Planet Earth

Can Other Planets Tell Us Where We Are Going?

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How likely is it that the Earth will suffer either a human-made or a natural disaster that will leave this planet a desolate wasteland? As we near a new century, some scientists warn us that unless we alter our attitude toward the environment and realign our priorities from economic supremacy to environmental protection, we face the inevitable finality of planetary genocide. Planetary catastrophes due to natural causes—movement of crustal plates, climatic change, collisions in space, etc.—are a given concern. However, it is the impact of human activities on Earth that is the "great imponderable" when predicting how Earth's environment could change in ways harmful to life as we know it. Life has flourished on Earth for more than a billion years, but today, evidence abounds of human impact on this living planet (Zipko 1990; Gordon & Suzuki 1991; Bybee 1991).

> *Thousands of fires set to clear land for farming and grazing pour smoke across the green canopies of rain forests. Over industrialized regions, a fine haze of smog absorbs incoming sunlight and outgoing heat. In some places, the natural contours of the land act as huge basins that concentrate the smog, causing whole cities to vanish in a murky, choking veil. In others, the smog blends with ordinary clouds, thickening the cover over wide areas marked by forests that are already stunted or killed* (Time-Life 1989, p. 108).

Can human activities alter the biosphere of Earth and ruin it forever?

> *We have been burning more and more fossil fuels since the dawn of the Industrial Revolution, taking carbon out of rocks and putting it into the atmosphere as carbon dioxide. We know we are doing this faster than the stirring of the Earth's spheres can remove it. If we keep this up, is it possible that we will someday destroy Earth's good health and turn our home into a runaway greenhouse? Will the human volcano heat planet Earth until all the seas go dry and lead melts in the sunlight? Are we already on the downhill path to Venus? We simply do not know enough yet about Venus, or even about Earth, to be sure of the answer. But judging by our neighboring world, we are playing with fire* (Weiner 1986, p. 174).

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One way to investigate whether human activities can severely alter Earth's ability to sustain life is to examine other planets with some characteristics that are similar to Earth, yet which are hostile to the life forms found on our world. We can use these planets as a kind of "experimental" Earth to ask, first, "What factors caused these planets to evolve differently from Earth?" and then, "What changes on Earth could lead to conditions like those found on other planets?" Answers to these questions may guide us to more accurate predictions about the potential effects of our actions on the sustained livability of our planet.

For example, scientists think that about one and a half billion years ago Mars and Earth were more similar than different (Haberle 1990). Although Mars still shares more of Earth's surface characteristics than any other planet in the solar system, somewhere in history the two planets took different evolutionary paths, leading to considerable differences in the present surface environments (Table 1).

Mars is the fourth planet from the sun, and our nearest neighbor after Venus. It is one of the terrestrial planets, which also include Mercury, Venus and Earth. All the terrestrial planets have some shared characteristics (Table 1), which lead some scientists to believe that all formed at about the same time, and from very similar materials. Their atmospheres are also believed to have formed by similar means, the release of gases during volcanic processes and impact melting, leading to very similar early atmospheres (Owen 1982). However, their present atmospheres are very different from each other, especially with respect to carbon dioxide (CO_2).

Earth recycles CO_2 through its outer region in three basic steps:

1. Biological and inorganic processes extract CO_2 from the atmosphere and deposit it in the oceans.
2. Formation of marine carbonate rocks and the burial of organic material in ocean sediments removes CO_2 from the oceans and incorporates it in ocean crust.
3. Plate tectonics recycles the ocean crust and releases some CO_2 back into the atmosphere through volcanic activity on the plate margins.

Table 1. Some selected facts about the solar system.

The Character	The Planetary Body		
	Venus	Earth	Mars
Distance from sun millions of kilometers	108.2	149.6 (93)	227.9
(millions of miles)	(67)	(93)	(142)
Length of year Earth days	224.70	365.25	687
Length of day	about 243 Earth days	23 hours 56 minutes	24 hours 37 minutes
Inclination of axis	3°	23°27′	25°12′
Eccentricity of orbit	.007	.017	.093
Equatorial diameter kilometers	12,100	12,756	6794
(miles)	(7600)	(7900)	(4200)
Mass relative to Earth	0.815	1.00	0.108
Surface temperature, range	475°C (range small)	−40 to 75°C	−120 to 25°C
Proportion of sunlight reflected	71%	33%	17%
Major constituents of the atmosphere	Carbon dioxide-CO_2	Nitrogen-N_2 Oxygen-O_2	Carbon dioxide-CO_2
Weight of 68 kg object (150 lbs on Earth)	130 lbs.	150 lbs.	55 lbs.
Number of moons	None	1	2
Planet's color from space	No true color	Blue	Rusty orange
Surface atmospheric pressure in millibars	@ 90,000	@ 1000	6 to 10
Life present*	No	Yes	No

*Life as we know it is only present on Earth, according to our current level of knowledge. For other planets, the presence of life in any form is conjectural.

The rate of this last step is very slow (on the order of tens of millions of years), so vast quantities of CO_2 (or carbon) are stored in crustal material in the form of carbonate rocks and buried organics (fossil fuels, etc.). Earth thus maintains a nearly constant (low) concentration of CO_2 in the atmosphere (Table 2).

Mars' CO_2 is also believed to be largely locked up in crustal materials (Owen 1982; Zaburunov 1992). However, in the case of Mars, it is thought that CO_2 is mostly in frozen state, as polar ice caps and buried permafrost within pore spaces in surficial materials. (Frozen CO_2 is what we call "dry ice.") Some CO_2 may also be present as carbonate rock which was originally deposited in bodies of water which have long since disappeared. However, if plate tectonics ever occurred on Mars (evidence suggests it unlikely), it ceased long ago, and recycling of CO_2 back into the atmosphere from its crustal reservoirs ceased along with it. Therefore, Mars has very little atmospheric CO_2: Although it makes up 95.3% of the total atmosphere, the atmospheric pressure is so low that the absolute amount of CO_2 is very small (Table 3).

Venus is the planet so like Earth that astronomers call it Earth's sister. Venus is not only Earth's closest neighbor among the planets, but also " . . . is similar to Earth in size and weight, in its inheritance of chemical elements, and in its distance from the sun" (Weiner 1986). Its heavy, permanent cloud cover prevents observation of its surface by telescope, but before the landings by the Russian Venera probes, it was widely believed to have surface conditions and atmosphere very similar to Earth's. That perception has now dramatically changed. Weiner (1986) wrote:

Table 2. The composition of dry air in Earth's atmosphere.*

Constituent gas	Symbol	Percentage of atmosphere by volume
Nitrogen	N_2	78.08
Oxygen	O_2	20.95
Argon	Ar	0.93
Carbon dioxide	CO_2	0.03
Trace gases (including helium, hydrogen, xenon, neon, ozone, methane and dust).	He, H, Xe, Ne, O_3, CH_4	<0.01

*Modified from Owen (1982), Hamblin and Christiansen (1990), and Student Handbook (1991).

Table 3. The composition of the lower atmosphere of Mars.**

Constituent gas	Symbol	Percentage of atmosphere by volume
Carbon dioxide	CO_2	95.32
Nitrogen	N_2	2.7
Argon	Ar	1.6
Oxygen	O_2	0.13
Carbon monoxide	CO	0.07
Water*	H_2O	0.03
Trace gases including hydrogen, xenon, neon, ozone*	H, Xe, Ne, O_3*	<0.01

*Variable with season and location.
**Modified from Owen (1982), Hamblin and Christiansen (1990), and Student Handbook (1991).

Table 4. The composition of the atmosphere of Venus.*

Constituent gas	*Symbol*	*Percentage of atmosphere by volume*
Carbon dioxide	CO_2	96.5
Nitrogen	N_2	3.5
Trace gases including argon, oxygen, xenon, neon, water	Ar, O_2, Xe, Ne, H_2O	<0.01

*Modified from Owen (1982), Hamblin and Christiansen (1990), and Student Handbook (1991).

> *We know now that its clouds are not water vapor but droplets of sulfuric acid. They are racked with storms, riven by thunder and lightning, and they shed perpetual downpours of acid rain. The air beneath the cloud layer is almost all carbon dioxide. It is so soupy that the atmospheric pressure at the surface of Venus is as great as the pressure 3,000 feet beneath the Atlantic Ocean.*
>
> *The clouds never part to let a ray of sunlight touch the ground, so the surface is dusky even at noon. It is a somber desert of brown, dun, and burnt ocher, and it shimmers like tarmac on a hot day. . . [Venus is] much too hot for rain to fall; the acid rains from the clouds boil, turn to vapor, and rise again long before they reach the desert (p. 172).*

The present Venusian atmosphere is composed mainly of carbon dioxide (98% CO_2) with atmospheric pressure 90 times greater than that on Earth (Table 4). Therefore, it is believed that nearly all Venus' CO_2 resides in the atmosphere, and that little, if any, is stored in its crust (Zaburunov 1992).

As seen in Tables 3 and 4, Mars and Venus have present surface conditions which are very unlike our world, but because of data gathered from planetary probes, a group of notable scientists believes the study of other planets is essential to the understanding of planet Earth, with Mars being especially important. Chris McKay, a NASA expert on Mars, states, "The possibility that Mars was once warm and wet makes studies of the planet essential to our understanding of how our own planet came to be the oasis that it is." (Tennesen 1989, p. 84). Astronomer Carl Sagan agrees, " . . . by understanding Martian history, we may be able to practice a bit of preventative medicine back here on Earth to ensure that our planet doesn't end up looking like that dry, cold orb" (Tennesen 1989, p. 84). Even though Venus is exotic and planetary scientists know less today about Venus than they do about Mars, Kunzing (1989), quoting the planetary geologist Steve Saunders, wrote:

> *Venus is the planet most like Earth. . . Looking at Venus is like running the experiment that produced Earth a second time, under slightly different conditions. It offers an expanded view of the geologic processes that have shaped both planets* (pp. 55–56).

While we hope Sagan's description will never fit our planet, we should help our students investigate the circumstances that caused Mars and Venus to develop to their present form. Then, taking into account the environmental problems caused by modern human activity, we should ask them to consider how to prevent our actions from taking Earth along a similar developmental path.

Before the industrial revolution, humans generally lived without causing major impact on the ecosystems in which they existed. They relied mainly upon their own physical strength and the strength of animals, with only simple machines to assist in their work. Population growth was controlled by famine, climatic disasters and disease. However, with the coming of the industrial revolution, large changes occurred which are still gaining momentum. Our standard of living has improved, transportation is more efficient, communication is rapid, and medical knowledge has dramatically reduced infant mortality and lengthened life spans. These are incontrovertible benefits. What, then, is in the debit column of the balance sheet?

Atmospheres & Greenhouse Effect

Earth's atmosphere is one of three interrelated nonliving parts of the biosphere. The other two parts are the lithosphere (or solid, outer portion of earth) and the hydrosphere (or the water portion of our planet). The atmosphere is a thin layer (around 500 km or 300 miles) of colorless, odorless gases (oxygen, nitrogen and others) surrounding Earth, which we commonly call air (Table 2). It provides important protection to Earth's surface, absorbing around 50% of incoming solar radiation, especially harmful shortwave radiation in the ultraviolet range.

The atmosphere is kept in place by Earth's gravity, and grows rapidly thinner as one moves further from the surface. More than 70% of the atmosphere lies within 11 km (about 7 miles) of Earth's surface, and this lowest layer of the atmosphere, the troposphere, is where most meteorological phenomena of concern to humans (such as clouds, storms, precipitation and other weather changes) occur.

Living organisms, now including humans, have contributed to the composition of the troposphere (at least) for much of its history. Today, there is growing controversy over the effects of human-induced changes in Earth's atmosphere. While some scientists argue there is room for doubt, James Hansen, atmospheric scientist at the NASA Goddard Institute for Space Studies, in testimony before a Senate committee on June 3, 1988, stated, "The greenhouse effect has been detected and is changing our climate now" (Revkin 1988, p. 50). "Greenhouse effect" is the term given for the role of water vapor, carbon dioxide and other substances that trap heat in the lower atmosphere. For Earth (or any other planet) to stay at a constant temperature on a long-term basis, energy input and output must be balanced. Energy from the Sun (mostly visible and near infrared radiation) is absorbed by Earth's surface and then reradiated back towards space as longer wavelengths (far-infrared or heat). However, carbon dioxide, water vapor, methane and select other gases in the lower atmosphere absorb some of this outgoing far-infrared radiation, and in turn, radiate some (approximately half) of that absorbed energy back toward the surface. As a result, the total energy arriving at Earth's surface is slightly greater than the radiation from the sun alone. To balance this greater influx of energy, the surface must radiate more energy back into space, and to do so, it must radiate at a higher temperature. Thus, the overall effect of the absorption of outgoing radiation by the atmosphere is to increase the temperature of Earth's surface. This is what is called the "greenhouse effect." As long as absorption of outgoing radiation remains constant, the temperature of the surface will remain at a constant, but slightly higher level, compared to that without the greenhouse effect.

It is here that an important lesson can be learned from comparison of Earth to other planets. Astrophysicists and cosmologists tell us that the universe is about 10–15 billion years old and the planets of the solar system condensed from gas and dust of the solar nebula five or six billion years ago. The composition of planetary bodies forming from the solar nebula was determined by the temperature at which each body formed, which were controlled by the distance of each forming planet from the Sun. Venus, Earth and Mars (and incidentally, Mercury) formed in the warm area close to the Sun where mineral grains were abundant. Because these planets formed in a similar environment within the solar nebula, their overall compositions were similar. Later, release of internal gaseous constituents during volcanic activity, gravitational contraction and meteorite impacts created fundamentally similar atmospheres composed of nitrogen (N_2), water vapor (H_2O), and most importantly—carbon dioxide. Although their earliest atmospheres were probably swept away by solar wind, each planet formed its later atmosphere by the same processes of planetary outgassing, and these atmospheres should have been broadly similar in composition.

On Earth, CO_2 was historically, and still is, removed from the atmosphere as dissolved carbonic acid (H_2CO_3) in precipitation (rain and snowfall, etc.). This dissolved carbonic acid enters the oceans, which act as an enormous reservoir for CO_2. CO_2 is extracted from the water primarily by biogenic processes, during photosynthesis and as a constituent of the skeletons of organisms such as corals, foraminifera, algae, mollusks and numerous others. Some of this extracted CO_2 is then incorporated into marine sediment, either in the form of carbonate rock (mostly skeletal debris) or as buried hydrocarbons (mostly undecomposed photosynthesis products). Marine sediments thus form a second major reservoir for CO_2. During plate tectonics, old ocean floor, including marine sediment, is carried back into Earth's interior in subduction zones, where volcanic processes release some of the stored CO_2 from sediments, returning it to the atmosphere. Some of the CO_2 from volcanic processes may also represent primitive carbon, part of the continuing outgassing of Earth. The CO_2 in the atmosphere warms Earth, as described above, while removal of CO_2 into oceans and sediments regulates this process, preventing Earth from becoming too hot. This means that the oceans (which are the major immediate sink for CO_2 in the air), and the atmosphere " . . . constitute a single system that functions as an integrated chemical plant. . . " (Broecker 1983) to produce the dynamic equilibrium leading to a climate that supports life on Earth.

It is believed that on Mars, the greenhouse effect has not been significant since its early evolutionary history because Mars is (probably) too small to continue to be tectonically or volcanically active today. There is evidence that Mars was once warm enough to have running water. CO_2 was probably much more abundant in the early atmosphere of Mars, and this abundant CO_2 could have produced sufficient greenhouse warming to allow bodies of liquid water on the surface. CO_2 would have been removed from the atmosphere into these bodies of water, as on Earth, in the form of dissolved carbonic acid. This removed CO_2 was then probably stored in the crust in carbonates formed in these bodies of water by (presumably) inorganic processes. However, because of Mars' much lower (nonexistent?) rate of volcanic activity, and its lack of plate tectonics, renewal of atmospheric CO_2 was negligible. Continued removal of CO_2 from the atmosphere, combined with Mars' greater distance from the sun, led to decreasing temperatures, and freezing or eventual sublimation (production of ice directly from vapor) of all its water. This in turn would drop temperatures even lower (since water vapor is also a greenhouse gas), causing the removal of more CO_2 by formation of "dry ice" ice caps; a snowballing process which eventually led to the development of the present conditions (Table 1). Mars presently has an average surface temperature of about −53°C (−63°F). Mars shows us that as the quantity of atmospheric CO_2 on a planet decreases, the planet's surface responds with decreasing temperatures.

Like Earth, Venus exhaled substantial CO_2 into the atmosphere during its early history. However, the uptake of CO_2 into ocean sediments either never took place on Venus, or was insufficient to substantially reduce atmospheric CO_2 levels. The consequence was a runaway greenhouse effect and overheating which caused all surface water if it was ever present, to evaporate, leaving Venus' surface so hot that even metallic lead could be melted by surface temperatures which can reach 430–480°C (800–900°F) (Weiner 1986). Without liquid water on its surface, there would be no hydrological cycle which is critical for life. Living things, both plants and animals, are another major factor in the balanced cycling of Earth's atmospheric CO_2. Without oceans or living organisms to remove CO_2 from its atmosphere, Venus has probably remained hot for hundreds of millions of years.

It is important to remember that all three planets (Earth, Venus and Mars) had similar atmospheric compositions, which then evolved in a complicated feedback along with climatic changes. Now we humans are tampering with our atmosphere, and especially with the CO_2 content of the atmosphere. Geologists and climatologists have suggested that with all other factors remaining constant, increases in the level of CO_2 in Earth's atmosphere cause global warming, while decreases of its level cause global cooling.

Carbon dioxide along with water vapor, methane and several other greenhouse gases are a natural part of today's Earth atmosphere "as well as the primordial sky" (Zaburunov 1992, p. 28). Throughout geologic history, Earth owes its hospitable climate to the greenhouse effect. Today, however, rising concentrations of CO_2 and other gases (such as methane and chlorofluorocarbons) lead to an increased threat of "runaway" greenhouse effect. In this scenario, Earth's temperature rises, and the warmer air is able to hold more water vapor. As the water vapor in the atmosphere increases, Earth's temperature rises even more. (Water vapor is actually the most important of the greenhouse gases in Earth's present atmosphere.) Such a positive feedback process, which also includes releases of stored methane in permafrost regions, and other similar effects, could generate ever increasing temperatures (Schneider 1989). Comparison to other planets shows us that such conditions would be more like those on Venus and are the exact opposite of those on Mars.

Considering this possibility, it is surprising that instead of balancing CO_2 levels, we are putting more into the atmosphere, through industrial activities, burning of fossil fuels (coal, oil and natural gas) for energy, and burning of forested regions to clear farmland. CO_2 levels are 25% higher now than they were in 1860, and the atmospheric burden of greenhouse gases is expected to continue growing. According to Botkin and Keller (1987), the projected level of atmospheric carbon dioxide for the year 2000 is 380 parts per million—20% higher than the present concentration. By the middle of the next century, the resulting warming could boost the global mean temperature from two to five degrees Celsius (Revkin 1988). The effects could be devastating:

> *Weather patterns could shift, bringing drought to once fertile areas and heavy rains to fragile deserts that cannot handle them. As runoff from melting glaciers increases and warming seawater expands, sea levels could rise as much as six feet, inundating low-lying coastal areas and islands. There would be dramatic disruption of agriculture, water resources, fisheries, coastal activity, and energy use* (Revkin 1988, p. 53).

To further complicate matters, while we are increasing CO_2, we are also destroying and disturbing plant life. This activity adds to the problem (burning or decomposing vegetation releases CO_2 to the atmosphere) and at the same time eliminates the biological agents which ordinarily help maintain CO_2's atmospheric balance. We are altering plant populations by cutting and burning rain forests, reducing farm land, and disturbing the productivity of aquatic plant life (phytoplankton).

Alterations of the Biosphere

The biosphere is that part of Earth which supports life, including the atmosphere, hydrosphere and the outer portion of the lithosphere, as well as the living organisms themselves. Human activities are producing dramatic changes in the living part of the biosphere, which are leading to similarly dramatic changes in the nonliving parts of our planet's surface. For example, forested areas are being clear-cut or burned at an increasing rate. The most common reasons for cutting trees is to sell timber and paper products, to clear land for agriculture, or to fill a fuel shortage. Burning of forests is common in tropical regions, to clear the land while returning the nutrients held by the trees back into the soil. However, forests—especially the tropical rain forests—also have important global ecological roles in balancing atmospheric CO_2 and other gases. The importance of forests in the CO_2–O_2 cycle has long been recognized, as we can see from this statement by Barker (1970):

> *A major factor causing increases in carbon dioxide and other atmospheric gases is the destruction of tropical rain forests, which reduces the amount of leaf area in the tropics hence the amount of carbon dioxide absorbed. It is estimated that the cutting and burning of tropical forests contributes about 20 percent of the carbon dioxide added to the atmosphere each year* (Barker 1970, p. 5).

Recently, some effects of phytoplankton (small free-floating aquatic plants) on global warming have also been recognized. Phytoplankton (especially the diatoms and dinoflagellates) form the base of most oceanic food chains. They also "have a major role in the control mechanisms that regulate the chemistry of the ocean-atmosphere system" (Broecker 1983,

Table 5. There are three main chemical reactions that are believed to contribute to the formation of acid rain. In the 1970s, scientists discovered that sulfur dioxide and nitrogen oxides (which are emitted by power plants, factories and cars), combine with water in the atmosphere to produce sulfuric and nitric acids that fall as a component of rain and snow. It is argued that this kind of rain is what causes the acidification of many lakes and streams.

1. Water	+ Sulfur dioxide	→ Sulfurous acid
H_2O	+ SO_2	→ H_2SO_3
2. Sulfurous acid	+ Oxygen	→ Sulfuric acid
2 H_2SO_3	+ O_2	→ 2 H_2SO_4
3. Water	+ Nitrogen dioxide	→ Nitric acid + Nitrous acid
H_2O	+ 2 NO_2	→ HNO_3 + HNO_2

p. 146). Ocean plant life contributes significantly to the reduction of carbon dioxide in the atmosphere; however, phytoplankton make an even larger contribution to temperature moderation than other plants because their metabolic activity also releases dimethyl sulfide into the atmosphere. Dimethyl sulfide acts as a nucleation agent forming clouds over the oceans. Cloud cover reflects the sun's energy back into space, producing global cooling.

Unfortunately, our activities as an industrial society are having harmful effects on aquatic plant life (Broecker 1983; Andrews 1987; Earthwatching 1990). Industrial smokestacks and car exhausts continuously pump sulfur oxides and nitrogen oxides into the atmosphere. These gases interact with water vapor in the atmosphere to produce many powerful acids, including sulfuric and nitric acids (Table 5). Acid rain affects aquatic ecosystems in a variety of ways. For example, soluble organic materials called chelating agents (which include amino acids, nucleotides and hydroxy acids) form compounds with metals that are otherwise insoluble and cannot be utilized by phytoplankton. The action of chelating agents is often very pH sensitive, therefore any disturbance of ocean pH as a result of acid rain could conceivably have severe consequences on phytoplankton growth. Reduction of phytoplankton would lead to increased CO_2 and decreased ocean region cloud cover, both of which would contribute to atmospheric warming.

Another human activity that produces serious impact on the ocean plant life is the toxic petroleum which finds its way into the oceans as a result of oil spills during drilling operations at sea, during transfer of oil from ship to ship, and in major accidents such as the Exxon Valdez disaster. Oil floats on the water's surface, blocking the passage of sunlight to the plants underneath and preventing the free exchange of gases with the atmosphere above. These problems are in addition to the purely toxic effects of oil, which poisons whole food chains by being absorbed by the phytoplankton directly and by being passed on to all the organisms which eat the phytoplankton. Although events on the scale of Exxon Valdez are infrequent, the cumulative effect of the many smaller releases that happen each year could have serious consequences on phytoplankton productivity, and therefore on climate as well.

Climate & Climatic Change

Climate is the long-term (many years) average of atmospheric conditions of a particular area, including air temperature, wind speed and direction, humidity and precipitation. Unlike weather, climate is somewhat predictable, because it involves average conditions over a long period of time. However, meteorological and geological evidence indicate that both substantial climatic change and considerable periodic climatic fluctuations have occurred throughout Earth's history, over a variety of time scales.

Although Earth's atmospheric composition is very different from Mars', the two worlds share similar global atmospheric circulation patterns and therefore have some climatic features in common. There are several reasons for these similarities:

1. The two planets are heated almost entirely (more than 99%) by solar radiation.
2. Differential heating of the atmosphere (the equatorial region receives more solar radiation than the poles) creates convection within the atmosphere, leading (ideally) to north-south air flow.
3. The rotation of the two planets is almost identical (Table 4). Since Mars and Earth have similar periods of rotation, and rotate in the same direction, they share similar atmospheric flow patterns. The Coriolis effect, a phenomenon brought about by a planet's rotation, causes winds to veer from their original directions. On each world, air is deflected to the right of its original path in the northern hemisphere and to the left in the southern hemisphere, changing the ideal north-south flow caused by convection into the more familiar east-west winds (trade winds, prevailing westerlies, polar easterlies) that characterize surface winds on Earth. These three factors (among others) produce the long-term predictable conditions known as climate. Still, climate does change—sometimes even drastically—as we witness from studying the history of Mars.

The plains of Mars' northern hemisphere display many networks of riverlike channels. The presence of these channels poses a problem, since the existence of water in liquid form is incompatible with the present physical conditions at the planet's surface. . . Runoff channels resemble terrestrial

> *rivers and seem to have been formed by the slow erosion of running water* (Masson 1988, p. 138).

Mars may have been the victim of some celestial event which led to its pronounced change in climate:

> *It is not clear why the climate of Mars could have changed so dramatically that lakes or oceans of liquid water would be lost. One possibility is that a catastrophic event such as a collision with a large planetesimal could have stripped away the early, thick atmosphere, creating the low pressure that today prevents liquid water from existing on the surface* (Snow 1991, p. 260).

It is possible that Mars' climate goes through periodic changes. Haberle (1990) states, "There is good reason to believe the climate of Mars changes cyclically," with cycles "on the order of 100,000 to one million years" (p. 80). Similar cycles on Earth, called Milankovich cycles for their discoverer, are thought to be responsible for the major Ice Ages of the last 2 million years. According to Haberle (1990), the characteristics of a planet's orbit around the sun can affect climate by changing the seasonal and latitude distribution of the sun's energy. These characteristics include the tilt of the rotational axis, the direction of the axis as it precesses, and the eccentricity of the orbit. The difference between seasons is more pronounced when an increase in the obliquity [tilt] exposes the poles to more sunlight. The precession of the axis determines which season of the year the planet is at perihelion (the point of closest approach to the sun); when this occurs during summer for one hemisphere *its* seasonal differences are greater. When the eccentricity of the orbit increases, the effects of precession are more pronounced. Decreases in obliquity and eccentricity cause the opposite effect: seasons that are less pronounced.

Periods in Mars' history which feature torrential rains may be one result of Mars' orbital cycles. The channels described by Masson (1988), cited above, attest to the presence of running water on the Martian surface. However, the pattern of erosion suggests that rather than modest rivers, there were vast deluges of water, for the Martian terrain resembles, on a gigantic scale, the Scablands in southern Washington state, where there was a catastrophic flood during the last Ice Age (Weiner 1986).

Further evidence to support the theory that Mars was once flooded by water has been described recently by a team of astronomers from the United States and France. They measured the amount of deuterium in traces of water vapor in Mars' atmosphere and found it to be six times the norm on Earth, implying that a large amount of water was once there and is now gone. Deuterium, the heavier of the two naturally occurring isotopes of hydrogen, is found in water both on Earth and in space (for example in Halley's comet) in about the same ratio to ordinary hydrogen. It is believed that the deuterium ratio on Mars was originally similar. Its presence on Mars, now six times the "normal" abundance, implies that a lot of the light isotope has been removed. It is thought that this could have happened by the breakup, through photodissociation, of water molecules (containing both hydrogen and deuterium linked to oxygen) in Mars' early atmosphere, followed by the escape of the lighter hydrogen into space, leaving behind a higher proportion of the heavier deuterium (Tennesen 1989, p. 86).

Even more intriguing is a recent theory proposed by a research team headed by Victor R. Baker from the University of Arizona in Tucson. On the basis of certain features of the Martian surface, analyzed from information gathered by Viking spacecraft, Baker and his research team have suggested:

> *A variety of anomalous geomorphological features on Mars can be explained by a conceptual scheme involving episodic ocean and ice-sheet formation. The formation of valley networks early in Mars' history is evidence for a long-term hydrological cycle, which may have been associated with the existence of a persistent ocean. Cataclysmic flooding, triggered by extensive Tharsis volcanism, subsequently led to repeated ocean formation and then dissipation on the northern plains, and associated glaciation in the southern highlands until relatively late in martian history* (Baker et al. 1991, p. 589).

The suggestion that long-term, natural variations in the Martian climate may have led to such extreme differences in conditions on Mars makes it even more imperative that we examine carefully all the possible climatic outcomes stemming from human activities on Earth.

Earth may not have experienced changes at the level of those on Mars, but both periodic and long-term climatic changes have occurred. As on Mars, most of these changes are the result of occurrences in space, changes in the relationship between Earth and the sun. The so-called Little Ice Age in the 17th century and the major Ice Ages, the last of which gripped Earth as recently as 18,000 years ago, are examples. It is not completely clear what caused these climatic shifts, although the major Ice Ages seem to be controlled, at least in part, by the cyclical variations of Earth's orbit around the sun, the Milankovich cycles described above. However, the Little Ice Age, which lasted for only about 250 years, cannot be connected with these long-term variations of the orbit. Instead, it may correspond with a variation in the behavior of the sun itself.

Astronomical records for that time are sparse and incomplete, but some modern researchers believe that sunspots were almost totally absent from the sun during the period from 1645 to 1715. (Sunspots were first discovered by Galileo in the early 1600s using his invention, the telescope.) This period of time, now known as the "Maunder minimum," and a possible similar period from 1460 to 1550, called the "Sporer minimum," would have had slightly less solar activity, as the sun is known to put out more energy when sunspots are abundant and less when sunspots are scarce (Weiner 1986, pp. 244–250). This decrease in solar output would lower Earth's temperature slightly. However, it is often true that small changes can have great impact, and often lethal effects, on a local population.

During the Little Ice Age, winters averaged only about 2½°C cooler than today. Nonetheless, this time period was marked by severe winters and short growing seasons throughout much of Europe and North America. The extremes of climate may even have led to the failure of some early European colonies in North America and the abandonment of some lands in northern Europe. By comparison, the average global temperature during the Great Ice Ages was nearly 5°C cooler than today (Weiner 1986, p. 129) and the cold conditions lasted for many thousands of years. If the hypothesis linking sunspots with short-term climatic variations is correct, some researchers speculate there is a chance of another Little Ice Age within the next century (Weiner 1986, p. 257).

Desertification is another climate change which is occurring now at an increasing rate. Deserts are not static features, but expand and contract in response to subtle changes in regional climate, land use and other factors. When devastating drought gripped East Africa from 1980 to 1986, experts claimed that the people who lived in the drylands ruined their environment because they did not understand it. More recently, however:

> *French geologists have uncovered evidence that climatic changes in Africa during the past 150,000 years are closely related to natural changes in the Earth's orbit about the Sun. . . Major variations in atmospheric patterns resulted in great variations of climatic zones, especially the deserts* (El-Baz 1990, p. 42).

Nicole Petit-Marie of the Laboratory of Quaternary Geology comments, "These processes were not man-induced but wholly-natural" (El-Baz 1990, p. 43).

Earth's major deserts and semiarid regions have mostly formed as a result of global atmospheric circulation patterns. The areas near the equatorial belt are strongly heated by sunlight. Over both land and oceans, water from the surface evaporates and enters the air. As the warm, moist air rises, it decompresses and cools. Because cool air cannot hold as much moisture as warm air, the cool air releases its moisture in the form of abundant rainfall over the tropical rain forests, which form a band around the equator from 15°N to 15°S latitude. The circulation of the atmosphere then brings the air back to the surface further from the equator; the sinking air heats adiabatically due to compression, and its relative humidity drastically decreases. As this warm, dry air reaches the surface, it absorbs moisture from the surface in the areas around the Tropics of Cancer and Capricorn, where the world's great desert regions are formed.

El-Baz (1990) writes:

> *If the amount of energy falling on the Earth never changed, the belts of deserts would stay in the same place. But the Sun rotates and its output varies slightly. In addition, the distance from the Earth to the Sun varies, and the Earth's position in its orbit alters. When the planet receives the most energy from the Sun, the air becomes warmer, more water evaporates and the equatorial cloud band expands: the deserts shrink. The converse happens during years which bring less energy from the Sun, and the deserts expand* (p. 43).

On the basis of climatic theory alone, only one-third of the land would be considered desert, and it is this area which is considered by the French study cited above. However, estimates from studies of soil and vegetation suggest that 43% of the total land is actually arid, and this proportion seems also to be growing, possibly as a result of human activities (Botkin & Keller 1987, p. 286). The leading causes of human-induced desertification involve the removal of natural vegetation that keeps moisture in the soil. Specific activities include overfarming, overgrazing, the conversion of rangelands in marginal areas to croplands (rainfall is insufficient to support crops for a long time) and bad forestry practices (i.e. cutting down all the trees in an area marginal for tree growth). Agricultural activities that poison the soil through the application of persistent pesticides or other chemicals and industrial practices that involve the improper disposal of toxic materials can also expand desert conditions. Even irrigation of soils in arid lands can lead to desertification because, when the water evaporates, salt residue remains that can build to toxic levels, killing vegetation (Bagi 1983; Botkin & Keller 1987; Cherif 1988).

Although humankind can do little to affect the Earth's orbital variations, we *can* practice good soil conservation, implement the proper management of forests and grasslands, use less damaging irrigation and other agricultural practices, and reduce pollution, all in an attempt to prevent Earth from becoming a "dry orb."

The Water Supply

Water is essential to the development of life on Earth and is vital material for sustaining the livability of the planet. While water is abundant on Earth, at the present time there is a shortage of *fresh* water, at least when we refer to the needs of civilization for water to drive agricultural and industrial activity. When we examine the other terrestrial planets, we notice a total absence of liquid, surface water. While geologists and climatologists are not sure about what happened to the water Mars originally held, most of Mars' water is believed to survive in aquifers under the planet's permafrost layer (Secosky 1989, p. 29). The remainder is believed to be held in the polar caps. On Venus, the extremes of the greenhouse effect, caused by its dense carbon dioxide atmosphere, and partially abetted by water itself, led to its present high surface temperature, with all water evaporated into the atmosphere.

On Earth, while water *abundance* is not a problem, 99% of the total supply is unusable by terrestrial organisms because of salinity (sea water) or availability (ice caps or glaciers). Earth's terrestrial populations (including most of humankind) rely on the very small remainder. Despite the importance and scarcity of fresh water, humankind indiscriminately discharges untreated industrial and municipal wastes into many freshwater systems. According to Botkin and Keller (1987), this includes heavy metals, radioactive isotopes, fecal coliform bacteria, phosphorus, nitrogen, sodium, pathogenic bacteria and viruses, and a variety of even less desirable materials. Thermal pollution caused by electrical power generating facilities and other industrial users of fossil fuels for heat has also become a problem. Just as we need to look beneath the surface of Mars (probably) to find water, we are finding it increasingly necessary to rely on underground aquifers on this planet to obtain water we have not already contaminated. In fact, even uncontaminated groundwater is becoming increasingly difficult to find, especially in the U.S.

Radiation

Essentially all the energy available on the surfaces of Venus, Earth and Mars comes from the sun in the form of electromagnetic radiation. The different kinds of radiation (such as radio waves, infrared rays, visible light, ultraviolet light, X-rays) are distinguishable by their wavelengths. X-rays and ultraviolet radiation, which are especially harmful to life, have very short wavelengths and correspondingly high energy. Planetary atmospheres absorb some of the incoming radiation before it strikes a planet's surface and also absorb outgoing radiation (greenhouse effect). Since Mars has a very thin atmosphere (1⁄100th of Earth's), radiation reaches its surface (and leaves from the surface) almost completely unhindered. On the other hand, on Venus, while short wavelength radiation from the sun passes through its thick CO_2 atmosphere, almost all the long wavelength (infrared) radiation coming from the surface is absorbed by the atmosphere before it can escape to space.

Earth's atmosphere is composed almost entirely of nitrogen and oxygen. In Earth's upper atmosphere, very short wavelength radiation (ultraviolet or UVB) strikes oxygen molecules, breaking some of them apart and leading to the production of ozone molecules (O_3), which are a combination of molecular and atomic oxygen. Ozone then absorbs slightly longer wavelength radiation (also ultraviolet UVB), preventing this harmful radiation from reaching Earth's surface. Because Mars' atmosphere has almost no oxygen, ozone cannot be created, and thus the shield that protects Earth from ultraviolet radiation is not available on Mars.

Humans are polluting the atmosphere on a global scale. For the last decade there has been concern that chlorofluorocarbons (CFCs) have significantly decreased the amount of ozone in the stratosphere. CFCs are used as refrigerants, as propellants in aerosol cans, and in making foam products. In certain complex interactions between the breakdown products of CFCs and gases in the upper atmosphere, ozone production is inhibited. It was reported in the early 1980s that during October in the southern hemisphere, the quantity of ozone over the south polar region diminished. In 1986, a group of scientists spent several weeks in Antarctica to study the reported decrease, or "ozone hole." They took detailed measurements of the quantity of ozone and found that the ozone over the south polar region was 50% less than in the late 1960s during the same time of year.

According to Theodore Snow (1991):

> *The conclusion of some of the scientists involved in the study is that the ozone hole is caused by chloroflourocarbons. This conclusion is based on measurements of other molecular species, on inconsistencies in other hypotheses, and on direct measurements of freon [one of the CFCs] in the atmosphere, showing that its abundance has increased by 50 percent over the same time period that the south polar springtime ozone abundance has decreased* (pp. 194–195).

Based on very recent satellite data, in the beginning of 1992, scientists discovered that during the months of September and October, about two-thirds of the ozone that once shielded Antarctica disappeared. They also believe the ozone is disappearing from the northern hemisphere at twice the rate previously suspected, and an ozone hole may soon form over the North Polar region. If this happens, the United States' Environmental Protection Agency ". . . predicts an additional 12 million skin cancer cases and 200,000 resultant deaths in the United States over the next 50 years" (Nadis 1992, p. 83).

When Viking photographed Mars, we received images of "gently rolling red landscapes that could almost have been a desert scene in the American Southwest" (French 1986, p. 230). But, there was no sign of life. The level of ultraviolet radiation found on Mars "ruptures the very bonds of molecules in living cells on earth," (Weaver 1973, p. 256). Also, "The martian soil may contain unusual and unexpected chemicals, possibly formed by the repeated blasts of ultraviolet radiation from the sun" (French 1986, p. 234).

Ozone is our world's protective blanket. Mars serves as a "worst case" example of the price humanity will pay if our planet should lose its ozone shield.

Conclusions

How has our planet evolved? Astrophysicists believe that 15 billion years ago, all the matter in the universe was concentrated in a single spot and exploded in a "Big Bang." Out of the vast cloud that ensued, billions of stars evolved and the universe was created. Earth's evolution began some 5 or 6 billion years ago when "planets of the solar system condensed out of the same cloud of galactic gas and dust as the Sun. . . " (Vagk 1978, p. 33). Earth's oceans formed about 4.4 billion years ago, the first prokaryotic, unicellular organism emerged no later than 3.4 billion years ago, and blue-green algae appeared around 2 billion years ago. These algae utilized chlorophyll to extract energy from sunlight, and thus photosynthesis came into being, with atmospheric-free oxygen increasing over the next 1.4 billion years, as a byproduct.

Gradually, more complex unicellular organisms and later, multicellular plants developed. With the continued increase of oxygen released during photosynthesis, animal life became possible, and at least 600 million years ago, multicelled animals developed and the sea was colonized by mollusks, annelid worms, arthropods and other familiar marine invertebrate phyla. Vertebrates appeared around 400 million years ago and "achieved complete terrestrial reproduction with the reptilian evolution of the amniotic egg about three hundred million years ago" (Vagk 1978, p. 35). In this picture, humans are very much latecomers; *Homo sapiens* did not appear until some hundred *thousand* years ago. Today, there may be up to 30 million species on Earth, with *Homo sapiens* being just one (Gordon & Suzuki 1991).

Evolution of both Earth, and life upon it, was somewhat gradual in the past, and many changes probably took millions of years to complete. Human activities have altered this pattern of gradual change. David Suzuki, in his C.B.C. Radio Programme, "It's a Matter of Survival" (July, 1989), constructed a scenario of Earth in 2039, just 50 years from now. His spokespersons are scientists who are involved in writing, researching and administering environmental organizations. Their message was not "Will there be a major global climatic change?" but rather "Why aren't we doing anything about it?" Their descriptions of conditions brought about by these changes were horrific: massive flooding, desertification, drought, famine, and the spread of tropical diseases and millions of environmental refugees. Their predictions are not wildly futuristic; rather, they refer to events that can happen within decades—perhaps during our lifetime, and certainly within the life span of our children. If nothing is done to alter our current attitudes and behavior towards Earth, it is not a question of probability, but certainty.

Although the standard of living of the industrial nations is the envy of the "developing" world, the ecological price that is being paid to maintain or exceed that standard is high and is now being questioned by many scientists and other concerned people around the world. Can we continue to scar our land through indiscriminate mining and logging? How much toxic waste can we spill into the air, the oceans, lakes and streams? Surely we are not prepared to precipitate this manner of destruction as part of the Earth's natural evolution.

What if we ignore these warnings? Do we have any insight into what might happen to our planet? Could other planets have experienced the same conditions? The answer is a qualified "yes." We have as examples the planets Mars and Venus. Although each is now different (from Earth and from each other), they share similarities that give us insights into how our planet might evolve in the future. With this knowledge it is now up to us to take steps to prevent Earth from turning onto the wrong path and becoming a hostile environment to life.

Education is a vital step in utilizing this understanding. Change must take place as a result of the action of every inhabitant of planet Earth. We must commit ourselves to a definite course of action, and make changes and sacrifices in our standard of living—because the alternative is unthinkable.

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