Viking Mars, Now 50 Years Old, Still Needs a Scientific Analysis

Steven A. Benner,*[1,2] Dirk Schulze-Makuch,[3,4,5,6] Jan Spacek,[1,7] and Clay Abraham[1,2]

1. Foundation for Applied Molecular Evolution, P.O. Box 7, 13709 Progress Boulevard, Alachua FL 32615 (www.ffame.org)
2. Firebird Biomolecular Sciences LLC, 1501 NW 68th Terrace, Gainesville FL 32605 (www.firebirdbio.com)
3. Institute of Physics and Astronomy, Technische Universität Berlin, 10623 Berlin, Germany,
4. GFZ Helmholtz Centre for Geosciences, Section Geomicrobiology, 14473 Potsdam, Germany.
5. Department of Plankton and Microbial Ecology, Leibniz Institute of Freshwater Ecology and Inland Fisheries, Stechlin, Germany
6. School of the Environment, Washington State University, Pullman, WA 99164, USA
7. Agnostic Life Find Association Inc. 13709 Progress Boulevard, Room N109, Alachua FL 32615

* Corresponding author at: sbenner@ffame.org
- schulze-makuch@tu-berlin.de
- Jan.spacek@alfamars.org
- cabraham@ffame.org

Abbreviations
GC. Gas chromatograph
MS. Mass spectrometer
NASA. National Aeronautics and Space Administration

Abstract:
Gas chromatography-mass spectrometry (GC-MS) data from the Viking Mars mission were misinterpreted in 1976 as showing that Martian soils contain no organic molecules, and therefore no life, even though the three life detection experiments delivered by Viking all reported life-positive data under the terms of their experimental design. This mistake has been propagated for a half century, including in textbooks and NASA-endorsed documents, even though it has been known since 2009 that the Martian soils contained perchlorate, perchlorate destroys organic materials in ways that might generate the GC-MS results, and *Curiosity* in 2013 observed such processes in Gale Crater on Mars, as have other rovers since. Anomalies in the propagated misinterpretation, including a contradiction between the "strong Martian soil oxidant" hypothesis and quantitative results in the carbon assimilation experiment, were "explained away" in 1976, in some cases by invoking results of experiments that had not yet been done. Today, a scientific back-and-forth is long overdue to develop an understanding of what Viking told us about the possibility of life on the near surface of Mars. Starting this back-and-forth here, we note how the Viking results are compatible with a soil that contains *Bacterial Autotrophs that Respire with Stored Oxygen On Mars* (BARSOOM), a lifestyle adapted to its environment, including sparse resources that drive dormancy, scarce atmospheric oxygen, and a cold and briny fluid only intermittently available, perhaps when the water-ice fogs seen by Viking indicate that the relative humidity exceeds 100%.

Fifty years ago, on 20 August and 9 September 1975, the Viking 1 and Viking 2 missions were launched from Cape Canaveral to map the planet and seek life on Mars. Each mission comprised an orbiter and a lander, with the two landers arriving separately at sites on *Chryse Planitia* and *Utopia Planitia*. The three life detection experiments, run in duplicate, gave interpretations generally consistent with extant Martian microbial life, at least under the terms of their design (Klein et al., 1976):

- A small amount of radioactive organic carbon was "fixed" from radiolabeled $^{14}CO_2$ and ^{14}CO (Horowitz, 1977), a “life-positive” result from experiments designed to seek Martian photosynthesis (Horowitz et al., 1972).
- A substantial amount of radioactively labeled $^{14}CO_2$ was released from ^{14}C-labeled nutrients (Levin and Straat, 2016), another life-positive result from an experiment designed to detect Martian respiratory metabolism (Levin, 1972).
- Oxygen (O_2) and $^{14}CO_2$ were released and exchanged when the Martian soil was humidified (Oyama et al., 1976), a third life-positive outcome, here based on the premise that microbes would exchange gasses with their atmosphere agnostic of their specific metabolic survival strategy (Ponnamperuma and Klein, 1970).

Today, textbooks generally teach the opposite interpretation of those results, that the Viking experiments *failed* to detect signs of life living today at those sites (Lunine, 2005). This was a direct result of a (mis)-interpretation of experiments done with each of two gas chromatography-mass spectrometry (GC-MS) instruments at the two sites (Benner et al., 2025). Those instruments had expected to detect (at least) organic molecules that come naturally to Mars via meteorites. They might also have detected organics from indigenous Martian life, if it were present. The instruments *actually* detected freons, methyl chloride (CH_3Cl), and methylene chloride (CH_2Cl_2), which emerged from strongly heated samples of Martian soil (Biemann et al., 1977).

The freons had been seen by the GC-MS instruments in flight. Therefore, the freons were easily assigned to be contaminants brought from Earth.

However, the organic chlorides were not seen in flight. Thus, the primary paper describing the GC-MS results, co-authored by Klaus Biemann (who led those experiments), stated that "[t]he methyl chloride, or part of it, could conceivably be indigenous to Mars" (Biemann et al., 1977).

This interpretation changed in Biemann's first review article in *Science* (Biemann et al., 1976). There, Biemann placed "methyl chloride" in a table beneath the heading "Terrestrial contaminants" (Figure 1). The next review, written by Norm Horowitz, referred to these chlorinated organic materials as "cleaning solvents" (Horowitz, 1977). Today, Biemann's Wikipedia page states that Biemann's partnership on the Viking program "failed to detect organic matter on its surface," (Wikipedia, 2025a) even though those experiments had actually reported no such failure.

In 1976, methyl chloride was known to not be a "cleaning solvent". Methyl chloride is a gas that boils at -24 °C. Further, in 2010, Rafael Navarro-Gonzales and his colleagues showed experimentally that methyl chloride is generated when organic materials are strongly heated with perchlorate (ClO_4^-)(Navarro-Gonzales et al., 2010). Perchlorate had been discovered in the Martian soil by the Phoenix lander one year earlier (Hecht et al., 2009).

A dialectical discussion ensued. Some suggested that the Navarro-Gonzales explanation for the Viking GC-MS observations was controversial (Biemann and Bada, 2011). Navarro-Gonzales and McKay responded (Navarro-Gonzales and McKay, 2011). The *Curiosity* Sample Analysis at Mars (SAM) suite that landed in 2012 soon saw chlorinated organics emerging from heated samples taken from Gale Crater. These were assigned to a reaction between perchlorate and instrument-delivered organics in Gale Crater (Glavin et al., 2013). Subsequent experiments saw similar results from likely indigenous organics (Eigenbrode et al., 2018; Freissinet et al., 2025).

Thus, the methyl chloride and methylene dichloride observed by the Viking GC-MS experiments are now interpreted as evidence *for* organic molecules in the *Planitia* soils, not evidence *against* their presence.

Biemann had considered the possibility that the Martian soils contained nitrate (Biemann et al. 1977), which would also have destroyed the organics upon heating before the GC-MS instrument had a chance to detect them. But he evidently did not consider perchlorate as a possible indigenous oxidant that might destroy organic molecules upon strong heating, before they could be seen in the GC-MS. Nor evidently did anyone else in 1976.

As it turned out, the GC-MS mis-interpretation trumped all other results. Gerald Soffen, the Project Scientist for the Viking missions, is famously quoted as saying: "That's the ballgame. No organics. No life." (David, 2023). And in a fascinating example of culture in science discussed elsewhere (Benner, 2026), the incorrect interpretation of the Viking experiments has been influential for nearly half a century, even in NASA-endorsed documents as recently as three years ago (Meadows et al., 2022).

Calling the “ballgame” had an unfortunate result: It prevented establishment of a dialectic needed for the scientific process to operate (Benner, 2009). In that dialectic, two sides would have formed around the Viking data. One would have sought to interpret the Viking results as evidence *for* a local extant Martian biosphere. The other would have sought to interpret the Viking data as the results of *non*-biological chemistry. The burden of proof (Benner, 2009; Benner 2026) would have gone back and forth, with new Earth-based experiments and new missions advancing in each cycle our understanding of the biological possibilities of the accessible surface of Mars.

However, with the "ballgame" called, only one side of the dialectic emerged, notwithstanding efforts by Gil Levin and Patricia Straat, who had designed the label release experiment, to argue that they had found actionable evidence of Martian life (Levin and Straat, 2016).

Favoring non-biological chemistry, a "strong oxidant" was proposed to explain the absence of meteoritic organics at *Chryse* and *Utopia* (Oyama and Berdahl, 1979). That oxidant was invoked to *also* be responsible for the release of $^{14}CO_2$ from ^{14}C-radiolabeled nutrients in the Levin-Straat experiment. No logic compelled this connection, since oxidative destruction of meteoritic organics could occur over millennia, while the $^{14}CO_2$ release from nutrients occurred in minutes. Further, the release of O_2 from in the gas exchange reaction was not interpreted as evidence for O_2 absorbed directly in the soil, but as the product of an unknown oxidant that reacted to generate O_2 upon humidification. This unknown oxidant was also seen as causing the release of $^{14}CO_2$ from nutrients, even though the mystery oxidant was evidently destroyed in seconds upon humidification, while the $^{14}CO_2$ release continued for hours.

That “life-negative” model took on a life of its own. As the Viking experiments were winding down, apparent contradictions were recognized, but dismissed. For example, the experiment seeking photosynthesis had seen ^{14}C-radiolabel (about 0.01% of the total label presented) released from the Martian soil from presumed organic molecules made in the soil from radiolabeled $^{14}CO_2$ and ^{14}CO (Horowitz et al. 1977). The amount of label released was three sigmas above background (Horowitz, 1977).

Norm Horowitz, who directed the experiment designed to seek photosynthetic carbon fixation, recognized the contradiction between the observation of ^{14}C fixation (over 5 days) and the "strong oxidant" hypothesis (Horowitz, 1977), He wrote in 1977:

> "[I]t was surprising that in such a strongly oxidizing environment even a small amount of organic material could be fixed in the soil. It is not easy to point to a nonbiological explanation for this result."

Horowitz, however, dismissed this anomaly by referencing *future* experiments, writing

> "[i]nvestigations into the problem are now under way in terrestrial laboratories with synthetic Martian soils formulated on the basis of the data from the inorganic analyses carried out by the Viking landers. A solution to the puzzle will probably also explain why the organic-analysis experiment detected no organic material in the Martian surface. Until the mystery of the results from the [photosynthesis] experiment is solved, a biological explanation will continue to be a remote possibility".

As we teach students, never trust interpretations of the results of experiments that have not yet been done (Benner, 2009).

Further, Horowitz's carbon fixation experiment embodied a still larger anomaly. After the $^{14}CO_2$ and ^{14}CO radioactive gasses were vented at 120 °C after the soils had five days to fix ^{14}C, the soils were heated to 635 °C to (by design) pyrolyze the ^{14}C-labeled organics that had been made by (possible) photosynthesis (Horowitz et al., 1977). Released organics were then (again by design) trapped in diatomaceous earth (Chromosorb). Surprisingly, that experiment also saw a "large amount of $^{14}CO_2$ and ^{14}CO" released at 635 °C over what had been flushed out at 120 °C. Those radioactive materials were not trapped in the Chromosorb. Table 1 in Horowitz et al. (1977) records this large amount of radioactivity as "Peak 1". Quantitating the observations, ca. 1% of the radioactivity initially delivered as $^{14}CO_2$ and ^{14}CO" was retained at 120 °C and then released at 635 °C (assuming 10% counting efficiency) (Horowitz et al. 1977). This was ~100 fold more than the radioactivity trapped on Chromosorb after heating to 635 °C, radioactivity assigned to the pyrolytic fragments of fixed ^{14}C-labeled organic molecules.

Horowitz and his co-authors attributed this pyrolytically released $^{14}CO_2$ and/or ^{14}CO to those gasses having been absorbed on "the soil grains and walls of the chamber" (Horowitz et al., 1977), tightly enough to not have been released at 120 °C. This is indeed possible. If the soil was alkaline and not already saturated with Martian atmospheric CO_2, it could have absorbed $^{14}CO_2$ as carbonates or bicarbonates that were stable at 120 °C but not 635 °C.

However, if the soil contained perchlorates, this workflow would have formed $^{14}CO_2$ via perchlorate oxidation of (photosynthetically) fixed ^{14}C-labeled organics. This would indicate ~100 fold more carbon fixation in those sample than initially inferred, a quantity of fixation more comparable to the quantitative details of the Levin-Straat label release results.

But these anomalies remain overlooked, even today. Horowitz's Wikipedia page today states that "Horowitz's experiments provided the first indication that there is no current life on Mars' surface" (Wikipedia, 2025b), even though these experiments had at the time been interpreted as showing carbon fixation, fixation that was to be taken as a sign of Martian life, under the terms of the experimental design (Horowitz et al., 1972). Further, even though perchlorate and its impact on organic analysis in processes that involve strong heating has been known for (at least) 15 years, no one evidently has re-considered the anomalies recognized at the time as arising via perchlorate oxidation at 635 °C. Here, the Horowitz ^{14}C fixation data parallels the GC-MS data, recognizing that because it uses radiolabel, the carbon fixation experiment is considerably more sensitive than the GC-MS data, and the radiolabel makes unambiguous the source of the oxidized organics.

It is never too late to apply good scientific method (McKay et al., 2025)

This history, of course, shows how real science is messier than we might prefer (Neveu et al., 2018). However, even after a half century, it is not too late to begin the back-and-forth dialectic with respect to extant life on Mars, a dialectic that begins with the Viking results.

Indeed, with human travel to Mars imminent, it is very important to consider the possibility of indigenous Martian life. Crewed exploration of Mars will provide many new opportunities to understand the geological and environmental context of near surface Martian environments. We now know that near surface water-ice is abundant in mid-latitudes on Mars (Morgan et al., 2021). That water will likely be mined robotically in anticipation of human arrival as a raw material for *in situ* propellant manufacture. This water will offer a hugely important astrobiological sample. Dust storms allow that water-ice to sample much of the accessible surface of Mars. Studies of life in exotic Terran habitats show that such water-ice would contain dormant Terran microbes, if it were on Earth (Navarro-Gonzales et al, 2003).

What metabolism might be proposed by life-positive models to allow life to survive in near-surface Martian environments, especially at the *Chryse* and *Utopia* sites, presumably much less hospitable than the Martian near surface water-ice? On those plains, the environments:

- are cold.
- are much drier than in near-surface ice, with liquid water present only transiently, and perhaps only when the relative humidity exceeds 100%, for example, in the Viking observed ice-water fogs.
- have abundant salt, making any liquid water that is present very briny.
- have solar irradiation as an energy source, but are also exposed to harsh ultraviolet portions of its electromagnetic spectrum, together with cosmic particles that are presumed to damage any life forms.

Damaging irradiation can, of course, be filtered out. For example, single-cell coccolithophores on Earth form plates or scales of calcium carbonate, which can contain shields against harmful radiation without wasting organic chemical resources (Xu et al., 2016). Alternatively, on Earth, in cold and dry soils at high altitude or latitude, life often does not use solar irradiation for energy. Instead, it often relies on trace gas metabolism for primary production (Islam et al., 2020; Ji et al., 2017).

Further, the presence of salts need not be detrimental, but could actually be beneficial for microbial life adapted to Mars. Hygroscopic salts might attract sparse water from the Martian atmosphere in deliquescence-efflorescence cycles (Schulze-Makuch, 2024). These would provide the fluid often thought to be a universal requirement for life (Baross et al., 2007).

An important argument against possible life on Mars is the observation that Terran life has not invaded the saltiest niches on Earth, such as the calcium chloride brines in Antarctica (Dickson et al., 2013) and salt brines at the south end of the Dead Sea (Tosca et al., 2008). However, Terran life avoids such brines because they are not tolerated by Terran proteins built from Terran amino acids (Duong-Ly and Gabelli, 2014; Chick and Martin, 1913). However, life in the salty brines on Mars evolving as the planet cooled and dried would have likely evolved alternative biopolymers with different building blocks compatible with the water activity in those brines. Indeed, the repertoire of amino acids needed for proteins evolved to perform in low activity water might be different from those evolved to perform in the relatively pure water. Observation of such amino acids on Mars, connected to the biophysics of their performance in low water activity, would be a biosignature.

A Metabolic Hypothesis. Bacterial Autotrophs Respiring with Stored Oxygen On Mars

Near-surface Martian life, like any semi-dormant life in a resource-scarce environment, needs preparedness. It must be ready to become non-dormant on the occasional moments where water becomes available with adequate warmth (Davila and Schulze-Makuch, 2016).

Based on these generalizations, how would a dialectical discussion around a proposed lifestyle for putative Martian organisms at *Chryse* and *Utopia* begin today? Let us follow one possible thread, one that presumes that those hypothetical microbiota get energy from filtered sunlight or another energy source (e.g. trace gases out of equilibrium, like CO). Even with H_2O available only as water vapor, a Martian microbe could fix carbon via the reaction $CO_2 + H_2O + \text{energy} \rightarrow$ "CH_2O" + O_2, where CH_2O represents a generic carbohydrate. The discussion would begin by hypothesizing that Horowitz observed exactly this process in his experiments intending to seek Martian photosynthesis.

But what would Martian microbes do at night? During nighttime on Earth, plants respire via the reverse reaction ("CH_2O" + $O_2 \rightarrow CO_2 + H_2O$). Martian nights are much colder, so dormancy may be the preferred majority survival strategy. However, at dawn with an increase of relative humidity in the Martian atmosphere, natural selection may have evolved a Martian microbe adapted for *Chryse* and *Utopia* to rapidly turn on respiration. According to this life-positive model, this respiration capacity was observed by the Viking experiments where ^{14}C-radiolabeled nutrient released radiolabeled $^{14}CO_2$ (Levin and Straat, 2016). This is also supported by the observation of frost and fog at the Viking landing sites, indicating that the relative humidity reached 100% at times.

But how would life-positive models account for the observed release of O_2 when the soil was humidified, seen in the gas exchange experiment? Again, the need to be ready to emerge from dormancy is relevant. On Earth, Terran bacterial autotrophs can recover O_2 that they create during the day from the atmosphere at night. On Mars, however, atmospheric O_2 is four orders of magnitude scarcer than on Earth. Thus, it makes sense for a Martian bacterial autotroph to store O_2 overnight, to be ready should the opportunity arise to use it for metabolism. In this view, the O_2 released in the Viking gas exchange experiments was biologically stored O_2. (As a historical note, in 1997, physicist Freeman Dyson remarked that photosynthetic organisms adapted for Mars would need to "conserve the oxygen that they produce by photosynthesis" (Dyson, 1997)).

Readiness may also explain another observation in the gas exchange experiment . In addition to releasing O_2, the Martian soil was observed to exchange a substantial amount of $^{14}CO_2$ and/or ^{14}CO. In life-positive models, to be ready to come out of dormancy, an adapted Martian organism might pre-absorb these, $^{14}CO_2$ a carbon source or ^{14}CO as an energy source, ready to immediately start creating organic molecules in the event that it encountered water and/or energy as scarce resources. The microbe would be prepared to immediately fix that pre-stored $^{14}CO_2$ in that event.

Thus, for this half of the back-and-forth, we might expect the lifestyle adapted for *Chryse* and *Utopia* would support a Bacterial Autotroph Respiring with Stored Oxygen On Mars, with the acronym BARSOOM. This acronym is coincidentally the name that Martians call their planet in a story by Edgar Rice Burroughs (Burroughs, 1912*)*. A BARSOOM lifestyle in hypothetical microbes on the Martian *Planitiae* provides a possible accounting for all results seen by Viking.

The Back-and-Forth Dialectic, Belatedly

None of this "proves" that the Viking results arose from BARSOOM life. Nor is “proof” possible in science. The purpose of this note is to start the back-and-forth cycle of argumentation that should have started a half century ago as a result of the Viking 1976 experiments. Indeed, this dialectic cycle *would* have started had the GC-MS data not been mis-interpreted, the observed release of O_2 had not therefore been seen to indicate a strongly oxidizing surface prohibitive of all organic molecules, and the "ballgame" not been prematurely called. With the BARSOOM hypothesis laid out, now it is time to rebut it.

We can start that rebuttal now. For the experiment observing photosynthetic carbon fixation, earlier work by Horowitz had shown that low wavelength ultraviolet light could produce a false positive (Horowitz et al., 1972). This was why the Viking experiments did not use solar light coming to the Martian surface, but brought along their own light bulbs. An interim report has been published developing this hypothesis (Hubbard, 1979).

The life-positive side of the debate might respond by noting that carbon fixation was observed on Mars even *without* light, perhaps an analog of the "dark reaction" in Terran photosynthesis. Alternatively, the hypothetical BARSOOMs may have fixed carbon using another energy source.

This would lead to a new mission design, perhaps as part of the IMPRESS architecture that sends multiple small experiments to multiple sites without the expense of a soft lander (Spacek, 2024; Spacek and Benner, 2022).

Likewise, Quinn and his colleagues have done experiments that generated hypochlorite (ClO^-, bleach) from perchlorate under intense gamma irradiation (Quinn et al., 2013). Hypochlorite can oxidize some of the ^{14}C-labeled nutrients (e.g. ^{14}C-formic acid) applied to Martian soil in the Levin-Straat experiment, generating $^{14}CO_2$. Life-negative models would see this as a mechanism by which the Viking ^{14}C-label release experiment delivered a false positive result.

A life-positive response to continue the back-and-forth might note that these laboratory experiments used a gamma ray flux many orders of magnitude higher than experienced at the Martian surface. This was done in the hope of simulating millennia of gamma ray exposure. However, while speeding the formation of hypochlorite, the experiment did not give enough time for hypochlorite to react with itself to decompose to innocuous products. This self-reaction of bleach is a reason why this commercial laundry product has a shelf life of a year or two.

On Mars, millennia were available, implying a steady state concentration of hypochlorite far below those needed to explain the Levin-Straat observations. More experiments might then test the rate of self-destruction of hypochlorite when entrapped in perchlorate crystals. This would lead to more laboratory experiments and, perhaps, another mission to resolve that question.

Conclusion

This is, of course, only a small sample of the back-and-forth argumentative discussion of the Viking experimental results that could have emerged had the "ballgame" not been called based on a misinterpretation of the GC-MS results. That discussion is now more urgent than ever, especially now that vivianite-organics have been detected as possible biosignatures in an ancient river bed on Mars (Hurowitz et al., 2025), and human visitation to Mars is contemplated, if not imminent. The 2025 NASEM report *Science Strategy for the Human Exploration of Mars* states that the search for life is Mars exploration's topmost science priority (NASEM, 2025).

A next generation of missions to do experiments to detect extant life on Mars must start before astronauts arrive on Mars. After they arrive, those experiments will become more complex, especially due to increased opportunities for contamination from Earth. Thus, future Mars exploration must have this scientific back-and-forth, and this should begin today.

Address correspondence to:
Steven A. Benner, Ph.D.
Foundation for Applied Molecular Evolution
13709 Progress Blvd Ste 7
Alachua, Florida
USA
E-mail: sbenner@ffame.org

References

Baross J, Benner, SA Cody, GD, et al. *The Limits of Organic Life in Planetary Systems.* The National Academies Press: Washington, DC; 2007

Benner SA, Schulze-Makuch D, Abraham C, et al. The mistaken assignment in this paper of Martian methyl chloride as a "terrestrial contaminant" obstructed Mars exploration for a half century continuing to today. *Science* eLetter 2025; doi: 10.13140/RG.2.2.24032.55041/1

Benner SA. How modern scientists handle anomalies. Evolution of coronaviruses and searching for life on Mars. In *Anomalies in Science* (Cleland CE, Dietrich, MR eds.) Springer; 2026; in press.

Benner SA. *Life, the Universe and the Scientific Method.* FfAME Press: Gainesville, FL; 2009

Biemann K, Bada JL. Comment on "Reanalysis of the Viking results suggests perchlorate and organics at midlatitudes on Mars" by Rafael Navarro-Gonzalez et al. *J Geophys Res* 2011; 116(E12); doi: 10.1029/2011JE003869

Biemann K, Oro J, Toulmin P, III, et al. Search for organic and volatile inorganic compounds in two surface samples from the Chryse Planitia region of Mars. *Science* 1976; 194(4260):72-76; doi: 10.1126/science.194.4260.72

Biemann K, Oro J, Toulmin P, III, et al. The search for organic substances and inorganic volatile compounds in the surface of Mars. *J Geophys Res* 1977; *82*(28):4641-4658; doi: 10.1029/JS082i028p04641

Burroughs ER. Under the moons of Mars. *The All-Story Magazine* 1912

Chick H, Martin CJ. The precipitation of egg-albumin by ammonium sulphate. A contribution to the theory of the "salting-out" of proteins; *Biochem J* 1913; *7*(4):380-398; doi: 10.1042/bj0070380

David L. Mars life reveal? Evidence of diverse organic material on the red planet. *Inside Outer Space.* https://www.leonarddavid.com/mars-life-reveal-evidence-of-diverse-organic-material-on-the-red-planet/

Davila AF, Schulze-Makuch D The last possible outposts of life on Mars *Astrobiology* 2016; 16(2):159-168; doi: 10.1089/ast.2015.1380

Dickson JL, Head JW, Levy JS, et al. Don Juan Pond Antarctica: near-surface CaCl2-brine feeding Earth's most saline lake and implications for Mars. *Sci Rep* 2013; 3(1):1166; doi: 10.1038/srep01166

Duong-Ly KC Gabelli SB Salting out of proteins using ammonium sulfate precipitation. In *Methods in Enzymology* (Vol. 541), /Academic Press: New York, 2014; pp. 85-94.

Dyson FJ. Warm-blooded plants and freeze-dried fish: How humanity will colonize the solar system. *Atlantic* 1997; 280(50):69-80.

Eigenbrode JL Summons RE, Steele A, et al. Organic matter preserved in 3-billion-year-old mudstones at Gale crater Mars. *Science* 2018; 360(6393):1096-1101; doi: 10.1126/science.aas9185

Freissinet C, Glavin DP, Archer Jr PD, et al. Long-chain alkanes preserved in a Martian mudstone. *Proc Natl Acad Sci USA* 2025; 122(13):e2420580122; doi: 10.1073/pnas.2420580122

Glavin DP, Freissinet C, Miller KE, et al. Evidence for perchlorates and the origin of chlorinated hydrocarbons detected by SAM at the Rocknest aeolian deposit in Gale Crater. *J Geophys Res: Planets* 2013; 118(10):1955-1973; doi: 10.1002/jgre.20144

Hecht MH, Kounaves SP, Quinn RC, et al. Detection of perchlorate and the soluble chemistry of martian soil at the Phoenix lander site. *Science* 2009; 325(5936):64-67; doi: 10.1126/science.1172466

Horowitz NH The search for life on Mars. *Sci Am* 1977; 237(5) 52-61.

Horowitz NH, Hobby GL Hubbard JS. Viking on Mars: the carbon assimilation experiments. *J Geophys Res* 1977; 82(28):4659-4662; doi: 10.1029/JS082i028p04659

Horowitz NH, Hubbard JS, Hobby GL. The carbon-assimilation experiment: the Viking Mars lander. *Icarus* 1972; 16(1):147-152; doi: 10.1016/0019-1035(72)90142-X

Hubbard JS. Laboratory simulations of the pyrolytic release experiments: An interim report. *J Mol Evol* 1979; 14(1–3):211–221; doi: 10.1007/BF01732379

Hurowitz JA, Tice MM, Allwood AC, et al. Redox-driven mineral and organic associations in Jezero Crater, Mars. *Nature* 2025; 645(8080):332–340; doi: 10.1038/s41586-025-09413-0

Islam ZF, Welsh C, Bayly K, et al. A widely distributed hydrogenase oxidises atmospheric H2 during bacterial growth. *Isme J* 2020; 14(11):2649–2658; doi: 10.1038/s41396-020-0713-4

Ji M, Greening C, Vanwonterghem I, et al. Atmospheric trace gases support primary production in Antarctic desert surface soil. *Nature* 2017; 552(7685):400–403; doi: 10.1038/nature25014

Klein HP, Horowitz NH, Levin GV, et al. The Viking biological investigation: Preliminary results. *Science* 1976; 194(4260):99–105; doi: 10.1126/science.194.4260.99

Levin GV, Straat PA. The case for extant life on Mars and its possible detection by the Viking labeled release experiment. *Astrobiology* 2016; 16(10):798–810; doi: 10.1089/ast.2015.1464

Levin GV. Detection of metabolically produced labeled gas: The Viking Mars lander. *Icarus* 1972; 16(1):153–166; doi: 10.1016/0019-1035(72)90143-1

Lunine J. *Astrobiology. A Multidisciplinary Approach*. Pearson: New York; 2005.

McKay CP, Quinn RC, Stoker CR. The Viking biology experiments on Mars revisited. *Icarus* 2025; 431:116466; doi: 10.1016/j.icarus.2025.116466

Meadows V, Graham H, Abrahamsson V, et al. Community report from the biosignatures standards of evidence workshop. *arXiv e-Prints* 2022 arXiv:2210.14293

Morgan GA, Putzig NE, Perry MR, et al. Availability of subsurface water-ice resources in the northern mid-latitudes of Mars. *Nat Astron* 2021; 5(3):230–236; doi: 10.1038/s41550-020-01290-z

NASEM (National Academies of Sciences, Engineering, and Medicine) 2025. *A Science Strategy for the Human Exploration of Mars*. Washington, DC: The National Academies Press. https://doi.org/10.17226/28594.

Navarro-González R, McKay CP. Reply to comment by Biemann and Bada on "Reanalysis of the Viking results suggests perchlorate and organics at midlatitudes on Mars. *J Geophys Res* 2011; 116(E12): E12002; doi: 10.1029/2011JE003880

Navarro-González R, Rainey FA, Molina P, et al. Mars-like soils in the Atacama Desert, Chile, and the dry limit of microbial life. *Science* 2003;3 02(5647):1018–1021; doi: 10.1126/science.1089143

Navarro-González R, Vargas E, de La Rosa J, et al. Reanalysis of the Viking results suggests perchlorate and organics at midlatitudes on Mars. *J Geophys Res* 2010; 115(E12); doi: 10 .1029/2010JE003599

Neveu M, Hays LE, Voytek MA, et al. The ladder of life detection. *Astrobiology* 2018; 18(11):1375–1402; doi: 10.1089/ast.2017.1773

Oyama VI, Berdahl BJ, Carle GC, et al. The search for life on Mars: Viking 1976 gas changes as indicators of biological activity. *Orig Life* 1976; 7(3):313–333; doi: 10.1007/BF00926949

Oyama VI, Berdahl BJ. A model of martian surface chemistry. *J Mol Evol* 1979; 14(1–3):199–210; doi: 10.1007/BF01732378

Ponnamperuma C, Klein HP. The coming search for life on Mars. *Q Rev Biol* 1970; 45(3):235–258; doi: 10.1086/406590

Quinn RC, Martucci HF, Miller SR, et al. Perchlorate radiolysis on Mars and the origin of martian soil reactivity. *Astrobiology* 2013; 13(6):515–520; doi: 10.1089/ast.2013.0999

Schulze-Makuch D. We may be looking for martian life in the wrong place. *Nat Astron* 2024; 8(10):1208–1210; doi: 10.1038/s41550-024-02381-x

Spacek J. International Mars Penetrator Ride-Share System (IMPRESS) to screen mars for extant life before 2030. In *2024 Astrobiology Science Conference*. American Geophysical Union: Washington, DC, 2024.

Spacek, J., Benner, S.A. Agnostic Life Finder (ALF) for large-scale screening of Martian life during in situ refueling. *Astrobiology* 2022; 22, 1255-1263; doi: 10.1089/ast.2021.007

Tosca NJ, Knoll AH, McLennan SM. Water activity and the challenge for life on early Mars. *Science* 2008; 320(5880): 1204–1207; doi: 10.1126/science.1155432

Wikipedia. Klaus Biemann. Wikipedia; 2025a. Available from: https://en.wikipedia.org/wiki/Klaus_Biemann [Last accessed 23 October 2025].

Wikipedia. Norman Horowitz. Wikipedia; 2025b. Available from: https://en.wikipedia.org/wiki/Norman_Horowitz [Last accessed 23 October 2025]

Xu J, Bach LT, Schulz KG, et al. The role of coccoliths in protecting *Emiliania huxleyi* against stressful light and UV radiation. *Biogeosciences* 2016; 13(16):4637–4643; doi: 10.5194/bg-13-4637-2016

Figure 1. The mistaken movement of methyl chloride, a compound that “could conceivably be indigenous to Mars" in the paper containing the bulk of the primary data (Biemann et al. 1997), to become a “Terrestrial contaminant” (Biemann et al., 1976) in this Table from the *Science* review, obscured not only the correct interpretation of the GC-MS results, but also drove interpretations of the three life-seeking experiments in ways contrary to their interpretations by design. This hindered the pro-con back and forth discussion of the Viking results essential to assess the astrobiological potential of Mars, and harmed Mars exploration for 50 years (Benner 2026; Meadows et al. 2022)