initial values, something that would be achieved very quickly for all surfaces exposed even at glancing angles to the Sun. Note the three increases in surface temperature as the spacecraft approaches and then recedes from the Sun during the Venus flybys. Color images are available online.

**FIG. 9.** Reductions in microbial bioburden due to synergistic effects between temperature ($T$) and vacuum ($\text{Vac}$) conditions at various temperatures for the VEEGA trajectory. The reduction from $\text{Vac}$ alone for temperatures below 210 K (Section 2.2) is shown in red, with different color contours indicating the reductions from $T + \text{Vac}$ working together. Above $\sim 230$ K, at least a single LD (1, $-10$ log reduction) would be accumulated. Color images are available online.
reductions through the secondary phase of UV. Beyond 10 AUs, the vacuum limit becomes more important than the synergistic effects of $T + \text{Vac}$ combined due to low temperatures and the $T + \text{Vac}$ curve flattens out. Vacuum, however, remains a secondary factor to sterilize exterior surfaces compared with the secondary phase UV out to $\sim 600$ AUs. This far from the Sun, the Sun itself is simply another star, and so, the vacuum-only sterilization rate becomes the most important factor for all spacecraft external and internal surfaces.

### 4.2.2. Internal surfaces.

For internal surfaces, as seen in Section 3, the determining factor is temperature. It is not anticipated that sterilization processes will dominate when controlling the internal temperatures of spacecraft, given the tight energy budget of spacecraft. However, the CPMS can be used to determine what fractional bioburden will remain at any given internal temperature. At the vacuum-only limit (210 K; Figs. 5 and 9), 38.5 years would be required to achieve one $LD$ on all interior surfaces of the EC spacecraft, much longer than the expected duration of the planetary mission. However, for temperatures actively maintained above $\sim 210$ K, time to sterilization is reduced. The amount of the reduction is shown in Fig. 11. Achieving a $LD$ at 1 year after launch would require at least 251 K on internal surfaces, or slightly more than 0.2 years for 273 K. Clearly, for any reasonable assumption about temperature, internal components will take significantly longer than external components to achieve similar levels of sterilization. However, it is possible to sterilize the interior at relatively low temperatures for typical cruise durations to planetary targets. As such, if more rapid sterilization of interior components is desired, a simple and effective way to carry out this sterilization would be to increase the interior temperature slightly in vented spacecraft components (e.g., the EC Vault that holds electronic gear) for extended periods while in cruise.

### 4.3. Spacecraft disposal and remaining bioburden

For spacecraft orbiting planets with moons for which contamination of icy moons is a concern, such as Jupiter and Saturn, spacecraft are typically deorbited into the primary planet’s atmospheres once fuel becomes low. This is done to prevent even the very small possibility of an uncontrolled impact into the icy moons that could result in the transfer of viable organisms. However, given the long tours the spacecraft complete, would any microorganisms be expected to remain viable at disposal? This calculation can be completed for two historical examples: the Galileo spacecraft at Jupiter and the Cassini spacecraft at Saturn.

#### 4.3.1. Galileo.

The Galileo spacecraft was launched on October 18, 1989. The heliocentric orbit that took Galileo out to Jupiter included one Venus and two Earth gravity assists (EGAs), leading the spacecraft to spend significant time within the inner Solar System. Notably, when inside the orbit of Earth, the high-gain antenna (HGA) would not
be pointed toward the Sun during communications, preventing this part of the spacecraft from shielding other spacecraft surfaces from the solar flux. Arrival at Jupiter occurred on December 7, 1995, and the spacecraft was deorbited into Jupiter’s atmosphere on September 21, 2003 (i.e., an 8-year tour of the Jovian system). From launch to disposal, this gives 5086 days (13.93 years) spent in the space environment. The bioburden at launch for Galileo is not well constrained and there is no published record of any sterilization procedures before launch. As such, we shall assume the average value for terrestrial contamination for nonsterilized spacecraft of \(3.89 \times 10^6\) spores/cells per kg of dry mass established by Schuerger et al. (2019). For Galileo, the dry mass was 1884 kg, suggesting a total bioburden of 7.33 \(\times\) 10^6 spores/cells at launch.

The majority of these spores/cells are likely located deep within the spacecraft and are influenced only by the temperature and vacuum to which these interior surfaces are heated. If they were completely unheated, which is to say that vacuum is the only significant deleterious factor, the reduction in bioburden that would be expected over the mission would be approximately \(-5 \times 10^{-2}\) logs per hour of reduction due to the synergistic effects of vacuum and solar heating. This would result in an LD achieved every 200 h of exposure for external surfaces at Jupiter. However, for surfaces coated with white paint, the equilibrium temperature is too low for additional reductions above the vacuum limit due to solar heating. UV exposure will cause relatively quick reductions also to all exterior surfaces, no matter how coated or blanketed. For surfaces not previously exposed to the Sun, primary UV (\(-20\) logs h^{-1}) will require \(\sim 12\) min at Jupiter before the secondary phase of UV reduction is activated at \(-4.12\) log reductions. From there, secondary UV (\(-0.4\) logs h^{-1}) will require an additional 14 h and 42 min of exposure before one LD is achieved, or 14 h and 54 min in total. Given that the spacecraft was constantly changing attitude to carry out observations of different targets within the jovian system and to communicate with Earth, it is likely that all external surfaces on Galileo achieved an LD over the 13.93-year mission, thereby sterilizing the exterior. Note that these values are lower limits, and it is likely that sterilization occurred much earlier in the mission, while the spacecraft traveled through the inner solar system where bioburden reductions would take place orders of magnitude more quickly.

### 4.3.2. Cassini.

The Cassini spacecraft was launched on October 15, 1997, and was deorbited into Saturn’s atmosphere on September 15, 2017, for a total of 7275 days (19.97 years) in space. Like Galileo, Cassini followed a VEEGA orbit, arriving at Saturn on July 1, 2004, following a nearly 7-year cruise and progressing over \(\sim 13\) years of the orbital tour. As with Galileo, no extraordinary procedures for sterilization were undertaken, and we also assume the Schuerger et al. (2019) value of \(3.89 \times 10^6\) spores/cells per kg of dry mass value for the bioburden of Cassini at launch. This yields \(9.81 \times 10^9\) viable spores/cells at launch when using Cassini’s dry mass of 2523 kg.
As the Cassini mission was longer lasting than the Galileo mission, a greater reduction in bioburden would be anticipated on the interior. If all the bioburden was located in the interior and no heating of the interior took place during the mission, a reduction of \(-5.24\) logs would be expected, leaving a bioburden of \(5.65 \times 10^4\) viable spores/cells at disposal. However, interior heating would need only be sufficient to produce an average temperature of 218 K over the mission in order for Cassini to have accumulated one LD at disposal.

For exterior surfaces, the Sun is significantly less strong at Saturn compared with Jupiter. As such and as shown in Fig. 10, any gold MLI blankets would experience only \(1 \times 10^{-4}\) logs per hour of reduction due to synergistic \(T + \text{Vac}\) effects. This would require \(\sim 1 \times 10^5\) h (11.4 years) of exposure, suggesting that solar heating is not a significant biocidal factor for the Cassini mission, at least not during the Saturn tour. However, such solar heating could be very important while the spacecraft was within the inner Solar System. UV exposure is likewise reduced at Saturn. For surfaces not previously exposed to the Sun, primary UV (\(-6\) logs \(h^{-1}\)) will require \(\sim 41\) min at Saturn before the secondary phase of UV reduction is activated at a \(-4.12\) logs. From there, secondary UV (\(-0.11\) logs \(h^{-1}\)) will require an additional 53 h and 27 min of exposure before one LD is achieved, for a total of 54 h and 8 min. Again, as with Galileo, it is likely that every spacecraft surface spent at least this much time oriented toward the Sun, given the frequent changes in spacecraft attitude required to make observations and communicate with Earth. Again, as with Galileo, note that these values are lower limits, and it is likely that sterilization occurred much earlier in the mission, while the spacecraft traveled through the inner solar system where bioburden reductions would take place orders of magnitude more quickly.

4.4. Applying the CPMS to realistic and convoluted spacecraft structures

The figures that provide solar UV fluence rates and bioburden reductions (Figs. 3 and 7) versus spacecraft attitude angle to the solar vector provide a framework for considering each individual component and its separate attitude angle. As a whole, attitude angle will then vary over the spacecraft as different components have different orientations. To visualize this effect for a typical configuration, a three-dimensional stereolithograph (STL) of the Cassini spacecraft (Kumanchik and Lopez, 2012) was obtained and illuminated in MATLAB with a distant light source and no ambient light. The fraction of exposure to the Sun of each component is shown in Fig. 12 for a light source located to the upper right. The amount of illumination from the Sun can be calculated for this snapshot by multiplying the values of flux (Figs. 3A or 7A) by the fraction of exposure to the Sun shown in Fig. 12, or using the values and variations in that flux to derive the variation in temperature via Eq. 5.

In reality, the spacecraft would be expected to alter its position over time, and so, a complete representation of the evolution of the biocidal effect over the course of the mission would need to convolve the time spent in each position with the level of exposure to the Sun to develop a time-dependent understanding of the biocidal effect on each component. Fortunately, three-dimensional models of spacecraft are obtained as a matter of course in the development of vehicles. Furthermore, any maneuvers the spacecraft completes are controlled and simulated by spacecraft engineers. Therefore, by using the formulae from this study, future spacecraft teams should be able to easily calculate exactly how much biocidal effect they might expect on all spacecraft surfaces during a cruise phase to their specific target body. Indeed, spacecraft flight
controllers may even choose to rotate the spacecraft during the cruise phase to ensure that all surfaces are sterilized early in the mission.

The representation of Fig. 12 provides an adequate visualization but does have shortcomings. The largest of these is that the spacecraft exists as a series of patches and the software does not calculate shadows. Any future software intended to calculate accumulated dosages would need to take this factor into account. Notably, the HGA on Cassini, or any other likely spacecraft traveling to the outer planets, is so large that it can act as a shield for solar heating and UV. Indeed, if the HGA remains pointed toward the Sun, a likely position for communications since Earth remains close to the Sun in the sky from the perspective of a spacecraft at the outer planets, all other components of the spacecraft might remain in shadow.

5. Conclusions

A CPMS model has been created by adapting the LMS model of Schuerger et al. (2019), which includes the effects of the three factors that are significant for reducing microbial bioburdens on spacecraft. The CPMS model was used to predict the effects of vacuum, solar heating, and solar UV flux on the EC for a direct trajectory and a VEEGA trajectory, requiring more time and several gravity assists. For both these trajectories, \( T + \text{Vac} \) acting synergistically were the most important biocidal factors on the exterior of the spacecraft and in the spacecraft interiors.

Under the direct trajectory, exterior surfaces are rapidly sterilized with tens of thousands of LDs absorbed to the spacecraft exterior. Even surfaces with glancing angles toward the Sun also obtain at least one LD over the course of the mission. Most of the reduction on external surfaces occurs earlier on in the mission when the spacecraft is closest to the Sun. As such, if external sterilization is desired, this would be the best time to rotate the spacecraft to ensure that all surfaces receive sufficient UV irradiation or solar heating to achieve the desired levels of accumulated LD dosages. All interior spaces of the EC spacecraft heated to at least 240 K will accumulate at least one LD over the course of the direct trajectory to Jupiter.

Under a VEEGA trajectory, substantially higher reductions result from the spacecraft spending much more time near the Sun and more time in transit overall. Considering the most severe biocidal factor, \( T + \text{Vac} \) acting synergistically, the exterior absorbs hundreds of thousands of LDs over the course of the mission, a factor of 20 × higher than in the direct trajectory. Meanwhile, UV doses, while somewhat less important, are 8 × greater in the VEEGA trajectory compared with the direct Hohmann trajectory. In both cases, the greatest biocidal effect results from the three phases of the spacecraft spends closer to the Sun (≤1 AU) during the VEEGA flybys. It is at these times when rotating the spacecraft would be most effective at sterilizing the exterior. Meanwhile, interior surfaces heated above 230 K would also absorb at least one LD.

From these simulations we are able to generalize about bioburden reduction in transit to the outer Solar System on spacecraft in general. In the most restrictive case of unheated spacecraft located further than 600 AU from the Sun, all internal spacecraft surfaces would sustain at least one LD (~10 logs of reduction in population) in ≤38.5 years. As all spacecraft are heated and nearly all spacecraft spend significant time closer to the Sun than 600 AU, by virtue of their launch from Earth, all external spacecraft surfaces will be sterilized within a shorter time frame. Different effects dominate in different parts of the Solar System. Synergism between \( T + \text{Vac} \) dominates on surface reductions out to 3.3 AU, UV irradiation dominates between 3.3 and 600 AU, and out past 600 AU the effects of vacuum-alone dominates for all exterior and interior surfaces.

Using the CPMS model, we find that there was likely no remaining bioburden on the external surfaces of either the Galileo or Cassini spacecraft at their disposal into the planetary atmospheres of Jupiter and Saturn, respectively. Furthermore, if the internal temperature of the Galileo spacecraft averaged at least 222 K over the course of its lifetime, there likely would be no remaining viable bioburden on the interior surfaces, suggesting that the spacecraft was already sterilized at disposal. For Cassini, this would be true if the internal temperature averaged at least 218 K.

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Supplementary Material

Supplementary Data

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Abbreviations Used
BPM = broken-plane maneuver
COSPAR = Committee on Space Research
CPMS = Cruise-Phase Microbial Survival
DSM = deep space maneuver
EC = Europa Clipper
EGA = Earth gravity assist
GCR = galactic cosmic ray
HGA = high-gain antenna
HZE = high-mass and high-energy particle
JOI = Jupiter Orbit Insertion maneuver
LD = lethal dose
LMS = Lunar Microbial Survival
MLI = multilayer insulation
MSL = Mars Science Laboratory
SPE = solar particle event
SWP = solar wind particle
VEEGA = Venus-Earth-Earth gravity assist
VGA = Venus gravity assist