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The maintenance of ambiguity in Martian exobiology

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Abstract

How do scientists maintain their research programs in the face of not finding anything? Continual failure to produce results can result in declining support, scientific controversy and credibility challenges. We elaborate on a crucial mechanism for sustaining the credibility of research programs through periods of non-detection: the maintenance of ambiguity. By this, we refer to scientific strategies that resist closure or an experiment's premature end by creating doubt in negative findings and fostering hope for future positive results. To illustrate this concept, we draw upon the recent history of Martian exobiology. Since the 1960s, planetary scientists have continually tried and failed to find evidence of life on Mars. And yet, interest in extraterrestrial life detection remains high, with more missions to Mars underway. Through three destabilizing events of non-detection, we show how exobiologists sustained the search for Martian life by casting doubt on negative findings, pointing to other possible unexplored routes to success, and finally reconfiguring operations around new methods or goals. New approaches may take the form of shifts in scale, method and object of interest. By pivoting to a different scale, method or object, exobiologists have continued to study a subject continually lacking proof of existence and made important discoveries about life on Earth.

Keywords

Mars, exobiology, astrobiology, extraterrestrial life, ambiguity, NASA

After a seventh-month cruise and much anticipation, NASA's Mariner 4 arrived at Mars on July 14, 1965 – the first successful robotic probe to do so after a string of failures. Approaching the Red Planet, the craft's science instruments came alive, taking close-up pictures of the Martian surface and measuring energetic particles and magnetic fields.

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The next day, while cruising around the planet, the spacecraft briefly passed through Mars's shadow, completing its science mission. Within hours, the first data came down to Earth at an excruciatingly slow 33.3 bits per second.

For scientists raised on the science fiction of HG Wells and Edgar Rice Burroughs, Mariner 4 was to be a reckoning. For centuries, astronomers and lay observers had debated a singular question: Is there life on Mars? Though few still believed in an advanced civilization on Mars, many held out hope for vegetation or microbial life (Dick, 1996; Weintraub, 2018). In 1965, even leading planetary scientists did not know for sure. Stuck behind Earth's obscurant atmosphere, ground-based observations of Mars produced fuzzy images that were difficult to resolve. And yet in the years leading up to Mariner 4, astronomers had discovered tantalizing clues attesting to an Earth-like Mars – a similar size and rotation, spectroscopic measurements of water in the Martian atmosphere, the seasonal darkening of certain regions and possibly even canals (built by whom?), but no definitive proof of the presence of life (Horowitz, 1986: 82–90). With a remote-sensing probe flying by the planet for the first time, scientists could observe the Martian environment in greater detail and perhaps settle this pressing astrobiological question.

As the first of Mariner 4's twenty-one, grainy, black and white images returned, line by line, the Mars observed did not match the earlier idea of Mars 'as the abode of life' (Lowell, 1908). Mariner 4′s pictures showed an arid, ancient surface riddled with large impact craters resembling more our Moon than the Earth. Scientists knew that giant impacts of this size were only possible during the early formation of the Solar System billions of years ago. On Earth, dynamic weather and erosion had scrubbed such features off the surface. The cratered surface of Mars had a stunning implication, as a junior member on Mariner 4′s imaging team later explained:

> So, we found a fossil surface on Mars, which meant that there had been no Earth-like erosion and weathering for billions of years and, therefore, no oceans, rainfall, and rivers. We knew right then, from this primitive set of pictures, that Mars was not like the Earth. It didn't have an Earth-like history. … Naturally, the expectation of life on Mars plummeted (Murray, 1997: 39).

As additional data came down, the picture got bleaker. Mariner 4′s instruments failed to detect a magnetic field around Mars capable of trapping radiation like the Van Allen belts that blanket the Earth and protect fragile life from harsh solar weather. A radio occultation experiment indirectly measuring Mars's atmosphere found, as well, a much thinner atmosphere than previously estimated. If it did exist, life on Mars would have to survive under extraordinarily harsh conditions. Or, as a *New York Times* editorial in late July 1965 put it, 'Mars is probably a dead planet' (New York Times, 1965).

However dispiriting, Mariner 4′s results did not end the search for extraterrestrial life on Mars. Since then, NASA has sent nineteen successful robotic missions to Mars, exploring vast swaths of the planet, and still has not found any conclusive proof of life – not all NASA-funded Mars missions have been explicitly exobiological in their intent, but if these missions make indirect detections of life such as measurements of atmospheric composition or take pictures of the Martian surface, we include them here. Despite repeated lack of success, interest in extraterrestrial life detection and its home discipline of astrobiology remains high, with more missions planned, including a long-desired sample return of Martian soil anticipated soon (Muirhead et al., 2020). Detection, we are told in public statements, is imminent: if not on Mars, then perhaps in the deep sub-surface oceans of certain moons of Jupiter or Saturn or newly discovered Earth-like exoplanets in faraway solar systems (Houser, 2017; Naeye, 2020).

How, then, do scientists maintain their research programs in the face of not finding anything? As we argue, continual failure to produce results can result in declining support, scientific controversy and even credibility challenges. What we call the *problem of non-detection* is not unique to astrobiology. Some experiments detecting solar neutrinos (Pinch, 1986) or gravity waves (Collins, 2004) have endeavored to observe exceedingly rare or difficult-to-measure events, going decades before a verified detection. The quest to cure cancer or discover cold fusion in more applied fields seems beyond our current capabilities despite years of research and billions of dollars spent.

Drawing upon the history of Martian exobiology, we elaborate on a crucial mechanism for sustaining the credibility of research programs through periods of non-detection: *the maintenance of ambiguity.* By this, we refer to scientific strategies that resist closure or an experiment's premature end by creating doubt in negative findings and fostering hope for future positive results. Maintaining ambiguity cautions against totalizing interpretations of scientific results that foreclose upon future avenues of inquiry, offering invitations instead to deepen or extend existing research programs. Seen through this lens, exobiological evangelist Carl Sagan's frequently repeated quotes that 'the absence of evidence is not evidence of absence' or 'extraordinary claims require extraordinary evidence' take on a clearer meaning and purpose (Sagan, 1997).

Through three destabilizing events of non-detection in astrobiology – the disappointment of Mariner 4 in 1965, the failure of the Viking landers to find life in 1976, and the contested announcement of microbial life in a Martian meteorite recovered from Antarctica in 1996 – we document attempts to recover and continue the search for life on Mars. We draw upon archival research, planning documents, oral histories, news reports and publications from leading astrobiologists to assemble our narrative. We show how concerns over ambiguity were often front and center in all three cases, as scientists planned their experiments and later defended their (null) results. From these episodes, we identify three general actions used to maintain ambiguity. First, scientists can shift their search in terms of scale or location, looking in new places. Second, scientists can shift their methods, adopting new techniques or theoretical frameworks that reframe the question. Third, scientists can shift their object of interest altogether, searching for antecedents or indirect traces of the original phenomena, including fossilized remains or the building blocks of life. At various times, scientists have used combinations of all three strategies to keep astrobiology alive without finding extraterrestrial life. Moreover, these strategies extend beyond mere retrospective rhetoric from public-facing scientists and into the realm of scientific practice. In maintaining ambiguity, astrobiologists have radically transformed the nature of their work and the field of astrobiology more generally.

The problem of non-detection and the maintenance of ambiguity

The credibility of modern science rests upon a multiplicity of witnesses attesting to a matter of fact (Shapin and Schaffer, 1985). Since experimental replication is rare and technically challenging, scientists frequently turn to witnessing. From public demonstrations of experiments to virtual witnessing through scientific publications, legitimate science is what one sees and is seen (Shapin, 1984).

But what happens if there is nothing to see? Non-detection or null results have received little attention beyond the ‘file drawer problem’, where statistically insignificant findings are less likely to be published than statistically significant ones (Rosenthal, 1979). In most scientific fields, failure of this kind is accepted as a logical outcome of high-risk/high-reward research strategies (Yin et al., 2019). Null findings become a rite of passage for all scientists on their way to significant breakthroughs. Countless heroic stories of scientific discovery repeat tales of perseverance through continual disappointment. Upon failing, scientists are advised to pick themselves up, learn their lesson and move on (Parkes, 2019).

There is more to seeing nothing, scientifically-speaking, than moving along. On a practical level, null results challenge the routine operations of scientific research programs. Because funding for basic research ‘is given on the basis of promises … of future achievement’, funding agencies often substitute past results to judge the credibility of proposals and principal investigators (Turner, 1990: 190). Not producing results, therefore, becomes a reliable way of not being funded in the future. Beyond getting funding, scientists also tend to choose problems that are not only interesting but, more importantly, ‘doable’ (Fujimura, 1987). By this, Fujimura refers to problems that carefully align experiments, laboratories and the broader social world in ways that facilitate scientific productivity. Areas of inquiry that have repeatedly produced limited or no results may not seem doable in the eyes of scientists.

On a more fundamental level, non-detection threatens the legitimacy of the research program itself, that of ‘generalized perceptions that actions of an entity are desirable, proper, or appropriate’ within a scientific system (Suchman, 1995: 574). Null results may call into question both the experimental design and experimenter (Schaffer, 1988, 2011). And while a single failure may be expected, a pattern of non-detection can generate a deeper crisis of faith in scientific endeavors against a background of theoretical predictions, prior results and the enormous costs to do big science (Hossenfelder, 2018; Shrout and Rodgers, 2018; Smolin, 2006).

In disrupting scientific practice, moments of non-detection resemble violations of the interaction order that cause someone to ‘lose face’. To repair the situation, participants may engage in ‘face-work’, such as changing the subject, apologizing or joking, that restores their dignity (Goffman, 1967). Unlike face-work in everyday life, where avoidance and corrective strategies are always available to courteous participants, scientists cannot easily resolve the situation short of willful misconduct. Nature and the ‘mangle of practice’ (Pickering, 1995) must have their say too.

If non-detection strikes at the very legitimacy of a research program, simply telling those to keep the faith and hope for the best may not be enough to sustain the search. Especially when the stakes are high, offering ex post explanations for failure may not satisfy external funders or skeptical colleagues. In such cases, demonstrable acts of repair may be necessary to restore confidence. Our perspective builds consciously upon the sociology of science and technology and theories of social action to offer an alternative perspective for managing the problem of non-detection through what we call *the* *maintenance of ambiguity*. We situate non-detection within the general problem of generating scientific knowledge, reinterpreting the social mechanisms used to close scientific controversies toward different ends (Collins, 1985). Rather than close controversies, scientists can instead keep them open, using the resulting interpretive flexibility to create a space for action (Leifer, 1988; Mahoney and Thelen, 2009; Padgett and Ansell, 1993; White, 1992). Purposeful ambiguity becomes not only semantically productive (McMahan and Evans, 2018; see also Ceccarelli, 2001; Sillince et al., 2012) but scientifically productive as well (Star and Griesemer, 1989; Vertesi, 2020). Ambiguity is no longer just an inevitable part of an uncertain world but also a strategic resource that can be cultivated and deployed (Best, 2012). Applied to the problem of non-detection, the maintenance of ambiguity provides a face-saving way for scientists to delay expectations and continue their research by insisting ‘the jury is still out’.

Such a strategy, however, is inherently risky. Because credibility rests in resolving ambiguity, scientists cannot indefinitely delay closure. Far from just offering up retrospective excuses for their null results, scientists must demonstrate they are working toward resolving non-detection by trying new things. Maintaining ambiguity, therefore, must be a skillful act, balancing the epistemic and reputational consequences of staying flexible with its productive qualities (Stark, 2009). Doing so requires scientists to look beyond the rhetorical realm, where ambiguity is often constructed after the fact. It is not enough to behave or speak ambiguously. Instead, scientists must occupy and continuously navigate (sometimes circuitously) structural positions that are themselves ambiguous (Padgett and Ansell, 1993). As we describe in greater detail below, these actions can include *shifts in location, method, and object*, keeping open the ‘space of possibilities’ and giving scientists more moves to play before calling it quits (Bourdieu, 1993: 176). Such moves help generate perceptions of productivity while desired breakthroughs remain elusive.

While delaying experimental closure, scientists may often end up producing exceptional amounts of unanticipated knowledge as they shift location, method or object. This epistemologically generative quality of maintaining ambiguity (Merton, 1987), we argue, sets our perspective apart from related theorizing on proprietary knowledge, ignorance, uncertainty or the unknown that has similarly explored spaces of non-knowledge (Croissant, 2014). At least in the case we document below, scientists maintaining ambiguity are neither victims of ‘undone science’ (Frickel et al., 2010) nor purposeful ‘merchants of doubt’ (Oreskes and Conway, 2010). In Martian exobiology, ambiguity was rarely the end but rather the means to continue doing science.

Is there life on Mars?

‘The detection and analysis of planetary life is one of the major challenges of contemporary science’, hailed a 1959 report of eminent biochemists and microbiologists (Space Science Board [SSB], 1959: 2). Physics and chemistry had demonstrated that energy and matter were likely the same throughout the universe, but ‘life in contemporary science’, complained the report, ‘still means *terrestrial life*’ (SSB, 1959: 2). Did biology work beyond our planet like chemistry or physics? Or was life and its study unique to Earth? ‘At stake in this uncertainty’, asserted these same biologists in 1965, ‘is nothing less than knowledge of our place in nature’ (SSB, 1966a: 5).

These and other questions animated the new field of exobiology, a combination of the words ‘extraterrestrial’ and ‘biology’, at the dawn of the space age. As astronomers, physicists, chemists and engineers geared up to extend their research into outer space, biologists demanded a seat at the table and a piece of the pie, promoting the idea of searching for life on other planets. Mars, in particular, became the central focus of early exobiologists as the only Earth-like planetary body close enough to be studied using ground-based observation and direct robotic exploration. Venus, Earth’s closest neighbor in the solar system, attracted early NASA robotic missions too, but its thick atmosphere had always prevented a rich cultural history of intense speculation about life on its surface (Markley, 2005), and for post-war astronomers, Venus’s pressure and heat ruled out all but the most radical conceptions of life. Though some held out hope for finding life in the clouds of Venus or perhaps in the faraway gas giants of the outer Solar System (Morowitz and Sagan, 1967), Mars represented for most the first best chance of finding life on other planets. ‘Considering the main variables of the survival of biological systems’, argued leading space scientists in 1965, ‘it is generally agreed that Mars is the most promising objective for efforts to detect extraterrestrial life’ (SSB, 1966b: 488).

Decades later, exobiologists have yet to find any unambiguous proof of extraterrestrial life on Mars or elsewhere but continue to maintain a vigorous program of exploration and investigation. The field’s problem of non-detection, we argue, reframes the received history of exobiology. The exobiology community took shape in the late 1950s. Following Sputnik’s launch in 1957, Nobel prize-winning molecular biologist Joshua Lederberg successfully lobbied the newly-minted National Aeronautics and Space Administration (NASA) to fund the search for extraterrestrial life. Dick (1996), Ezell and Ezell (1984), Strick (2004) and Wolfe (2002) have shown how Lederberg’s campaign was animated by his fear of contamination: Unsterilized spacecraft would introduce Earth microbes to the lunar surface, forever confounding the search for life there, and returning astronauts and vehicles might back contaminate Earth with alien life. Far from abstract or improbable, such fears drew upon a rich imaginary assembled from the history of island exploration, demonstrating the real problems of forward and back contamination (Webb, 2021).

Lederberg organized the field quickly between 1958 and 1960 by combining an emerging interest in extraterrestrial biology with established origin-of-life research (Oparin, Haldane, Miller-Urey). In 1958, NASA administrator Hugh Dryden made Lederberg head of a new sub-group of the National Academy of Sciences (NAS) Space Sciences Board (SSB) dedicated to ‘extraterrestrial life’. One of Lederberg’s first organizational moves was to split the sub-panel’s membership into bi-coastal communities – EASTEX and WESTEX – that formed the core of the emerging field of exobiology. EASTEX focused primarily on scientific questions on the origin of life, while WESTEX studied problems of contamination. When NASA formally established its Life Sciences Office in early 1960, exobiology and spacecraft sterilization were specific areas of focus. In recognition of exobiology’s growing stature, the SSB and NASA in 1964 prioritized the search for life on Mars as the next great scientific endeavor after the moon landings of Project Apollo (SSB, 1966a, 1966b).

In existing histories, two major themes emerge on exobiology’s development: *credibility* and *patronage*. In search of scientific credibility, Lederberg and others had to perform significant boundary work to distance nascent exobiology from related endeavors and critiques that threatened to undermine the new discipline's legitimacy. These included science fiction stories about alien life, NASA's human spaceflight spectacles, and accusations from mainstream biologists George Gaylord Simpson (1964) and Abelson (1961) that exobiology was a wasteful pseudo-science lacking a verifiable subject. To counter these claims, exobiologists sought credibility in two ways. First, they connected the problem of contamination to Cold War fears of biological warfare and the need for international cooperation from all space-faring nations to avoid spoiling outer space environments (Wolfe, 2002). With the sharing of potentially weaponized research in high-energy physics or atmospheric science off-limits, spacecraft sterilization policies proved to be a rare space policy interface between the US and USSR. Second, exobiologists cultivated connections with preexisting legitimate sciences, including astronomy, biochemistry, and genetics (Strick, 2004). Many leading members were well into successful careers in their respective fields, giving them greater autonomy to pursue potentially less reputable research areas like exobiology. Thus, the field borrowed consciously from existing pools of scientific legitimacy to gain a foothold in the emerging space sciences.

NASA patronage also left an indelible impact on how exobiology approached the search for life. Rather than use military funds or grants from the National Science Foundation or National Institutes of Health (all of which had previously supported the work of many community members), exobiologists looked to NASA for support. Unlike other government agencies supporting research and development, NASA was founded principally as an engineering organization empowered by Congress to build rockets to put people and probes into space (Conway, 2016). Though NASA support included some money for basic research, most funds were dedicated to developing spaceflight missions such as robotic orbiters, landers and rovers designed to explore alien environments. This mission-oriented approach to funding imparted a big science style to exobiology at odds with the smaller lab-based research practices that previously defined biology (Ezell and Ezell, 1984).

In light of these themes, exobiology (more commonly known as 'astrobiology' since the 1990s) is a crucial case for understanding the problem of non-detection. First, the field's legitimacy has always been vulnerable to attack from skeptics. Despite connections to Cold War politics and scientific elites in the past, exobiology's status continues to be questioned. 'In the absence of unambiguous proof for its existence', recently complained a leading biologist, 'almost nothing can be said about extraterrestrial life about which the opposite is not also true. The scarcity of evidence gives considerable latitude, and, in certain circles, astrobiology has become a resounding but meaningless catchword in the competition for grant money' (Lazcano and Hand, 2012: 160). Such critiques lead to a second point. The tremendous cost of searching for life on other planets raises the stakes when justifying science support. Exobiology is not cheap. Future missions to resolve 'whether we live in a biological Universe or one in which life on Earth is a singularity' may have a 'combined cost … comparable to that of the Large Hadron Collider, whose final price tag hovered around $8–9 billion' (Lazcano and Hand, 2012: 161).

By challenging the field's legitimacy and institutional support, the problem of non-detection rises to an existential threat for astrobiology. Existing histories, however, often diminish or downplay this threat. Multiple researchers have shown how exobiology formed and gained legitimacy among other biological sciences. Here we are interested in how, once going, exobiologists sustained their credibility following crucial moments of crisis, the successive high-profile non-detections that have characterized the field. Even Dick's in-depth chronicles of major events, *The Biological Universe: The Twentieth Century Extraterrestrial Life Debate and the Limits of Science (1996)*, and *Life on Other Worlds: The Twentieth Century Extraterrestrial Life Debate (1998)* stop short of analysing changing strategies during these critical 'aftermath' periods. How did exobiologists keep the field viable in the weeks, months and years following destabilizing (and demoralizing) events? How did the scientific rhetoric and practice of exobiologists shift to maintain ambiguity? In the analysis that follows, we unpack these strategic shifts as critical field sustaining work stemming from an overarching reluctance to conclude the question of life-on-Mars in the negative.

Event 1: Mariner 4 and shifts in scale

In early 1965, as Mariner 4 zoomed toward Mars, most, if not all, exobiologists believed there was some sort of life waiting to be found. The hoped-for extraterrestrial life existing on Mars based on telescopic observations adjusted from intelligent civilizations at the turn of the century to simple, hardy vegetation similar to lichen. Plant life proponents pinned their hopes on bluish-green areas of the surface initially labeled 'oceans' when first spotted through telescopic observations by Christian Huygens in the seventeenth century, that appeared to wax and wane with the Martian seasons – a phenomenon later called 'seasonal changes' or 'seasonal darkening'. The American astronomer Slipher (1955: 432) wrote in *National Geographic* that 'many astronomers now feel sure the large dark areas represent vegetation'. It was in this context in the early 1960s that Lederberg and Sagan (1962: 1474) advocated for 'high-resolution reconnaissance in planetary fly-by missions' like Mariner 4 to determine whether 'the areas where organic matter is concentrated also show the greatest seasonal changes?' The dominant expectation among exobiologists in the first half of 1965 was that fly-by photos would reveal evidence of a living, Earth-like Mars.

Soon after Mariner 4 beamed back the 21 photographs that convinced *The New York Times* to declare Mars a 'dead planet', scientists with interest in exobiology mounted a vigorous defense in both the press and scientific literature, arguing the question was far from settled. Their message was simple: Despite appearances, these images were not the knock-out punch the press and skeptics in the scientific community trumpeted. And they had to counter more than just the *Times*. A wave of news stories appeared via wire service declaring the Mariner 4 images 'practically demolished that belief except for the most faithful' and constituted a 'most devastating blow' to the hopes that life would be detected (Myler, 1965: 13).

One of the first to respond was Colin Pittendrigh (Anonymous, 1965), a biology professor at Princeton and co-chair with Joshua Lederberg of the National Academy of Sciences' Committee on Mars Exploration. He accused the raft of headline writers of committing a 'very serious misjudgment bordering on irresponsibility'. 'The pictures don't cover the whole surface of Mars', he pointed out and continued, 'they in no way indicate that organic material does not exist anywhere on the planet'. For Pittendrigh, who had received exobiology funding from NASA, the returns from Mariner 4 were ambiguous, not conclusive. He suggested that 'other sections of the planet's surface which were not photographed by Mariner may be different from those portions revealed in the photos'.

This ambiguity was echoed in an October 1965 postscript to the National Academy of Sciences' year-long study on *Biology and the Exploration of Mars*. Among the many recommendations in the report was for a dramatic expansion in Martian exploration. The study team asked, 'Do the results of Mariner IV change our earlier conclusions and recommendations?' (SSB, 1966a: 20). The panel, chaired by Pittendrigh, answered with a resounding no. The 'meager facts' of Mariner 4 gave 'neither the advocate nor the critic of Martian exploration' sufficient 'empirical and inferential certainty' to dismiss the potential for life on Mars. To do so either denied 'the resourcefulness of self-replicating systems' to survive under the extreme conditions observed or reached a 'premature inference' on data that demanded analysis 'for many years before their full meaning becomes clear'.

Norman Horowitz, a Cal Tech geneticist who worked on the Mariner 4 camera team, also fought the popular closure of the life on Mars question. Writing in *Science* that 'Mariner IV neither proved nor disproved the existence of life on Mars', Horowitz (1966: 791) suggested that the camera and the spacecraft's trajectory were insufficient to settle the debate. 'The possibility of performing an unambiguous life-detection test from a fly-by or an orbiter is remote'. Echoing his colleagues, Horowitz also stressed the need to shift the search from space to the surface. 'To solve this problem, we will probably have to land a capsule on Mars and have it survive long enough to make some measurements and transmit them back to Earth'. Without the 'ground truth' of a lander, interpreting 'photographic reconnaissance' of Mars for biological purposes was a speculative endeavor, similarly concluded Carl Sagan and two collaborators (Kilston et al., 1966: 80).

The returns from Mariner 4 had exobiologists on their back foot, fighting the power of pictures in the court of public and scientific opinion. In response, they characterized the photographic results as inconclusive and ambiguous. Yes, there were close-up pictures of the surface, but only a small sliver of the planet was imaged; life could exist in other areas. Yes, the fly-by had come closer to Mars than ever before. Still, the ultimate 'truth spot' for exobiology was the surface, requiring a robotic or human landing to assess adequately (Gieryn, 2006).

Shifts in scale

Despite Mariner 4′s disappointment, the space science community still rallied behind continued Martian exploration. Ambiguity over Mariner 4′s results suggested several ways forward for the exobiological community. An obvious next step was to keep the search focused on Mars but obtain more data from perspectives not offered by Mariner 4′s fly-by, both from orbit and the surface. We call these *shifts in scale*: expanding the search for life on Mars in terms of both time and place. Shifts in scale included not only a long-dreamed landing on Mars but also the 'constant synoptic scrutiny' of a

Mars-orbiting spacecraft (Lederberg, 1965: 13). Planned Martian orbiters and landers might work in concert, pairing the much-needed ground truth of *in situ* analysis with global data collected in orbit. Rather than rely on a quick fly-by, such orbiters and landers could be long-lived, operating over months to even years and offer more opportunities to detect rare events. Upon pushback from Congress, NASA's planetary program distributed desired shifts in scale across multiple, smaller missions rather than centralizing them in a single mega-project. A Mars lander was put off until at least 1973, while additional fly-bys (Mariners 6 and 7 in 1969) and orbiters (Mariners 8 and 9 in 1971) laid the groundwork for intensive Martian exploration.

Flying by Mars a week after the first Moon landing in July 1969, Mariners 6 and 7 returned more images of a lifeless, cratered Mars similar to those from Mariner 4. The fly-by provided new evidence that Mars's poles – long thought to contain abundant frozen water and therefore be a potential abode of life – were almost entirely comprised of frozen carbon dioxide. As Mariner 6 and 7′s camera team observed in late 1969, the 'results thus reinforce the conclusion, drawn from Mariner 4 and ground-based observations, that scarcity of water is the most serious limiting factor for life on Mars' (Leighton et al., 1969: 65). An onboard ultraviolet spectrometer scanning the surface of Mars suggested that solar radiation easily penetrated Mars's thin atmosphere, given the lack of a magnetic field similar to Earth (Barth et al., 1969). Any unprotected organism on the Martian surface would be exposed to a lethal dose of radiation by terrestrial standards within seconds. The case for Martian life appeared bleaker than ever.

After Mariners 6 and 7, the planetary science community splintered into groups of pessimists like Murray (1972) and optimists like Sagan (1972) over the likelihood of finding life on Mars. Some pessimists put the chances of finding life on Mars at 0.1% or less. In 'our present state of ignorance', countered Sagan (1971: 511) in a classic expression of maintaining ambiguity, 'such probabilities are merely skepticism indices, calibrating the frame of mind of the speaker'. As Sagan explained, Mariners 4, 6 and 7 again captured a fraction of Mars in a brief moment, missing, by design, seasonal variations over months and other dynamic processes that might open up conducive microenvironments for life.

Sagan's hopes were buoyed by Mariner 9 – the first spacecraft to orbit another planet. Observing Mars over an extended eleven-month period beginning in November 1971, Mariner 9 returned 27 times the amount of data of previous fly-bys, mapping nearly 80% of the planet's surface. New shifts in scale gave exobiologists a wealth of findings to maintain ambiguity over the potential for Martian life. Mariner 9′s discoveries amounted to no less, as Hartmann and Raper (1974) put it, than a 'New Mars', a more active, evolving planet with strong evidence for geological dynamism and even flowing water in the past.

Arriving amid an enormous dust storm that obscured the planet's surface for over a month, Mariner 9 documented a planet unexpectedly shaped through wind erosion and dynamic weather patterns. More striking were new images of four gigantic inactive volcanoes and 'sinuous dendritic channels', some hundreds of kilometers long, likely cut by water at some point in Mars's early history (Houck et al., 1973: 470). Though the mission did little to change perceptions of present Martian inhospitality, Mars's past perhaps evidenced a different story advanced by the optimists. If liquid water once existed on

Mars, could life have arisen on the planet? If life evolved under these challenging conditions, could it still exist in hidden oases or microenvironments insulated from the harsh Martian climate? The Mariner series of remote sensing probes had advanced scientific understanding of Mars but were never designed as proper life detection experiments. In situ life detection required a shift in scale, landing on Mars's surface to bring scientific instruments into physical contact with samples of Martian soil and atmosphere.

Exobiologists got their wish with Viking. Formally approved in 1969 and launched after a two-year delay in 1975, the Viking mission provided scientists with the 'first "on the ground" view of Mars' (Mars Science Advisory Committee, 1973: III-5). Viking was, at the time, the most complex and expensive NASA robotic spaceflight mission ever attempted, drawing together five NASA spaceflight centers, dozens of contractors, hundreds of participating scientists and thousands of supporting staff at a cost of $1 billion in then-year dollars (~$7 billion today). The mission concept combined two landers and two orbiters working together over an extended period to study Mars as an entire planetary system.

Since the early 1960s, exobiologists had been at the forefront of Martian exploration by demanding greater and greater shifts in scale to resolve ambiguities in the data. From fly-bys to orbiters to landers, maintaining ambiguity required continual technological leaps forward to sustain the search for Martian life. However, Viking's enormous size and escalating budget raised the stakes of additional shifts in scale if scientists still found nothing. The 'return of unambiguous biology data … from the two Viking '75 spacecrafts', warned a 1974 report of the SSB's exobiology panel, 'can be expected to have a major impact on the planetary program' (SSB, 1975: 172). A positive finding might inaugurate a new scientific discipline, Martian biology, while a negative result could terminate the search for extraterrestrial life as a motivation for planetary exploration. But as exobiologists worried, 'the most likely and vexatious outcome' of Viking was an ambiguous result. 'Ambiguity in [Viking's] data', warned another SSB report, 'is likely to lead to a major controversy over the interpretation and significance of the results' (SSB, 1974: 54). Left unsaid was how simultaneously productive such ambiguity might be for the search for Martian life.

Event 2: Viking and shifts in method

On July 20, 1976, the first Viking lander touched down on Chryse Planitia, a smooth plain near Mars's equator. Two months later, a second Viking lander landed further north on Utopia Planitia. Onboard each lander was a sophisticated array of instruments designed to characterize the Martian environment and search for life. Viking provided the first opportunity to conduct in situ life detection experiments for exobiologists long desiring a shift in scale down to the Martian surface.

As mission scientists combed through the data over the next several months, the Mars revealed by Viking was again as surprising as it was disappointing. Viking carried five instruments capable of searching for signs of extraterrestrial life. The first, a camera, could resolve so-called 'macrobes' like vegetation or more complex creatures or perhaps traces of movement left behind. If a picture contained a thousand words, a single image might provide long-sought proof of Martian life more than any other data. Instead, Viking’s arresting wide-angle shots of the Martian surface – widely shared in magazines and newspapers at the time – captured an arid, cold landscape denuded of any visible vegetation or complex life. As a select group of the Lander Camera team later reported, ‘no evidence, direct or indirect, has been obtained for macroscopic biology on Mars’ (Levinthal et al., 1977: 4468).

The second, a gas chromatograph mass spectrometer (GCMS), analyzed the chemical composition of the Martian atmosphere and soil samples. Though not a life-detection experiment per se, the GCMS could still search for organic compounds down to a few parts-per-billion, based upon the familiar carbon-hydrogen-nitrogen-oxygen chemistry essential to life on Earth. The GCMS found no such organics. More troubling were readings of oxidizing agents in the soil that – at least on Earth – would rapidly break down any organic materials. Given the presence of oxidized soil, Mars appeared even more hostile to terrestrial life than previously anticipated. While leaving the possibility open for more exotic biochemistries, the GCMS team reported, ‘the results of the organic analysis experiment do not rule out completely that there are living organisms in the samples analyzed, but they should not give encouragement to those who hope to find life on Mars’ (Biemann et al., 1977: 4654).

The next three life-detection experiments – the Gas Exchange experiment (GEx), the Labeled Release experiment (LR) and the Pyrolytic Release experiment (PR) – were packaged into a single miniaturized microbiological laboratory slightly larger than a gallon milk jug. All three experiments exposed Martian soil samples to various substances and then monitored them for signs of metabolic activity from soil microorganisms. Early results seemed promising. As Viking Biology team leader Chuck Klein noted, preliminary evidence suggested ‘very active surface material’ that looked ‘very much like a biological signal’. However, project scientists could not rule out chemical processes that might ‘mimic biological activity’ (Lambright, 2014: 67). The GEx and LR experiments indicated a highly reactive soil sample when initially exposed to a bath of nutrients, but strangely no additional reactions when the sample was exposed to the nutrient bath again. The PR experiment at one landing site initially produced an anomalously high result but failed to replicate this finding over the next eight experimental runs. The only consensus Viking scientists could arrive at was a ‘cloud of ambiguities’ (McElheny, 1976). When paired with the GCMS’s null results and similar findings at both landing sites, most Viking scientists conceded that a non-biological explanation likely accounted for the surface chemistry puzzle.

Interpreting the results in a November 9 news conference, Chuck Klein adopted an ambivalent posture toward the data: ‘I would say that on the basis of incomplete evidence … we cannot say conclusively that there is life on Mars. I would also say that we cannot say conclusively that there is not life on Mars’ (Chaikin, 2008: 168). Rather than give a firm yes or no answer, Carl Sagan, perhaps the most public-facing of the Viking scientists, urged for ‘an increased tolerance for ambiguity’ from the press and public at large (Chaikin, 2008: 168). Viking’s scientists repeated the usual rhetorical justifications used on past missions. The Viking mission had only landed in two locations on Mars and dug a few centimeters into the ground. Vast portions of Mars remained unexplored. But, for most, Viking’s ambiguous results translated into a ‘public perception of failure to find life’ on Mars (Lambright, 2014: 73). ‘Even though some ambiguities remain’, wrote

Norm Horowitz (1977: 61), now a scientist on Viking's Biology Team, 'there is little doubt about the meaning of the observations of the Viking landers: At least those areas on Mars examined by the two spacecraft are not habitats of life'.

Shifts in method

As Viking's scientists puzzled through the incongruous results, active soil sample chemistry but a relatively inactive and perhaps even self-sterilizing Martian surface environment, they arrived at the consensus that only the return of an unsterilized sample of Martian soil to Earth for detailed laboratory analysis promised to resolve these ambiguities (SSB, 1977). Safely collecting and returning a sample of Martian soil would require yet another dramatic technological leap forward. But in the absence of overwhelmingly positive exobiology results from Viking, NASA refused to support further shifts in scale. 'Instead of beginning a great new era of Mars exploration', summarized space historian Conway (2015: 2), 'the Viking missions nearly signified its end'.

Whereas past Mars missions had garnered strong support from the planetary science community, Viking's mixed results soured further Mars exploration for some, like Cal Tech geochemist Gerry Wasserburg, who chaired the SSB's influential Committee on Lunar and Planetary Exploration. Concerned that all future Mars missions 'would be jeopardized by continued ambiguous biology results', Wasserburg advocated for a reprioritization of future planetary science missions, abandoning Mars and turning toward other planets, especially those in the outer solar system (Lambright, 2014: 81). Not one to mince words, Wasserburg branded optimists like Sagan as 'fanatics' in their quest to continue the search for life on Mars. NASA administrators agreed with the reprioritization, opting in the late 1970s to push forward on an orbiting space telescope (Hubble) and a Jupiter orbiter and atmospheric entry probe (Galileo), rather than more Viking missions to Mars. NASA would not return to Mars for another two decades (see Figure 1).

Viking's ambiguity not only exhausted further shifts in scale but also 'clobbered exobiology', as Viking Project Scientist Gerry Soffen later recalled (Chaikin, 2008: 168). Over the next decade, exobiology entered into a pronounced period of retrenchment, as dedicated NASA exobiology funding declined and all but disappeared (see Figure 2). The name 'exobiology' itself fell out of favor, replaced by various names like planetary biology, global biology or biospheric research. The field and its constituents also changed. For exobiologists like Soffen or Joshua Lederberg, Viking was the last time either actively worked in the field. For others like Penelope Boston or Chris McKay – then young graduate students in the early 1980s – pursuing Martian exobiology required them to go 'underground', awaiting the day when interest in Mars from funding agencies resumed (Betancourt, 2016).

Exobiology did not die off, however. It just changed form through new shifts, not in scale, but in *method*. Shifts in method undertaken in the 1980s rethought the 'why' and 'how' of life detection, retooling for when scientists might return to Mars. Rather than attempt to find and isolate Martian life in a laboratory context, shifts in method situated Martian life (or its absence) within a broader, comparative context. After allying with biochemistry and microbiology in the 1960s, exobiology in the 1980s grew closer to

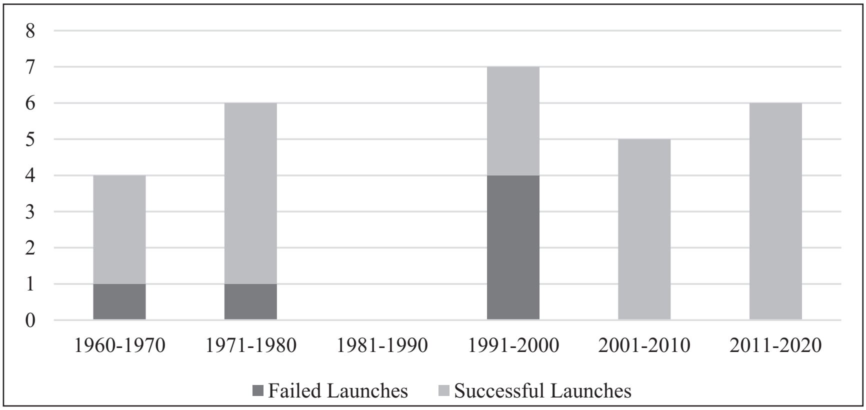

Figure 1. U.S. Robotic Spacecraft Launch Attempts on Mars, 1960-2020.
Data is drawn from Siddiqi (2018).

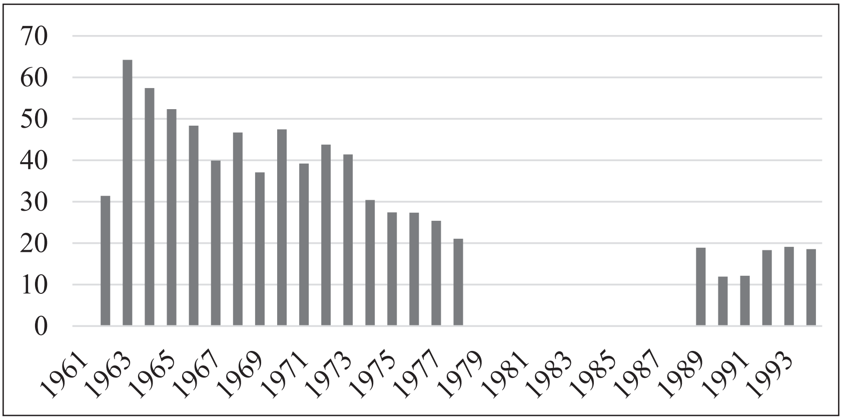

Figure 2. NASA Exobiology Funding, 1961–1994 (in millions of FY'19 dollars).
Data is drawn from various years of *NASA Budget Estimates*. Adjustments for inflation use the NASA New Start Index to normalize historical costs.

emerging ecological and environmental sciences. And given no more Mars missions, for the time being, exobiologists refocused their efforts on Earth.

Exemplifying these shifts in method was the emerging research program of biologist Lynn Margulis (then partner of Carl Sagan). As she argued in 1980, 'if there is no life in the solar system beyond our own, what is left for the planetary biology program to do? It is time to look back at the Earth, the only planet, as far as we know, upon which life has originated and evolved' (Margulis, 1980: 26). Successive shifts in scale on Mars over a decade and a half had resulted in a surprising development: Planetary scientists now knew more about the atmosphere, climate and planetary dynamics of Mars than they did about Earth. Unlike Mars, Earth had never been studied systematically as an abode of life. Scientists like Margulis began coordinating with geologists, oceanographers, climatologists and other natural scientists to untangle the ‘dynamic processes that maintain Earth as a planet and sustain life’ and, in turn, understand the ‘origin and evolution of life as a planetary phenomenon’ (Margulis, 1980: 26). Central to this endeavor were space technologies that made it ‘possible to observe for the first time globally averaged biological processes’. Sensing probes, long-term orbiters, and various scientific instruments used on Mars could be repurposed to study Earth.

Despite the focus on Earth, Mars did not take a back seat. Scientists began to see Mars more as a road not taken or Earth’s experimental control given the planet’s inhospitality. Timed with growing recognition of anthropogenic climate change, scientists sought to isolate the effects of life itself on the changing environment. Mars, as a dead planet, made for a compelling contrast to the more dynamic and increasingly human-shaped Earth. Typical of this view were the conclusions of the SSB’s Post-Viking Biology panel:

> It is customary to think that life exists only on planets that provide the proper conditions for its maintenance. But the realization is growing that life itself may modify a planet’s surface and atmosphere to optimize conditions for its existence. … We have clearly reached the point where human activities are exerting global effects on the composition of the Earth’s atmosphere and perhaps its temperature. … Since the surface of Mars provides a natural global system for comparison with Earth, we submit that studies of biology and chemical evolution on our neighboring planet will shed important light on these terrestrial questions – questions that could be significant to our ultimate survival. (SSB, 1977: 2)

Inspired by these comparisons, new life detection experiments looked to the emerging environmental sciences. If a planetary biota interacted with its environment, evidence of a physical or chemical disequilibrium in a planet’s atmosphere (e.g., an overabundance of methane or some other compound produced by living organisms) would provide strong evidence for life (Hitchcock and Lovelock, 1967). Such a detection strategy would not require expensive landers or orbiters but could be done using astronomical observations of a planet (Lovelock, 1975). These insights informed the emerging Gaia hypothesis of James Lovelock and Margulis, which treated the Earth as a self-regulating living system. ‘Thinking about life on Mars’ gave Lovelock (1979: 5) ‘a fresh standpoint from which to consider life on Earth and led me to formulate a new, or perhaps revive a very ancient concept of the relationship between the Earth and its biosphere’.

Deepening the comparison between Earth and Mars were researchers also interested in the earliest origins and evolution of life on Earth. While few held out hope for life on Mars in the present, considerable attention turned to the planet’s first billion years. Viking Orbiter images of extensive valley systems on Mars (Carr, 1981; Squyres, 1984) provided strong evidence that at some point in the distant past, Mars was both warmer and wetter, perhaps akin to early conditions on Earth. Rather than search for extant life on Mars, exobiology might instead adopt the methods of paleontology to search for fossilized remains of life. More importantly, scientists did not even have to return to Mars to begin this research.

Since the late 1970s, the National Science Foundation had funded the search and collection of meteorites in Antarctica, which, for reasons of geology and environment, ranks among the best meteorite hunting grounds in the world (Marvin, 2015). When paired with new Viking data, geologists realized by the early 1980s that some of these Antarctic meteorites were likely of Martian origin billions of years ago (Bogard and Johnson, 1983). Though serious astrobiological study of these meteorites did not begin until the 1990s, their discovery bolstered new mission concepts and scientific experiments that might peer into Mars's primordial history (McKay, 1986).

Finally, research into extreme environments on Earth reopened the possibility for more exotic forms of life that could exist on Mars. Right after Viking's disappointment in the late 1970s, underwater dives to the deepest parts of the Earth's oceans uncovered unexpected biological communities powered by energy extracted not from the Sun but rather from the nutrients and heat generated from hydrothermal vents (Oreskes, 2003; see also Helmreich, 2011). In addition, subsequent deep drilling of the seafloor and underground mines revealed an unexplored 'deep biosphere' of microorganisms beneath the surface previously thought to be impossible (Edwards et al., 2012, see also Onstott, 2020). These findings encouraged Mars exobiologists to expand their conceptions of life and where life might exist or have existed in the past.

Shifts in method reframed exobiology's core questions and experimental designs to sustain the search for life on Mars. These changes, subtly at first, transformed exobiology into the broader discipline of astrobiology discussed in the next section. Shifts in method undertaken in the 1980s informed the next generation of Mars missions like Mars Observer and Mars Pathfinder that finally got off the ground in the 1990s. Gone were explicit microbiological experiments like on Viking. Instead, future Mars missions sought to 'follow the water', characterize the Martian climate, or carefully map geological forces – all to understand Mars, both past and present, as a living planetary system (Kieffer et al., 1992). Far from a period of dormancy, exobiology in the 1980s proved to be a time of rebuilding. If and when interest in Mars returned, exobiologists would be ready and retooled to continue searching for Martian life.

Event 3: ALH and shifts in object

The fortunes of the search for extraterrestrial life seemed to change almost overnight on Tuesday, August 6, 1996. At 1:51 pm eastern time, the Associated Press sent a one-sentence story across their wire service: 'A meteorite that fell to Earth after possibly being ejected from Mars may bear chemical evidence that life once existed on that planet, NASA officials said Tuesday' (Sawyer, 2006: 136). The news was an unwelcome leak referencing an article about to be published in *Science*, authored by a team of NASA scientists led by exobiologist David S. McKay (McKay et al., 1996). Within twenty-four hours, the story was front-page news all over the world. The next day, U.S. President Bill Clinton delivered a televised statement from the White House South Lawn: 'If this discovery is confirmed, it will surely be one of the most stunning insights into our universe that science has ever uncovered' (Dick, 2018: 32). Minutes later, across town at NASA Headquarters, Administrator Daniel Goldin introduced McKay and his team, along with a sample of the meteorite (named ALH84001), to a room packed with journalists and reporters (Chaikin, 2008). McKay leaned into his microphone and declared, 'we *think* we have found evidence for past life on Mars'. He followed up this hedged claim with another caveat: ‘This is a controversial story, and there will be a lot of disagreement’ (Sawyer, 2006: 157).

Unlike the Viking biology experiments’ discouraging and dampening effects for the search for life on Mars in the 1970s and 1980s, the inconclusive findings related to meteorite ALH84001 were parlayed into an unprecedented growth period for the field. This included a new name – ‘astrobiology’ – and the founding of the NASA Astrobiology Institute (NAI). But most influentially, it led to the drafting of the ‘Astrobiology Roadmap’, a document that reoriented the reinvigorated and expanded field (Blumberg, 2003). The Roadmap, which has been periodically revised and updated, routed scientific attention toward the robotic exploration of Mars, including a sample return mission and the search for biosignatures on the ocean world moons of Jupiter and Saturn, as well as the rapidly growing list of newly-detected exoplanets.

Right from the start, the claim that meteorite ALH84001 contained traces of ancient Mars life was tenuous (Anders, 1996). The evidence was far from an obvious slam dunk and believing it required a holistic interpretation of four different lines of evidence gleaned from various microscopic examinations and chemical analyses of the meteorite’s interior. When Goldin secretly briefed Clinton’s chief of staff, Leon Panetta, in the weeks leading up to the announcement, he characterized the Agency’s ambiguous stance toward the finding as ‘skeptical optimism’ (Sawyer, 2006: 126).

Introducing McKay and his team at the NASA press conference, Goldin noted that the evidence before them was ‘exciting, even compelling, but not conclusive’, and that they were ‘not here to say they found *ultimate* proof or evidence’ (Dick, 2018: 30; Goldin, 1996). McKay’s presentation, during which he laid out the four lines of evidence and showed images of tube-shaped forms imaged by an electron microscope, also lacked strong declarative statements: ‘It is our interpretation that this and similar features have a high probability of being Martian microfossils’ (C-SPAN, 1996). McKay even concluded on an inconclusive note: ‘We have no confirming evidence. We have these lines of evidence and none of them in itself is definitive. But taken together, the simplest explanation to us is that they are the remains of Martian life’ (C-SPAN, 1996).

McKay’s claims were subjected to considerable criticism, especially from experienced paleobiologists and paleochemists. Edward Anders, a chemist at the University of Chicago who had worked on the Apollo-returned Moon rocks, came out of retirement to lambast the announcement as ‘half-baked work that should not have been published’. He ridiculed the ‘turd-like shapes’ and argued that ‘five maybes don’t make a certainty’ (Sawyer, 2006: 177). At a more civil register, teams of scientists began independent investigations of fragments of ALH84001, questioning each of the four lines of evidence contributing to the biological hypothesis. Between 1997 and 2004, a more plausible non-biological explanation for each line of evidence appeared in scientific literature, eventually collapsing the ambiguity of ALH84001 into another non-detection (Golden et al., 2001). The scientific consensus today is that ALH8001 does not suggest the presence of past life on Mars.

Shifts in object

Even before the ALH episode, the expansion of exobiology into a more broadly defined astrobiology was already in the works behind the scenes at NASA. In 1995, Wesley

Huntress, then NASA's Associate Administrator for Space Science, drafted plans to make NASA Ames the 'lead center' under his new banner of 'astrobiology'. This would accompany an increase in funding for biological sciences at NASA within Goldin's overall 'Origins' initiative and framework (Blumberg, 2003: 465). The basic idea was to institutionalize the shifts in method in post-Viking exobiology from a mission-based search for life in situ on Mars to a more expansive research program of investigating "the origin, distribution, and future of life in the universe'. Goldin, Huntress and others seized on the media sensation and public interest surrounding the ALH announcement to accelerate and amplify this already proposed shift by elevating the status of the search for extraterrestrial life relative to other existing NASA initiatives (National Research Council, 2003: 8).

The most immediate evidence of astrobiology's changing fortunes was the increased celebrity of NASA scientists and administrators evident from their frequent high-profile media appearances and newfound access to political power. President Clinton instructed Vice-President Al Gore to quickly organize a public symposium featuring members of McKay's team in advance of hosting a second private summit at The White House comprised of NASA experts and other distinguished scientists, including evolutionary biologist Stephen J Gould. On November 22, the DC-based think tank Space Policy Institute convened 'Life in the Universe: What Might the Martian Fossils Tell Us?' followed by Gore's summit on December 11 (Taylor, 1999: 124). Never before had experts on extraterrestrial life had the ear of the public and the president.

Several significant field-building events within NASA signaled an increased interest and activity in the search for extraterrestrial life. In 1996, stemming from Huntress's organizing efforts, the NASA Strategic Plan designated the Ames Research Center the 'Agency lead' in astrobiology (Blumberg, 2003: 465). A month after the ALH announcement, Ames hosted the 'Astrobiology Workshop', a meeting attended by over 100 scientists with relevant expertise to discuss 'the scope of astrobiology, strengthening existing efforts for the study of life in the universe, identifying new cross-disciplinary programs with the greatest potential for scientific return, and suggesting steps needed to bring this program to reality' (DeVincenzi, 1996: 1). In 1997, Goldin created the NASA Astrobiology Institute (NAI), a virtual research network directed from Ames that linked a shifting consortium of university-based researchers. The first call for proposals for NASA astrobiology funding was sent out in October 1997. A final crucial event in this growth phase was the 'NASA Astrobiology Road Map Workshop', held in 1998 at Ames from July 20 to 22, where a select group of experts came together to explicitly define the areas of interest and methods of investigation most likely to yield results (Blumberg, 2003: 465). This set of preferences outlined in the Roadmap became the key rubric for judging proposals for NAI funding from university-based researchers. It is in this crucible, amped-up by ALH's popularity and ambiguity, that shifts in astrobiology's preferred object of interest gained momentum, defining a suite of new questions to answer besides the elusive Big One.

Published in 1998, the NASA Astrobiology Roadmap outlined these *shifts in object*. Mars and the Earth were joined by new areas of interest: certain moons of Jupiter and Saturn and the growing list of newly-detected exoplanets. For Mars, the debate over ALH strengthened the long-standing desire for a sample return mission. Shortly before he died in 1996, Carl Sagan wrote that while ‘the evidence for life on Mars is not yet extraordinary enough … it suggests sending spacecraft missions to special locales on Mars which may have been the last to surrender their warmth and wetness’ (Sagan, 1997: 60). Other experts, including John Grotzinger at MIT, argued that ALH’s ambiguity could only be settled by ‘pristine rock samples’ brought back from Mars – an almost verbatim restatement of Post-Viking exobiology goals (Taylor, 1999: 127). But while the surface of Mars was still in question, exobiology’s return to Earth in the 1980s and the discovery of extremophiles living deep underground led to an expansion of interest to potentially more viable subsurface environments farther afield.

In the summer of 1996, when ALH was still a closely guarded secret at NASA, two other planetary science discoveries brought new objects of astrobiological interest into focus. NASA’s Galileo spacecraft, which arrived at Jupiter in 1995, returned images of the surface of Jupiter’s moon Europa, which bolstered existing theories that beneath the thick icy crust lay a large subsurface ocean – one that might be an abode for life. The Astrobiology Roadmap in 2003 captured this shift in object to ‘ocean world’ moons of Jupiter and Saturn, noting that the discovery of the deep subsurface biosphere on Earth

> has revolutionized our thinking about the potential for life on other planets like Mars or Europa, where surface conditions are fundamentally inhospitable for life. The necessity to explore the deep subsurface of other Solar System bodies has identified the need to develop robotic drilling systems that can penetrate hundreds to thousands of meters below the surface, where interior habitable zones of liquid water and life-sustaining redox chemistry might exist (National Aeronautics and Space Administration [NASA], 2003).

And Europa was not alone; ‘Similar conditions may exist on … [Jupiter’s moons] Ganymede and Callisto. In addition, a complex prebiotic chemistry and zones of liquid water might exist on [Saturn’s moon] Titan’ (NASA, 2003). Instead of focusing on Mars, the Astrobiology Roadmap reflected the expansion of inquiry to understanding the conditions for life and shift in object to other heavenly bodies. One ‘example investigation’ from the Roadmap captures this nicely, suggesting scientists ‘explore the atmosphere and surface environments of Titan for evidence of complex organic chemistry and water, to provide a context for understanding potential habitability and prebiotic chemistry’ (NASA, 2003).

In the early 1990s, astronomers also confirmed the first definitive detections of exoplanets, planets orbiting stars other than the Sun, which expanded the purview of the search for life in the cosmos even farther. Beginning in 1992 and culminating in 1995 with the headline-making detection of an exoplanet orbiting the nearby star 51 Pegasi, exoplanet discoveries had prompted Huntress to expand the narrowly focused exobiology into the more expansive astrobiology (National Research Council, 2003: 8). Sending spacecraft to distant exoplanets was impossible, but remotely detecting life on them was not out of the question, as Lovelock and others had hypothesized earlier. So, astrobiologists added exoplanets to their expanding universe by crafting a new category of ‘detectable’ called a ‘biosignature’ – not life itself, but tell-tale physical or chemical byproducts of life (Helmreich, 2011). A biosignature is defined as ‘any substance or phenomenon that provides scientific evidence of past or present life’. The seventh and final science goal listed in the Roadmap was to 'recognize signatures of life on other worlds'. This included biosignatures in 'samples measured in situ' and 'samples returned to Earth' but also in 'remotely measured planetary atmospheres and surfaces', which brought physically inaccessible exoplanets into astrobiology's orbit (NASA, 2003).

NASA also continued to fund Earth-based studies focused on extremophile microbes to understand the origins of life. In 2010, one of these studies led by astrobiologist Felisa Wolfe-Simon resulted in a NASA announcement strikingly similar to the ALH episode. Scientists working at the hypersaline and alkaline Lake Mono in California claimed to have discovered a new form of life, a microbe (called GFAJ-1) utilizing normally poisonous arsenic to sustain growth. Despite a triumphant press conference featuring NASA administrators and scientists, the claim that the microbe represented a so-called 'second genesis' and shadow biosphere on Earth – 'aliens under our noses' – was similarly overturned (Marcheselli, 2021). In a recent article about the controversy, Marcheselli argues that astrobiology's 'legitimacy and sustainability' flows from devising specific questions – discreet unknowns – in this case, how likely is life to result from abiotic conditions? The ALH controversy, by contrast, shows that there is not only power in unanswered questions but also ambiguous answers.

Even though the ALH claims were eventually disproven, the surge in public and political interest during the moment when these results were still ambiguous was sufficient to supercharge exobiology's metamorphosis into the more mainstream astrobiology. Experts expanded their interest beyond Mars and the Earth toward the icy moons of Jupiter and Saturn and the atmospheres of newly detected exoplanets, manufacturing further ambiguity in the search for life in the cosmos by requiring the close study of these objects as well.

In 2016, reflecting on the twentieth anniversary of the ALH announcement and controversy, Kathie Thomas-Keprta, a key member of the NASA team behind the *Science* article, told a reporter from Space.com that 'the search for evidence of life on Mars is plagued by ambiguities' (Choi, 2016). However, in discussing the ALH episode, Helmreich notes how 'space science leverages uncertainty into institutional support' (Helmreich, 2011: 692). Thomas-Keprta's characterization of ambiguity as a threat to the field misses the crucial ways in which ambiguity has enabled the field to grow and for work to continue in the enduring absence of a positive result. Even though McKay and his team were unable to sustain their claim that the ALH meteorite contained 'traces of life', what Helmreich terms a 'direct biosignature', the initial ambiguity proved fertile ground for setting a new mode of victory: The remote detection of 'indirect biosignatures' on distant exoplanets.

Conclusion

How do scientists maintain a research program that consistently yields negative results? Until now, that question has largely been 'why maintain it?' In the case of gravity waves, experimental physicists pointed to a widely accepted theoretical framework that predicted the elusive phenomena should exist to justify continued activity (Collins, 2004: 297). But exobiologists lack such a framework and have been harshly criticized for persisting in their investigations. Critics of exobiology attempting to answer the 'why?'

question have suggested that never-say-die researchers are delusional, stubborn, conspiratorial, emotionally invested in a positive result, fanatical or suffering from cognitive dissonance (Horowitz, 1977: 61; Lambright, 2014: 74; Launius, 2012: 267). Their persistence in the face of a continued lack of evidence has been characterized as poor judgment, and their research program derided as fruitless.

Our approach, by contrast, does not require imputing impure motives or maladjusted mental states to these scientific actors. By shifting the question from ‘why’ to ‘how’, we reveal that sustaining the field was neither bad science nor unproductive. On the contrary, maintaining ambiguity is an underappreciated way to produce useful scientific knowledge. Unlike skeptical researchers of climate change or the health effects of cigarettes, leading astrobiologists are not ‘merchants of doubt’, sowing alternative facts to obscure the truth in search of profit (Oreskes and Conway, 2010). For one, everyone knows that life exists, at least on Earth. For another, astrobiologists have generated considerable knowledge about planetary systems, atmospheric science, geochemistry, oceanography, extremophiles and even basic biology in the process of not finding their self-described holy grail. Indeed, these knowledge spillovers were a direct result of maintaining ambiguity.

This article focuses on exobiology’s three biggest disappointments to investigate how the field has managed to sustain itself in the face of repeated negative results. Through the *maintenance of ambiguity*, exobiologists and astrobiologists have consistently avoided reaching a negative conclusion to the field’s animating questions. The maintenance of ambiguity involves casting doubt on negative findings, pointing to other possible unexplored routes to success and, finally, reconfiguring operations around new methods or goals. By pivoting to a different scale, method or object, astrobiologists have persisted in studying a subject continually lacking proof of existence and made important discoveries about life on Earth.

Whether these shifts are specific to exobiology or can be found in other scientific fields responding to the problem of non-detection, we leave open to further investigation. Though null results are endemic to all experiments, we would expect legitimate strategies for maintaining ambiguity to differ across fields in ways amenable to STS analysis. Upon finding nothing, looking in unexplored places or collecting additional data is common to most sciences. Changing the object, however, may be a more limited or risky option, especially if scientists and funders have made significant investments toward finding the original object of interest. It was no accident, we argue, that exobiology’s transformation into astrobiology and with it the concomitant shift in object from direct to indirect signs of life came in the midst of a nadir of external support and the exit of founding members. As a result, scientists interested in continuing the search for life on other worlds had a freer hand to reimagine their experiments and even discipline as a whole than they might have amid yet another expensive Mars mission.

Turning back to existing histories of exobiology, we found that the problem of non-detection has not received considerable attention. Most scholars have chosen to focus on the formation of the field and then chronicle major events. In these, little has been said about the complicated aftermath of public failures to detect life and the strategic moves that follow and allow the search to continue. To this end, we have not explored the traditional history of science theme of discipline formation but instead highlighted *discipline* *sustainment* under unfavorable conditions (Westfall, 2012). Unlike works covering the planning and execution of famous missions, we have examined the finessing of their fallout and the ‘face-work’ of scientists after attempts to find alien life have come up empty. Drawing upon the sociology of scientific knowledge, we provide a key insight into how controversial and seemingly unsuccessful scientific programs remain viable. In the aftermath of each non-detection event we studied, we found different variations from different sets of scientific actors on the same basic strategy: Resisting totalizing negative conclusions through maintaining ambiguity.

Highlighting the utilization of ambiguity is further essential because practitioners do not seem aware that this is a recurring practice with concrete benefits, a resource to ‘keep the wheels of science turning’ (Proctor, 2008: 5). The default stance in science is to view ambiguity as always negative. Princeton astrobiologist Christopher F Chyba provides a clear example of this negative framing of ambiguity when he writes, ‘after the Viking landers’ failure to find life on Mars in 1976 – or, worse, the landers’ seemingly ambiguous answer to this question – exobiology fell out of favor in planetary science’ (Chyba, 2017). Scientists are trained to design experiments to minimize or resolve ambiguity once and for all. Faced with inconclusive or negative results, scientists lament ambiguity as something continually hampering their work. It is surprising then to see exobiologists, some of whom have become pop culture icons of scientific knowledge and certainty, quickly pivot to promoting and leveraging ambiguity and uncertainty following high-profile non-detections (McGoey, 2012: 3).

Suddenly, ambiguity becomes something to maximize as justification for resisting closure to the question – both among the wider scientific community judging the merits of the field and the public footing the bill for these expensive investigations. Ambiguity and its active maintenance in different moments of crisis have had underappreciated benefits as a resource for sustaining and growing exobiology into present-day astrobiology.

The use of this strategy across six decades by different scientists signals the field’s unique status as enduring but always liminal. In addition to lacking its central subject, exobiology also lacks stable institutional homes, disciplinary autonomy and consistent scientific and political champions – even the name of the field has undergone periodic revision. You cannot earn a PhD in astrobiology (NASA’s astrobiology ‘Career path suggestions’ website suggests earning a doctorate in astronomy, biology, chemistry, geology or physics). There are no famous departments or physical institutes of astrobiology. It is difficult to point to one astrobiologist as the most famous or influential. Yet, due to widespread fascination with the possibility of extraterrestrial life, the educated public overestimates the disciplinary cohesion and institutional support for astrobiology, assuming the field is much more solid than it is. If the usual trajectories for a new scientific field are to either become established as a full-fledged discipline in charge of a unique subject or to fail at this and either cease to exist or endure as a fringe pseudoscience, exobiology and astrobiology have taken a rare third path made possible by the maintenance of ambiguity.

Such a scientific state of affairs, however, cannot continue indefinitely, and it is likely only possible under particular circumstances. For scientists to maintain a relatively well-defined field without finding the phenomena they are looking for requires more than just an ever-enticing goal; social supports like a large and robust economy, high levels of government funding and a widespread belief in the value of scientific research into big questions appear to be requisites. Even with these in place, appeals to ambiguity cannot work forever. At some point, like the boy who cried wolf, the claims that the proof is out there will exceed the willingness to believe of others they depend on for legitimacy and funding.

In this article, we have tracked the search for extraterrestrial life from a Mars fly-by to the Martian surface, to the microscopic insides of a Mars meteorite, then to the subsurface oceans of the icy moons of Jupiter and Saturn, and biosignatures in the atmospheres of exoplanets beyond our solar system. As a direct consequence of these past failures and pivots, present-day NASA scientists exploring the surface of Mars with remote-operated rovers do not profess to be searching for life directly. They have learned to advertise more ambiguous, but achievable, goals: finding geological evidence of past habitable conditions and signs of ancient life. Their latest shift in object centers on a planned Mars sample return with the prospect of detecting life downplayed. But behind the measured public relations rhetoric, the desire and drive to find life beyond the Earth – on Mars or elsewhere – is alive and well. How long can the search continue without finding anything? Where might they turn next? The limits of this strategy have not yet been reached, but limits must exist. Will one of the new private space companies attempt a search for extraterrestrial life? Would that program be able to survive another negative result by maintaining ambiguity? And what if scientists one day do detect a biosignature in an exoplanet atmosphere? How will they pivot to counter naysayers outside the field who engage in their version of the maintenance of ambiguity, resisting the conclusion that extraterrestrial life does exist? The truth may yet be out there, but not without cultivated ambiguity.

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