Losing the Geomagnetic Shield:
A Critical Issue for Space Settlement

Philip K. Chapman[1]
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Abstract. The geomagnetic field seems to be collapsing. This has happened many times in the deep past, but never since civilization began. One implication is that the cost of space settlement will increase substantially if we do not expedite deployment of initial facilities in low Earth orbit. Another implication, less certain but much more damaging, is that the collapse may lead to catastrophic global cooling before the end of this century. We must establish self-sufficient communities off Earth before that happens.

1. The ELEO Shelter

As Al Globus *et al* have pointed out,[2] the annual radiation dose in equatorial low Earth orbit (ELEO, below 600 km altitude) is less than the limit for occupational exposure that is recommended by the International Commission on Radiological Protection. The first extraterrestrial habitats and assembly plants will need little if any radiation shielding if they are located in such an orbit, reducing the mass that must be launched from Earth by orders of magnitude. These fortunate conditions create a haven in ELEO where we can develop the infrastructure for space settlement at relatively low cost. This is a major opportunity to shrink the technical and economic barriers to growth of a true interplanetary society.

The most important functions of early facilities in ELEO include:

1. Assembling and launching missions to obtain radiation shielding materials at low cost (probably water or slag from a near-Earth asteroid).
2. Developing experience concerning the long-term physiological requirements for living and working in space (with or without frequent transfers to and from free fall), in order to specify acceptable rotation rates and centrifugal pseudo-gravity levels.
3. Undertaking research related to closed ecologies in space, including low-gravity agriculture.
4. Expediting commercial operations in order to minimize both the upfront investment and the payback period. Activities may include:
    a. assembling and deploying the first solar power satellites[3]
    b. recovering platinum-group metals as well as water from asteroids
    c. processing industrial materials (e.g., nickel-iron) returned from asteroids
    d. processing and storing propellants (e.g., LOX/LH_2 from terrestrial or asteroidal water)
    e. maintaining and servicing reusable orbital transfer vehicles
    f. assembling and fueling spacecraft for missions beyond Earth orbit
    g. checking out satellites before deployment
    h. undertaking contract research for corporations and government agencies
    i. manufacturing products in free fall for sale on Earth
    j. building new habitats and other infrastructure in LEO and beyond
    k. developing and operating tourist facilities
    l. simulating conditions in future settlements, in space and on the Moon and Mars.

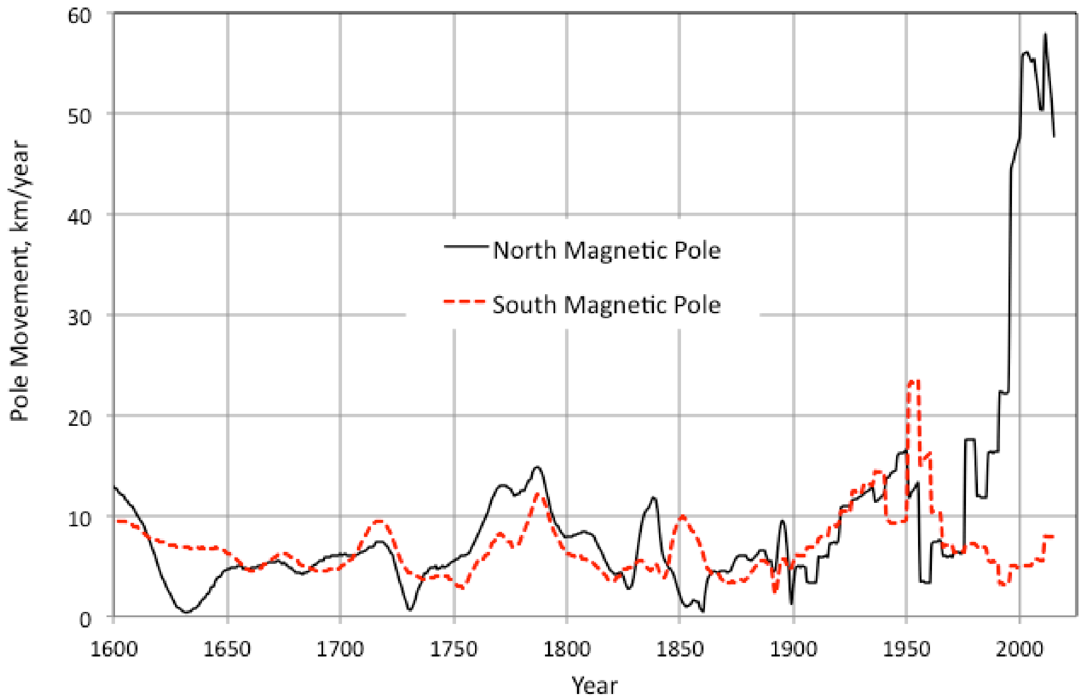

Figure 1: Wandering Magnetic Poles

Finding an extraterrestrial source of shielding has a high priority, not only because it will be needed for expansion of the extraterrestrial enterprise, but because recent changes in the geomagnetic field mean that the benign environment in ELEO is deteriorating quite rapidly. It is possible that conditions will soon return to normal, but it is more likely that we are now in the early phases of a *geomagnetic excursion* (a.k.a. a *geomex*, for short)—i.e., one of the occasional episodes in which the field undergoes what geologists consider a temporary disruption, typically lasting a few thousand years.

The most recent confirmed geomex is called the Laschamp Event. It happened 41,000 years ago, so the changes now under way are geophysical phenomena with which we have no direct experience. The geological data show that the global field became disorganized, with multiple N & S poles scattered around the world. The average field strength fell to 5% of the previous value, increased to 25% with the poles reversed, and then collapsed again before returning to normal.[4] Since the geomagnetic field is our principal defense against galactic cosmic rays (GCRs), the intensity of radiation reaching the Earth doubled.[5] The overall duration was a little less than a thousand years, including 440 with the poles reversed.

The strength of the geomagnetic field has been decreasing[6] at a rate of 5% per century ever since systematic ambient magnetic measurements began in the mid-19th Century. In November 2013 the European Space Agency (ESA) launched a trio of magnetometer satellites called Swarm, which have confirmed that the decline is now ten times faster (i.e., 5% per decade!)—and the collapse may be accelerating.[7] These data actually refer to the dipole moment, a measure of the geomagnetic field that assumes it is dipolar (like that of a large bar magnet inside the Earth), but this is no longer an adequate model.

The northern magnetic dip pole (the point where the field is vertical) has been drifting around in northern Canada for centuries. As shown by the black curve in Figure 1,[8] the movement was typically less than 10 km/year. The drift speed of the southern dip pole, shown by the dashed red curve, tracked that of the northern pole (more or less, most of the time), reflecting the fact that the movement was basically a wobble of the geomagnetic dipole.

In the late 1990s, the northern dip pole underwent a sudden, spectacular acceleration to 55 km/year. This means that the dipole is tilting by almost 5^o/decade, which is just as fast as in the Laschamp Event. The pole is now at 86^oN 160^oW, and racing past the geographic pole toward Siberia. If this motion continued, compasses would be pointing at some place in the tropics within 130 years, but the field will probably become thoroughly disorganized long before then.

The drift of the southern dip pole actually slowed when the northern pole accelerated, indicating that the dipole is no longer intact. This is also shown by changes in the region of low magnetic field called the South Atlantic Anomaly (SAA), which is rapidly expanding north and west across South America into the Pacific. The trend[9] suggests that the SAA will cross the geographic equator within a couple of decades, and that it will cover most of the southern hemisphere by 2050.

The principal exposure of satellites transiting the SAA is to relatively low energy particles trapped in the radiation belts. Rotation of the Earth carries the Anomaly through any inclined orbital plane twice each day, although it is already so large that some satellites encounter it on several successive orbits. When the SAA extends across the equator, the radiation environment in ELEO will become much worse, because a satellite in that orbit will pass through it in every revolution. Beyond that, continued growth of the SAA is equivalent to disintegration of the geomagnetic field, leading to exposure of satellites in any orbit to energetic GCRs. Reducing radiation to levels acceptable for human exposure will then require much more shielding—up to 7 metric tons (MT) of water per square meter! Delay could thus require launching thousands of tons of shielding material from Earth, greatly increasing costs.

2. The Climate Question

Losing the geomagnetic shield will also cause problems on Earth. At sea level, the atmosphere provides a shield weighing 10.3 MT/m^2, but aircrew, frequent flyers and people living at high altitude will suffer a significant increase in radiation exposure. A second problem is that a weaker field will increase vulnerability to geomagnetic storms, which can destroy sensitive electronic equipment and also overload long power transmission lines, causing widespread blackouts. A third possibility is that the geomex foreshadows extreme global cooling before the end of this century.

Recognition that we have reached the limits of this little planet is a principal motivation for the space settlement initiative. The UN median projection is that world population will reach 11.2 billion by 2100, 50% more than now. Giving them all a standard of living comparable to that now enjoyed in the United States would require an increase by a factor of 5.4 in the world GDP. It is not at all clear that this is possible within the constraints imposed by resource availability and environmental effects. The social, economic and environmental problems faced by our descendants will become much more difficult, perhaps insurmountable, if they must cope with a much colder climate as well.

The purpose of this analysis is not to question the role of anthropogenic CO_2 in the observed global warming during the latter half of the 20th Century, but only to point out that the new geomex is a factor that has not yet been considered. If the evidence discussed in the Appendix is valid, the climate could soon cool to levels without historical precedent, and it could stay that way for many centuries to come.

That scenario is bad enough, but there is another that is much more alarming.[10] It is hard to accept but not inconceivable that the geomex could signal the start of the long descent of our planet into the next glacial stage of the ice age. That transition, when it comes, will be by far the worst catastrophe since civilization began.

We don't yet know enough for a reliable assessment of this risk, but we need to find out. Widespread alarm is not yet warranted, but serious analysis of the hazards is clearly necessary. It is time to start thinking about the unthinkable.

The long-term human future requires an unlimited interplanetary civilization. The possibility of serious global cooling demands timely development of a self-sufficient extraterrestrial society that can ensure continued progress, no matter what happens on Earth. We have time to undertake research and to develop needed infrastructure in space, but procrastination could be fatal.

3. Conclusions:

- We must take advantage of the geomagnetic shelter in ELEO within the next several decades, before the field disintegrates. Urgent action is needed.
- One of the first objectives must be to obtain cheap radiation shielding materials from extraterrestrial sources.
- The apparent link between a geomex and the climate has become one of the most crucial scientific issues of our time, demanding a major research effort aimed at a better understanding of the causes and probable consequences.
- At the very least, we need to develop contingency plans for accelerating space settlement if it becomes clear that major climate changes threaten terrestrial institutions.

Appendix: A Prospect of Winter

A.1 The Current Ice Age

The history of the Earth includes several prolonged ice ages. It is disconcerting to realize that we are living in one of them, called the Quaternary Glaciation, a sequence of long *glacial stages* and brief warm *interglacials* that began 2.58 Mya (million years ago).[11]

The glacial stages originally lasted 40,000 years, but they have become longer (and also colder) and now span 100,000 years. During those times, ice sheets up to an astounding 3 km thick (10,000 ft!) buried much of the Northern Hemisphere, including large areas in Europe and North America. So much water was locked up in the polar ice caps that the sea level was at least 130 m (425 ft) lower than now.

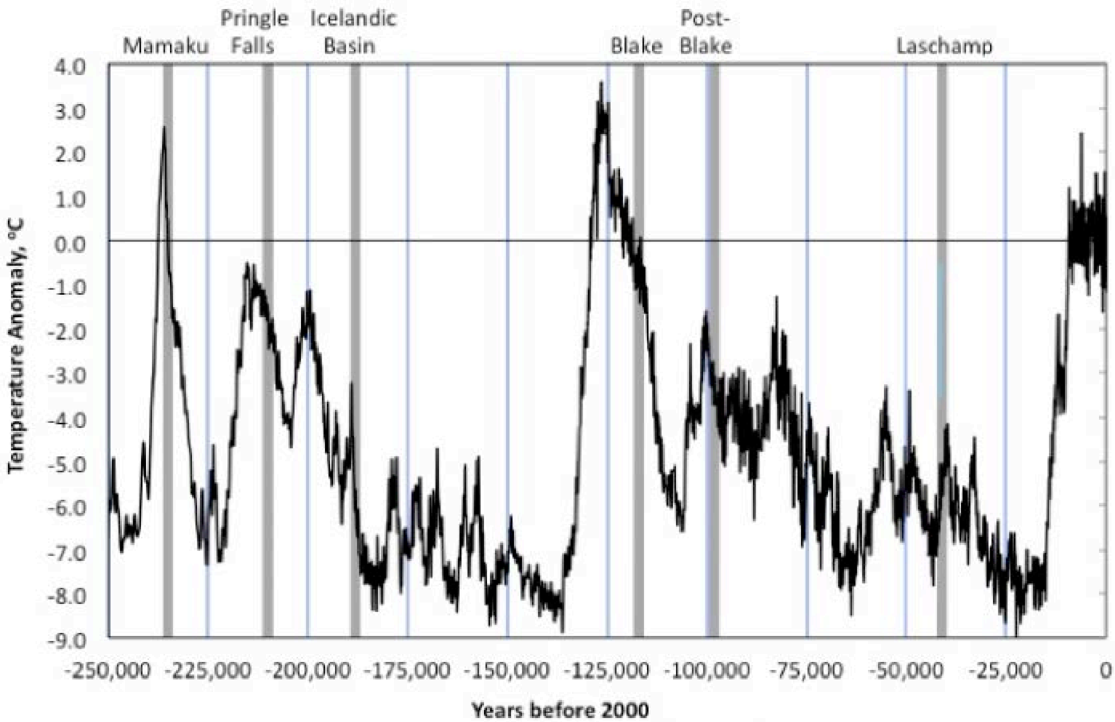

Figure 2: The Vostok Record

The interglacials have been quite variable, but average about 10,000 years in length. The relatively benign Holocene Epoch, which began 11,700 years ago and has thus encompassed the entire development of human civilization, is really just the latest interglacial.

The conventional view is that the next glacial stage is inevitable but will not happen for thousands of years, so the threat is not considered a high priority. This is based on the assumption that linearized models of the climate are adequate, and on "Milankovitch forcing"—i.e., on the theory that slow changes in sub-Arctic insolation (i.e., the intensity of sunlight), caused by calculable cyclic variations in the eccentricity of the Earth's orbit and in the tilt and precession of its polar axis, are the only significant cause of the transitions between interglacial and glacial stages. The idea is that the snowline remains farther south during a cooler summer, slightly increasing the average albedo of the Earth. This reflects more sunlight into space, so that the next year is even cooler. The resulting positive snow-albedo feedback causes an accelerating descent into full glaciation. The process reverses when warm summers return.

Recent research recognizes that this is far too simplistic. It is now clear that complex, coupled, non-linear dynamical phenomena are fundamental to the climate system,[12] leading to abrupt changes, multiple equilibria, autonomous limit cycles and chaotic behavior (i.e., large, unpredictable responses to minute inputs).[13]

The jagged curve in Figure 2 shows temperature anomalies (deviations from the average temperature in the Holocene), reconstructed from an ice core at Vostok, Antarctica,[14] during two glaciations and three interglacials. Throughout the ice age, the overall pattern has been rapid warming at the start of an interglacial and a slow decline in the average temperature throughout the subsequent glaciation. A complex sequence of smaller oscillations is superimposed on this background. Each one has an irregular but roughly triangular profile, like miniature versions of the glacial/interglacial cycle. The cold periods are called *stadials* and the intervening warmer peaks are *interstadial*s. The temperature changes are sometimes abrupt, with local warming or cooling up to 10^{o}C in a decade.[15,16]

These waveforms are characteristic of relaxation oscillations, which are a type of limit cycle exhibited by many non-linear systems, including electronic oscillators, flashing signal lights, bowed violin strings, prey-predator relations, the heartbeat, aerodynamic flutter, and the pulsations of variable stars. If the climate cycles are in fact relaxation phenomena, they presumably reflect spontaneous exchanges of energy and/or mass between the atmosphere, the oceans, the polar icecaps, biomass, etc. Like your heartbeat, they do not need external stimuli for each cycle, so they will continue as long as the sun supplies energy. Your heartbeat changes phase or frequency in response to external triggers (such as a shock or exercise), and so do the stadial/interstadial cycles: the external climate triggers may include the astronomical changes underlying Milankovitch forcing, volcanoes, snow-albedo feedback, cloud-formation feedback, grand solar minima (i.e., multi-decadal periods of low solar activity), and changes in the geomagnetic field.

A.2 Geomagnetic Reversals and Excursions

It is a common misconception that the geomagnetic field is constant. The geologic record shows substantial changes on time scales ranging from decades to millions of years, including many reversals in which the north and south magnetic poles swapped places. These events reflect poorly understood processes in the geodynamo (the molten self-exciting electromagnetohydrodynamic outer core of the Earth that generates the field).

The long interval between full polarity reversals, called a *chron,* seems to be random[17] but is typically several hundred thousand years. The present *Brunhes chron* began 780 kya (kiloyears ago), when the field assumed what we now consider the normal orientation. The previous *Matuyama chron* began 2.58 Mya, when the field reversed from the earlier, normally oriented *Gauss chron.*

These reversals are readily identified from remanent magnetization in many stratigraphic records, so they are used as convenient markers for the internationally accepted divisions of deep time.[18] Thus the Gauss-Matuyama reversal is taken as the beginning of the Pleistocene Epoch (and the Quaternary Glaciation).

Geomagnetic excursions occur much more frequently than full reversals. At least 16 of them have been confirmed during the current chron,[19] and there were many more before that.

A.3 Excursions and Cooling

The vertical grey bars in Figure 2 show the approximate dates of named excursions during the last 250,000 years. The figure suggests that each geomex was associated with a stadial that lasted much longer than the geomex itself, but the accuracy in dating the separate geomagnetic and temperature records is insufficient to be sure. The correspondence is however clear in natural archives (such as stalagmites[20] and some stratified sediments) that contain both remanent magnetization and temperature proxies, even though the uncertainty in the absolute date may be thousands of years.

Longer-term studies[21] indicate that a stadial occurred in conjunction with every geomex during the last 400,000 years, and probably with all of them during the Brunhes chron. In some cases, the geomex happened when a stadial was already underway, perhaps accelerating the cooling. There were of course many additional stadials without an associated geomex, either free-running or triggered by other stimuli.

Some analysts[21] interpret the correspondence as meaning that the orbital cycles underlying Milankovich forcing somehow influence the geodynamo, triggering a geomex, so that the geomagnetic collapse is a consequence rather than a cause of the change. This does not explain why excursions and associated stadials occur at times (as now) when Milankovitch theory predicts no change.

A more plausible explanation[22] is that the increased influx of GCRs due to a geomex nucleates low clouds that increase the albedo, triggering a stadial or exacerbating one that has already started. There is increasing evidence for this theory from laboratory experiments[23] and satellite observations.[24] In this view, geomagnetic reversals and excursions occur every now and then because of instabilities in the geodynamo, with or without external influences.

For present purposes, it may not seem important whether a geomex triggers a stadial or is merely a marker for one that is caused by other influences. Either way, the implication is that global cooling is coming. Improved understanding of the physical basis for the apparent linkage is however very important, because it will help us predict and prepare for the changes we may face in coming decades.

A.4 Geomagnetic Winter

The protracted cooling associated with a geomex is called a *geomagnetic winter*. If this pattern holds in the present instance, the climate at the end of this century could be colder than at any time since the Holocene began—and these frigid conditions might last for thousands of years. Adaptation would be difficult and expensive, but not impossible.

In this scenario, arctic conditions extend far to the south, replacing forests and arable land with permafrost and ruining many existing residential areas and industrial facilities. Cities now temperate face brutal weather, with long cold seasons, heavy snowfall and frozen waterways. Agriculture faces freezing conditions, shorter growing seasons, the need for different crops and the loss of usable farmland, but expanded use of greenhouses might compensate for some of these effects. Many wild species of plants and animals suffer irrevocable loss of habitat, leading to extinction of those that cannot migrate or adapt.

A.5 The Glaciated Planet

As Figure 2 indicates, the last interglacial peaked around 126 kya at a temperature 3.5^{o}C above the Holocene average, and the subsequent cooling accelerated after the Blake geomex.[20] The interglacial before that also reached higher temperatures than the Holocene, but it may have been disrupted by the Mamaku, Icelandic Basin and Pringle Falls excursions. Unfortunately, this seems to be the pattern: every geomex that occurred during every interglacial for which adequate records exist apparently led to very severe cooling, often including the onset of the next glacial stage.[21]

Nobody really knows whether the new geomex signals the end of the Holocene, but the possible consequences are so extreme that we cannot ignore the possibility.

At first, the glacial transition may differ from geomagnetic winter only in that it keeps getting colder and colder. It may be centuries before the glaciers come grinding down from the north—but come they will, obliterating everything in their path. Forests and farmland will vanish, and few if any buildings or other works of man will survive. London and Paris and New York will be ground to dust under ice kilometers thick, and all the glories and all the infrastructure of northern civilization will be gone beyond recall. Many advanced nations will cease to exist, forcing their entire populations to migrate to lower latitudes, whether or not the indigenous people object. Less-developed tropical nations may not disappear under the ice, but they too may suffer dire consequences because they lack the technological and economic resources to cope with either the climate changes or the uninvited influx of glacial refugees.

A massive effort will be needed to save what we can from the doomed northern nations, and the necessary cultural triage will be deeply controversial. We need to begin (1) creating an inventory of irreplaceable facilities, scientific specimens, artistic and historical artifacts and architectural treasures; (2) building a consensus about which of them can and should be moved south before they are lost; (3) developing technologies that can sustain or improve life in a glaciated world; (4) seeking international agreement about organization of a radically different world; and (5) planning the most extensive relocation ever contemplated.

Information about conditions in the next glacial stage comes primarily from studies of the last one.[25] Most of the world that escapes the ice will become frigid, dry, dusty, windy and desolate. The rainfall will decrease almost everywhere, in some places by 90%; many rivers and lakes will disappear, while others will freeze. Tropical rainforests will shrink into isolated refugia. The deserts that now cover 10% of the land between $\pm 30^{o}$ latitude will quadruple in area. Dust storms will be much more common than rainstorms, especially downwind from the deserts. The falling sea level will drain harbors, kill coral reefs, destroy ecologies in wetlands and in coastal and littoral zones, and expose desiccated mud flats that become additional sources of windblown dust. The atmospheric concentration of CO_2 will fall as the colder seas become more absorbent, severely limiting photosynthesis and making plants more susceptible to the arid conditions (by opening leaf stomata).

A.6 Countermeasures and Adaptation to Glaciation

Geoengineering projects aimed at controlling the climate have been suggested many times, but almost all studies in the last several decades have assumed that global warming is the only threat that needs consideration.[26] Proposals to minimize global cooling need much more investigation before judging their feasibility, cost and consequences. Some possibilities:

- Controlling snow-albedo feedback by a sustained international effort to melt or remove snow at the margins of the Northern Hemisphere snow cover.[27]

- Building a dam across the Bering Strait[28] that could control circulation in the Arctic Ocean, leading to an increase in salinity that would reduce sea ice and warm the climate in northern Canada and Siberia.
- Releasing methane (CH_4) from the immense hydrate deposits under the Arctic permafrost and on the continental shelves. Methane is a much more potent greenhouse gas than CO_2, but its atmospheric lifetime is only about a decade, due to oxidation to CO_2 and H_2O. A large release might provide a temporary warming pulse that could interrupt the glacial transition.

The glaciated world may be unavoidable, but it will be survivable, at least for some smaller population that fits within the reduced carrying capacity of the planet. In some respects, the required adaptations will be similar to those needed for space settlements. Most people will live in enclosed cities[29] (a.k.a *arcologies*) with partially closed ecologies, perhaps underground or underwater. Intensive greenhouse agriculture, genetically-modified plants, fish farming and cultured meat products[30] (i.e., meat grown *in vitro*) will replace food from rainfed cropland and pastures that no longer exist. Solar power satellites in geosynchronous orbit, one of the first major products of the extraterrestrial enterprise, will provide ample, inexhaustible, baseload electric power wherever on Earth it is needed. Enclosed zoos and other biological archives will preserve breeding populations, frozen embryos, seeds or DNA from selected plant and animal species endangered by the glaciation.

Even if the glacial transition is slow enough to permit making these fundamental changes in terrestrial civilization, they would require an increasing investment of resources while economic productivity declines and political problems multiply. It is unlikely that technological adaptation can entirely compensate for the loss of water supplies, agricultural land and biomass productivity in Canada, the U.S., India and China, so critical food shortages may lead to massive, violent riots and to widespread starvation. The probable outcome is a freezing nightmare of chaos and famine during the first few centuries, until desperate wars over resources or territory have killed enough people.

Once the next glacial stage has begun, the good times will not return on Earth for a thousand centuries. That is a span of time that is simply incomprehensible in human terms: it might as well be forever. The ultimate adaptation to this interminable disaster is an extraterrestrial civilization that can grow and prosper during all those centuries, extending not only throughout the solar system but across the gulf between the stars. We will foreclose that future if we don't get started before the coming of the ice.

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[1] Phil Chapman is a geophysicist and former NASA astronaut. His email address is phil.chapman@alum.mit.edu For more information, see his Wikipedia page.

[2] Globus, A. & Strout, J., "Orbital Space Settlement Radiation Shielding," preprint at http://www.nss.org/settlement/space/GlobusRadiationPaper.pdf

[3] For information about solar power satellites, see the extensive library on the subject that is maintained by the National Space Society at http://www.nss.org/settlement/ssp/library/index.htm

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[28] Borisov, P.M. (1969), "Can We Control the Arctic Climate?" *Bulletin of the Atomic Scientists*, XXV #3 (1969) 43-48. A copy is available in Google Books at https://books.google.com/books?id=SwcAAAAAMBAJ&pg=PA43&dq

[29] La Ville Souterraine in Montreal (http://montrealvisitorsguide.com/reso-underground-city-la-ville-souterraine/) and the underground PATH in Toronto (http://www.aviewoncities.com/toronto/path.htm) offer a foretaste of what life in an arcology might be like.

[30] For a non-technical discussion of cultured meat, see an article by Marta Zaraska in *The Washington Post* (May 2, 2016), online at https://www.washingtonpost.com/national/health-science/lab-grown-meat-is-in-your-future-and-it-may-be-healthier-than-the-real-stuff/2016/05/02/aa893f34-e630-11e5-a6f3-21ccdbc5f74e_story.html