Exploring the Solar System (V): Atmospheres and Climates

The variations in atmospheric conditions that constitute weather and climate are exceedingly transitory compared with geologic changes, but on the scale of a human lifetime they are considerably more important. Just how differently the earth's atmosphere might behave if the sun's output of heat were to drop or to drastically increase, for example, is uncertain, but some perspective on the earth's situation is beginning to emerge from studies of atmospheric phenomena on other planets. There are now four planets (Earth, Mars, Venus, and Jupiter) with substantial atmospheres that have been examined at close range by spacecraft as well as studied by means of ground-based instruments, and they reveal a considerable diversity of atmospheric phenomena.

Jupiter, for example, is exotic in that its atmosphere is heated as strongly by the planet itself as by the sun, and this internal heat source influences and perhaps controls circulation patterns that are markedly different from those of the earth. Equally different are the hothouse climate and rapid rotation of the upper atmosphere on Venus, although the planet itself hardly rotates at all. Mars, on the other hand, is meteorologically similar enough to the earth that it has already become a proving ground for testing the limits of models of terrestrial weather phenomena.

Jupiter is visually the most spectacular of the planets in its atmospheric markings. The main winds blow east and west around the planet and appear to be strongest at the equator, but vertical currents seem to account for the alternately light and dark bands that give Jupiter its striking appearance. The bright zones are thought to be high clouds (possibly ammonia crystals) created by rising currents, the darker bands features at lower altitudes where sinking motions occur. Additional data on these and other phenomena were obtained last month as Pioneer 11 swept by the planet. The spacecraft also obtained pictures of the more quiescent polar regions (Fig. 1) and the surrounding high-latitude regions where less is known about the atmospheric motions.

There is debate about the dynamics of the jovian atmosphere, particularly whether the heat given off by the planet itself or that received from the sun (recent results from Pioneer 11 suggest that the ratio of the two is about 1 to 1) is the predominant driving force. The dynamics are of interest not only to meteorologists, but to exobiologists and chemists, who are arguing the question of whether life or its chemical precursors might be found on the giant planet. Carl Sagan of Cornell University, among others, has proposed that organic molecules are present in the atmosphere and account for the colors that are observed. An alternative view is that inorganic compounds of sulfur or, as John Lewis of the Massachusetts Institute of Technology recently proposed, of phosphorus, are adequate to explain the observed colors. Whatever the correct explanation, there is only a thin horizontal slice of Jupiter's atmosphere in which temperatures are expected to be neither too hot nor too cold to support life. If convection is vigorous in this part of the atmosphere, leading to a rapid overturning and mixing of the atmosphere, then organic molecules would be quickly carried out of the favorable region and burned up or frozen, eliminating any chance for an evolutionary process that might produce more complex organic molecules and possibly life. In a more stable and quiescent atmosphere, on the other hand, organic molecules cannot so easily be ruled out.

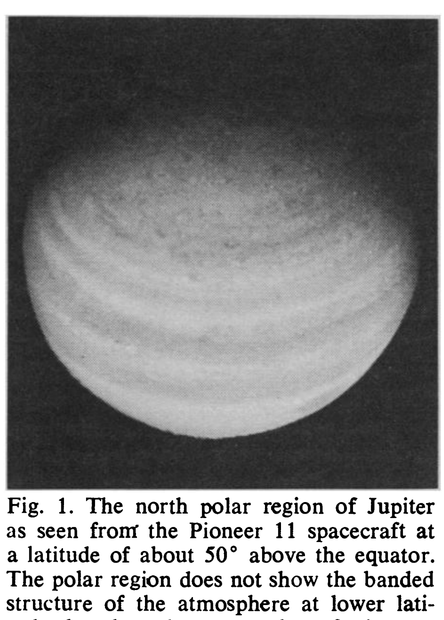

Fig. 1. The north polar region of Jupiter as seen from the Pioneer 11 spacecraft at a latitude of about 50° above the equator. The polar region does not show the banded structure of the atmosphere at lower latitudes but does show a number of what appear to be convection cells, indicative of the heating of the atmosphere from below by Jupiter itself. [Source: Ames Research Center]

The average stability is one of the properties of an atmosphere that meteorologists frequently use to characterize its dynamic behavior. On the earth, the sun's differential heating of equator and poles gives rise to eddy motions (cyclones and anticyclones) that distribute hot air above cold, resulting in a very stable atmosphere. The martian atmosphere, which is also driven by the sun's heat, is only slightly less stable. At the other extreme is the solar atmosphere itself, which is heated from below and is very unstable, giving rise to very intense convection. Jupiter is thought to be somewhere in between, either just barely stable or slightly unstable, because it is heated by both the sun and the planet, but so far there is no agreement as to the mechanisms that produce the observed flow patterns.

What is known is that atmospheric phenomena can be very long-lived on Jupiter. The bands that encircle the planet have been observed, unchanged in any major way, for many decades. The great red spot, now thought to be a large convective feature or storm in which updrafts create high, colored clouds, has persisted for an equally long time.

Whatever the dynamics of the jovian atmosphere turn out to be, it and its constituents (largely hydrogen and helium) are clearly very different from those of the earth. Not so on Venus, however, which may be an example of a runaway greenhouse climate only narrowly escaped by the earth (see Box).

The atmosphere of Venus is at least 80 percent carbon dioxide. Small amounts of water vapor and other gases have also been detected. A dense cloud bank covers the planet and has made visual observations of all but upper-atmospheric phenomena impossible. The cloud material has a refractive index that is characteristic of liquid sulfuric acid. The acid molecules have not been directly observed, but if they are indeed present they may explain the low humidity observed in the upper atmosphere, since H_2SO_4 is very hygroscopic. Other acids may also be present, including the strongest acid known, HSO_3F, according to Andrew Young of the Texas A & M University.

The Uniqueness of the Earth's Climate

The Apollo astronauts reported that the earth's blue skies and white clouds, as viewed from space, made it by far the most inviting object they could see. The growing information about other planetary bodies in the solar system tends to confirm that view. Mercury and the moon are harsh, airless, and desolate places, and Mars, with its high winds, extreme variations of temperature, and frequent dust storms, is scarcely less so. Venus, once considered the earth's sister planet, is so incredibly hot and inhospitable, with its massive atmosphere and acid clouds, as to approximate descriptions of hell. The huge outer planets, constituted largely of fluids and with crushing gravitational pulls, bear a closer resemblance to dead stars than to the earth. Their icy moons, with few exceptions, are scarcely more inviting. Thus the earth, particularly in its suitability as a habitat for life as we know it, appears to be unique in the solar system.

On closer inspection, however, many geophysical and geochemical similarities can be found between the earth and its nearest neighbors, Mars and Venus. All have similar densities and hence bulk compositions that cannot be too different. According to preliminary evidence, all three planets have undergone separation of elements to form metallic cores and lighter, silicate-rich mantles and crusts. Their surfaces are topographically rough. Evidence of volcanism and crustal deformation are present on Mars and the earth and are expected on Venus. All have atmospheres which appear to have had a similar volcanic origin and roughly comparable initial constituents.

What then differentiates the earth from its neighboring planets and gives it a climate that is relatively benign? According to planetary scientists, there appear to be three main factors—the presence of liquid water, the presence of life and, to a lesser extent, the presence of a massive moon.

The role of liquid water on the earth's surface was crucial for the composition of the atmosphere, the moderate surface temperatures and, probably, the origin of

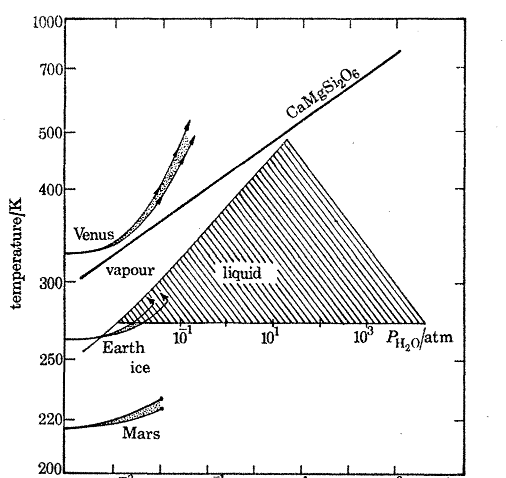

Fig. 1. The increase in surface temperature on Venus, Mars, and the earth that would have occurred in an evolving atmosphere of four parts H_2O and one part CO_2. The region in which water can exist as liquid is shown by the hatched area. [Adapted from S. I. Rasool, NASA Headquarters, Washington, D.C.]

life. Water could have existed as a liquid only on the earth, and not on Mars or Venus, under the conditions thought to have prevailed when their atmospheres were first formed. The reason is to be found in the relative distances of the planets from the sun's warmth. Radiative equilibrium temperatures in an evolving atmosphere of carbon dioxide and water vapor are such that ice is the stable phase on Mars, while Venus is so hot that all water remains as water vapor. On the earth water not only ended up as a liquid (Fig. 1) but, because carbon dioxide is chemically unstable in the presence of liquid water, helped to remove another atmospheric constituent. Most of the carbon dioxide on the earth is now locked up in the surface rocks. Water vapor and carbon dioxide both absorb infrared radiation strongly and hence, as major constituents of an atmosphere, could generate a powerful greenhouse effect and raise surface temperatures sharply—an evolutionary course that was narrowly avoided on the earth. (By one estimate, displacement of the earth as little as 6 million miles closer to the sun would have resulted in a runaway greenhouse, leading to a climate similar to that of Venus.) And water was, in all probability, the medium in which life evolved in its early stages.

Life itself has been a major cause of the differences between the earth and its neighbors. Oxygen, a chemically reactive element that would normally be combined with other elements, is found on the earth in its free state because of the continuing photosynthetic action of green plants and some bacteria. With oxygen as a major constituent, the earth's atmosphere has a number of nonequilibrium processes, including those which lead to the establishment of the ozone layer that screens the earth's surface from the full intensity of the sun's ultraviolet radiation. Free oxygen also makes possible a variety of chemical processes on the earth's surface, such as combustion and its biochemical equivalent in metabolism.

Finally, only the earth of the inner planets has a massive satellite, which may account for the planet's relative climatic stability and, possibly, for its strong magnetic field. On Mars, large oscillations in the obliquity or tilt of the planet's axis are thought by some to lead to gross changes in the martian climate. The oscillations are due to an interaction between two dynamic phenomena —the precession of the equinox as the tilted axis describes a conical motion and the precession of the planet's orbit plane as the entire orbit wobbles in and out of alignment with the rest of the solar system. The earth's obliquity changes very little, at present, because the presence of the moon shortens the equinoctial precession period, precluding a resonant interaction with the orbit plane precession. Without the moon, however, the earth's obliquity would oscillate even more than that of Mars, leading to far greater climatic instability than we presently experience and endangering the course of biological evolution. And at least one theory of the earth's magnetic field, which is much stronger than those of Mars and Venus and which screens the earth from the solar wind particles ejected by the sun, depends on the dynamic influence of the moon's presence.—A.L.H.

The Mariner 10 spacecraft observed low-contrast ultraviolet markings on Venus. These resemble terrestrial clouds, but, unlike Jupiter's markings, they do not appear to be correlated with any other atmospheric features and their origin is still a mystery.

Motions in the venusian atmosphere are thought to be driven by the sun's heat, but the mass of the atmosphere is such (100 times that of the earth's atmosphere) that there appear to be two distinct regimes. In the deeper atmosphere it is the differential heating between equator and poles that is thought to drive the circulation, and winds are expected to be relatively weak. Sunlight reaching the surface of the planet would be reradiated as infrared radiation, which is absorbed readily by carbon dioxide, trapping the sun's heat near the surface. If this greenhouse effect is strong enough, and it is the favored explanation for the high surface temperatures observed on Venus then models which postulate gentle rising motions at the planet's equator and sinking motions near the poles (known as a Hadley cell) can account for all the observations, according to Peter Stone of the Massachusetts Institute of Technololgy. The circulation is so efficient in distributing the sun's heat that there are almost no horizontal variations in temperature within the deep atmosphere, in contrast to the situation on the earth and Mars.

The upper atmosphere is more complicated. Diurnal effects (temperature contrasts between day and night) are thought to play a role in driving winds that are observed to be as strong as 100 meters per second. Several explanations have been advanced for these winds, which circle Venus from east to west with a period of about 4 days. The most popular are various versions of the moving flame model, so-called because a flame moving in a circular path under a pan of fluid will induce it to circulate in the opposite direction. On Venus the motion of the subsolar point, where the sun's heating is the strongest, is thought to have a roughly similar effect, but detailed models of the process have proved difficult to work out. Solar tidal forces and a Hadley cell in the upper atmosphere have also been proposed as the driving mechanism. The question of what drives the upper atmospheric winds is thus still open.

Like Venus, Mars also has an atmosphere composed primarily of carbon dioxide, but in other respects its meteorology is more earthlike. There is also a wealth of data on Mars, providing atmospheric scientists with a chance to test terrestrial concepts in a different, but analogous context. Compared to the earth, Mars has a much thinner and dryer atmosphere, temperatures are more extreme, and huge topographic contrasts on the planet's surface have a larger effect on weather patterns. Mars lacks oceans, which have a moderating effect on the climate on the earth, and the martian surface is rocky and covered in many regions with dust. On occasions such as the planet-wide dust storm observed by Mariner 9, the dust can become air-borne, greatly altering weather conditions. Because the atmosphere can condense out on the polar caps, Mars may also provide an example of climate instability and climate change on a scale far more drastic than anything in the earth's recent geological history.

Terrestrial Weather on Mars

There have been no direct measurements of wind velocities on Mars, but a variety of indirect measurements and calculations based on numerical models have given planetary scientists a reasonably good idea of the main circulation patterns. The driving force is the sun's unequal heating of equatorial and polar regions, which seems to generate atmospheric waves and cyclonic and anticyclonic eddy motions like those on the earth. Indeed, cloud patterns indicative of fronts, cyclonic storms, and a wide range of terrestrial weather phenomena have been observed in the winter hemisphere. The circulation pattern displays a lack of symmetry about the equator that contrasts strongly with Venus and Jupiter but is characteristic of the earth.

The process of applying to Mars the atmospheric theories developed for the earth is leading to the discovery of new phenomena. Tidal winds, for example, are not a particularly exciting subject on the earth—large effects occur only at altitudes of 80 to 90 kilometers, where they seem to have little impact on the atmosphere as a whole. But when Richard Zurick, now at the National Center for Atmospheric Research in Colorado, calculated tidal winds on Mars, he found velocities at 40 kilometers large enough to promote substantial mixing of the atmosphere. This may explain what has been a puzzle, how carbon monoxide produced by the dissociation of carbon dioxide at altitudes above 30 kilometers could be transported to lower altitudes, where it can recombine to form carbon dioxide. That some kind of mixing or transport is occurring is known because no buildup of carbon monoxide has been detected in the upper martian atmosphere, but tidal oscillations have not generally been supposed capable of transporting molecular species to a significant degree.

The debate over whether Mars has experienced great climate changes in the past has not come to any resolution. Atmospheric scientists and students of celestial mechanics have pointed out a number of ways in which a reservoir of carbon dioxide in the polar caps, if it exists, could and most probably would be evaporated every 100,000 years, leading to a more massive atmosphere, to a warmer climate, and possibly to the presence of liquid water on the martian surface. Some geologists point to the channels visible on the surface as evidence that this sequence has in fact occurred many times. Others disagree, claiming that there is no geologically recent evidence of the erosion that a more massive atmosphere and water would be expected to cause. At root is the unanswered question of how much carbon dioxide the polar caps actually contain. One of the side benefits of the debate, however, has been that a variety of simple climate models developed for the earth have also been found useful on Mars, strengthening the belief that the two atmospheres are dynamically similar in many respects.

Another example of the applicability to other planets of meteorological understanding developed on earth concerns hurricanes, the great storms of the earth's tropics. Models of hurricanes have been adapted to explain the dynamics of the great dust storm on Mars by Peter Gierasch of Cornell and Richard Goody of Harvard. The interesting twist of their model is that airborne dust, which can absorb the sun's radiation and warm the atmosphere, plays the role of water vapor in an earthly storm. The great red spot on Jupiter, it now appears, may also be similar to a hurricane, although the comparison is more speculative.

Understanding of atmospheric phenomena is far from complete, even on earth. But the study of the atmospheres of other planets would appear to be ready to contribute to knowledge of the physics and chemistry behind weather and climate on earth.

—ALLEN L. HAMMOND