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「エコ・テクノロジーの宇宙的観察」

コーネル大学天文学および宇宙科学教授　カール・セーガン

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Profile of Lecturer

Professor Carl Sagan

Carl Sagan is the David Duncan Professor of Astronomy and Space Sciences and Director of the Laboratory for Planetary Studies at Cornell University. He has played a leading role in the Mariner, Viking and Voyager expeditions to the planets, for which he received the NASA Medal for Exceptional Scientific Achievement; the Prix Galabert, the international astronautics prize; the NASA Medal for Distinguished Public Service (twice); and the John F. Kennedy Astronautics Award of the American Astronautical Society. His scientific research has enhanced our understanding of the greenhouse effect on Venus, dust storms on Mars, the organic haze on Titan, the origin of life, and the search for life elsewhere. Dr. Sagan has served as Chairman of the Division for Planetary Sciences of the American Astronomical Society, as President of the Planetology Section of the American Geophysical Union, and as Chairman of the Astronomy Section of the American Association for the Advancement of Science. For 12 years he was Editor-in-Chief of *ICARUS*, the leading professional journal devoted to planetary research. He is currently President of the Planetary Society, a 100,000 member organization which is the largest space-interest group in the world; and Distinguished Visiting Scientist, Jet Propulsion Laboratory, California Institute of Technology.

In addition to more than 600 published scientific papers and popular articles, Dr. Sagan is author, co-author or editor of more than twenty books, including *Broca's Brain, Comet, Contact* and *The Dragons of Eden*, for which he was awarded the Pulitzer Prize. He was responsible for the Pioneer 10 and 11 plaques, and the Voyager 1 and 2 interstellar records, messages about ourselves sent to possible other civilizations in space. His Emmy and Peabody Award winning television series COSMOS became the most widely watched series in the history of American public television, and has now been seen in 60 countries by over 250 million people. The accompanying book also called *Cosmos*, is the best-selling science book ever published in the English language.

In recent years, Dr. Sagan and his colleagues have been engaged in research on the long-term consequences of nuclear war, uncovering previously unsuspected dangers for our civilization and our species. Partly for this work, he has been given the Annual Awards for Public Service of the Federation of American Scientists and of Physicians for Social Responsibility, as well as the Leo Szilard Award for Physics in the Public Interest of the American Physical Society. Dr. Sagan has also received the Explorer's Club 75th Anniversary Award "for achievements in furthering the spirit of exploration," the Joseph Priestley Award "for distinguished contributions to the welfare of mankind," and the Honda Prize "for contributions towards ... a new era of human civilization."

講師略歴

カール・セーガン

カール・セーガンは、コーネル大学天文学および宇宙科学のデービッド・ダンカン教授、同大学惑星研究所長である。同氏は、マリナー、バイキング、およびボイジャーの惑星探査において、指導的な役割を果たし、その傑出した科学的業績に対してアメリカ航空宇宙局(NASA)メダル、国際的な宇宙航行学賞であるガラベール賞、卓越した公共の福祉に対するNASAメダル(2度)、およびアメリカ宇宙航行学会のジョン・F・ケネディ宇宙航行学賞が贈られている。同氏の科学的研究は、金星の温室効果(greenhouse effect)、火星における砂塵あらし(dust storms)、タイタンの有機雲(organic haze)、生命の起源、および地球以外に存在する生物の探査に関するわれわれの知識を高めてきた。セーガン博士は、アメリカ天文学会・惑星科学部会会長、アメリカ地球物理学会・惑星学部会会長、および米国科学振興協会・天文学部会会長として奉職した。同氏は、12年間、惑星研究の国際的な専門雑誌『イカルス』の編集長であった。同氏は、現在、10万人の会員を擁し宇宙に関心をもつ人々の世界最大の組織である惑星協会(The Planetaty Society)会長であり、カニフォルニア工科大学ジェット推進研究所の特別客員科学者である。

600編以上の科学論文、および一般記事の出版に加え、セーガン博士は、『ブロッカ博士の頭脳』、『彗星』、『異星人との知的交信』それにピューリッツァ賞を受けた『エデンの恐竜』を含め、20冊以上の書籍の著作者、共著者あるいは編集者となっている。同氏は、宇宙の他の文明にあてて、われわれのメッセージを伝えるパイオニア10号、および11号の金属板、ボイジャー1号、2号のレコードに関する責任者であった。同氏がエミー賞・ピーボディ賞を受賞したテレビ・シリーズ『コスモス』は、アメリカ公共放送の歴史の中で、最も広汎に視聴されたシリーズであり、現在まで60ヶ国、2億5千万人以上の人々によってみられている。同時に、『コスモス』と題された書籍は、これまで英語で出版された科学書のなかで、最高の売れ行きを示している。

最近では、セーガン博士とそのグループが、核戦争のもたらす長期的な影響に関する研究を進めてきた結果、われわれの文明、および人類に対して、これまで疑われもしなかったような重大な意味合いを明らかにすることになった。

この仕事の一部に対して、社会的責任に関するアメリカ科学者・物理学者連盟より公共の福祉に対する年間巧績賞およびアメリカ物理学会よりレオ・スジラード賞を受賞している。セーガン博士はまた「探険家精神を発展させた巧績」で探険家クラブ75周年記念賞を、また「人類の福利厚生に顕著な貢献をなした」としてジョセフ・プリーストリー賞を受けた。そして、「人類の文明に新しい時代をもたらした」として、本田賞を受賞した。

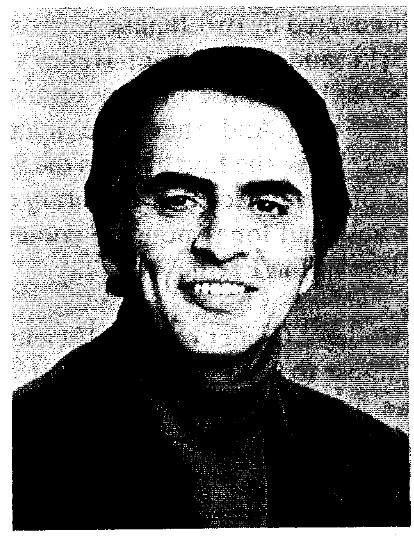
May 15, 1986

このレポートは昭和60年11月18日、ホテル・オークラにおいて行なわれた1985年度本田賞授与式の記念講演の記録です。

Planetary-scale Eco-technology

Lecture at the Conferring Ceremony on the 18th of November 1985, in Tokyo

Professor Carl E. Sagan
The Winner of The Honda Prize 1985



I. Introduction

I am very grateful. I thank the Honda Foundation, and Honda-san, for this high honor. I also whish Honda-san a very happy 79th birthday.

My topic is planetary-scale eco-technology. To me, eco-technology signifies a wisely considered technology, devoted to humane purposes, in which there are no significant negative consequences even when the technology proliferates on a global scale. Such an ideal is far from being achieved in our time.

Technology can now affect not just our everyday lives, but even the climate, environment and ecology of the entire planet — and, in the relatively near future, other planets as well. To deal with problems on so grand a scale, we need to adopt a planetary perspective — to see the Earth as a world, one among many others. The study of other worlds can help us to understand and improve this one, and so avert the very real catastrophes that lurk in our technology.

Even every early human technology may have been able to affect the climate — for example, slash-and-burn agriculture may have been sufficient to change how reflective the surface is, and therefore what fraction of incident sunlight goes into warming the Earth. After the Industrial Revolution, humans contrived new ways, largely accidentally, to make major environmental changes. In this talk, I concentrate on two recent cases in which humans have found a weakness, a vulnerability in the global environment and planetary ecosystem.

II. Cometary Impact and Climatic Change

To begin, however, I would like to start with something that may seem quite irrelevant: comets. Comets are much on our mind tonight because Halley's Comet is on one of its periodic forays into our part of the solar system. Among a fleet of five spacecraft from twenty nations that will encounter the comet next March are two Japanese spacecraft, Sakigake and Suisei — the first interplanetary spacecraft of Japan, or indeed of any purely Asian nation. They represent a very welcome broadening of the remarkable human activity of exploring other worlds, which should properly be carried out on behalf of the entire human species.

A comet is not very much, essentially a dirty snowball a few kilometers in diameter, coming to us from far beyond Pluto, the most distant known planet. A few of the comets are captured into shorter period orbits and remain in the planetary part of the solar system.

Each of the curves in Figure 1 represents the orbit of a comet; but shown is only a small fraction of the known comets. You can see, for example, the orbit of a comet discovered by two Japanese astronomers, Ikeya and Seki, and the orbit of Halley's Comet. The figure gives us a sense of how abundant the largest comets are. And there are many more smaller comets. Since the Earth orbits the Sun right in the middle of this collected of cometary orbits, it follows that you wait long enough a comet should come very close to the Earth.

In 1910, Halley's Comet came sufficiently close for its tail almost to graze our planet. Honda-san recalls — we were discussing this at lunch — the concern that was felt all over the Earth in the year 1910 that we would become engulfed in poisonous cometary gases. Because the tail of a comet is so diffuse, the 1910 apparition was not cause for serious concern. However, there is a very real danger implied in Figure 1 — sooner or later, a comet will hit the Earth. With the present abundance of comets in the inner solar system, you can calculate that every few tens of millions of years a comet should strike the Earth, a significant comet, a comet a few kilometers across or larger.

Remarkably, there is evidence that 65 million years ago something this large did impact the Earth. In the sedimentary column, in the rocks of that time, there is a concentration of a particular chemical element, iridium, which is very abundant in extraterrestrial objects such as asteroids and comets, and much less so on the Earth's surface. The iridium is spread all over the world, and provides strong evidence that an asteroid or a comet around 10 kilometers across struck the Earth. There is no known crater of appropriate size and age on the land area of the Earth, and therefore the impact probably occurred in the oceans (Figure 2). Because the comet is wider than the ocean is deep, an immense crater would have been excavated on the ocean floor, flinging hundreds of millions of tons of fine particles high into the atmosphere. The dust would have spread all over the Earth, blocking sunlight, and therefore darkening and cooling the Earth for years. But 65 million years ago, when the iridium-rich clay was formed, is also the time of the Cretaceous/Tertiary Event, one of the Great Dyings in the history of life on Earth. The dinosaurs had been the loards of the Earth; they had been in existence for over 140 million years; they had conquered the land, the sea and the air. Our mammalian ancestors survived by keeping out of their way. And yet, all the dinosaurs on Earth were destroyed 65 million years ago, in a mass extinction, as were most species of life on the planet.

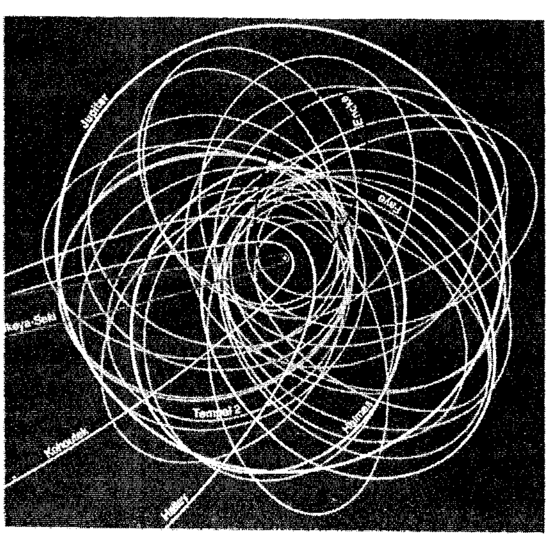


Figure 1: A few of the known cometary orbits, shown in relation to the orbit of Jupiter (large circle). Among the comets shown are Ikeya-Seki, Encke's and Halley's. The Earth orbits the Sun in this profusion of comets. Courtesy, National Aeronautics and Space Administration.

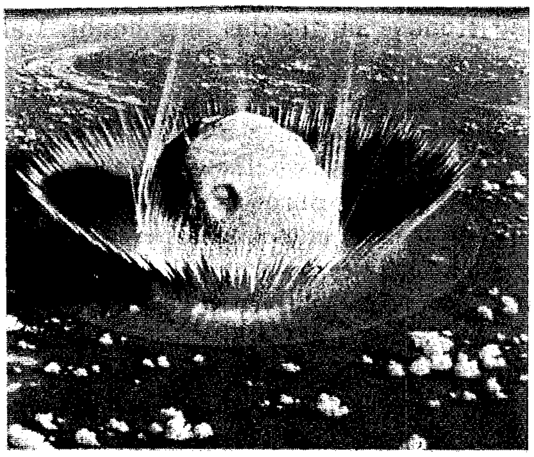


Figure 2: A large cometary nucleus, 10 kilometers across, is just about to strike the Earth — 65 million years ago in this schematic representation. The resulting explosion is thought to have propelled huge clouds of pulverized ocean bottom into the atmosphere all over the Earth, producing a time of cold and dark that resulted in the extinction of the dinosaurs and most other species. Nuclear Winter is a similar effect. Painting by Don Davis. From the book Comet, by Carl Sagan and Ann Druyan, Copyright _ 1985 (Tokyo: Shueisha; New York: Random House)

In Figure 3 is an artist's conception of the time: the cold and the dark resulting eventually in the deaths of all the dinosaurs. You may be able to see a small mammal, perhaps one of our ancestors who were, because of the death of the predators, able subsequently to expand their habitats and evolve. We owe our own existence to the deaths of the dinosaurs, and therefore, to the Cretaceous/Tertiary Event. But if climatic catastrophes on a grand scale occur on Earth every now and then, no species is guaranteed its tenure on this planet. (In fact the vast majority of species that ever lived on Earth are now extinct.) We also conclude that large quantities of fine particles injected into the atmosphere can produce dramatic changes in the climate. This is an important lesson for us, not because a comet is likely to hit the Earth in the near future, but because there are other activities, well within our powers, by which humans can inject the same quantity of fine particles into the atmosphere as rendered the dinosaurs extinct. I will return to this subject.

III. The Greenhouse Effect

Climatic change occurs on all time scales, not just tens or hundreds of millions of years. Consider the last ten thousand. Today, large areas of northern midlatitudes are forrested (although humans are destroying forrested lands at a fearsome rate). Very little of the surface — Greenland and much of Antarctica are exceptions — is covered with ice year-round. But ten thousand years ago, the situation was very different. Then, the fraction of the Earth that was forrested was very small (Japan was among the forrested areas), and the fraction that was covered with glaciers was very large. What is now the city of Chicago was under a kilometer of snow and ice. This change from the Wisconsin Ice Age to the present more clement conditions is very dramatic, although not nearly as striking as the inferred climatic change of 65 million years ago.

There is no reason to think that either of these climatic changes was brought about the activities of living beings. The Wisconsin Glaciation is thought to be due to quasiperiodic variations in the Earth's orbit and axial inclination. Humans, of course, were present 10,000 years ago, although not our technological civilization. But the existence of such changes in the world climate raises a question about the vulnerability of the planetary ecosystem. How resistant to change is the environment of the Earth? Humans now have extraordinary technological capabilities. Is it within our power, purposely or inadvertently, to change the climate of our planet to such an extent as to put into jeopardy our civilization, perhaps even our species? Unfortunately, the answer seems to be, "Yes."

Let me spend just a moment describing in a simple way how the planetary climate works. Figure 4 is a photograph of the Earth from space, one of the many lovely spacecraft images which grace our time. They permit us to look at our planet from space, to recognize its vulnerability, and, incidentally, to note that, in these pictures at least, no

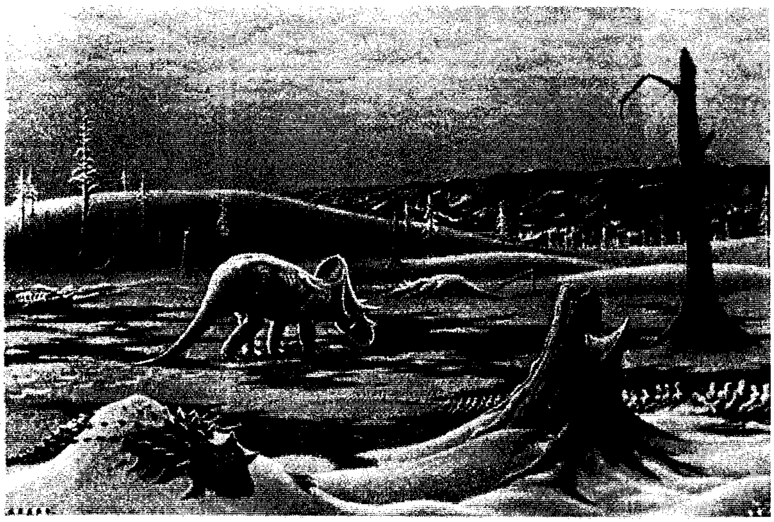


Figure 3: A triceratops wanders forlornly over the frozen and darkened late Cretaceous landscape in this illustration of the probable consequences of a cometary impact 65 million years ago. Painting by Don Davic. From the book Comet, by Carl Sagan and Ann Druyan, Copyright _ 1985 (Tokyo: Shueisha; New York; Random House)

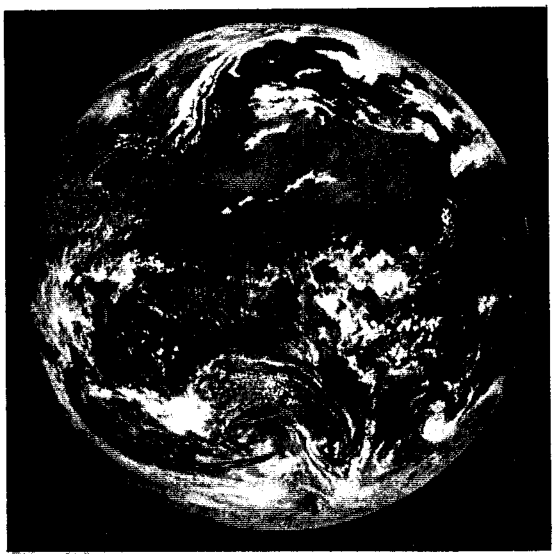


Figure 4: Photograph in ordinary visible light of the planet Earth from geosynchronous orbit. *Meteosat* image. Courtesy, European Space Agency.

national boundaries are apparent. Now, the climate of the Earth is due mainly to sunlight. It is sunlight which heats our world. We recognize how cold it is at night, and how frigid it is during the long Arctic or Antarctic winters, when there is very little sunlight. If the Sun were turned off, the temperature of the Earth would drop so far that the oxygen and nitrogen in the atmosphere would freeze out, producing a layer of frozen oxygen and nitrogen something like ten meters thick.

Not all the incident sunlight strikes the surface of the Earth, because the Earth has an atmosphere and coulds. some sunlight strikes the clouds, say, and is reflected back to space. Also, not all the sunlight that reaches the ground is absorbed by the ground. Most of it that strikes, let's say, a desert, is absorbed, but some is reflected back to space. So, how reflective the Earth is, how much light it reflects back to space, is an important determinant of the climate of the Earth. If you make more clouds, or if you make the gound brighter, you reflect more sunlight back to space and you cool the Earth. If you have fewer clouds, or if you make the ground darker, you absorb more of the sunlight, and so you make the Earth warmer. Thus, any human activities which affect cloudiness or the reflectivity of the Earth can change the global climate. Even a small change in the average temperature of the Earth can have profound ecological and agricultural consequences.

If you were to calculate how warm the Earth is merely from how much sunlight the surface absorbs, you would conclude that the temperature of the Earth was well below the freezing point of water. The oceans would be frozen. What then is wrong with this calculation? What's wrong is that we have neglected what is called the "Greenhouse Effect." We have neglected the retention of heat by the atmosphere of the Earth. The air in front of us is transparent in ordinary visible light. That's why we can see one another. But if our eyes were sensitive at, say, a wavelength of 15 micrometers in the infrared, this would be a very difficult lecture, because none of us would be able to see more than a few centimeters in front of his or her nose. Air is black at some wavelengths in the infrared. The Greenhouse Effect works because ordinary visible sunlight passes through the largely transparent atmosphere, strikes the Earth, and heats the ground; but when the ground tries to radiate back to space in the infrared, the water vapor, carbon dioxide and other gases in the atmosphere tend to be opaque, the ground is impeded from radiating to space, the heat is retained, and the surface of the Earth gets warmer.

Figure 5 is a photograph of the Earth from space in one of the opaque regions of the infrared spectrum. The view is exactly that of Figure 4, but at these wavelengths we can see no radiation from the surface of the Earth; we are looking at the gases and clouds of the high atmosphere. So, life on Earth is possible only because of the Greenhouse Effect, mainly due to a little water vapor and a little non-poisonous carbon dioxide in our atmosphere. A minor constituent of the atmosphere can have a major influence on the environment of our planet. This fact again provides a warning: it is now possible for humans to make major changes in the Earth's climate.

You might weigh the possibility that the Greenhouse Effect is an error — that scientists haven't properly understood it, that it's not so important. But we have an extremely useful example of a massive greenhouse effect that nature has kindly provided us. It lies just next door. The nearest planet is Venus. It is covered with clouds of concentrated sulfuric acid; its surface is hidden, far below. The Venus atmosphere contains an enormous quantity of carbon dioxide, 300,000 times as much as in our atmosphere. Some sunlight penetrates through the Venus atmosphere, but when the surface, tens of kilometers below, attempts to radiate back in the infrared, almost all of that infrared radiation is kept

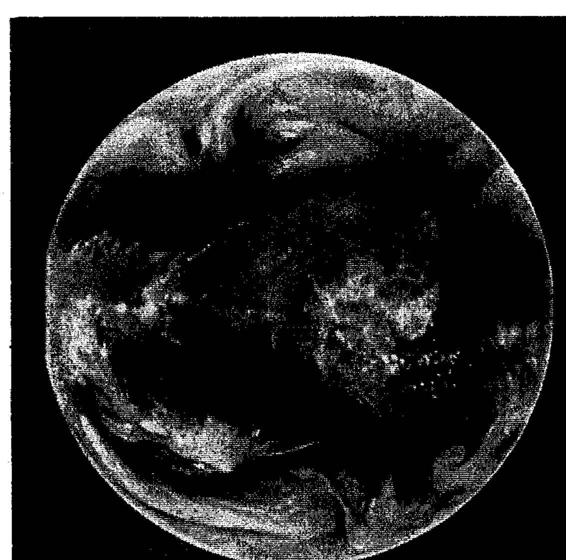


Figure 5: Photograph in a near infrared water vapor band of the planet Earth from geosynchronous orbit. *Meteosat* image. Courtesy, European Space Agency

in by the massive atmosphere. As a result, the surface temperature rises to about 470 degrees Centigrade, enough to melt tin or lead. Venus is so hot solely because of the massive Greenhouse Effect. Because of the Greenhouse Effect, Venus is very much like the classic Western description of Hell. A little Greenhouse Effect is a good thing; our oceans are not frozen because of the Greenhouse Effect. But a big Greenhouse Effect can be extremely dangerous.

The abundance of carbon dioxide in our atmosphere is not fixed; it is increasing with time — because of the burning of fossil fuels: oil, coal, wood, peat, natural gas and so on. When you burn a lump of coal, let's say, you combine the carbon in the soil with the oxygen in the atmosphere, which releases energy (which is why you burned the coal in the first place). But burning that lump of coal also produces carbon dioxide — one atom of carbon from the coal and two atoms of oxygen from the air — which goes into the atmosphere and remains there. No present or foreseeable technology can scrub much carbon dioxide out of the atmosphere. Once in, it stays for very long periods of time, until it is inhaled by a tree, say, or sediments out as carbonates in the ocean.

We have been adding to the carbon dioxide content of the atmosphere because of industrial growth and the wish to keep people warm, certainly benign intentions. Hardly anyone imagined that there might be negative consequences for the climate. But as a result, the carbon dioxide content is steadily increasing, the Greenhouse Effect is getting more efficient, and the temperature of the Earth is slowly rising. We can calcualte at the present rates of world industrial growth how much the temperature of the Earth will increase. By the middle of the next century, it will increase by several centigrade degrees, a very significant global temperature change. In a century to a century and a helf, the temperature change may be so large that significant glacial ice will melt, and eventually there is the real possibility of the collapse of the West Antarctic Ice Sheet — which has so large a volume that if it fell into the ocean, sea level would rise by meters to tens of meters. This is a little bit like absent-mindedly sitting in a full bathtub; the water, of course, leaves the bathtub for the bathroom floor. An ocean level rise of this extent is enough to inundate essentially all the coastal cities on the planet, a catastrophe of serious proportions. It certainly has economic consequences even more severe than the economic catastrophes that former Primer Minister Fukuda was telling us about earlier today.

To resolve this issue, what can be done? First of all, we must be sure we understand it; we must be sure that national leaders understand it. But that's not enough, beause this is a problem that will not much affect us; it will mainly affect our children and our grandchildren. Accordingly, it raises an important ethical issue: Are we willing to take expensive steps now to avoid catastrophe in the next century, to benefit those who will come after us? Or are we only concerned with ourselves and the present, with short-term profits, and unconcerned with the long-term future of the planet? How sure do we have to be about the catastrophe to devote how much money to preventing or ameliorating it? These are important questions and, it seems to me, central issues for eco-technology.

If we were truly committed to our descendants, what could we do about the Greenhouse Effect? First, we could arrange for the much more efficient use of fossil fuels. Lip service is given in some countries to "energy conservation" and, at the same time, fossil fuels are subsidized by governments, which makes their use inefficient. If fuels were more expensive, they would be used more efficiently. A longer-term, not mutually exclusive, possibility is to make a major transition to alternative energy sources — where appropriate, to solar, tidal, or geothermal power, to safe fission reactors, and eventually to fusion technology. Whatever the problems with these other energy sources — bequeathing to our descendants dangerous, long-lived radioactive wastes is also a serious matter — they do not pollute the atmosphere with infrared-absorbing gases; they do not contribute to the Greenhouse Effect. The pursuit of alternative energy sources might be a promising long-term solution if initiated soon enough.

However, this is not only a problem between our generation and future generations, it is also a problem between one nation and another. Atmospheric carbon dioxide does not respect national boundaries. For example, the largest coal reserves in the world are in the United States, the Soviet Union, and China. Now, consider China, where an ambitious program of industrial development is going on, employing that nation's massive coal reserves. What are the incentives for China to hold back on the burning of fossil fuels in its industrial development if the consequences ultimately will be, say, exacerbating the conversion of the American

Midwest or the Ukraine into scrub desert? The greenhouse warming of the Earth is a problem of global dimensions; it cannot be solved by one country alone. Soviet coal burning can affect the climate in South America, and American oil use the climate in South Africa. The problem can be solved only through the concerted effort of all the industrial nations. Unfortunately, the present international system is not optimized for activities on behalf of the human species; each nation looks out almost exclusively for itself. There are many other cases of this sort — acid rain, for example, or virulent epidemics, or compromise of the protective ozone layer by halocarbons in refrigerators and aerosol spray cans — in which the human species is presented with a growing danger whose long-term solution requires the cooperation of all industrial nations, whether or not they happen to find each other ideologically compatible.

IV. Nuclear Winter

There seems to be another category of planetary-scale climatic catastrophe that is within human ability to bring about or prevent; this one a likely consequence of nuclear war. The United States and the Soviet Union have infected the world with over 55,000 nuclear weapons, almost all of which are more powerful than the weapons that destroyed Hiroshima and Nagasaki in 1945. Fifty-five thousand nuclear weapons! If you define a city as having 100,000 inhabitants or more, there are only about 2,300 cities on the planet. The United States and the Soviet Union have some 20,000 strategic weapons — weapons that can be delivered to the homeland of the adversary. That means that the United States and the Soviet Union can destroy every city on the planet with two weapons per city, and still have 15,000 strategic nuclear weapons left over. The problem, I suppose, would be what to do with the remainder, to say nothing of the 35,000 tactical weapons which are not considered in this calculation.

I would like, therefore, briefly to outline some of the global scale consequences of nuclear war, and in particular the recent findings — now corroborated by many scientific groups in many countries, and acknowledged by the U.S. Department of Defense as serious.

The prompt consequences of nuclear war are well-known. I certainly do not have to recount them to this audience. Estimates of the prompt fatalities in a so-called central exchange range from a few hundred million people up. A recent estimate by the World Health Organization has it that in a 5,000-megaton nuclear war — that is, using between a third and a half of the strategic arsenals of the United States and the Soviet Union — 1.1 billion people would be killed outright, and another 1.1 billion people would die if they did not receive prompt medical attention, which of course they would not, because the doctors and the hospitals are in the target zones. So, among the immediate consequences of nuclear war in the northern mid-latitude target zone, which might well include Japan, might be as much as 40 percent of the human population of the planet killed. What about the other 60 percent?

Consider the tens of thousands of targets in a full nuclear war. Some will be destroyed by high-yield groundbursts which propel immense quantities of rock powder directly into the stratosphere. Others will be destroyed by airbursts which produce fires that in turn generate immense quantities of dark sooty smoke in the lower atmosphere or troposphere. The burning of cities is the most ready source of soot. If there is a firestorm — which is anticipated for about half the cities attacked — the soot will rapidly rise into the stratosphere. Otherwise, the simple heating by sunlight of soot clouds not removed by rainfall will again carry the dark smoke to high altitudes, where it may remain for a year or more. Meanwhile, the dust and smoke spread first in longitude, and then in latitude. Some of it will cross the equator and enter the Southern Hemisphere.

These clouds are calculated to be so opaque, on average, as significantly to attenuate the sunlight that reaches the surface. This alone is enough to cool and darken the Earth. However, there is another effect. The Greenhouse Effect is due to gases such as water vapor and carbon dioxide, which do the bulk of their infrared absorption in the lowest several kilometers of the Earth's atmosphere. But if, following a nuclear war, sunlight is mainly blocked at higher altitudes, sunlight will never reach these greenhouse gases. The dust and soot in a nuclear war can therefore shut the greenhouse down — at least partially. This will lower the temperatures still more. Potentially, the combined effects can be catastrophic. The adverse climatic consequences of a nuclear war are called Nuclear Winter.

In the northern midlatitude target zone, where the war would mainly be fought, the temperatures drop the most. Japan lies in these latitudes, and fine particles from nuclear explosions in the Soviet Union and China would be blown by the prevailing Westerlies eastward; Japan would be an early climatic casualty in a nuclear war.

We do not know how long Nuclear Winter would last; this is among the least certain aspects of the calculations. There are some who think, as in our original calculations, that it might last only a year or two. But others suggest that there are climatic feedback effects — the ice/albedo effect or the sea ice/oceanic thermal inertia effect — that may greatly increase the duration of Nuclear Winter.

Even a tiny fraction of the nuclear arsenals are able to bring about this catastrophe. In fact, the simultaneous burning of a hundred cities seems more than adequate.

The temperature decline, the partial darkness, ancillary radioactivity, toxic smogs from the burning of modern cities, the later increase in ultraviolet sunlight penetrating the now depleted ozone layer, decreased resistance to disease from radiation-compromised immune systems, and the likelihood of epidemics and pandemics suggest that nuclear war would destroy our global civilization. It would certainly destroy agriculture and therefore agricultural exports.

Consider a country like Japan. Suppose that by some miracle no targets in Japan are struck, no radioactivity from China falls on Japan, and even that the dark smoke does not cover Japan. Even then, the consequences for Japan would be catastrophic, because Japan imports more than half its food. The great food resources of the northern midlatitudes — the American Midwest and the Ukraine, for example — would have been destroyed. And then consider the likely consequences of Nuclear Winter for Japan and the prompt effects of whatever nuclear weapons would be exploded in Japan, and the drifting clouds of radioactivity from the mainland, and you can see that even a country that was not intimately involved in the quarrel between the United States and the Soviet Union might nevertheless be utterly destroyed in a nuclear war. The same is true of countries such as Nigeria or Indonesia or Brazil. The consequences of nuclear war are now global; the destruction of agriculture and the consequent world-wide mass starvation are a major source of the secondary fatalities which have been estimated in a major recent study commissioned by the International Council of Scientific Unions as several billion. That's what would happen to the remaining 60 percent of the human population.

We have contrived, in utter ignorance of the fact, a doomsday machine, an instrument capable of catastrophically altering the global climate and therefore of destroying, certainly, our civilization, and perhaps even the human species. Here again the global population of the planet Earth is exquisitely vulnerable to decisions made in the industralized and especially the nuclear-armed nations. Our technology has brought us fearsome, awesome powers.

The number of strategic nuclear weapons in the combined arsenals of the United States and the Soviet Union has grown steadily with time (Figure 6). The horizontal band at the bottom of the chart indicates a number of strategic weapons so small that, even if cities were preferentially targeted, Nuclear Winter probably could not happen. Nevertheless, it is still large enough to maintain strategic deterrence. Above it is a transition zone, in which Nuclear Winter might or might not ensue. Above

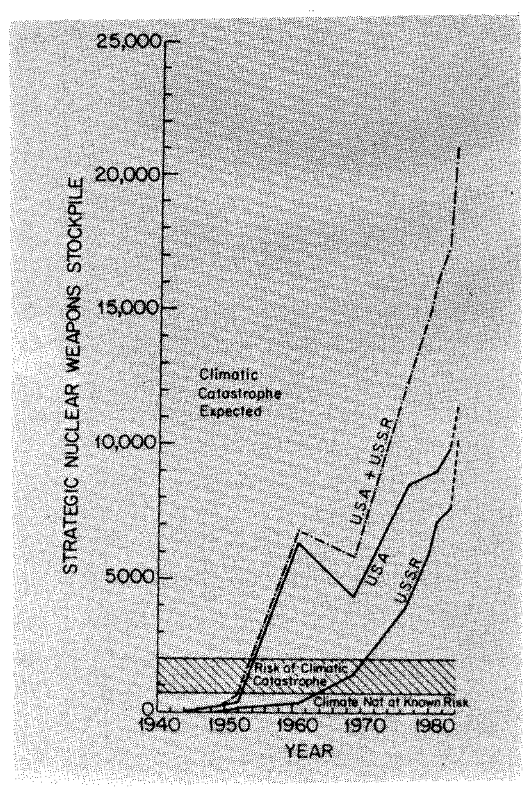


Figure 6: Growth of the U.S. and Soviet strategic arsenals with time. Data from U.S. Department of Defense sources. Reproduced from "Nuclear War and Climatic Catastrophe: Some Policy Implications," by Carl Sagan, *Foreign Affairs*, Winter, 1983/4, p. 257.

that is a very large region in which a nuclear war would almost certainly lead to Nuclear Winter. The three curves show the increase in the U.S. strategic arsenals as a function of time; the increase in Soviet strategic arsenals as a function of time; and the increase of the sum of the U.S. and Soviet arsenals. The comparatively small British, French and Chinese strategic arsenals are ignored in this diagram, although they, too, might be enough to generate Nuclear Winter.

You can see that the United States entered the region where a planetary climatic catastrophe could be initiated roughly in the early 1950's; the Soviet Union entered that region roughly in the middle 1960's. Neither nation had any notion of the potential environmental consequences of their actions, because Nuclear Winter was not discovered until 1982. The United States and the Soviet Union both proclaim that they are in favor of massive reductions in nuclear weapons but, despite their protestations, every year each increases its strategic arsenals — for what rational purpose it is very difficult to understand. As Prime Minister Fukuda said in one way, and I as say here in another, the arsenals of both nations are vastly in excess of what is necessary, if that's the word, to destroy the global civilization.

If there is any issue which is central to eco-technology on a planetary scale, this is it. There is a powerful, ethical imperative that the peoples of the world must now face, to bring about the reversal of this curve, so that the number of nuclear weapons steeply declines each year — until we reach such small arsenals that at least Nuclear Winter could not be brought about in the case of nuclear war. The consequences are so serious, the stakes are so high that it is not enough to be assured by the governments that everything is under control, so we are not to ask awkward questions. It is not enough to be told that we've had forty years without nuclear war, so nuclear wars can't happen. The only situation in which we will be truly safe is if the strategic arsenals of the United States, the Soviet Union and other nations are so small that even a conspiracy of world leaders could not bring about Nuclear Winter. That is the only situation in which our civilization would be moderately secure, commensurate with the risk it faces. Otherwise we are betting our lives on the sanity and sobriety of all leaders, military and civilian, of all nuclear-capable nations now and into the far future, as well as on the reliability of nuclear weapons technology. We are betting there will be no communications failures, no misunderstood orders, no madness in high office. But the stakes are too high for such a bet. What is clearly and urgently needed is a massive, verifiable, and bilateral reduction of these hideous arsenals of mass-destruction.

The discoveries of an increasing greenhouse effect, and of the prospect of Nuclear Winter were unexpected and largely accidental. Nuclear Winter was not uncovered by the vast military establishments of the nuclear weapons states. And this raises a further disquieting question. What other potential environmental catastrophes have we not yet been wise enough to foresee? A concerted international effort to identify and seek solution to other circumstances where human technology can compromise the planetary environment needs urgently too be made. So far as I know, there are no competent scientific institutions, private or governmental, anywhere in the world that are systematically investigating this general problem.

V. Eco-techology and other planets

A deeper understanding of possible anthropogenic environmental disasters on Earth can be achieved by studying other planets. Venus, with its 470°C surface temperature is a cautionary tale on the effects of a massive carbon dioxide greenhouse effect. One of the first hints that something like Nuclear Winter might be possible emerged from the 1971 finding by the American Mariner 9 spacecraft that great dust storms on Mars can significantly cool the surface of that planet.

There's something else very interesting about Mars: the climate used to be much close to that of Earth. Today, the Martian atmosphere is thin, the temperatures are low, and liquid water is impossible: it would immediately freeze, or evaporate if it were above the freezing point. There is no liquid water on Mars today.

And yet there is evidence of enourmous amounts of water in the ancient Martian past. The planet is today covered with networks of ancient river valleys. Liquid water once flowed on Mars, even though there cannot be any liquid water today. Something has changed on Mars to make a climate that was much closer to our own into a kind of deep ice-age environment.

Mars, like Venus, is an object lesson in how a world not very different from ours can experience severe environmental changes. Of course, no one argues that there was once a nuclear war on Mars or that excessive amounts of coal were once burned on Venus. That's not what I'm saying. But the apparent vulnerability of worlds like our own to relatively small perturbations is an important and sobering discovery of modern planetary research. Greenhouse and Nuclear Winter studies of the Earth, and the Cretaceous/Tertiary extinction event point in just the same direction.

During the last few million years, our species has made extraordinary technological advances. In the last few thousand, in the last few hundred, and especially in the last few decades, the pace of technological advance has quickened. It has brought many wonders: major advances, for example, in medicine, that everyone recognizes as humane and desirable, relieving terrible human suffering. But technology also has a dark underside. The unrestrained, unthinking advance of technology can pose serious perils to the survival of our civilization and our species. The immense power of human technology now presents us with the oppotrunity to alter the environments of entire worlds — particularly our own. It is monumental foolishness to have almost god-like powers and not to understand them. Even worse is to understand and then to misuse these powers.

If we are not so foolish as to have a nuclear war, if we are not so foolish as to continue massive contamination of the atmosphere with carbon dioxide and other gases, we can imagine a time when we thoroughly understand and control these technologies, when human wisdom is equal to the great challenge of preserving and enhancing the environment of our small planet. Then, it will be possible to consider practical means of "terraforming" other worlds — converting them to possible abodes for human and other forms of terrestrial life. This should be considered, of course, only after we are sure that there is no indigenous life on those planets, and only after we have thoroughly understood their physical environments. Since greenhouse effects warm and Nuclear Winter equivalent particles cool, there appear to be ways, not wholly beyond our present capabilities, to warm Mars and cool Venus sufficiently to make them much more habitable to humans. For Venus, some hundred million tons of finely divided organic matter of asteroidal or cometary origin may be adequate to turn off the massive greenhouse effect on that planet. For Mars the principal challenge is to release into the atmosphere buried, frozen and chemically-bound volatiles to increase the greenhouse effect, after first lowering the planetary reflectivity. In both cases, microorganisms and macroscopic plants, genetically engineered for the purpose, may be essential intermediaries. Eventually, the terraforming of other, more distant, worlds may be undertaken, rendering humanity a species abiding on many worlds. But first we must save this one.

VI. Conclusion

The time has come for a new and humane eco-technological ethic. We must find ways of convincing all the industrial nations that it is in their interest to abide by such an ethic. Technology must be used not for short-term and local advantages only, but for long-term benefits embracing the generations yet to come and all the nations and peoples of the Earth.

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