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As Published: https://doi.org/10.1007/s10453-019-09597-9

Publisher: Springer Netherlands

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Cite this article as: Tristan A. Caro, Matthew Wendeln, Matthew Freeland, Noelle Bryan, Samantha M. Waters, Alexa McIntyre, Patrick Nicoll, Sasha Madronich and David J. Smith, Ultraviolet light measurements (280–400 nm) acquired from stratospheric balloon flight to assess influence on bioaerosols, Aerobiologia https://doi.org/10.1007/s10453-019-09597-9

Ultraviolet light measurements (280 to 400 nm) acquired from stratospheric balloon flight to assess influence on bioaerosols

Tristan A. Caro[1]; Matthew Wendeln[2]; Matthew Freeland[3]; Noelle Bryan[4]; Samantha M. Waters[5], Alexa McIntyre[6]; Patrick Nicoll[7]; Sasha Madronich[8]; David J. Smith[9*]

[1] UC Berkeley, Department of Integrative Biology, 5112 Valley Life Sciences Building, Berkeley CA, USA, 94720, tcaro@berkeley.edu
[2] 4941 N. Troy Street, #3, Chicago, IL, USA, 60625, matthewjwendeln@gmail.com
[3] 240 Sidney Street, #111, Cambridge, MA, USA, 02139, mfreeland@gmail.com
[4] Massachusetts Institute of Technology, Department of Earth, Atmospheric and Planetary Sciences, 77 Massachusetts Avenue, 54-918, Cambridge, MA, USA, 02139, nbryan5@mit.edu
[5] Universities Space Research Association, NASA Ames Research Center, Moffett Field, California, USA, 94035, samantha.m.waters@nasa.gov
[6] Department of Physiology and Biophysics, Weill Cornell Medicine, New York, NY, USA, 10065, abm237@cornell.edu
[7] Blue Marble Space Institute of Science, NASA Ames Research Center, Moffett Field, CA, USA, 94035, patrick.m.nicoll@nasa.gov
[8] National Center for Atmospheric Research, Boulder, CO, USA, 80307, sasha@ucar.edu
[9] NASA Ames Research Center, Space Biosciences Division, M/S: SCR-239, Moffett Field, California, USA, 94035, 1-650-604-4819, david.j.smith-3@nasa,gov

Short Communications: 3 figures; 0 tables; 15 references.

Key Words: Ultraviolet light; balloon; troposphere; stratosphere; bioaerosols

Corresponding Author: David J. Smith, NASA Ames Research Center, Space Biosciences Division, M/S: SCR-239, Moffett Field, California, USA, 94035, 1-650-604-4819, david.j.smith-3@nasa,gov

Abstract

Viable microorganisms collected from the Earth's upper atmosphere are mysterious considering the intensely biocidal ultraviolet (UV) light conditions dominating rarefied air. Historically, most investigations examining the relationship between bioaerosols and UV conditions in the upper atmosphere have relied upon model-generated data. To address the shortage of *in situ* UV measurements in the upper troposphere and lower/middle stratosphere, we flew a meteorological balloon equipped with a UV radiometer and other core environmental sensors. The balloon payload launched from Illinois, USA, on 6 October 2018 and acquired UVA (315-400 nm) +UVB (280–315 nm) measurements for ~2 hours up to 30.9 km. Above the atmospheric boundary layer, UVA+UVB values registered around 6 mW·cm^{-2}, results that were largely consistent with Tropospheric Ultraviolet-Visible (TUV) model predictions. Performed in a low-cost, reusable manner with commercially available instruments, we show that reliable UV flux data can be acquired with meteorological balloon payload systems. This short communication provides relevant UVA+UVB results for aerobiology and astrobiology studies evaluating the survivability of microorganisms in the upper atmosphere.

Introduction

Recent research has shown that microbial cells (e.g., bacteria, archaea, and fungi) are present throughout Earth's atmosphere and a portion of the biomass remains viable when aerosolized (Smith et al. 2018). Both viable and inactivated bioaerosols can potentially influence climate and human health (Griffin 2007). Understanding the relationship between transport time in the atmosphere and biocidal conditions – primarily that of ultraviolet (UV) light which is destructive to DNA and other biomolecules (Madronich et al. 2018) – is fundamental for survivability predictions in the field of aerobiology. Despite relative proximity of the stratosphere and with airborne vehicles passing through it regularly, there are few *in situ* measurements of UVA (315–400 nm), UVB (280–315 nm) and UVC (100–280 nm) levels. In fact, most UV values cited in past stratospheric microbiology investigations come from modeled estimates (Khodadad et al. 2017; Smith et al. 2011). While technically challenging to capture at extreme heights above the Earth's surface, UV light data are critical for assessing the damaging effect of solar radiation on bioaerosols, particularly when long range transport times can last days (Smith et al. 2013) or even weeks (Creamean et al. 2013).

Previous microbial experiments on large scientific balloons flew UV radiometers but failed to record light data (Khodadad et al. 2017; Smith et al. 2014). Thus, our work builds upon past efforts, using the same UV radiometer but with a smaller and reusable payload system flown on a meteorological balloon. Herein, we report the successful acquisition of UVA+UVB measurements (280–400 nm) on 6 October 2018, at altitudes up to 30.9 km.

Methods

Flight planning was conducted with burst software (https://github.com/cuspaceflight/cusf-burst-calc) and a path predictor tool (http://predict.habhub.org/). Open source code for UV and positional data was stored at https://github.com/mdfreeland/FlightDataLogger. For comparing UV measurements to modeled predictions, we used the Tropospheric Ultraviolet-Visible (TUV) method from Madronich and Flocke (1999).

The primary payload was constructed out of a single molded piece, 2.5 cm thick Styrofoam container. A commercial UV radiometer (Solar Light Inc.) was installed to collect UVA+UVB data (PMA2107 for 280-400 nm), UVC data (PMA2122 for 249-259 nm) and had a dual-input data logger (PMA2100). Both UVA+UVB and UVC sensors were positioned on top of the payload, exposed to ambient conditions.

A secondary tracking payload consisted of a Byonics MT-1000 2-m transceiver and APRS modem transmitting 1 watt at 144.390 MHz over a half-wave dipole antenna. The APRS payload was suspended 3-m below the telemetry payload to limit interference between the data logging systems and radio transmission. For redundancy, GPS position and altitude was sent via a SPOT Gen II satellite system every 10 min. A 1.2-m parabolic parachute was connected between the payload and the balloon for descent.

Results

On 6 October 2018 at 17:45:45 UTC, the balloon was released near Logan Township, IL (40°39'09.1"N; 89°49'15.8"W) and landed ~145 km northeast of the launch site near Marseilles, IL (41°14'16.0"N; 88°44'03.2"W) at 19:55:05 UTC (**Figure 1**). Once above the predicted atmospheric boundary layer, measured UVA+UVB values (**Figure 2**) were approximately 6 mW·cm^{-2}, increasing gradually with altitude and peaking at roughly 22 km. On ascent, above 5 km, a maximum flux of 9.53 mW·cm^{-2} and a minimum flux of 4.02 mW·cm^{-2} were observed. These UV measurements agreed with predicted TUV modeled values for the trajectory (**Figure 3**) calculated for 18:00:00 UTC (noon local time) on launch day, assuming clear conditions. The TUV model extended estimates up to 40 km, while the balloon-based measurements were only made up to an altitude of 30.9 km. UVC (206–280 nm) estimates were included in the TUV model even though the readings at 249-259 nm were not reliably acquired in-flight by the PMA2122 sensor (data not shown). The TUV model predicted reductions in UVC with decreasing altitude due to the absorption of UVC in the stratosphere by oxygen and ozone (O_3) molecules. UVC values depicted, 0.1–1 µW·cm^{-2}, would be expected above 24–28 km where the highest concentrations of atmospheric O_3 can be found. Similarly, the TUV modeled UVB contribution increased at higher altitudes due to less UVB absorption by O_3.

Discussion

Our UVA+UVB data (280–400 nm) provided a rare *in situ* snapshot of the harsh solar radiation conditions encountered by airborne microorganisms traveling at extreme heights in Earth's atmosphere. Our recorded values average about 6 mW·cm^{-2} for 7–31 km (**Figure 2**) thus suggesting biocidal doses (Khodadad et al. 2017). Our observed minimum (4.02 mW·cm^{-}2) and maximum (9.53 mW·cm^{-}2) measurements help constrain UV levels expected for upper atmosphere transport. It has long been assumed that bioaerosols in the free troposphere and lower stratosphere would be vulnerable to inactivation and mutation (Griffin et al. 2017) even when co-transported with dust (Smith et al. 2011); the intensity of UV conditions measured by our payload support this notion. UV mutagenesis rates were previously explored by Kim and Sundin (2000) who concluded that UVB doses increased rifampicin resistant (Rif^R) mutants of *Pseudomonas syringae* B86-17, a bacterial phytopathogen commonly associated with cloud water. Interpretation of such results can be strengthened examining UV levels in the atmosphere: according to our data, bioaerosols in the free troposphere and lower stratosphere for 53 min would experience an average instantaneous UVA+UVB flux of 6 mW·cm^{-2} with a total combined UVA+UVB dose of 1.9 kJ. Comparatively, Kim and Sundin (2000) showed that a dose of this magnitude yielded 280 Rif^R mutants per 10^8 surviving cells *in vitro*. Atmospheric UV measurements will help with interpretations from surveys of bioaerosol diversity (Dueker et al. 2018; Smith et al. 2018) and size distributions (Choudoir et al, 2018) by constraining survivorship probabilities. We point the readers to Madronich et al. (2018) for an extended discussion about the spectral sensitivity of airborne microorganisms to solar light.

For the benefit of future balloon teams, sources of variation within our method will be addressed. First and foremost, factors such as season, latitude, longitude, altitude, time of day, clouds and other bulk aerosol conditions can influence reflectivity and total UV irradiance levels measured (Madronich et al. 2018). Investigators must also take into account the torsional oscillation of the payload and changing angle of incident sunlight. We flew a sensor with an evenly illuminated flat diffuser plate positioned on top of the payload system where shading from other components would be minimal. Assuming no shading of the direct solar beam, the observed signal fluctuations could be explained if the horizontal alignment of the diffuser plate was perturbed during the flight as the payload rotated. In general, detected irradiance would be proportional to the cosine of the angle of incidence, which can be estimated by adding/subtracting the plate tilt angle to the true solar zenith angle. Taking the solar zenith angle during the flight as about 45^o, a diffuser tilt angle of about 15^o would explain the magnitude of our observed variations. Thus, we suspect the slight disparity of values recorded during ascent and descent were due to the drifting solar zenith and variable atmospheric conditions (e.g., the presence/absence of clouds). Starkly different rates of payload ascent and descent (5.04 $m \cdot s^{-1}$ and 19.4 $m \cdot s^{-1}$ respectively) support the notion that payload movement was the main source of variation. Altogether, this would explain why the midpoints of the UVA+UVB data (~6 $mW \cdot cm^{-2}$), rather than the high/low peaks, had the best agreement with the TUV model that assumed a perfectly horizontal detector.

Surprisingly, stratospheric UV measurements cannot be found frequently in literature. *In situ* measurements seem essential for confirming establishing laboratory studies in the field of aerobiology. The UV results reported here align with previously-conducted experiments, for instance, a laboratory simulation performed by Smith et al. (2011) that used UV fluence rates collected from a balloon mission flown in 1979 (McPeters et al 1984). The team established a UVA+UVB dose of 8.66 $mW \cdot cm^{-2}$ for the stratosphere experiment (Smith et al. 2011); in comparison, UVA+UVB measurements acquired by this balloon payload averaged about 6–8 $mW \cdot cm^{-2}$.

Despite an attempt to also capture UVC measurements on our balloon payload, intense out-of-band contamination (i.e., spectral leakage) skewed the sensor's data. Therefore, it would be worthwhile for future teams to attempt UVC data acquisition in the stratosphere. Such measurements would be relevant to researchers studying the effects of intensely biocidal conditions on microbial survival and mutation. Intriguing similarities between UV conditions in Earth's stratosphere and UV levels on the surface of Mars have been noted by the astrobiology research community (Khodadad et al. 2017). Indeed, the complete combination of Martian conditions (high radiation and desiccation; low temperature and pressure) can be difficult to replicate in laboratory settings using artificial light sources. Our UVA+UVB values reported herein match closely to those expected on Mars (~5 $mW \cdot cm^{-2}$) (Schuerger et al. 2003). This overall alignment should encourage teams using the Earth's middle stratosphere to simulate conditions found on the Red Planet.

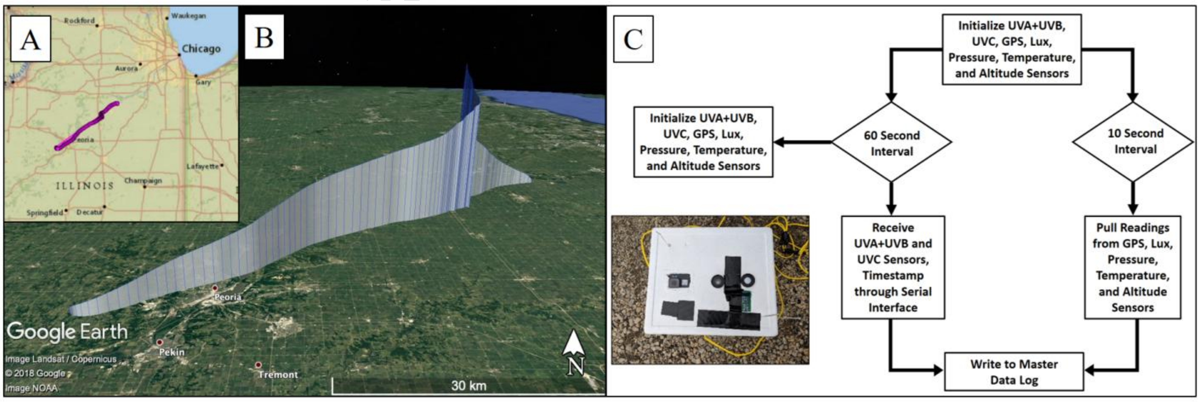

Figure 1. (A) Balloon payload was launched 6 October 2018 near Logan Township, Illinois, USA (40°39'09.1"N; 89°49'15.8"W); **(B)** Payload traveled northeast for approximately 145 km over a 2 hr mission (map credit: *Google Earth*, accessed 1 February 2019); **(C)** Box chart describing the data logging system for the balloon payload carrying a ultraviolet (UV) light radiometer, with two independent sensors (UVA+UVB; UVC) positioned on the uppermost portion of the system.

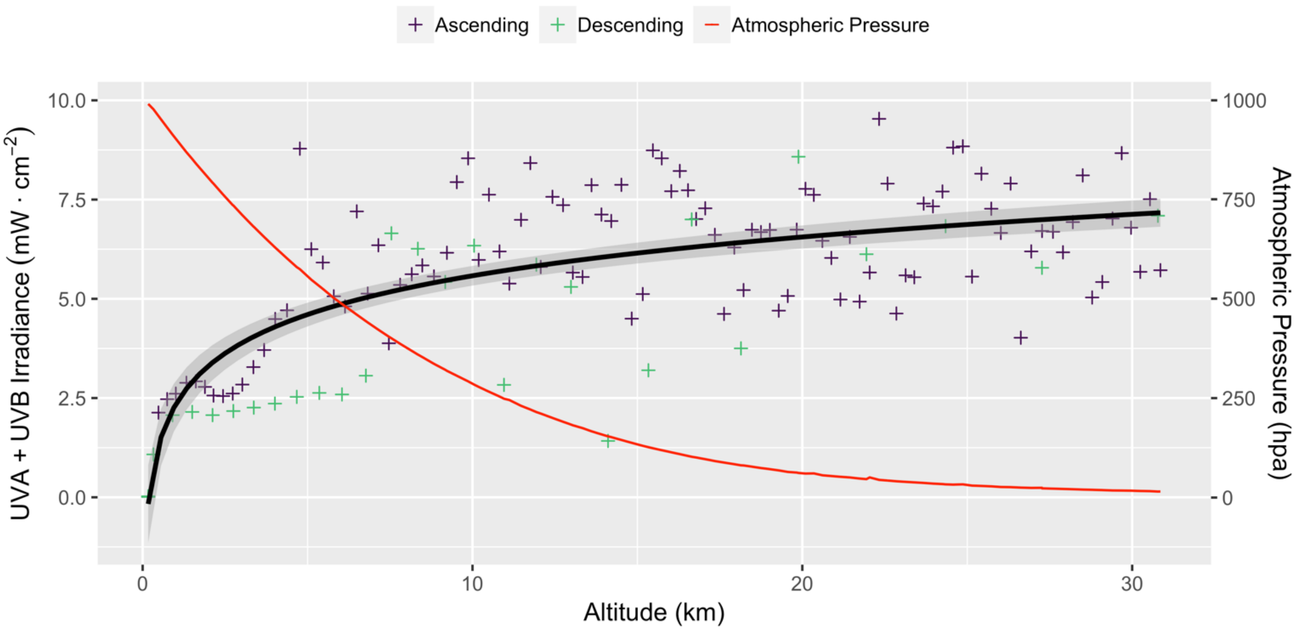

Figure 2. Ultraviolet (UV) light data collected by the balloon payload carrying two separate sensors for acquiring UVA+UVB (280-400 nm) and UVC (249-259 nm) with measurements up to 30.9 km in the stratosphere. UVA+UVB data (*violet* for ascent; *green* for descent) presented. A logarithmic model (*black)* provided a confidence interval of 0.95 (in *gray*). Atmospheric pressure readings (*red*) were monitored on balloon ascent and descent.

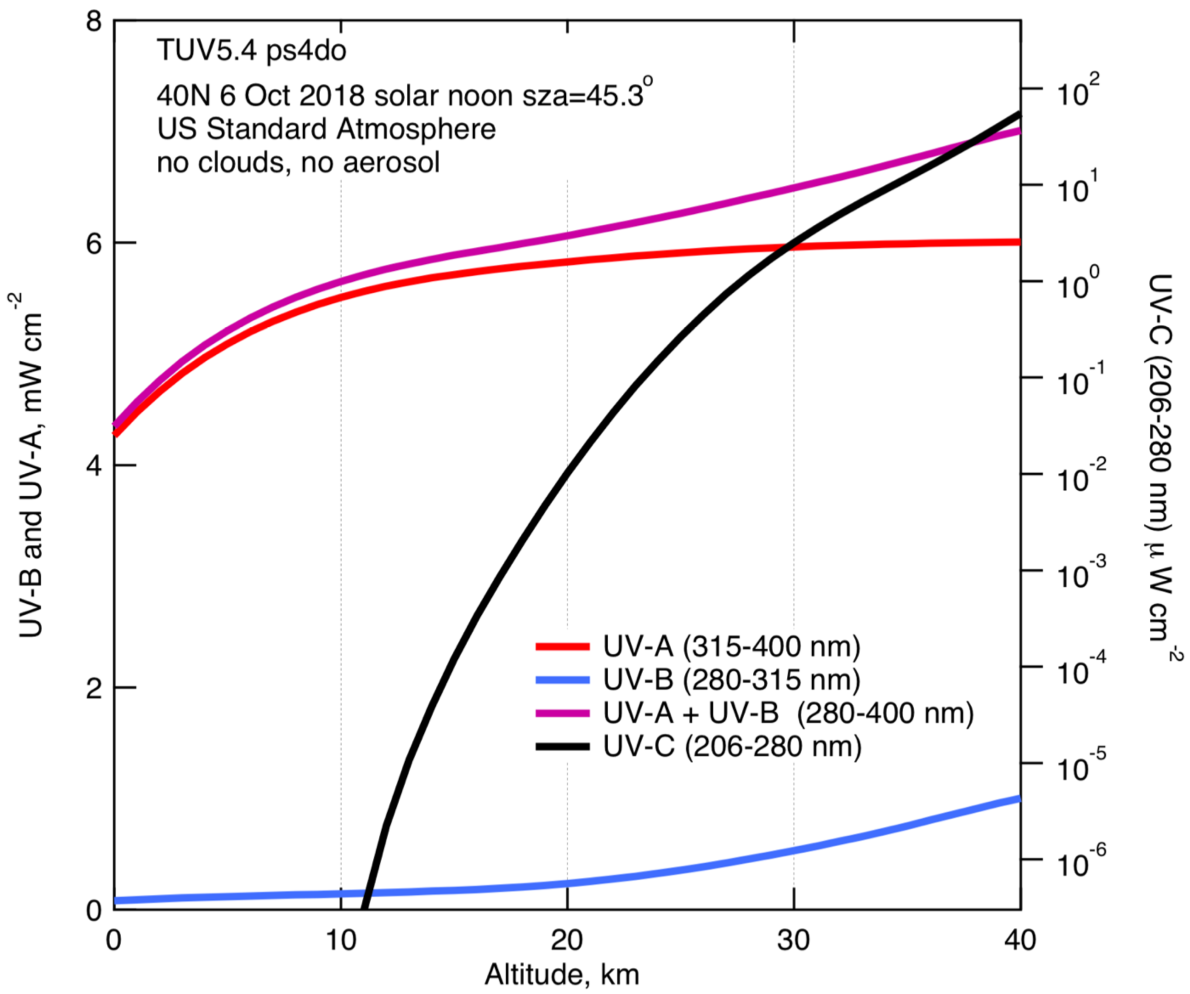

Figure 3. Modeled ultraviolet (UV) light predictions for the balloon mission location (up to 40 km) produced by the Tropospheric Ultraviolet-Visible (TUV) method, assuming clear sky conditions at solar noon for local conditions. Note the logarithmic scale for modeled UVC values.

Acknowledgements
Our study was supported by the NASA Astrobiology Program and a grant from NASA Planetary Protection (15-PPR15-0007). The National Center for Atmospheric Research is sponsored by the National Science Foundation. We thank Moshe Levy from Solar Light Co., Inc., for his assistance with radiometer calibration and data logging discussions. We acknowledge Dr. Britt Koskella and Dr. Steven Lindow for their insights and project support. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States government. The views and opinions expressed herein do not necessarily state or reflect those of the United States government and shall not be used for advertising or product endorsement purposes.

References

Choudoir, M.J., Barberán, A., Menninger, H.L., Dunn, R.R., & Fierer, N. (2018) Variation in range size and dispersal capabilities of microbial taxa. *Ecology*, 99(2), 322-334.

Creamean, J. M., Suski, K. J., Rosenfeld, D., Cazorla, A., DeMott, P. J., Sullivan, R. C., et al. (2013). Dust and biological aerosols from the Sahara and Asia influence precipitation in the Western U.S. *Science*, 339(6127), 1572–1578. doi:10.1126/science.1227279

Dueker, M.E., French, S., & O'Mullan, G.D. (2018) Comparison of Bacterial Diversity in Air and Water of a Major Urban Center. *Frontiers in Microbiology*, 9, doi: 10.3389/fmicb.2018.02868

Griffin, D. W. (2007). Atmospheric movement of microorganisms in clouds of desert dust and implications for human health. *Clinical Microbiology Reviews*, 20(3), 459–477. doi:10.1128/CMR.00039-06

Griffin, D.W., Gonzalez- Martin, C., Hoose, C., & Smith, D.J. (2017). Global-scale atmospheric dispersion of microorganisms. In Amato, P., & Delort, A (Ed.), *Microbiology of Aerosols* (pp. 155-174). Hoboken: John Wiley & Sons.

Khodadad, C. L., Wong, G. M., James, L. M., Thakrar, P. J., Lane, M. A., Catechis, J. A., & Smith, D. J. (2017). Stratosphere conditions inactivate bacterial endospores from a Mars spacecraft assembly facility. *Astrobiology*, 17(4), 337–350. doi:10.1089/ast.2016.1549

Kim, J. J., & Sundin, G.W. (2000). Regulation of the rulAB mutagenic DNA repair operon of Pseudomonas syringae by UV-B (290 to 320 nanometers) radiation and analysis of rulAB-mediated mutability in vitro and in planta. *Journal of Bacteriology*, 182(21), 6137-6144. doi:10.1128/JB.182.21.6137-6144.2000

Madronich, S., & Flocke, S. (1999). The role of solar radiation in atmospheric chemistry. In P. Boule (Ed.), *Environmental Photochemistry* (pp. 1–26). Berlin, Heidelberg: Springer Berlin Heidelberg. doi:10.1007/978-3-540-69044-3_1

Madronich, S., Olof Björn, L., & McKenzie, R.L. (2018). Solar UV radiation and microbial life in the atmosphere. *Photochemical & Photobiological Sciences*, 17(12), 1918–1931. doi:10.1039/C7PP00407A

McPeters, R. D., Heath, D. F., & Bhartia, P. K. (1984). Average ozone profiles for 1979 from the NIMBUS 7 SBUV instrument. *Journal of Geophysical Research: Atmospheres*, 89(D4), 5199–5214. doi:10.1029/JD089iD04p05199

Schuerger, A. C., Mancinelli, R. L., Kern, R. G., Rothschild, L. J., & McKay, C. P. (2003).

Survival of endospores of bacillus subtilis on spacecraft surfaces under simulated Martian environments: implications for the forward contamination of Mars. *Icarus*, *165*(2), 253–276. doi:10.1016/S0019-1035(03)00200-8

Smith, D.J., Griffin, D. W., McPeters, R. D., Ward, P. D., & Schuerger, A. C. (2011). Microbial survival in the stratosphere and implications for global dispersal. *Aerobiologia*, 27(4), 319–332. doi:10.1007/s10453-011-9203-5

Smith, D.J., Timonen, H. J., Jaffe, D. A., Griffin, D. W., Birmele, M. N., Perry, K. D., et al. (2013). Intercontinental dispersal of bacteria and archaea by transpacific winds. *Appl. Environ. Microbiol.*, 79(4), 1134–1139. doi:10.1128/AEM.03029-12

Smith, D.J., Thakrar, P. J., Bharrat, A. E., Dokos, A. G., Kinney, T. L., James, L. M., et al. (2014). A Balloon-Based payload for Exposing Microorganisms In the Stratosphere (E-MIST). *Gravitational and Space Research*, 2(2), 70-80.

Smith, D.J., Ravichandar, J. D., Jain, S., Griffin, D. W., Yu, H., Tan, Q., et al. (2018). Airborne Bacteria in Earth's lower stratosphere resemble taxa detected in the troposphere: Results from a new NASA Aircraft Bioaerosol Collector (ABC). *Frontiers in Microbiology*, 9, 1752–1752. doi:10.3389/fmicb.2018.01752