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Tips and Tools

Education and public outreach: communicating science through storytelling

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ABSTRACT Education and public outreach activities can be challenging for most active scientists, for very good reasons. Allotment of time to participate in outreach activities could be a major challenge. However, when such activities are incorporated into one's academic and research plan, they can be enriching. Here, the author describes his experience in what began as on one-off participation at an outreach event, leading to a series of speaking events addressing the public at the monthly meetings of several astronomy clubs/societies, observatories, etc. in the states of Texas, Louisiana, New Mexico, and Colorado. They have often involved the use of motifs and characters from popular science fiction, literature, and movies and when possible, getting the audience actively involved in the presentations. Furthermore, the discussions following each presentation have been enriching in terms of getting a broad perspective of the perceptions that people in general have, regarding the origins of life, microbiology, extremophiles, and astrobiology.

KEYWORDS education and public outreach, astrobiology, extremophiles

> "The miracle is this: the more we share the more we have"
>
> -Leonard Nimoy 1931–2015

Everyone loves hearing a story. More so, if it engages and involves components they can easily relate to. Analogies, metaphors, and similes are often tools that can be and are used to drive home a point in both informal and formal discussions. For example, in standup comedy shows, humor and wit play pivotal roles in getting points across. In science and academia, most practitioners are understandably deep into the routine of teaching classes, evaluating student's performances, mentoring students, writing papers, and research grants in addition to performing other duties and responsibilities required of a faculty member or a postdoc. Time becomes a scarce commodity that gets rationed during the course of a semester to accommodate the entire spectrum of such routine activities.

In recent years, much onus and emphasis are given to "science outreach" (1–5). Participation in conferences in which science is explained to an audience familiar with science but from other disciplines is itself a form of outreach. Public outreach offers a plethora of opportunities to explore means of making scientific ideas, concepts, and information accessible to a general audience.

One example that is of relevance in this context is the FameLab International science communication competition (3). Implemented by NASA's Astrobiology Program in 2012, FameLab is designed for early career scientists with a focus on best practices of efficient communication. The author was a participant in the inaugural FameLab event held at the Lunar and Planetary Institute, Houston on 13 January 2012. That first debut exposure to "science outreach" turned out to be an eye-opener. The initial exposure to outreach

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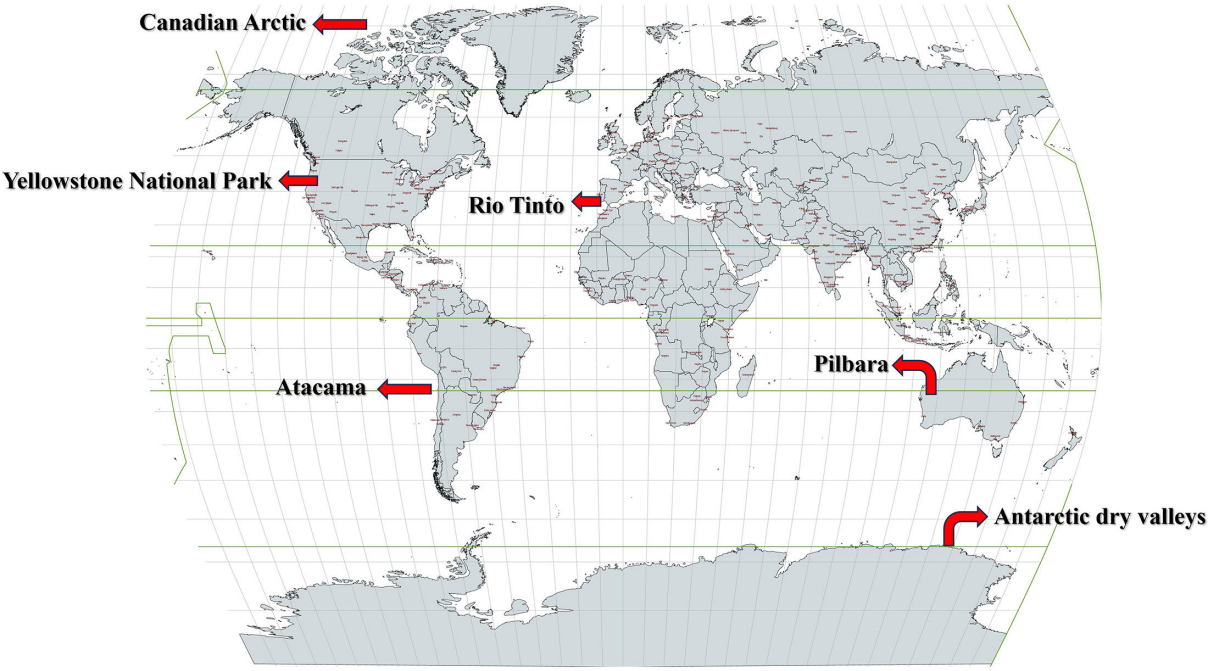
TABLE 1 Geographical locations harboring diverse extremophiles

Landscape	Location
Yellowstone National Park (6–10)	Wyoming (USA)
Death Valley (11)	Nevada-California (USA)
Acid mine drainage system in Iron Mountain (12)	California (USA)
High altitude ecosystem in the Atacama desert (13)	South America
Guaymas Basin (14)	Gulf of California
White smokers near the Tonga islands (15)	The Pacific
Rio Tinto (Spain) (16)	Spain
Lake Tyrrell in Australia (17)	Australia
Juan De Fuca Ridge (18, 19)	Pacific Northwest coast (USA)
Subsurface lakes (20)	Antarctica
Solfataric springs (21)	Japan
Lake Natron (22, 23)	Africa
Global distribution of submarine hydrothermal systems (24)	Mid-oceanic ridges

through participation in the FameLab event led to a series of outreach opportunities for the author.

PROCEDURE

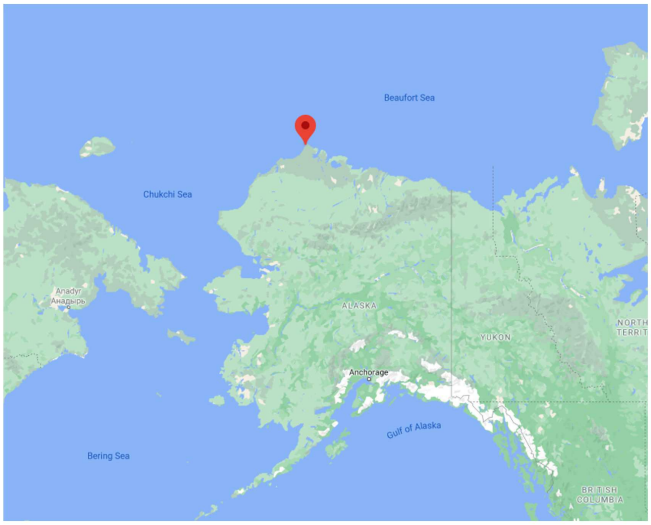
A typical format of an outreach presentation addressing a lay audience that utilizes the art of storytelling is described here. The presentation could begin with using a character from popular science fiction, through whose "eyes" the story can be narrated. Doing so forms a connection with the audience capturing their attention. This is then followed by instilling a sense of adventure and travel which captures the imagination of the audience. In order to do so, the use of such fictional characters is often combined with a travel story, narrated as a journey across the world. Since the author's presentations are



Map source: mapchart (https://www.mapchart.net/world-advanced.html) was used to illustrate the Mars analog sites described by Martins Z, *et al* (2017), Earth as a Tool for Astrobiology—A European Perspective. Space Science Reviews 209:43-81.

FIG 1 Slide showing some of the Mars analog sites on Earth as described by Martins et al. (27). These sites are characterized by diverse extremes of various physical and chemical factors in which microbiological life has been found and is being explored on Earth. Mapchart [https://www.mapchart.net/world-advanced.html (Creative Commons Attribution-ShareAlike 4.0 International License {CC BY-SA 4.0})] was used to illustrate the Mars analog sites.

Hypersaline aqueous environments at subzero temperatures near Utqiaġvik, Alaska.



Subzero (-6°C) brines (11.5%-14% salinity concentration) from cryopegs, i.e. unfrozen sediments within permafrost that contain relic (late Pleistocene) seawater brine, and sea-ice brines.

The cryopeg brines are home to dense bacterial communities.

Cooper ZS, Rapp JZ, Carpenter SD, Iwahana G, Eicken H, & Deming JW (2019). Distinctive microbial communities in subzero hypersaline brines from Arctic coastal sea ice and rarely sampled cryopegs. *FEMS Microbiol Ecol*, 95(12). doi:10.1093/femsec/fiz166

FIG 2 Slide showing site described by Cooper et al. (29). Microbes from unfrozen sediments within permafrost containing seawater brine (hypersaline) at extreme salinity and temperature (cold) were found here. The map was generated using Google maps (map data © 2024 Google, INEGI).

centered on astrobiology, the scope for such a theme is ample. Using a narrative style that could be either linear or non-linear, the author takes the audience on a "virtual" trip (through a powerpoint presentation) covering various geographical locations around the world (Table 1).

Such a storytelling approach is effective in introducing the various conditions in which microorganisms have been found. In doing so, attention is drawn to how some of the conditions in these ecosystems are analogous to what is found in places like Mars (25, 26). The audience is first introduced to the global map distribution of some of the analog sites (Fig. 1) (27, 28). This is then followed by slides on each of the sites explaining the conditions, such as temperature, pressure, etc. One such slide is shown in Fig. 2 in which microbes from unfrozen sediments within permafrost containing relic (late Pleistocene) seawater brine (hypersaline) are given as an example of microbial occurrence at extreme salinity and temperature (cold) (29).

There is ample scope for using and referencing motifs from science fiction, literature, poetry, and characters in the popular culture that members of the public are familiar with. On occasions, depending on the age group of those in the audience, and their level of interests, they have been asked to read out from the presentation (slides) playing the role of some of the popular fictional characters. For example, someone under the ages of 12–14 in the audience could read out a slide in which the popular character "Extra Terrestrial (E.T.)" (30) or an "Artificial Intelligence (AI)-generated alien character" (31) is shown "explaining" the planetary protection policy encompassing the principles of prevention of backward and forward contamination of planetary bodies (32–34) (Fig. 3).

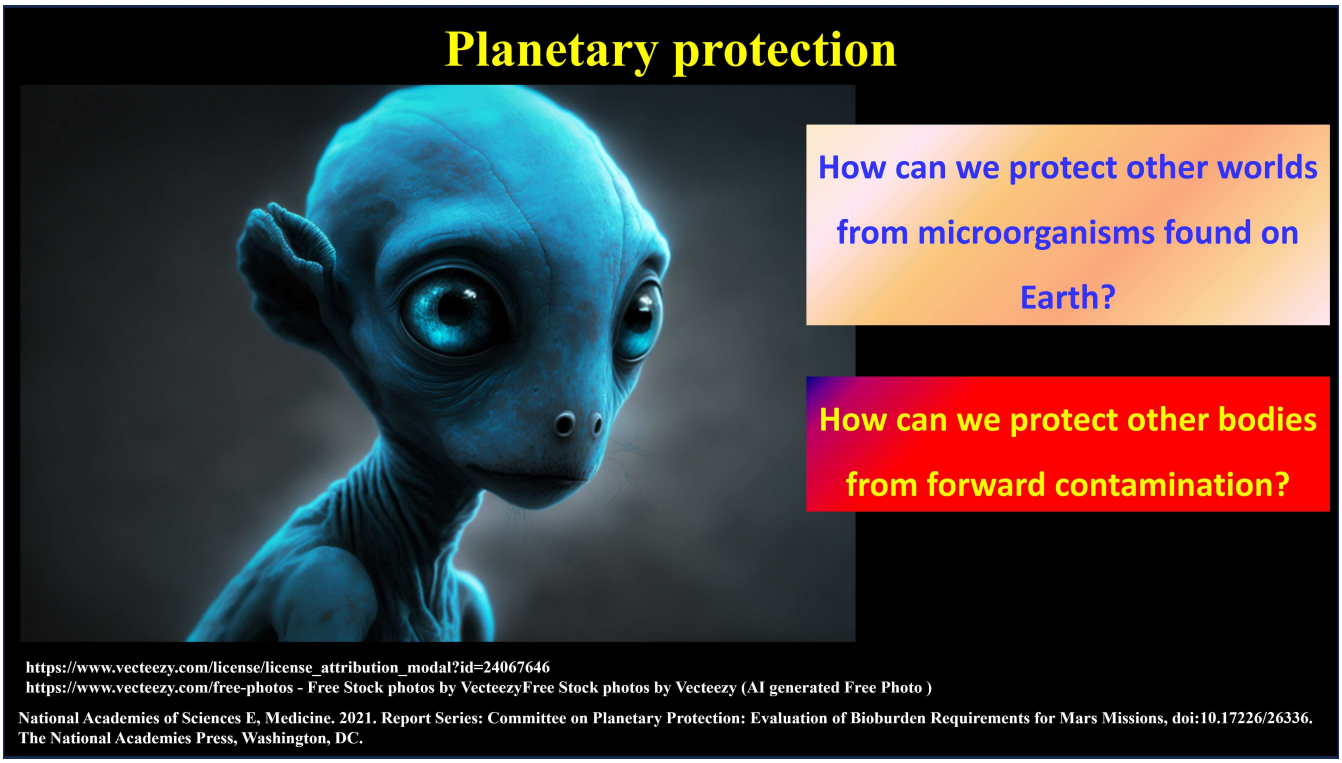


FIG 3 Example of a slide showing the use of an AI-generated alien picture "portrait of a blue alien with smooth skin and big adorable eyes" (31) to explain the components of Planetary Protection Policy (35).

This keeps them engaged, involved, and gets the message across. The key to the whole process is to finish the presentation by referring to the original fictional character, with which the presentation was started. This gives a sense of completeness to the presentation and as personal anecdotal responses have shown, the audience remembers the details better this way, as evidenced through interactions/discussions with the members of the audience after a presentation/talk.

The initial exposure to outreach through participation in the FameLab event in 2012 was followed by an EPO (education and public outreach) talk (on "radiation resistant microorganisms"), lasting 45–50 minutes, at the MARS FEST (Death Valley National Park), in March 2013, addressing a gathering of more than 50 members of the general public who were visitors at the park.

The MARS FEST presentation was instrumental in highlighting the effectiveness of such novel means of communicating science to the general audience not familiar with many of these scientific concepts/ideas. This then led to a series of EPO presentations at various museums, planetariums, and the monthly meetings of astronomical societies, in Texas, Louisiana, Colorado, and New Mexico (36–40).

These presentations have covered a broad range of topics including extremophiles (41–45), and the highly interdisciplinary field of astrobiology (46), exo-oceans (47), space microbiology (48–53), planetary protection policy (32–34), and the origins of life (54–58).

As recently as June 2023, a poster was presented, and a spotlight presentation was made at the annual meeting of the American Society for Microbiology, ASM Microbe 2023, in which the author described the EPO activity to an audience comprising academicians and researchers in the field of microbiology (59).

Societal impact and outreach

As an outcome of such active engagement in EPO, such experiences have helped in maintaining a strong track record of supporting and mentoring minority, high school,

undergraduate, and beginning graduate students. When their contributions have been substantial, they have been included as co-authors in peer-reviewed publications (41, 42, 56, 60, 61).

Overall, science communication can be an avenue for honing one's communication skills, engaging people from various walks of life, exploring one's creativity in meeting the challenges such communication opportunities offer. Overall, since outreach events are often done in an informal manner, it becomes an enriching experience for both the communicator and those who are being communicated to.

CONCLUSION

Education and outreach activities will be increasingly relevant toward dissemination of science to the lay audience. Our understanding of the limits of life is expanding with the continuous discovery of microbes tolerating a broad range of physical/chemical factors from the deep sea, below ice, hypersaline lakes to those from cleanrooms, and the International Space Station (62–64). Several studies simulating environments such as those occurring on Mars, Titan, etc. have been examining the effects of these conditions on microbial survivability (65, 66), which has implications for both planetary protection measures as well as searching for life elsewhere (67). Disseminating such knowledge as well as from other disciplines of science to a broader audience has implications as an educational endeavor. It has immense potential in engaging the public in science and inculcating the spirit of inquiry and curiosity. Additionally, outreach can be a serious hobby to pursue, and thus a "win-win" situation. Last but not the least, innovative means of communication in science when used effectively can make an impact in the Science, Technology, Engineering and Mathematics (STEM) fields.

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REFERENCES

1. James SM, Singer SR. 2016. From the NSF: the national science foundation's investments in broadening participation in science, technology, engineering, and mathematics education through research and capacity building. CBE Life Sci Educ 15:fe7. https://doi.org/10.1187/cbe.16-01-0059
2. Golle J, Catarino AI, Bordalo JM, Moscoso JA. 2022. How science outreach with children can promote equity and diversity. Trends Cell Biol 32:641–645. https://doi.org/10.1016/j.tcb.2022.04.005
3. Scalice D, Dolci W, Brochu L, Merriman T, Davis H, Billings L, Voytek MA. 2019. FameLab USA: improving science communication skills for early career scientists. Astrobiology 19:614–623. https://doi.org/10.1089/ast.2017.1809

4. McClure MB, Hall KC, Brooks EF, Allen CT, Lyle KS. 2020. A pedagogical approach to science outreach. PLoS Biol 18:e3000650. https://doi.org/10.1371/journal.pbio.3000650
5. Fergusson J, Oliver C, Walter MR. 2012. Astrobiology outreach and the nature of science: the role of creativity. Astrobiology 12:1143–1153. https://doi.org/10.1089/ast.2012.0873
6. Podar PT, Yang Z, Björnsdóttir SH, Podar M. 2020. Comparative analysis of microbial diversity across temperature gradients in hot springs from Yellowstone and Iceland. Front Microbiol 11:1625. https://doi.org/10.3389/fmicb.2020.01625
7. Keller LM, Colman DR, Boyd ES. 2023. An active microbiome in old faithful geyser. PNAS Nexus 2:pgad066. https://doi.org/10.1093/pnasnexus/pgad066
8. Peach JT, Mueller RC, Skorupa DJ, Mesle MM, Kanta S, Boltinghouse E, Sharon B, Copié V, Bothner B, Peyton BM. 2022. Longitudinal analysis of the five sisters hot springs in Yellowstone national park reveals a dynamic thermoalkaline environment. Sci Rep 12:18707. https://doi.org/10.1038/s41598-022-22047-w
9. Boyd ES, Jackson RA, Encarnacion G, Zahn JA, Beard T, Leavitt WD, Pi Y, Zhang CL, Pearson A, Geesey GG. 2007. Isolation, characterization, and ecology of sulfur-respiring *Crenarchaea* inhabiting acid-sulfate-chloride-containing geothermal springs in Yellowstone national park. Appl Environ Microbiol 73:6669–6677. https://doi.org/10.1128/AEM.01321-07
10. Kozubal M, Macur R, Jay Z, Beam J, Malfatti S, Tringe S, Kocar B, Borch T, Inskeep W. 2012. Microbial iron cycling in acidic geothermal springs of Yellowstone national park: integrating molecular surveys, geochemical processes, and isolation of novel fe-active microorganisms. Front Microbiol 3. https://doi.org/10.3389/fmicb.2012.00109
11. Descamps ECT, Monteil CL, Menguy N, Ginet N, Pignol D, Bazylinski DA, Lefèvre CT. 2017. *Desulfamplus magnetovallimortis* gen. nov., sp. nov., a magnetotactic bacterium from a brackish desert spring able to biomineralize greigite and magnetite, that represents a novel lineage in the *Desulfobacteraceae*. Syst Appl Microbiol 40:280–289. https://doi.org/10.1016/j.syapm.2017.05.001
12. Edwards KJ, Bond PL, Gihring TM, Banfield JF. 2000. An archaeal iron-oxidizing extreme acidophile important in acid mine drainage. Science 287:1796–1799. https://doi.org/10.1126/science.287.5459.1796
13. Schmidt SK, Gendron EMS, Vincent K, Solon AJ, Sommers P, Schubert ZR, Vimercati L, Porazinska DL, Darcy JL, Sowell P. 2018. Life at extreme elevations on atacama volcanoes: The closest thing to mars on earth? Antonie Van Leeuwenhoek 111:1389–1401. https://doi.org/10.1007/s10482-018-1066-0
14. Jolivet E, L'Haridon S, Corre E, Forterre P, Prieur D. 2003. *Thermococcus gammatolerans* sp. nov., a hyperthermophilic archaeon from a deep-sea hydrothermal vent that resists ionizing radiation. Int J Syst Evol Microbiol. 53:847–851. https://doi.org/10.1099/ijs.0.02503-0
15. Emerson D, Moyer CL. 2010. MICROBIOLOGY OF SEAMOUNTS common patterns observed in community structure. Oceanog 23:148–163. https://doi.org/10.5670/oceanog.2010.67
16. Fernández-Remolar DC, Gómez-Ortiz D, Malmberg P, Huang T, Shen Y, Anglés A, Amils R. 2021. Preservation of underground microbial diversity in ancient subsurface deposits (>6 Ma) of the rio tinto basement. Microorganisms 9:1592. https://doi.org/10.3390/microorganisms9081592
17. Tully BJ, Emerson JB, Andrade K, Brocks JJ, Allen EE, Banfield JF, Heidelberg KB. 2015. De Novo sequences of Haloquadratum Walsbyi from Lake Tyrrell, Australia, reveal a variable genomic landscape. Archaea 2015:875784. https://doi.org/10.1155/2015/875784
18. Anderson RE, Beltrán MT, Hallam SJ, Baross JA. 2013. Microbial community structure across fluid gradients in the Juan de Fuca ridge hydrothermal system. FEMS Microbiol Ecol 83:324–339. https://doi.org/10.1111/j.1574-6941.2012.01478.x
19. Kashefi K, Lovley DR. 2003. Extending the upper temperature limit for life. Science 301:934. https://doi.org/10.1126/science.1086823
20. Cavicchioli R. 2015. Microbial ecology of Antarctic aquatic systems. Nat Rev Microbiol 13:691–706. https://doi.org/10.1038/nrmicro3549
21. Crossman L, Holden M, Pain A, Parkhill J. 2004. Genomes beyond compare. Nat Rev Microbiol 2:616–617. https://doi.org/10.1038/nrmicro961
22. Sorokin DY, Berben T, Melton ED, Overmars L, Vavourakis CD, Muyzer G. 2014. Microbial diversity and biogeochemical cycling in soda lakes. Extremophiles 18:791–809. https://doi.org/10.1007/s00792-014-0670-9
23. Schagerl M, Renaut RW. 2016. Dipping into the Soda Lakes of East Africa, p 3-24. In Schagerl M (ed), Soda Lakes of East Africa doi:10.1007/978-3-319-28622-8_1. Springer International Publishing, Cham.
24. Takai K, Nakamura K. 2011. Archaeal diversity and community development in deep-sea hydrothermal vents. Curr Opin Microbiol 14:282–291. https://doi.org/10.1016/j.mib.2011.04.013
25. Léveillé R. 2014. Mars analogue sites, p 1–4. In Amils R, Gargaud M, Cernicharo Quintanilla J, Cleaves HJ, Irvine WM, Pinti D, Viso M (ed), Encyclopedia of Astrobiology. Springer, Berlin Heidelberg, Berlin, Heidelberg.
26. Foucher F, Hickman-Lewis K, Hutzler A, Joy KH, Folco L, Bridges JC, Wozniakiewicz P, Martínez-Frías J, Debaille V, Zolensky M, Yano H, Bost N, Ferrière L, Lee M, Michalski J, Schroeven-Deceuninck H, Kminek G, Viso M, Russell S, Smith C, Zipfel J, Westall F. 2021. Definition and use of functional analogues in planetary exploration. Plan Space Sci 197:105162. https://doi.org/10.1016/j.pss.2021.105162
27. Martins Z, Cottin H, Kotler JM, Carrasco N, Cockell CS, de la Torre Noetzel R, Demets R, de Vera J-P, d'Hendecourt L, Ehrenfreund P, Elsaesser A, Foing B, Onofri S, Quinn R, Rabbow E, Rettberg P, Ricco AJ, Slenzka K, Stalport F, ten Kate IL, van Loon JJWA, Westall F. 2017. Earth as a tool for astrobiology—A European perspective. Space Sci Rev 209:43–81. https://doi.org/10.1007/s11214-017-0369-1
28. Hipkin VJ, Voytek MA, Meyer MA, Léveillé R, Domagal-Goldman SD. 2013. Analogue sites for mars missions: NASA's mars science laboratory and beyond – overview of an international workshop held at the woodlands, Texas, on March 5–6, 2011. Icarus 224:261–267. https://doi.org/10.1016/j.icarus.2013.02.021
29. Cooper ZS, Rapp JZ, Carpenter SD, Iwahana G, Eicken H, Deming JW. 2019. Distinctive microbial communities in subzero hypersaline brines from arctic coastal sea ice and rarely sampled cryopegs. FEMS Microbiol Ecol 95:fiz166. https://doi.org/10.1093/femsec/fiz166
30. Ahn A. 2022. *An original model of E.T. is sold at auction for $2.56 million*. Available from: https://www.npr.org/2022/12/20/1144332719/et-auction-mechatronic-model-sold. Retrieved 20 Dec 2022.
31. Külbel M. n.d. *Portrait of a blue alien with smooth skin and big adorable eyes" free stock photos by vecteezyfree stock photos by vecteezy*. Available from: https://www.vecteezy.com/photo/24067646-portrait-of-a-blue-alien-with-smooth-skin-and-big-adorable-eyes-ai-generated; https://www.vecteezy.com/free-photos
32. Olsson-Francis K, Doran PT, Ilyin V, Raulin F, Rettberg P, Kminek G, Mier M-PZ, Coustenis A, Hedman N, Shehhi OA, et al. 2023. The COSPAR planetary protection policy for robotic missions to mars: a review of current scientific knowledge and future perspectives. Life Sci Space Res (Amst) 36:27–35. https://doi.org/10.1016/j.lssr.2022.12.001
33. Siegel B, Spry JA, Broyan J, Castro-Wallace SL, Sato K, Mahoney E, Robinson J. 2023. Development of a NASA roadmap for planetary protection to prepare for the first human missions to mars☆. Life Sci Space Res (Amst) 38:1–7. https://doi.org/10.1016/j.lssr.2023.03.009
34. Rummel JD, Race MS, Horneck G, Princeton Workshop Participants. 2012. Ethical considerations for planetary protection in space exploration: a workshop. Astrobiology 12:1017–1023. https://doi.org/10.1089/ast.2012.0891
35. National Academies of Sciences E, Medicine. 2021. Report Series: Committee on Planetary Protection: Evaluation of Bioburden Requirements for Mars Missions doi:10.17226/26336. The National Academies Press, Washington, DC.
36. Tirumalai M. 2019. "Life at earth's extremes: lessons for looking for life elsewhere" at the space week celebration. International museum of art & science (IMAS), McAllen, TX, USA.
37. Tirumalai MR. 2018. "The wondrous world of extremophiles and astrobiology" at combined arms, Houston, TX Available from: https://www.facebook.com/events/combined-arms/talk-the-wondrous-world-of-extremophiles-and-astrobiology/329565394269226
38. Tirumalai MR. 2021. *Science Cafe - "Life at Earth's Extremes*. Museum of Nature and Science and Sigma Xi Las Cruces, NM. Available from: https://www.lascruces.gov/CivicAlerts.aspx?AID=4670&ARC=5961

39. Tirumalai MR. 2014. *Radiation Resistant Bacteria and Implications for Our Search for Life Elsewhere*. Baton Rouge Astronomical Society Baton Rouge, LA. Available from: http://brastro.org/phpBB3/viewtopic.php?p=9407
40. Tirumalai MR. 2019. Mars: lessons from earth's microbes. In Corpus Christi museum of science and history (CCMSH), Corpus Christi, TX
41. Tirumalai Madhan R, Stepanov VG, Wünsche A, Montazari S, Gonzalez RO, Venkateswaran K, Fox GE. 2018. *Bacillus safensis* FO-36b and *Bacillus pumilus* SAFR-032: a whole genome comparison of two spacecraft assembly facility isolates. BMC Microbiol. 18:57. https://doi.org/10.1186/s12866-018-1191-y
42. Tirumalai MR, Rastogi R, Zamani N, O'Bryant Williams E, Allen S, Diouf F, Kwende S, Weinstock GM, Venkateswaran KJ, Fox GE. 2013. Candidate genes that may be responsible for the unusual resistances exhibited by *Bacillus pumilus* SAFR-032 spores. PLoS One 8:e66012. https://doi.org/10.1371/journal.pone.0066012
43. Tirumalai M.R, Fox GE. 2013. An Icebs1-like element may be associated with the extreme radiation and desiccation resistance of *Bacillus pumilus* SAFR-032 spores. Extremophiles 17:767–774. https://doi.org/10.1007/s00792-013-0559-z
44. Gioia J, Yerrapragada S, Qin X, Jiang H, Igboeli OC, Muzny D, Dugan-Rocha S, Ding Y, Hawes A, Liu W, et al. 2007. Paradoxical DNA repair and peroxide resistance gene conservation in *Bacillus pumilus* SAFR-032. PLoS One 2:e928. https://doi.org/10.1371/journal.pone.0000928
45. Seckbach J, Oren A, Stan-Lotter H. 2013. Polyextremophiles : life under multiple forms of stress. Springer, Dordrecht ; New York.
46. Des Marais DJ, Nuth JA III, Allamandola LJ, Boss AP, Farmer JD, Hoehler TM, Jakosky BM, Meadows VS, Pohorille A, Runnegar B, Spormann AM. 2008. The NASA astrobiology roadmap. Astrobiology 8:715–730. https://doi.org/10.1089/ast.2008.0819
47. McClain CR, Bryant SR, Hanks G, Bowles MW. 2022. Extremophiles in earth's deep seas: a view toward life in exo-oceans. Astrobiology 22:1009–1028. https://doi.org/10.1089/ast.2021.0120
48. Tirumalai MR, Karouia F, Tran Q, Stepanov VG, Bruce RJ, Ott CM, Pierson DL, Fox GE. 2019. Evaluation of acquired antibiotic resistance in *Escherichia coli* exposed to long-term low-shear modeled microgravity and background antibiotic exposure. mBio 10:e02637-18. https://doi.org/10.1128/mBio.02637-18
49. Tirumalai MR, Karouia F, Tran Q, Stepanov VG, Bruce RJ, Ott CM, Pierson DL, Fox GE. 2017. The adaptation of *Escherichia coli* cells grown in simulated microgravity for an extended period is both phenotypic and genomic. NPJ Microgravity 3:15. https://doi.org/10.1038/s41526-017-0020-1
50. Sobisch L-Y, Rogowski KM, Fuchs J, Schmieder W, Vaishampayan A, Oles P, Novikova N, Grohmann E. 2019. Biofilm forming antibiotic resistant Gram-positive pathogens isolated from surfaces on the international space station. Front Microbiol 10:543. https://doi.org/10.3389/fmicb.2019.00543
51. Yang J, Thornhill SG, Barrila J, Nickerson CA, Ott CM, McLean RJC. 2018. Chapter 1 - Microbiology of the built environment in spacecraft used for human flight, p 3–26. In Gurtler V, Trevors JT (ed), Methods in Microbiology. Vol. 45. Academic Press.
52. Venkateswaran K, Vaishampayan P, Cisneros J, Pierson DL, Rogers SO, Perry J. 2014. International space station environmental microbiome - microbial inventories of ISS filter debris. Appl Microbiol Biotechnol 98:6453–6466. https://doi.org/10.1007/s00253-014-5650-6
53. La Duc MT, Nicholson W, Kern R, Venkateswaran K. 2003. Microbial characterization of the mars odyssey spacecraft and its encapsulation facility. Environ Microbiol 5:977–985. https://doi.org/10.1046/j.1462-2920.2003.00496.x
54. Camprubí E, de Leeuw JW, House CH, Raulin F, Russell MJ, Spang A, Tirumalai MR, Westall F. 2019. The emergence of life. Space Sci Rev 215:56. https://doi.org/10.1007/s11214-019-0624-8
55. Tirumalai MR, Rivas M, Tran Q, Fox GE. 2021. The peptidyl transferase center: a window to the past. Microbiol Mol Biol Rev 85:e0010421. https://doi.org/10.1128/MMBR.00104-21
56. Tirumalai MR, Tran Q, Paci M, Chavan D, Marathe A, Fox GE. 2018. Exploration of RNA sequence space in the absence of a replicase. J Mol Evol 86:264–276. https://doi.org/10.1007/s00239-018-9846-8
57. Rivas M, Fox GE. 2020. Further characterization of the pseudo-symmetrical ribosomal region. Life 10:201. https://doi.org/10.3390/life10090201
58. Fox GE. 2016. Origins and early evolution of the ribosome, p 31–60. In Hernández G, Jagus R (ed), Evolution of the protein synthesis machinery and its regulation. Springer International Publishing, Cham.
59. Tirumalai MR. 2023. *"Education and Public Outreach - Through Astronomy Clubs, Museums and Planetariums", Session PT024 - Poster Spotlight Presentation (POM)*. ASM Microbe. Available from: https://www.abstractsonline.com/pp8/#!/10789/presentation/6661
60. Tirumalai MR, Anane-Bediakoh D, Rajesh S, Fox GE. 2021. Net charges of the Ribosomal proteins of the S10 and spc clusters of halophiles are inversely related to the degree of halotolerance. Microbiol Spectr 9:e0178221. https://doi.org/10.1128/spectrum.01782-21
61. Tirumalai MR, Sivaraman RV, Kutty LA, Song EL, Fox GE. 2023. Ribosomal protein cluster organization in asgard archaea. Archaea 2023:5512414. https://doi.org/10.1155/2023/5512414
62. Merino N, Aronson HS, Bojanova DP, Feyhl-Buska J, Wong ML, Zhang S, Giovannelli D. 2019. Living at the extremes: extremophiles and the limits of life in a planetary context. Front Microbiol 10:780. https://doi.org/10.3389/fmicb.2019.00780
63. Bijlani S, Stephens E, Singh NK, Venkateswaran K, Wang CCC. 2021. Advances in space microbiology. iScience 24:102395. https://doi.org/10.1016/j.isci.2021.102395
64. Moissl-Eichinger C, Cockell C, Rettberg P. 2016. Venturing into new realms? Microorganisms in space. FEMS Microbiol Rev 40:722–737. https://doi.org/10.1093/femsre/fuw015
65. Burchell MJ, Galloway JA, Bunch AW, Brandão PFB. 2003. Survivability of bacteria ejected from icy surfaces after hypervelocity impact. Orig Life Evol Biosph 33:53–74. https://doi.org/10.1023/a:1023980713018
66. Musilova M, Wright G, Ward JM, Dartnell LR. 2015. Isolation of radiation-resistant bacteria from mars analog Antarctic dry valleys by preselection, and the correlation between radiation and desiccation resistance. Astrobiology 15:1076–1090. https://doi.org/10.1089/ast.2014.1278
67. Miner KR, Hollis JR, Miller CE, Uckert K, Douglas TA, Cardarelli E, Mackelprang R. 2023. Earth to mars: a protocol for characterizing permafrost in the context of climate change as an analog for extraplanetary exploration. Astrobiology 23:1006–1018. https://doi.org/10.1089/ast.2022.0155