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Epilogue

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"Astrobiology" was originally defined as "the consideration of life in the Universe elsewhere than on Earth" (Lafleur, 1941). But as the field has advanced, we have learned to place no artificial barrier between the study of life on Earth and life that may exist elsewhere in the cosmos. Astrobiology today is "the study of the living Universe" (NAI, 2004), be it here or elsewhere. It would be foolish to narrow the definition, for the approaches we take in searching for extraterrestrial life are strongly informed by our understanding of life on Earth, and our understanding of the origin and evolution of terrestrial life is informed both by the study of other planetary environments and by Earth's environment within the Solar System and Galaxy. As Carl Sagan (1974) remarked decades ago, we are able for the first time in human history to assess life on Earth "in a cosmic context." The assessment is still nascent and inchoate, but as the chapters in this book illustrate, the floodgates have opened and our knowledge is expanding quickly now. We will soon know much more.

Besides "astrobiology," the study of life in the Universe has also been called "cosmobiology" (Bernal, 1952), "exobiology" (Lederberg, 1960), and "bioastronomy" (IAU, 2004) (see Sections 2.3.1 and 2.4 for discussion). Under its exobiological label, the entire field was famously criticized by the biologist George Gaylord Simpson (1964), "in view of the fact that this 'science' has yet to demonstrate that its subject matter exists!" If astrobiology meant only the study of extraterrestrial life itself, Simpson's criticism would still have weight, four decades later. But his criticism would nevertheless seem peculiar to many physicists and astronomers. After all, much of the important research in physics and astronomy concerns exactly those objects or phenomena whose existence remains uncertain – consider the search for high-temperature superconductors, the Higgs boson, or proton decay. Each of these could turn out not to exist, and the last was in fact demonstrated not to occur with the frequency predicted by an attractive theory (Georgi, 1982). Even black holes were studied for decades before compelling evidence of their existence accumulated (Melia and Falcke, 2001). In this sense, astrobiology simply extends into biology a circumstance that is familiar, even commonplace, to a number of its sister sciences.

Astrobiology is posed on the brink of remarkable and historic discoveries. Barring catastrophic failure, NASA's upcoming Kepler mission should determine later this decade the statistical frequency of Earth-size worlds around other stars (NASA, 2004). The question whether other planets like Earth exist has been asked for 2,400 years or more, at least since Aristotle posed the question in *De Caelo* (Aristotle, 1941 trans.) – and ruled out the possibility on theoretical grounds (Section 1.2.1). It is extraordinary that within a few years humanity will no longer have to grope for answers to this question. Instead we will *know* how common are other earths, around what kinds of stars they form, and in what heliocentric orbits. We should not let our civilization sleepwalk through this extraordinary transition in our knowledge of Earth's place in the Universe.

We are on the verge of extraordinary discoveries in other areas as well. We are coming to know Mars as a planet that had, and may still have, substantial liquid water (Chapter 18). Intriguingly, methane has been observed in the martian atmosphere at a concentration of 10 ppb (Section 18.8). Since the CH_4 photochemical lifetime in the martian atmosphere is only $\sim$300 yr, and the observed CH_4 is inhomogeneously distributed, there must be an active source. Krasnopolsky *et al.* (2004) favor methanogenesis by oases of living subterranean microorganisms as a hypothesis, though abiogenic volcanic sources are the conservative explanation until further evidence supports the biological claim. This is not a new caution. Decades ago, Pollack and Sagan (1967) warned against the temptation to

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attribute enigmatic martian features to biology: "The varieties of life on Earth and of possible organisms that we can imagine on Mars are so large that virtually any change in surface features can be 'explained' by a necessarily vague attribution to biological processes." But even if biological explanations should be invoked only when all non-biological ones fail, our growing knowledge of terrestrial extremophiles together with discoveries about contemporary Mars, now make martian life seem to be a very open question.

The exciting discoveries hardly stop at Mars. On Earth we are elucidating the deep hot biosphere (Chapter 14). At Jupiter, we have collected strong evidence that a second ocean of liquid water exists in the solar system, beneath the surface of Europa, and perhaps also for Ganymede and Callisto (Chapter 19). Whether Europa's ocean is sterile or not is a question we can hope to answer later this century.

Beyond possible microbial life, the continuum of questions posed by astrobiology extends to quantitative investigations of the evolution of intelligence on Earth (Marino *et al*., 2004), its future technical evolution, and relatedly, theoretical and empirical investigations of the prospects for intelligence and technology elsewhere (Chyba and Hand, 2005). Since early in the past century, far-seeing observers have warned that humanity may soon enter a realm where technical intelligence and its own directed evolution advances so quickly that our successor civilization can hardly be grasped (Bernal, 1929; see also Hart, 1985; Vinge, 1993). Yet well before then, exponentiating computation and biotechnology will put great power in the hands of small groups of the technically competent (Carlson, 2002), and it is not clear how we can manage this new world (Chyba and Greninger, 2004). The same technological prowess that radically advances our capacities in the search for extraterrestrial life drives new challenges to human civilization. If astrobiology is the study of the living Universe, the discipline must also learn to speak to the human future, a thing uniquely precious regardless of whether we are entirely alone or part of a grand biological Universe.

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