1. Preamble

“Heliophysics encompasses environmental science, a unique hybrid between meteorology and astrophysics, comprising a body of data and a set of paradigms specific to magnetized plasmas and neutral [gases] in the heliosphere, interacting with themselves and with gravitating bodies and their atmospheres.”—George Siscoe, in Wikipedia on “Heliophysics”

2. A Decent Respect to the Cosmos

“We are a way for the cosmos to know itself.”—Carl Sagan

When, in the course of human events, it becomes necessary for a group of scientists to adopt a larger view of their world within the cosmos, and to assume, among the sciences, the importance and stature to which the laws of nature and physics entitle them, a decent respect to the cosmos and to natural science requires that they should declare the circumstances by which they are so impelled.

We heliophysicists hold certain truths to be self-evident: That the planets orbiting most stars are endowed through their creation from primordial matter with a particular elemental composition; That this composition and their thermal environment depend upon and are derived from their orbital distance from the star; that the state of their matter is determined in part by their thermal equilibrium, which could be within a habitability zone. Further, planets within such a habitability zone may come to possess liquid water oceans, a gaseous humid atmosphere, and primordial matter of a composition that enables the formation of complex aperiodic molecules capable of storing information and replicating. Such replicating molecules will be subject to randomly induced variations with differential reproductive success, forming the basis for natural selection and evolution of still more complex molecules and assemblages thereof.

We further hold that planets everywhere in the cosmos are profoundly influenced on human time scales by more subtle natural effects including energetic electromagnetic and atomic radiations, variability of their star’s magnetic dynamo and external magnetic field (including outbursts of matter and energy that modify the stellar winds and interplanetary space), variable magnetic coupling between the stellar wind and magnetized or unmagnetized planets, variations in planetary magnetic dynamos and their external magnetic fields, variations in the admittance of external cosmic radiation into our stellar system, and a number of other effects.

Prudence, of course, dictates that sciences long established should not be modified for light and transient causes; and, accordingly, all experience has shown that human scientists are more disposed to preserve the status quo paradigm, while such a paradigm proves useful, than to correct themselves by incorporating every suggested embellishment, or abolishing the forms with which they have been successful and to which they are accustomed.

But, after a long series of studies have now shown how commonplace and prevalent planetary systems are in the cosmos, each with different characteristics from our own yet constrained by the same laws of nature and physics as our own, and with no success in contacting alien civilizations anywhere in our galaxy, it is time to recognize the cosmic significance of our own stellar-planetary system over the age of the cosmos, as the sole known example of successful generation and evolution of life.

In support of this, let facts be submitted to a candid world.
3. Earth and Space as Life Science

Well, that was fun. Somewhere along the line, I picked up an enthusiasm for the language of the enlightenment as expressed in our nation’s founding documents. I entered life as a scientist through undergraduate training as an electrical engineer, which I found to be excessively demanding. That is, it did not accommodate my interests in elective course diversity. I will not claim a love of History, but I was interested in Evolution, Philosophy, and Psychology and Writing. So I switched to Physics and, after I had made myself virtually unemployable, developed an interest in teaching at the secondary level, which was not very remunerative but did pay the bills. The “back to nature” movement of the day (1970s) also held an attraction, so I took a teaching job in a rural district of Vermont, purchased the ancient (1796) former home of the village blacksmith, where a dozen children had been raised in a small space, and proceeded to teach myself the building arts while teaching Mathematics and Physical Science to middle schoolers and underclassmen, and high school Physics to seniors.

The teaching life was not fully satisfying to me, in part because I was still learning to do it and was by no means a “natural.” My classroom featured an entryway sign reading “Reduce Entropy!” perhaps reflecting my struggles with classroom discipline, but it also earned me the friendship of the (well-educated) school custodian. Still, I did very much enjoy teaching anything and everything related to astronomy, astrophysics, and Earth in space, and of course field trips at times, for observing the sky. I was an avid follower of National Aeronautics and Space Administration (NASA) missions and especially impressed by the deep space missions like Pioneer (and later, Voyager). I had been and continued reading Carl Sagan’s efforts to popularize science, with a focus on the conditions for life and the possibility of alien beings, as an introduction to the Drake equation, which readily sparked classroom discussion at every level, at times leading to further serious discussion and research.

The rural school was large enough to be well funded in a new building with a small school bus for field trips, yet small enough that there was a single teacher for each of Biology, Earth Science, Chemistry, and Physical Science. And of course, I doubled as a basic math teacher to fill out my assignments. I shared a preparation room with the Biology teacher, and we became good friends professionally and socially. He was a master teacher to my fresh-out-of-school newbie self and inspired my budding interest in life as a cosmic phenomenon. We held rollicking discussions of each Star Trek episode at the lunch table. It was all great fun, really, and could perhaps have become a lifetime pursuit had I found a sense of mastery, and a living wage. How bad was it? When, after a few years, my eye came to rest on graduate school prospects, I took a research assistantship, normally regarded by faculty as “slave labor,” that paid just as well as my teaching job had, and I still was able to take a full month off in the summer for travels.

4. Atmospheric Gases and Plasmas

In the process of winnowing graduate school possibilities, I made a decision that, since there were no planets or living things known to exist outside our solar system, I would focus on studies inside it. While recognizing that one must focus upon a specialty that may not directly involve biology or life, I wanted my studies to be in some way relevant to the formation of life and the physical conditions necessary for it to survive and thrive. I never saw the word “astrobiology” used until perhaps 2000, but it would have attracted me at the time I was shopping.

The opportunity that seemed most attractive offered in a prospectus to deploy instruments on suborbital (sounding) rockets that would fly over aurora borealis displays. At the National Oceanic and Oceanic Administration (NOAA) Space Environment Laboratory, the late Dave Evans made a strong pitch that it was possible to conceive, design, build, fly, and retrieve data from an instrument for analysis, all as part of a graduate student thesis project. It seemed to me at the time that my electrical engineering training made me a candidate for experimental work and that upper atmospheric studies would perhaps have some of the strongest links between studies that could be done in space and habitability of our planet. I might well have been swayed toward Earth observing systems operating in space, had that opportunity presented itself, but this was a bona fide opportunity and I went with it.

As soon as Dave and I began to discuss science and worked toward defining a thesis project, we turned to the then new observation that the hot plasma around the Earth had been discovered to contain singly ionized...
oxygen ions, which was quite startling to scientists in the field of space plasma observations at that time. Such plasmas were thought to come from the Sun and consequently to consist of hydrogen with some helium. Only high charge states of oxygen would be expected and only in very small relative abundances. So here was evidence that the Earth was losing heavy atoms from its atmosphere to space, where it was becoming part of the hot plasmas enveloping the Earth within its magnetosphere, as shown schematically in Figure 1. I began to read about Jeans’s escape and Polar Wind theories of the day and was soon hooked on the problem of how gases get separated by gravity, then get ionized and then escape into space. This problem proved sufficiently challenging to be a focus through my entire career.

The gravitational stratification of gases, with the lightest ones floating up to the top of the atmosphere, had been well studied for some time by the 1970s. It was known that the temperatures produced by solar radiation above the stratosphere were sufficient to cause significant escape of the lighter species hydrogen and helium. So to zeroth order, we expect the outgassing of Earth to have a composition not that different from the outgassing of the Sun, even though Earth is much smaller with correspondingly less gravity. The temperatures, and hence particle speeds, bore a similar relationship to very different escape velocities in the two cases.

5. Role of Electricity and Magnetism

The upper atmosphere is also ionized by extreme ultraviolet (UV) radiation from the Sun, with some of the incoming energy degrading into heat, so the gas is energized sufficiently to become a partially ionized plasma (the fourth state of sufficiently hot matter) embedded in heated gases. And once there is plasma in the presence of the geomagnetic field, that plasma becomes electrically coupled with every other plasma to which it is connected by magnetic field lines. The solar and geomagnetic fields readily connect with each other through a process first known as “reconnexion,” in a few places, much of the time. Depending on the topology of those fields, the ionospheric plasma is routinely connected to hot plasmas in the magnetosphere, and at times and in places to the solar wind plasma itself. At Earth the solar wind is moving at very high velocities except at the upstream blunt nose of the magnetosphere where it stagnates briefly. When the ionosphere is connected to the solar wind, its plasma is forced to move very rapidly (supersonically!) through the gas within which it has been created, and that relative motion, together with the electrical currents that transmit the mechanical stresses, lead to energy dissipation (frictional and resistive) in a number of forms, some of which include plasma waves driven by the free energy source.

Plasma waves further heat the plasma, which in turn loses energy to heating the gas, and everything gets hotter; hot enough, indeed, that thermal speeds of even the heavier ions exceed the planetary escape velocity and freely escape to deep space. Heating of the extremely light electrons enhances their escape from Earth, even though they are attached by electrical forces to the ions, and must drag the ions with them. Thus, electron heating also contributes to the escape of heavy ions from the ionosphere into space. Seeking to understand the plasma physics of the space environment has pushed us toward the study of ever smaller physical scales (electron motions) and time periods (plasma periods), so much so that many of us have become microscopists. A full understanding of magnetic reconnection, in particular, has required
multiple identical spacecraft flying in formation as little as several kilometers apart, resolving down to a few milliseconds in time. The range of scales we are now studying has stretched to many orders of magnitude, even within the cosmically limited confines of our solar system.

All of the processes contributing to the ionization and escape of atmospheric atoms from Earth scale with the intensity of the solar extreme UV radiation and with the intensity and magnetism of the solar wind. If the Earth’s star were to become much hotter, with a much more powerful stellar wind, the rate of loss of our atmosphere could become much larger than it is now. Fortunately, the current escape rate is not a material threat to the stability of our atmosphere, and it may have been even less of a threat in the deep history of our planet. The Sun is thought to have been much less bright in the past, perhaps even too dim to support liquid water, leading to the “faint young sun paradox.” A possible resolution of this is that the Sun itself had more mass early in its life, as well as a stronger solar wind causing loss of that mass, such that its energy output was more nearly constant over the early life of planet Earth. The spectrum of solar radiation is also thought to have evolved to be softer in the extreme UV, which is the part of the photon flux that interacts most strongly with the uppermost atmosphere. However, little consideration has been given to the effects of that hypothesis on atmospheric mass loss from Earth.

A complicating factor is that the geomagnetic field is known to have weakened and reversed many times in the past, with a widely varying frequency. It has currently been roughly 1 million years since the last reversal, with a mean period of 200,000 years leading up to the present. Earth’s magnetic moment has declined by 50% since biblical times and 10% during the current age of space exploration. Recently, the magnetic dip pole has been wandering across the pole quite dramatically. It thus seems probable that we find ourselves in an epoch of reversal, which generally takes a few to several thousand years to complete.

During the first month that I was a graduate student, I was impressed by a talk given by George Reid of the Department of Commerce Aeronomy Laboratory in Boulder, CO, on the subject of correlations between geomagnetic field reversals and the extinction of certain species of diatoms that float in the upper layers of ocean waters. He proposed a hypothesis to account for this that involved unusually large Solar flares (larger than the then-recent very large 1972 superstorm) and resultant geomagnetic storms at Earth that could be expected to temporarily erode the ozone layer globally, enhancing radiation stress on such diatom populations. I was very much charmed by the suggestion of such a connection between the Sun and life on a magnetic Earth, and that talk clinched my decision to study what was then called Astrogeophysics at the University of Colorado in Boulder.

6. From Space Meteorologists to Climatologists

The 22 year solar cycle modulates the intensity of the extreme UV radiation, among other aspects of the solar-terrestrial relationship, including the occurrence of coronal mass ejections and co-rotating interaction regions where fast solar wind overtakes and crashes into slow solar wind, separated by a standing shock wave (analogous to a “hydraulic jump” or tidal bore wave). The modulation of the UV flux is in turn seen clearly as a significantly greater presence of oxygen ions in the hot plasmas around Earth during the phase of the cycle in which the upper atmosphere is warmed by the high UV flux, leading to substantial increases in the scale heights of hydrogen and oxygen. Hydrogen gas loss rate is enhanced, suppressing hydrogen atom densities, while oxygen scale height is enhanced, leading to enhanced oxygen gas densities at ionospheric heights. With more oxygen and less hydrogen to work on, the ionized plasma processes produce more oxygen ion escape and participation in the hot plasma environment.

Many other aspects of Earth’s space environment are influenced by solar storms and the 22 year cycle, most notably the radiation environment of the Van Allen radiation belts as well as the interplanetary incidence of solar energetic particles. Both are capable of lethal effects on space hardware and astronauts. The 1972 solar storm mentioned above occurred between two of the Apollo missions and produced radiation levels at Earth and the Moon that would have been debilitating if not lethal for the Apollo astronauts, had they been en route to or at the Moon during those storms.

The effects of solar storms on Earth’s magnetic field are strongly felt on the planet by extended electrical conductors such as electrical power distribution networks, or in earlier centuries, by telegraph lines strung across the planet. Unsupportably large currents are at times induced and result in severe damage to
facilities that are part of such networks. Overcurrent damage at times leads to outages of important modern technological systems, including power distribution systems. At the same time, disturbances in ionospheric density result in communications and global positioning systems errors and anomalies that we depend upon for navigation. In response to these disruptions of civilization, we have been attempting to forecast “space weather” and thinking of ourselves as “space meteorologists.” When I am asked what I did for NASA, those terms spring immediately to my lips. An international, multiagency (read: bureaucratic) effort to study and forecast space weather has been organized, along the same lines as the National Weather Service for tropospheric weather in the United States. The effort naturally divides into (i) space meteorological research studies, leading to predictive system simulations, pursued mainly by the National Science Foundation (NSF) and NASA; and (ii) space environment monitoring and forecasting services pursued mainly by the NOAA. DoD resources are also brought to bear on these matters of practical importance to our space-faring world.

When space weather first became a priority for NASA, we explained ourselves as practitioners of a “Pasteur-like” science requiring fundamental research to address matters of practical significance to civilization. The appropriate time scales for this practical significance are considered comparable with the lifetime of typical NASA missions, ranging from a few years to a couple of tens of years, commensurate with the solar cycle. We are only getting started, but just as tropospheric meteorology progressed to climatology, it seems that we space meteorologists must evolve over time into space climatologists, adopting a longer view of the space environment and its variability.

7. Life and Death of Planet Earth

NB: I have borrowed this section heading and much of its content from an eponymous 2003 book by Peter Ward and Donald Brownlee (2003). The reader is encouraged to explore that book for greater detail and depth of argument than I have provided in this brisk overview.

During the 1970s and early 1980s, a significant new theme emerged in the study of Heliophysics (then known as solar-terrestrial relations). Jack Eddy (1976) pioneered the study of the Sun-Earth system in time, by drawing attention to the “Maunder Minimum” or prolonged cessation of solar activity that occurred roughly from 1645 to 1715, during which period very few sunspots were recorded. More tantalizing than the cessation of solar activity was the apparent rough correlation with a “Little Ice Age” that was noted mainly in Europe. Actually, however, the period of colder than normal winter temperatures in Europe was somewhat longer than the sunspot minimum period and current thinking is that the cold temperatures were the result of large volcanic eruptions rather than changes in the energy output of the Sun. Sometimes tantalizing ideas turn out to be nothing more than that.

Still, the Maunder Minimum and Little Ice Age produced a great deal of renewed interest in the variability of the Sun and its output, as well as the effects of such variability on our planet Earth, as well as its space environment extending to the Moon and beyond, as defined by our magnetosphere.

Venus has been studied intensively via a number of space missions, in part owing to its size similarity and proximity to Earth. However, differences far outweigh similarities: it has no magnetic dynamo, is spinning slower than any other planet and in the sense opposite to Earth. Crucially, its atmosphere is much more dense than ours but is devoid of water. At upper levels the atmosphere is rotating much more rapidly than the planet itself. Venus represents a possible outcome of an unstable greenhouse effect, in which the dominant CO2 of its atmosphere has trapped sunlight resulting in oven-like temperatures.

More recently, the Mars Atmosphere and Volatiles EvolutioN (MAVEN) mission has explored the various source and loss mechanisms that have operated on Mars, resulting in an atmosphere much less substantial than our own. Mars is a much smaller planet (one tenth the mass) than Earth, and it also lacks an organized planetary magnetic field, though it does have extensive regions of localized remnant magnetism that suggest an earlier magnetized epoch. If Mars ever possessed a conducting core with a magnetic dynamo like Earth’s, it was lost at some point, along with Mars’s atmosphere, and Mars became essentially uninhabitable, in comparison with Earth. More study will be necessary to answer the interesting question as to the order in which those events occurred.

Ideal as the Earth is for life right now, its very long-term future is fraught with danger. Assuming that humans muddle through the current population explosion and manage to limit their harmful effects to
tolerable or recoverable levels while becoming effective planetary stewards, the Earth is subject to a life cycle not unlike that of a living thing:

The geodynamo appears to be in the process of a reversal now, which will take at least a few thousand years to complete. It will continue to reverse up to several times per million years, with dramatic effects on auroral displays (which may be invisible owing to light and other kinds of pollution), but uncertain effects on humanity. At some point, it may cease to operate entirely, as it has on Mars and Venus, with effects that are not well determined or even understood, but constitute the nexus of Helio-climatology.

We expect that another Ice Age lies in our distant future within tens of thousands of years, driven by the well-understood Milankovich cycles of planetary orbits, with or without global warming. It will not be pleasant, unless we serendipitously manage to introduce enough greenhouse gases to offset all or part of it. Then again, the ice age will end, but our greenhouse emissions may or may not.

On even longer time scales, we expect that plate tectonics will continue and evolve the current continents back into a supercontinent in the Wilson Cycle. Assuming humans are around that long, ocean front property in moderate climates will be much more difficult to acquire in that far distant future. And CO₂ in the atmosphere will be sequestered into the overturning crust if it becomes too abundant, though that would already imply an atmosphere so altered as to be of dubious habitability.

The Sun will continue to increase its output more or less steadily over billion year timescales (now that its solar wind is down to a relative trickle) and the tectonic cycle will respond with increased sequestering of CO₂, until there is not enough CO₂ and/or too high temperatures for plant or animal life to survive, at which point all life on Earth will cease.

Earth exists in a heliospheric environment containing many smaller objects as well as planets, with a large number of volatile-containing objects residing beyond the heliopause in the Oort cloud, as shown in Figure 2. A number of studies suggest that a destructive impact by a large object from the outer solar system is among the least likely scenarios for ending the life of our planet. Small cometary impacts have long been with us and may even have contributed to our supply of water. While large bolide impacts are extremely unlikely, they clearly have not brought a total end to life when they did occur in the past and therefore are unlikely to do so if there is a recurrence. Nevertheless, the changes would certainly be of a magnitude comparable to the extinction of the dinosaurs.

As the Sun continues to evolve into a red giant, the oceans will evaporate and the lighter hydrogen will be lost to space. Depending upon the effectiveness of solar wind magnetic coupling to our atmosphere, oxygen may accumulate to the point of Venusian atmospheric density. Or the planet may be scoured clean of all volatiles. Owing to the lack of attention on the part of heliophysicists to date, little is known about how this will play out in the long-term future of our planet.

The sad fact is that the cosmos produces stars and planets around them with finite lifetimes and the ever-present possibility of sudden cataclysmic changes or even a disastrous ending for life as we know it.
If life has or will develop on any other planets anywhere, it will everywhere meet the same ultimate fate, though clearly not at the same time. Figure 3 summarizes these phenomena and places them within the context of our planet’s life cycle.

8. Outliving our Home Planet and Star

“A truly intelligent species will outlive its home planet.”—Todd Brennan

As focused as we humans are on ourselves and our own lives, we are perhaps the only species that is both aware of our own mortality and able to plan toward a future beyond that of any individual. I personally have been devoted to outliving my father, who died at age 54 of a stroke. Now I am working on outliving my mother, who passed at 78 years, but longer scales are on the horizon. While we all must accept death, we share a desire that something bigger than ourselves should outlive us and be shared with future generations consisting of our children and grandchildren. Our art, science, literature, governments, farmlands, and wilderness parks come to mind in that regard. Most of us want to be part of a city or a state or a nation that will outlive us and serve the needs of our future descendants. We basically want our species to live long and prosper. Just as a corporation should have a time horizon extending beyond the next quarter, we need a time horizon that extends far beyond our own lives. Considering the human population explosion and complete domination of our planet, together with our arguments and conflicts exacerbated by extremely destructive weapons, we would do well to plan how we can preserve and extend the life of our species to match or exceed the useful life expectancy of our planet. Nothing requires us to accept an earlier demise, and some see options beyond that.

Geologists and planetary scientists are largely of the opinion that interactions between our atmosphere and the solar atmosphere represent an influence that is secondary to the main thermal radiation from the Sun and the response of the condensed matter planet to that. They seem indifferent to the peculiar aspects of the terrestrial planets, such as the selective loss of water from Venus, and loss of both magnetism and volatile atmosphere, including liquid water, from Mars. They are even more indifferent to the corresponding effects on Earth or to their future trajectories.

Without making a more detailed case here, I wish to declare that the time has come for Heliophysics to join with the sciences of condensed matter planets in the study of the heliosphere and its planetary contents, over geologic and cosmic time scales. Our star is far more complex than a simple nuclear campfire that emits only...
a varying amount of thermal radiation. It is a magnetically active cauldron of incandescent plasma in turbulent convection, which stores and releases a substantial fraction of the total energy flow derived from nuclear fusion into a highly structured and variable stellar wind that bathes all of the planets, with evolutionarily important effects on their atmospheres, at the very least. There is plenty of space weather and it is of practical importance. But there is also a space climate of existential significance.

In recognition of the power of magnetism to organize and influence volatile and ionized matter no less effectively than gravity organizes condensed matter, I submit that it is time for Heliophysics as a discipline to adopt and pursue the study of such phenomena across all cosmic time scales, from stellar activity cycles and their longer-term evolution, to planetary magnetism cycles and their evolution, and even to the scales of heliospheric cyclic motions within the galaxy. That is, it is time for Heliophysics to adopt a larger view of our planetary system, with its so far unique attribute of life, and to assume, among the sciences, the importance and stature to which the laws of nature and physics entitle it.

References

Eddy, J. A. (1976). The Maunder Minimum. Science, 192(4245), 1189–1202. Bibcode:1976Sci...192.1189E. https://doi.org/10.1126/science.192.4245.1189

Heliophysics (n.d.). in Wikipedia, https://en.wikipedia.org/wiki/Heliophysics

Ward, P. D., & Brownlee, D. (2003). The life and death of planet Earth: How the new science of astrobiology charts the ultimate fate of our world. New York, NY: Macmillan. ISBN 978-0-8050-7512-0

Acknowledgments

This manuscript benefitted greatly from the constructive comments of the Editor and reviewer. The author is indebted but grateful to his parents, teachers, spouse, children, friends, colleagues, and representatives for equipping, preparing, and supporting him through a life of studying the Earth in its solar system, often based on direct measurements. He is particularly grateful for 36 years as a NASA employee, coinciding with his married life as a father and grandfather. Such studies have come to be known within NASA as Heliophysics, cast as complementary to Astrophysics, the science of objects generally outside our solar system, and studied on the basis of remote sensing. Having retired from NASA, he is also grateful for the opportunity to declare his advocacy for certain future directions of Heliophysics, and to explain how he arrived at this declaration through his life experiences to date, as expressed herein.