Comparative Planetology and the Atmosphere of Earth

A Report to the Solar System Exploration Division
National Aeronautics and Space Administration

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Following their spacecraft's translunar injection, the crew of Apollo 11 in 1969 photographed this view of Earth showing clouds over water.

Preface

Curiosity – the human desire to ask questions and to work hard at trying to find answers – is often cited as the main reason for exploring the planets of the solar system. Over the past 30 years, spacecraft reconnaissance of most of the planets has provided a great deal of stimulation, both to a very active community of planetary scientists, and to the much wider audience who follows the discoveries in the print and broadcast media.

By becoming familiar with new places in the solar system, we have grown to view the Earth from a different perspective. "Comparative Planetology and the Atmosphere of Earth" is an attempt to assess one aspect of this changing perspective; it is a collection of specific answers to the question: "How have studies of the other planets of the solar system helped us better understand the atmosphere of Earth?"

In the process of assembling this report, some new insights have been gained. During the eight years since the effort began, many of the original sections required revision, an observation that suggests a way to measure the recent progress of planetary science itself. A fundamental reassessment of our view of *atmospheric scaling laws* has taken place, reflecting an increased appreciation of the role played by smaller scale waves, eddies, and non-linearities in *global* dynamical processes. Discussions of climate history and evolution emphasize the newly discovered connections between geochemical cycles, stratigraphy, and climate. Several sections of this report include examples of how the newly acquired Voyager data from the outer planets extend the range of planetary environments that we are in a position to compare.

As might be expected when taking the broad overview of a subject, the report also points out gaps in both the planetary data set and the theoretical framework. Among the observational limitations are the lack of adequate time-series information about the physical state of planetary atmospheres and the paucity of chemical and stratigraphic analyses of surface rocks on Mars and Venus. Having looked carefully at what has been learned, we can hope that the experiments and theoretical work needed to fill in some of these gaps are part of the near future for planetary science.

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Pasadena, California
November 1989

Introduction

Soon after NASA developed the capability to launch payloads into space, the United States began exploring the other planets of the solar system. The first spacecraft data from another planet were returned by Mariner 2, which flew past Venus in 1962. Since then, NASA missions have collected scientific data from Mercury, Mars, Jupiter, Saturn, Uranus, and Neptune.

The main goal of this planetary exploration is to probe the nature and evolution of the planets and their atmospheres. However, the study of data from other planets can also be of value in improving our understanding of the atmosphere of Earth. Although direct measurement of the terrestrial environment is generally easier and less expensive, examination of the other planets, in certain instances, offers unique insights into atmospheric processes of Earth. Examples of these instances fall roughly into four categories: (1) Comparative Planetology, (2) Subtle Earth Effects, (3) Data Available Only from Other Planets, and (4) New Ideas.

1. Comparative Planetology

Every aspect of a planetary atmosphere that can be measured can also be compared with the corresponding characteristics of the atmosphere of every other planet, including Earth. **Discovering how planetary atmospheres are similar, and how they are different, allows scientists to test their understanding of the processes that shape these environments.**

Sometimes new observations confirm the predictions of existing models, providing confidence in the current interpretations. Often a surprising result will emerge, which stimulates thought that leads to new insights. In other cases, comparisons have **expanded our appreciation of the Earth itself by placing specific attributes of our planet into a larger context.** The familiar characteristics of the Earth's environment result from the actions of the same set of physical processes that have operated to varying degrees on other planets and at other times in history, producing the entire solar system, and possibly other solar systems.

2. Subtle Earth Effects

We care a great deal about subtle phenomena that can affect conditions on Earth. Terrestrial investigations are often designed to probe at least second- and third-order questions about the Earth's atmosphere, whereas planetary experiments usually address only the less detailed, first-order issues. However, some **subtle effects in the Earth's atmosphere are of much greater physical importance in the atmospheres of other planets** (e.g., the dramatic effect that the strength and rotation rate of Jupiter's magnetic field has on particles in the Jovian upper atmosphere, as compared to the same elements on Earth), and may be studied to advantage using planetary observations.

3. Data Available Only from Other Planets

Spacecraft have measured planetary environments that are similar to those found on Earth. In a few cases, because of special preservation or other unique conditions, the planetary data are **of comparable or higher quality than can be found in the terrestrial data set.** This situation is particularly applicable to the record of earlier times in solar system history. For these cases, the study of planetary data can contribute directly to our knowledge of the terrestrial atmosphere, and the findings of such investigations can be used to help design more specific probing of the Earth's environment. In addition, techniques developed to analyze data from planetary experiments are sometimes applied to terrestrial remote-sensing measurements.

4. New Ideas

One advantage to studying the exotic atmospheres of other planets is that, since they are similar to the Earth's atmosphere in some basic ways, examining these systems can provide **inspiration leading to new insights** into the behavior of the atmosphere of Earth.

A Collection of Examples

The scope of this project has been restricted to examples of ways in which studying the planets has contributed to our knowledge and understanding of Earth's atmosphere. In general, gaining new insight into the behavior of the atmosphere of Earth is a secondary reason for exploring the other planets of our solar system. This particular benefit of planetary exploration is a difficult one to quantify, and it is sometimes overlooked; we know vastly more about the Earth, and much of what we learn about the other planets comes through the application of terrestrial experience. This understanding actually flows in both directions.

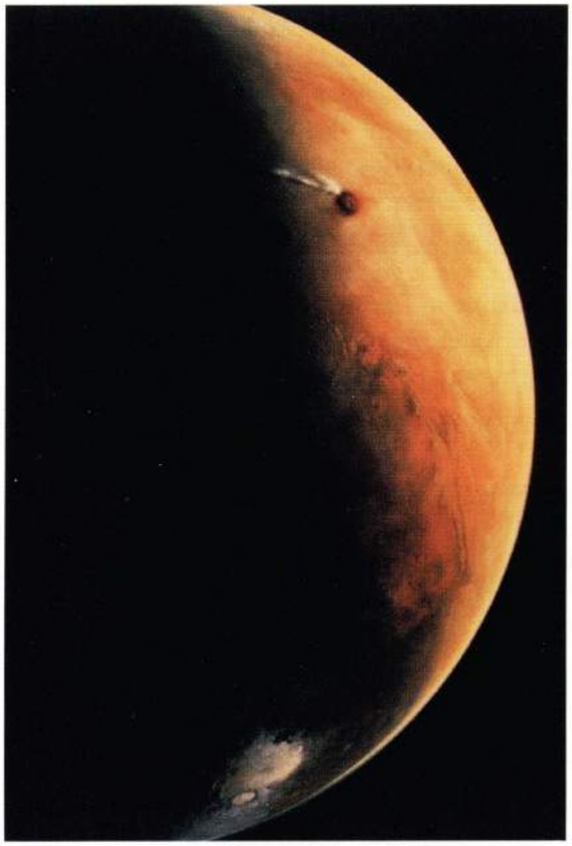
The examples presented in this report have been provided by members of the scientific community, whose help and encouragement are gratefully acknowledged [1]. The author, however, bears all responsibility for the shortcomings of the report. In particular, no attempt has been made to present a complete list of examples or a complete bibliography for the examples given.

1. Comparative Planetology

This section covers examples of comparisons that have been made among several objects of the solar system. The examples are drawn from many scientific disciplines, such as chemistry, physics, and geology. The cases selected show how comparative planetology can place the operation of physical processes that control each planetary environment into a more general context.

1.1 Evolution and Chemistry

a. Secondary Atmospheres



The dawn side of Mars, as captured by Viking Orbiter 2's camera in August 1976. Ascraeus Mons, one of the giant Martian volcanoes, appears at the top with water ice cloud plumes on its western flank; Valles Marineris, the great canyon, is across the middle; and Argyre, a large basin, is toward the south polar region near the bottom of the image.

Noble gases (helium, neon, argon, krypton, and xenon) are chemically inert in the atmospheres of planets and therefore are not likely to be lost by chemical reactions with surface rocks or other atmospheric gases. The heavier noble gases are unlikely to escape from the top of the atmosphere into space. These observations mean that present atmospheric concentrations of noble gases may preserve some information about the early history of atmospheres.

The ratios of abundances of noble gases in the atmospheres of the inner planets suggest that these atmospheres are composed mainly of gases that escaped from rocky planetary material after the planets formed, rather than being unprocessed remnants of the original solar nebula gas. Comparison of the noble gas ratios among Mars, Venus, Earth, meteorites, and the Sun and solar wind shows a strong connection between the atmospheric noble gas inventories of all the rocky bodies of the solar system and those gases retained by certain meteorites. A different ratio of gases is characteristic of solar sources. On Venus, currently, there seems to be a mixture of noble gases derived from both *solar* and *planetary* sources [2].

Information obtained by looking at isotopic variations within the noble gas inventories from several planetary sources provides additional constraints on the accretion process and the evolution of atmospheric composition [3].

b. Planetary Water

Theories of the way in which the Earth and other planets acquired water predict that Venus could at one time have held an amount of water comparable to the water present on Earth. Today, the atmosphere of Venus is very dry. Water from Venus may be lost by photolysis of water molecules, escape of hydrogen, and retention of oxygen in the surface rocks. The heavier isotope of hydrogen, deuterium, does not escape as efficiently as the lighter hydrogen isotope. The deuterium to hydrogen isotopic ratio measured by the Pioneer Venus spacecraft is about 100 times larger than that for Earth [4]. This difference suggests that Venus may have lost a good deal of water over its history; the planet may once have had a much larger inventory, as is required by one group of theories that attempts to explain how the objects of the inner solar system acquired their major volatile reservoirs.

Other theories raise the possibility that both the existing water and the observed deuterium enrichment in the atmosphere of Venus were caused by a steady influx of comets over the lifetime of the solar system [5]. Resolution of these conflicting ideas will require a more detailed examination of the amount of water in the atmosphere of Venus and of the number of comets that actually collide with the inner planets. The latter question, in turn, has obvious relevance to our assessment of the importance of comets as carriers of volatiles to the Earth.

Deuterium is also enriched on Mars relative to Earth. On Mars, the high ratio of deuterium to hydrogen in atmospheric water vapor may require a dense, warm, moist atmosphere in the planet's early history [6].

c. Carbon Cycles

Most of the Earth's carbon is stored in carbonate rocks (limestone); only a trace amount of carbon appears in the atmosphere, in the form of CO_2. Venus' atmosphere is 90 times more massive than that of Earth, and is composed almost entirely of CO_2. Mars has an intermediate amount of CO_2, several tens of times as much as in the atmosphere of Earth. The differences in these carbon reservoirs apparently have to do with water, which is rare on Venus, is common on Earth, and may be common but is frozen on the surface of Mars.

Liquid water allows the formation of carbonate ions, which can react with calcium and magnesium ions to precipitate carbonate rocks. Therefore, CO_2 can be removed efficiently from the atmosphere of Earth, where liquid water is present, but not on Venus. On Mars, special conditions may be required to make liquid water. Conditions on Mars may once have allowed liquid water to form on the surface. Once the atmosphere of Mars became too thin and cold, water may no longer have occurred as a liquid, and the amount of atmospheric CO_2 would have stuck at an intermediate value [7]. Geological activity, which in recent times has been much greater on Earth than on Mars, can play an important role in keeping the carbon cycle active on wet planets.

Differences in the operation of the carbon cycles may explain the climatic differences of the inner planets: warm conditions on Venus, temperate environment on Earth, and cold climate on Mars [8].

d. Nitrogen Cycles and the Role of Biogeochemistry

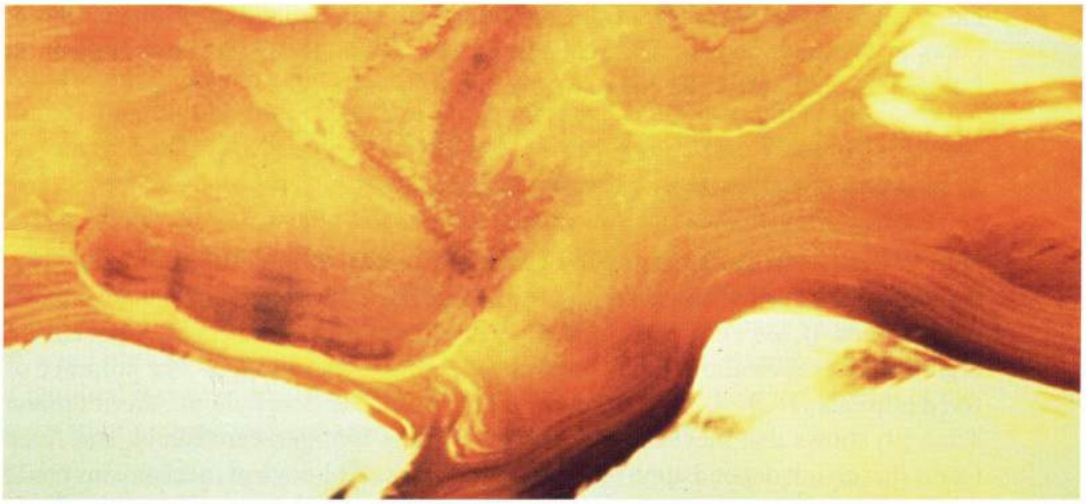
Nitrogen exists in the atmosphere of Earth primarily as molecular nitrogen (N_2). Biological organisms, however, require chemical forms of nitrogen that are bonded to hydrogen (*fixed* nitrogen, such as nitrates) for their existence. Specialized organisms living on Earth today break the N_2 bond to fix nitrogen. The presence of fixed nitrogen (HCN, C_2N_2, and others) in the N_2-rich atmosphere of Saturn's moon Titan [9] shows that mechanisms exist for cycling nitrogen between N_2 and fixed forms that do not depend upon biological processes. Abiological mechanisms could have been operating on Earth at the time of the origin of life. However, biology does play a unique role in shaping the Earth's atmosphere, as is illustrated by abundant free atmospheric oxygen, which is not present in other planetary atmospheres.

2.1 Climate and Atmospheric Dynamics

a. Theories of Climate Change

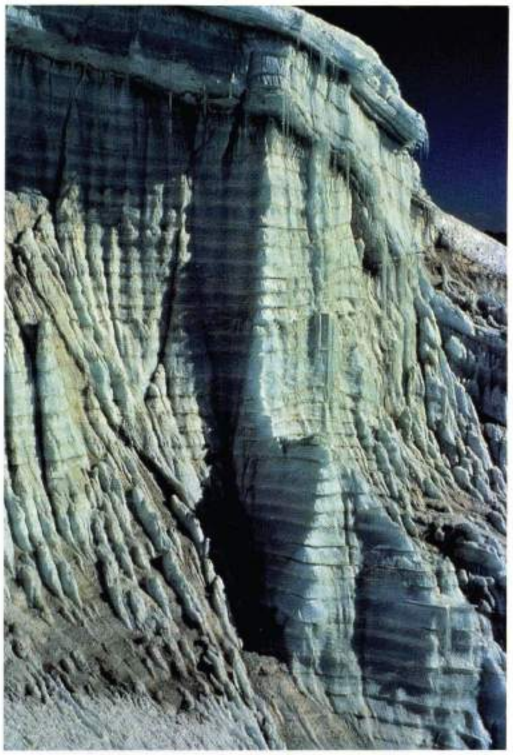
Overwhelming geologic evidence indicates that the climate of Earth has changed through history. However, identifying the causes of these changes is proving very

Although the atmosphere of Mars today is too cold for water to exist in liquid form, the presence of old river channels suggests that an earlier temperate climate may have allowed liquid water to flow on the planet. In this Viking photomosaic, part of the channel system at the mouth of Ares Vallis and near the southern boundary of Chryse Planitia in the northern subtropics shows channel segments and teardrop-shaped islands. Flow was from the south, as indicated by elongation of the islands. Similar patterns are found on Earth, particularly in areas of catastrophic flooding.



Evidence for periodic climate variations on two solar system bodies.

Periodic climate change on Mars is suggested by the existence of layered deposits at the poles, as seen in this Viking Orbiter photo of the north polar region (above). Periodic changes in the planet's orbit may produce climate variations that are expressed as layers. Similar mechanisms may also play a key role in regulating the ice ages of Earth.



Stratigraphic layering is also seen in the annual ice bands of the Andes Glacier in Peru, South America, Earth (right).

difficult. Evidence of climate changes on other planets may provide insight into the processes that operate on Earth. By comparing planets, a basic distinction may be made between (1) exogenic causes of climate change, such as variations in solar output or the density of interplanetary dust, and (2) endogenic mechanisms, such as dust loading from volcanic sources, and tectonically driven changes in surface properties or atmospheric composition. If a cause is exogenic, it can influence the climate on more than one planet at a time.

Mars is particularly fertile ground for this type of comparison. Surveillance of the planet by Mariner 9 and Viking spacecraft suggests that both periodic and secular climate change has occurred on Mars. The spacecraft images reveal extensive systems of channel features and gullies, raising the possibility of flowing water in a past era on the currently dry surface. Old, thick debris deposits at equatorial and south polar latitudes suggest a denser atmosphere early in the planet's history, as do some chemical attributes of the atmosphere and surface. The more extreme case of Mars, which is farther from the Sun, may shed light on the question of how the Earth maintained a warm atmosphere early in its history, when the Sun was less luminous than it is today.

Layered deposits in the polar regions of Mars probably indicate periodic climate variation, at least during the past few hundred million years [10]. This systematic layering phenomenon might be expected if periodic variations in Mars' orbital elements are responsible for climate changes. For Mars, primary periodic oscillations in the planetary orbit take place on time scales of 10^5 to a few times 10^6 years. The popular *Milankovitch theory* of ice ages for Earth is based upon subtle changes in the Earth's orbital elements [11].

As better observations of the stratigraphy of Mars are made, more detailed, quantitative comparisons with Earth will become possible. Use of the available lunar core samples for stratigraphic work, particularly to monitor changes in solar output or interplanetary dust, is hampered by the severe mixing of the soil (called *gardening*) produced by meteor impacts. Mapping the surface of Venus by the Magellan mission could open another world to stratigraphic investigations that may add to the record of climate change in the inner solar system.

b. The General Theory of Atmospheric Motions

The planets provide a wide range of conditions under which to observe large-scale fluid motions. Some basic parameters that vary greatly among the planets are: rotation rate, solar heating, tilt of axis, atmospheric surface pressure, internal heating, radiative time constant, and surface boundary conditions. A desire to connect the values of these basic parameters with the characteristics of atmospheric motions, energy, and momentum fluxes under the range of observed circumstances led to initial work on radiative and dynamical scaling laws [12].

Recognition of the importance of non-linear effects and smaller-scale waves and eddies in shaping the large-scale atmospheric circulation has been the focus of recent work. This insight has greatly complicated efforts to produce a general theory, and has given numerical modeling a preeminent function in this field. Planetary examples provide important tests of these ideas.

Rotation rate appears to be a major factor determining the poleward extent of the low-latitude *Hadley* circulation, the nature of atmospheric jet streams, and the behavior of baroclinic eddies in the mid-latitudes. Very extensive Hadley cells are found on slowly rotating Venus and Titan, whereas flows on rapidly rotating Jupiter and Saturn are more zonally confined (narrower). Mars and Earth are intermediate cases. The more extensive Hadley cells are associated with smaller pole-to-equator temperature gradients and less active eddy regimes [13].

The vertical temperature structure and global circulation of an atmosphere are interrelated; both are affected by the way in which external energy is deposited in the atmosphere. Dust, condensation processes, eddies, and axial tilt all contribute to determining the atmospheric energy deposition. The influence of dust on the large-scale atmospheric circulation on Mars [14], and of condensation processes on Jupiter and Titan, has received attention, as has the effect of eddy fluxes on the thermal stability for Mars [15], Venus [16], and Jupiter [17]. The axial tilt of Uranus, which has its pole sometimes pointing directly at the Sun, does not seem to affect the circulation as dramatically as early scaling laws would have predicted [18].

The transfer of momentum and heat into the atmosphere from the lower boundary is another external condition affecting atmospheric motions. The influence of a fluid boundary (atmosphere-ocean), as opposed to a solid one (atmosphere-land surface), has been compared to the fluid boundary between the upper and lower atmosphere of Jupiter [19]. In addition, the effect of heat transferred from the interiors of the Jovian planets upon atmospheric thermal structure, which in some ways is analogous to the seasonal exchange of heat between the Earth's oceans and atmosphere, has been investigated [20].

This mosaic of Viking Orbiter images of the southern hemisphere of Mars was taken very near the beginning of the southern summer. The south polar cap, a circular feature centered along the lower portion of the mosaic, is giving off carbon dioxide gas as it sublimes. Winds produced in part by the motion of this gas kick up dust, creating dust clouds along the cap edge. Especially well-defined dust clouds are seen at 10 o'clock and 2 o'clock. Dust storms were also formed that day by local heating and regional winds in the southern subtropics. Several such clouds occur at the top center of the mosaic.

A new synthesis of the relationships between measured physical parameters and the global circulation of planetary atmospheres has yet to be accomplished. Such relationships would be particularly useful for understanding climatic conditions on Earth in the past, and for anticipating climate variations as external parameters continue to change. Comparisons among the planets are playing a key role in the development of this field.

c. *Wave-Mean Flow Interactions*

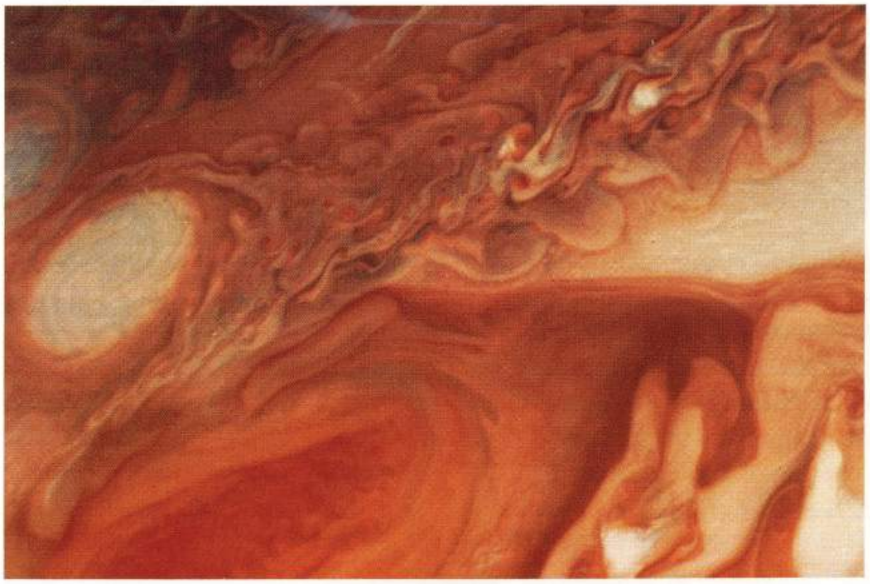
Eddies and other waves transport heat and momentum in the atmosphere of Earth, affecting the larger-scale circulation and temperature structure. Comparisons of the wave patterns with those of other planets are proving very instructive in a number of specific cases. For example, baroclinic waves, which are associated with typical mid-latitude storm systems, are responsible for a major part of the energy flux from low to high latitudes on Earth, particularly in winter. Baroclinic waves seem to serve a similar function on Mars, in an atmosphere 100 times thinner [21].

Heat and zonal momentum carried by planetary scale eddies from the troposphere also play a significant role in setting the distribution of temperatures in the Earth's stratosphere. The *quasi-biennial oscillation* is a well-known illustration of this process [22]; the *sudden stratospheric warming* is another. Analogous processes seem to occur in other planetary atmospheres. For example, multi-year variability in the equatorial winds of Venus has been observed; this phenomenon appears to be in certain ways similar to the quasi-biennial oscillation. The Venus data have stimulated new work on the factors that control several types of waves that can transport and deposit energy in atmospheric environments [23]. Polar heating during Martian global dust storms resembles the sudden stratospheric events on Earth; the analogy may shed some light on the sensitivity of the suspected energy transport processes involved to atmospheric conditions [24].

Fluid motions, called *gravity waves*, breaking at great altitudes, may provide the friction that induces the thermally indirect meridional circulation, which produces a cold summer pole at the mesopause of Earth. A similar source of friction that could also be induced by vertically propagating waves appears to be present in the stratosphere of Jupiter [25]. The behavior of gravity waves has further been invoked to explain characteristics of the flow in the upper atmosphere of Venus [26].

For Earth, only about 10^{-3} of all atmospheric energy flows can arise from transfer of eddy kinetic energy to zonal kinetic energy; on Jupiter, the transfer of energy from eddy to the zonal jets appears to be 100 times more efficient [27]. Although questions have been raised about the coverage of the Voyager data used to make the initial observations, further comparison of these very different cases can shed light on how wave-mean flow interactions operate, and will help in efforts to parameterize eddy energy fluxes in general climate models [28].

Atmospheric vortex activity on Jupiter and Earth.



A view from Voyager I (above): Jupiter's Great Red Spot, and beneath it, one of the planet's white ovals, both of which are anticyclonic vortices in the planet's atmosphere. A perspective image of Earth's Hurricane Diana (below), a cyclonic storm, as it approached North Carolina's coast in September 1984.

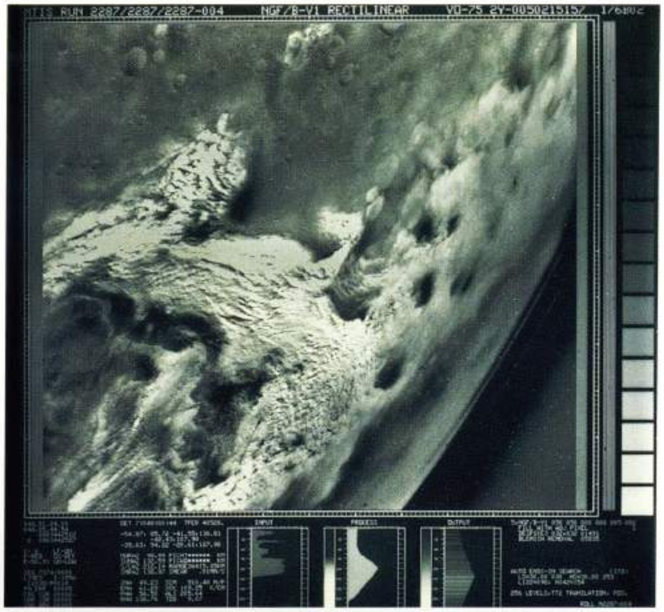
d. Atmospheric Storms

Several detailed characteristics of storms on Jupiter can be compared with those of Earth. Jovian storm-like features such as the Great Red Spot occur in the absence of a phase boundary, unlike terrestrial hurricanes, for example, which require the presence of the air-sea interface. Equatorial plumes on Jupiter may be examples of *wave-conditional instability of the second kind* (called wave-CISK), an instability thought to be responsible for tropical easterly waves over Africa and the 40- to 50-day oscillation over the Pacific Ocean [29]. The study of these features can improve our understanding of the range of conditions leading to storm genesis.

The stability of Jovian storms, which last for a very long time compared to the period of rotation around the storm center, could also provide useful ideas regarding long-lived Earth atmospheric mesoscale phenomena (e.g., *blocking*). The variation of storm size with latitude on Jupiter, and the number of storms of different sizes, might provide an interesting context for viewing the distribution of length scales of storms on Earth [30].

e. The Climatic Effects of Aerosols

Generally, the effect of dust on temperatures in the atmosphere of Earth is greatly overshadowed by the contribution of the latent heat of water vapor. The current global mean temperature of Earth is estimated to be only 2 to 3 degrees C cooler than it would be in the absence of aerosols. There is much less water vapor in the lower atmosphere of Mars than in the troposphere of Earth. Dust effects dominate, dust storms occur on a global scale, and the thermal stability of the atmosphere is controlled by the way dust absorbs solar radiation [31].

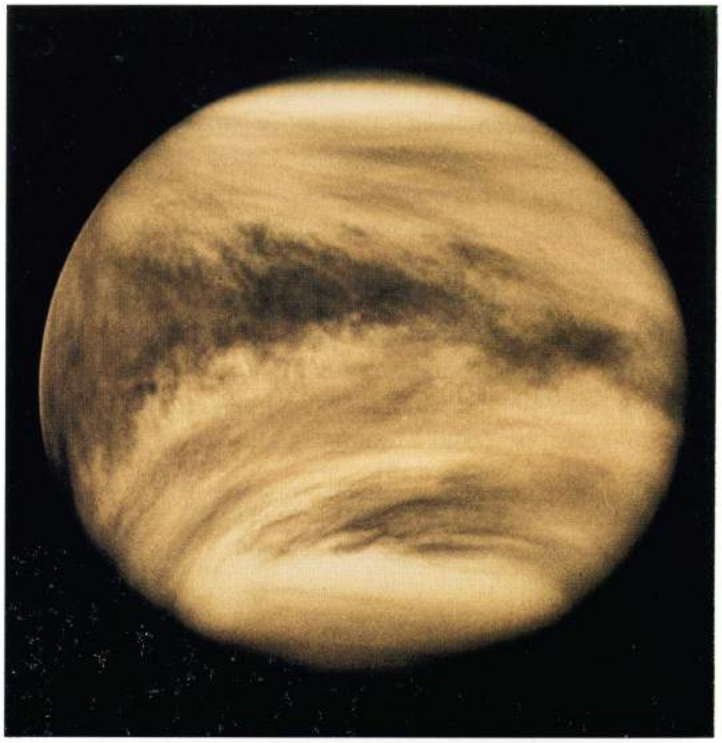


Dust in planetary atmospheres: A massive dust cloud represents the start of a Martian global dust storm as seen by Viking Orbiter 2 (above); the volcanic dust ejected by the eruption of Mount St. Helens in 1980 had a cooling effect on Earth's regional climate (below).

Dust becomes significant on Earth when volcanic eruptions occur, and it may have played a role in climate changes of the past. For example, atmospheric dust loading increased by an order of magnitude during the Last Glacial Maximum, according to the Antarctic ice core records. Glacial periods are associated with changes in the mean global temperature on the order of 5 degrees C. The increase in atmospheric dust could have caused an additional net global mean cooling of 2 to 3 degrees C, making a substantial contribution to the Ice Age climate [32].

As another example of the possible historical importance of aerosols, a large meteor may have struck the Earth and injected dust into the atmosphere. Several lines of inquiry suggest that a meteor impact may have, in this way, contributed to the extinctions of many living species on Earth at the end of the Cretaceous period [33].

Observations of the spread of Martian dust storms and the effect of dust on the Martian atmosphere were among the factors that led to the 1984 discussion of the *Nuclear Winter* phenomenon by a group of planetary scientists [34]. These researchers argued that fires ignited by a nuclear war could inject large amounts of dust into the Earth's atmosphere, cooling the surface, and possibly creating a climate crisis. The idea that smoke would quickly spread globally was first demonstrated by applying Martian dynamical modeling to Earth [35].



Dense, sulfuric-acid rich clouds on Venus obscure the hot surface of Earth's twin planet. Carbon dioxide gas in Venus' atmosphere creates a huge "greenhouse effect."

f. Sulfuric Acid Hazes

An important and complex problem linking chemical, dynamical, and radiative effects involves the characteristics of sulfuric acid hazes. On Earth, a thin continuous haze of sulfuric acid droplets resides in the stratosphere, whereas thicker but more localized hazes form in the troposphere. The most extensive sulfuric acid haze known in the solar system is found in the atmosphere of Venus. This cloud is both thick and continuous, and resides about 60 km above Venus' surface. Comparison of the Earth with Venus can contribute to our understanding of the haze phenomenon, and improve our understanding of its climatic importance [36].

g. Global Cloud Effects

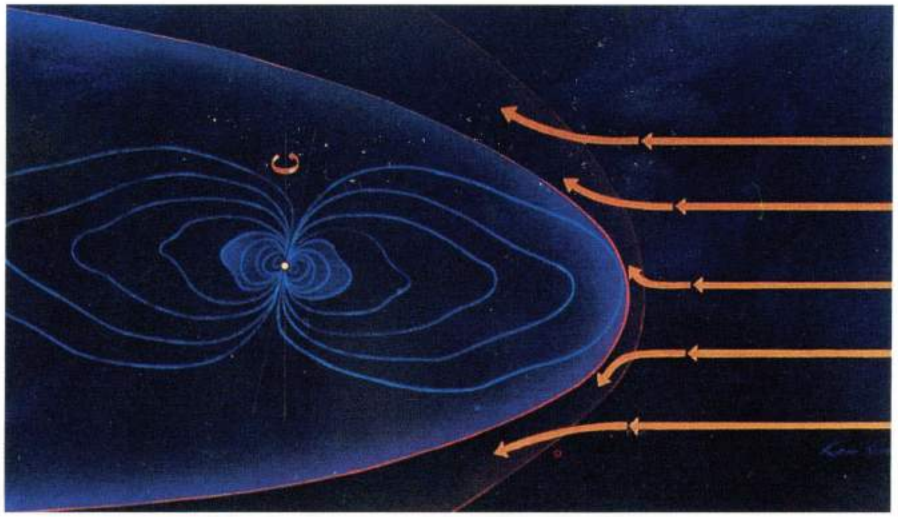
Cloud radiative feedbacks are among the major uncertainties in models of the general circulation of Earth. The seemingly simple question of whether increasing planetary cloud cover will raise or lower the surface temperature is as yet unanswered. The wide range of radiative, chemical, and dynamical conditions exhibited by Venus, Earth, Mars, Jupiter, Titan, Uranus, and Neptune provides an opportunity to test theories that strive to explain the general effects of cloud cover changes on the Earth's radiation balance [37].

Dimethyl sulphide (DMS), a chemical produced by marine phytoplankton, triggers the formation of cloud condensation nuclei in the marine atmosphere of Earth. Through this mechanism, biological regulation of the climate is possible because the amount of solar energy that reaches the surface of Earth depends on the cloud cover. As a result, the temperature at the ocean surface on Earth may be coupled to the behavior of phytoplankton populations [38]. The case of dimethyl sulphide illustrates the complexity of the cloud problem for Earth, and suggests the advantage of having data about other planets to compare with the observations of Earth.

1.3 Upper Atmospheres

a. Comparative Magnetospheres

The planets exhibit a wide range of basic types of magnetospheres. Comparing the different cases allows the separation of some of the specific effects of the planetary atmosphere, the planetary magnetic field, and the consequences of rotation on the region where the planet and the solar wind interact. The Moon has no atmosphere and no global magnetic field, but it does have very localized fields associated with permanently magnetized rocks. Mercury has essentially no atmosphere, but a global magnetic field does exist; Venus has an atmosphere but no global magnetic field; Mars has an atmosphere and possibly a weak field; Earth has both a magnetic field and an atmosphere; and Jupiter has an atmosphere and a rapidly rotating magnetic field that provides much energy to the magnetosphere [39].



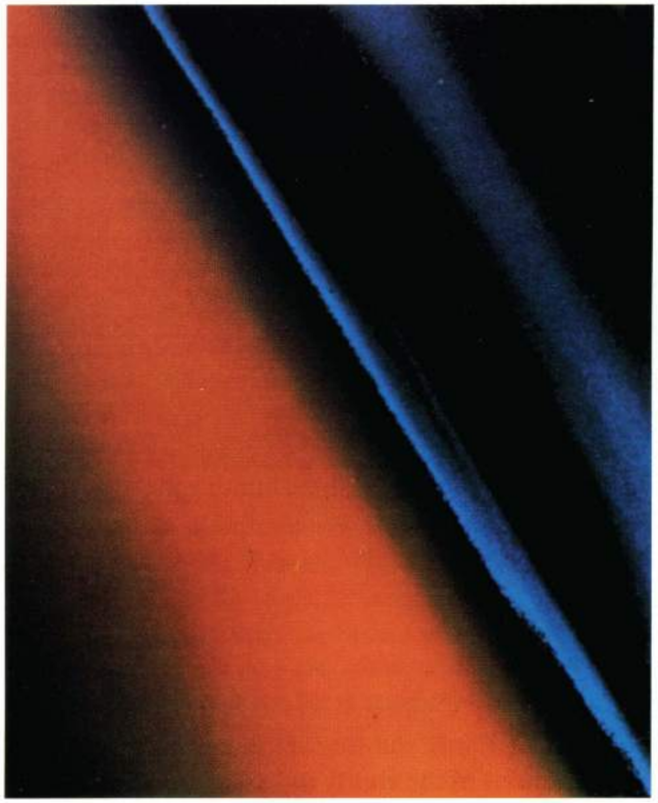
Jupiter has a strong magnetic field, which holds off the solar wind, forming a bow shock a great distance from the planet's surface. The Earth's magnetic field produces a similar feature.

Titan, sitting in the Saturnian environment, and Io, located in the Jovian ionosphere, are analogs in some respects to the instances of planets embedded in the solar wind. Recent Voyager data show Saturn, Uranus, and Neptune to possess significant magnetospheres associated with their internally generated planetary fields. The fields of Uranus and Neptune are especially puzzling, because in both cases, the magnetic and rotation axes are far out of alignment. These new examples are in important ways different from the cases of Earth and Jupiter, offering further opportunities to study magnetospheres with differing characteristics.

Questions of magnetospheric energy and mass exchange, bow shock formation, and solar wind contributions to planetary atmospheres are addressed in part by comparative studies. For example, the *flux transfer event* is believed to indicate the transient interconnection of field lines across a planetary magnetosphere. At Mercury, these events last about one second and are separated by tens of seconds. At Earth, they last tens of seconds and are separated by about eight minutes. At Jupiter, these events have about the same duration as at Earth, but are separated by a longer interval. This progression suggests that the size of the magnetosphere determines the size to which these features grow, but that they reach a limiting size controlled by the thickness of the magnetopause [40]. Observations of a single magnetosphere would not have suggested this result.

b. Neutral Atmosphere Escape

The escape of gases from the top of an atmosphere can occur through thermal and non-thermal processes. The planets exhibit a range of cases that allow several of the major processes to be compared. Both thermal and non-thermal escape processes are important on Earth [41]. At the low exospheric temperature of Venus, non-thermal escape mechanisms dominate, and may be studied in relative isolation. For Mars, the low gravity at the exobase makes thermal escape very important, and also permits some special loss mechanisms, such as dissociative recombination, to operate [42]. For the moons Io and Titan, some escaped gases remain in the planetary region for long periods, trapped by the gravity field of their large parent planets.



A high-altitude layer of haze particles is depicted using false color in this Voyager photo of Saturn's moon Titan.

2. Subtle Earth Effects

Sometimes a phenomenon is dominant in the atmosphere of some other planet, and occurs, but is less evident relative to other effects, in the atmosphere of Earth. This section contains examples of such instances. In a few cases, scientists have argued that the planetary example was discovered prior to its identification on Earth.

Since we are modifying our own atmosphere at a rapid rate, there is great interest and concern that we should recognize subtle changes that may portend serious problems. Planetary research may contribute to uncovering these changes in a timely manner. The following are examples of opportunities to study, in dramatic form, phenomena that also occur on Earth, by looking at the atmospheres of other planets in the solar system.

2.1 Chlorine Chemistry

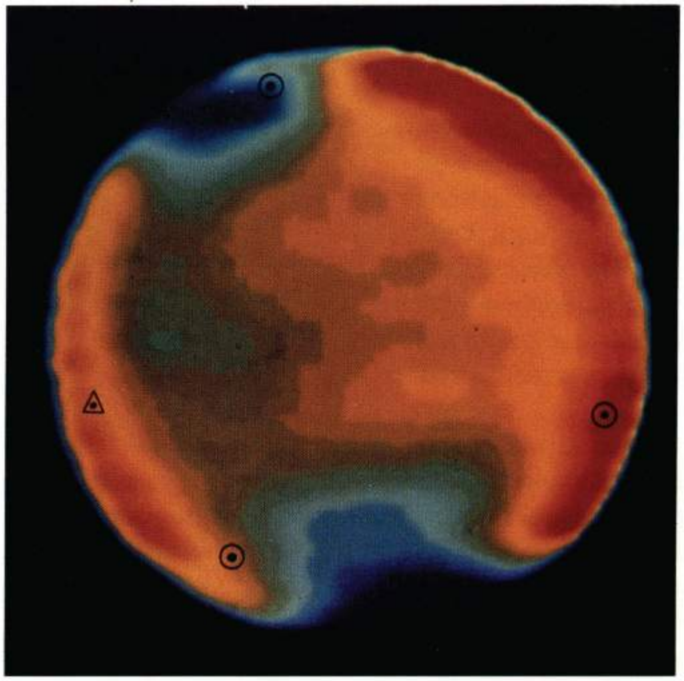
Free chlorine is about a thousand times more abundant in the atmosphere of Venus than on Earth; hydrochloric acid was discovered in Venus' atmosphere spectroscopically in the 1960s. The photochemistry of chlorine in Venus' atmosphere was first presented in 1971 [43]. Scientists found that chlorine serves as a catalyst for the destruction of *odd oxygen* (atomic oxygen and ozone). In 1975, the importance of chlorofluorocarbons (e.g., Freon) as a source of stratospheric chlorine on Earth was realized, and the catalytic effect of chlorine was cited as a possible threat to the protective stratospheric ozone layer [44]. This realization resulted in intensive scientific study, large-scale measurement campaigns to the polar regions of Earth, and ultimately led to legislation and international agreement limiting the use of chlorofluorocarbons [45].

2.2 Odd Hydrogen Chemistry

The lower atmosphere of Mars is depleted of nitrogen and chlorine relative to the stratosphere, or middle atmosphere, of Earth, but the Martian atmosphere does contain small amounts of water. Theories of the ability of hydrogen and hydroxyl radicals – products of the photochemical destruction of water – to catalytically destroy ozone in the stratosphere and mesosphere of Earth were tested by studying the latitudinal distribution of ozone on Mars. For Earth, the process of ozone destruction by the small amount of existing odd hydrogen in the stratosphere is complicated by nitrogen and chlorine chemistry. For Mars, odd hydrogen effects dominate [46].

2.3 The Greenhouse Effect

In the early 1960s, microwave emissions from Venus were interpreted as an indication of a very high surface temperature on that planet. The dense carbon dioxide atmosphere provided an obvious possible explanation. In equilibrium, the total energy absorbed by Venus from the Sun must ultimately be re-emitted to space. Even though Venus absorbs less total sunlight than Earth, due to its reflective cloud cover, the infrared opacity of this atmosphere assures that radiant energy reaching the surface of the planet will remain for a long time in the atmosphere, producing high surface temperatures. This phenomenon has been called the *greenhouse effect*, because one way in which a greenhouse is heated relies upon the ability of glass to transmit sunlight into the room, while the same glass is relatively opaque to the emerging infrared radiant energy. The contribution of carbon dioxide to this effect on Venus amounts to more than 450 degrees C, providing a dramatic test of our understanding of the greenhouse theory [47].



Contours of infrared emission from Venus in 1979 as seen from Earth-based observations. Cool circumpolar rings appear blue in this false-color image. The warmest areas, which are depicted as bright red, are the evening limb (right), and the dawn terminator (left).

Greenhouse heating of Earth has been known since the 1890s, but currently, the contribution of carbon dioxide to the net surface warming is only a few degrees. The climatic effect of introducing large amounts of carbon dioxide into the atmosphere of Earth by burning fossil fuels is a major concern [48]. Gram for gram, Venus and Earth have about the same amount of carbon, but on Earth, carbon is stored primarily in limestone (rock) and as part of living and dead organisms. The example of Venus, which may be a case of a *runaway greenhouse*, has helped focus attention on the possibility of feedback mechanisms leading from small increases in atmospheric carbon dioxide to larger increases in temperature on Earth (see Section 1.1.c on Carbon Cycles).

2.4 Equatorial Super-Rotation

One early tenet of global-scale meteorology was that an atmosphere could not maintain mean zonal winds with angular velocities greater than that associated with the rotation of the solid planet at the equator. A rapidly rotating jet (about 40 percent faster than the planetary rotation rate) in the Earth's upper atmosphere was discovered in the early 1960s from the perturbations of satellites' orbits [49]. This observation was viewed with skepticism for a number of years.

The middle atmospheres of Venus and Titan rotate 60 and 10 times faster than their equatorial surfaces respectively [50]. Attempts to understand these extreme circulations have focused around planetary waves. One class of studies has looked at zonal flow instabilities (see Section 1.2.c). Another group of studies emphasizes the vertical transport of zonal angular momentum near the equator by smaller scale waves. Students of Venus' particularly dramatic *4-day super-rotation* have invoked vertically propagating gravity waves, generated by thermal tides, to accelerate the flow at high altitudes [51]. An interesting note is that the absolute speeds of the super-rotating equatorial atmospheres of Venus, Earth, and Titan are all about 120 m/s. The significance of this observation to the process involved, if any, has yet to be identified.

2.5 The Influence of Molecular Weight on Convection

When water condenses in an atmosphere, it releases energy, called latent heat, which warms the surrounding air. This heating makes the air more buoyant, and can cause the atmosphere to convect. The process plays a key role in transporting heat, momentum, and water in the atmosphere of Earth, particularly at low latitudes. Water vapor has a smaller molecular weight than the predominant gas in the atmosphere (nitrogen), so moist air has an additional tendency to be buoyant.

On the outer planets, the molecular weights of condensibles (ammonia, methane) are greater than those of the predominantly hydrogen atmospheres. As a result, the contributions of latent heating and molecular mass to convective processes oppose each other, putting constraints on moist convection in Jupiter's atmosphere [52], and possibly ruling out methane convection on Uranus [53]. By comparing convection in these different atmospheres, the effect of molecular weight may be isolated.

2.6 Solar Asynchronous Thermal Tides and Slope Winds

The planet Mars offers an opportunity to study thermal effects that may be important on Earth, but are usually complicated by the influence of water vapor in the terrestrial cases. Certain thermal effects are also exaggerated on Mars by the thin atmosphere, which experiences diurnal temperature oscillations as large as 80 degrees C, and by the presence of huge topographic relief by terrestrial standards – several tens of kilometers. Two phenomena that have been studied in detail for Mars are thermal tides and slope winds. *Solar asynchronous tides* are caused by the interaction of the solar diurnal thermal tide with surface topography, and are responsible for important wind systems in Mars's atmosphere [54]. The amount of energy associated with such tides on Earth is not known, and remains an outstanding uncertainty in calculating the energy budget of the Earth's atmosphere.

Slope winds form when diurnal temperature variations occur uniformly over sloping surfaces, causing, for example, cool air to drain downslope in the late night and early morning. Such flows are also called valley winds, and are common on Earth. The study of slope winds on Mars began in the early 1970s [55], and examples of the more dramatic Mars cases [56] provide interesting comparisons with models of terrestrial valley winds used in pollution studies on Earth.

Jupiter's night hemisphere displayed surprising evidence of lightning (bright patches below center) and auroras (curved arcs at top) in this Voyager 1 image. The planet's north pole lies roughly midway along the auroral arc.

2.7 Thunderstorm Electrification

Spacecraft observations have found indications of thunderstorm activity on Venus, Jupiter, Saturn, and possibly Uranus [57]. These results are surprising, because not all the conditions that lead to lightning in Earth's atmosphere appear to be present in the other planetary atmospheres [58].

The typical mechanism for thunderstorm electrification on Earth requires the presence of a concentration of large particles that become charged, and are then separated by a strong updraft. On Earth, the updrafts are formed by air parcels with a high water content. The updrafts get their buoyancy from the release of latent heat (condensation) and from the fact that moist air is lighter than the surrounding dry air. On Venus, however, little or no water appears to be available to form buoyant updrafts [59]. No water droplets or ice particles exist, and the concentration of large particles required for charge separation is not observed [60]. On Jupiter and Saturn, water vapor and other easily condensible species tend to cause air parcels to fall rather than to rise, because in the atmospheres of these planets, moist air is heavier than dry air.

Spacecraft observations indicate that our understanding of the parameters that control thunderstorm activity is inadequate. One possibility is that cosmic rays electrify particles in some atmospheres, and that the charge is accumulated by cloud droplets. If such a process is significant in any other planetary atmosphere, it could also be a subtle effect in electrification of storms on Earth.

2.8 The Atmospheric Radio Source and Other Jovian Magnetospheric Phenomena

The first planetary atmospheric radio source to be discovered was that of Jupiter [61]. The atmosphere of Earth was subsequently found to be a radio source as well.

In general, plasma waves and radio sources in planetary magnetospheres are generated by the actions of energetic particles. The characteristics of these waves depend upon the distribution of energy in the particles, and on the properties of the background plasma and the magnetic field. Despite years of study, the origins of many of the radio emissions and plasma waves observed in Earth's magnetosphere remain controversial; particle energy distributions and the plasma and magnetic field proprieties fall in a surprisingly narrow range. By studying phenomena that are diagnostic of the processes involved in vastly different environments, scientists are beginning to resolve some of the outstanding questions.

Because of its strong field and rapid rotation, Jupiter is a very rich source of magnetospheric phenomena that occur, in a less dramatic way, on Earth. For example, mass is loaded into magnetospheric flux tubes from the atmosphere of the moon Io, which is embedded in the Jovian field. The mass-loaded flux tubes become unstable relative to lighter flux tubes further out in the magnetosphere. Study of this *interchange instability* at Jupiter has caused a reassessment of the importance of the same instability in the terrestrial magnetosphere [62].

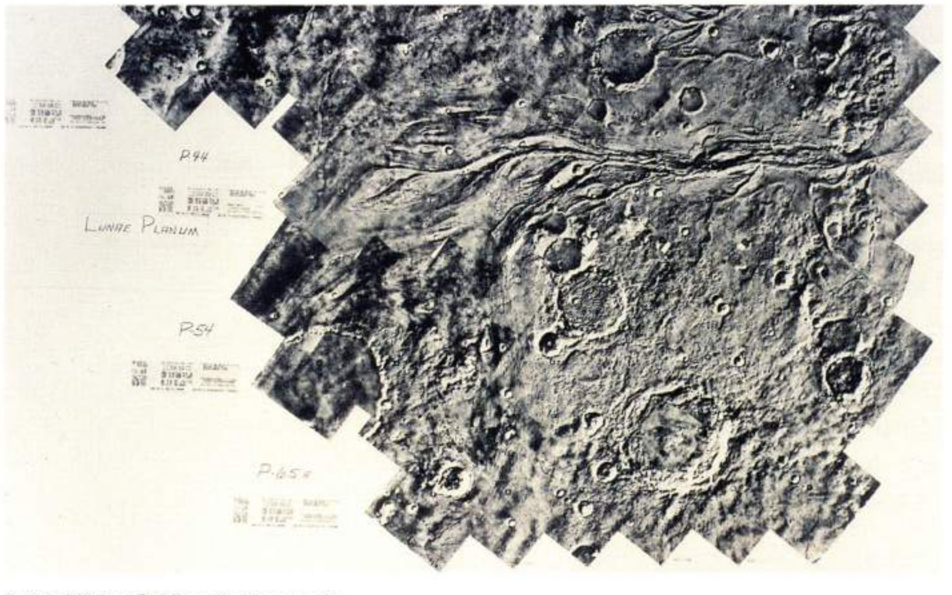
Another example of a phenomenon discovered in the Jovian ionosphere that may have a less pronounced terrestrial analog is the narrow-band plasma structure [63]. The importance of the mechanisms that produce these phenomena to planetary energy deposition and to the capture and loss rates of atmospheric constituents is a subject of current investigation.

3. Data Available Only from Other Planets

This section contains examples of situations in which, because of special preservation or other unique conditions, planetary data provide information unavailable in the Earth data set. For certain kinds of information about early solar system history, there can be no substitute for extraterrestrial data sources.

3.1 The First Billion Years

Of all the planets and moons (except Jupiter's Io) in the solar system, the Earth changes the most rapidly. The land surface is continuously altered by falling and running water, ice, biological activity, and volcanic and tectonic processes. Although the Earth formed some 4.5 billion years ago, the average piece of real estate is only about 250 million years old. The atmosphere has been tremendously altered as well, chiefly by plant and animal metabolism, chemical interaction with the surface, and possibly by the outgassing associated with continuing tectonic activity and external factors like comet and meteorite bombardment. Almost the entire record of atmospheric properties from the first quarter of the Earth's history, as well as terrestrial information about solar input, meteoritic bombardment, cometary influx, and any other agents that may have affected the atmosphere, has been erased.



In this Viking Orbiter photomosaic of the Martian surface in the northern subtropics, Maja Vallis (right) and Vedra Vallis (left) are deeply incised into the old, cratered terrain between Lunae Planum (bottom) and Chryse Planitia (top); North is approximately to the left.

We rely upon less active objects to provide clues to conditions in early solar system history. The average age of the Martian surface is estimated at 2 to 3 billion years, and locations on the Moon, Mercury, and some of the smaller objects in the solar system may retain relatively pristine surfaces dating back 4 billion years or more. These other surfaces are marked with various types of information about the early years of the solar system: the time history of comet and meteorite impacts, the early melting of planetary surfaces, outgassing behavior over time, variations in solar activity, and atmospheric escape. Both comets and meteorites may have made substantial contributions to the volatile inventory of Earth; large impacts might also have blown gas away from the atmosphere (a process termed atmospheric erosion). The larger planets of the solar system, from which gaseous escape is difficult, as well as some of the smaller, unaltered objects, may retain volatile samples similar to the earliest atmosphere of Earth.

3.2 Reducing Atmosphere Chemistry and the Origin of Life

The atmosphere of Titan is depleted of oxygen due to its low temperature. Water, which is a photochemical source of oxygen, can only form ice in the cold Titan environment, and water vapor is exceedingly rare. The chemistry of carbon and nitrogen in an oxygen poor atmosphere allows production of long chain organics. These organics are the types of molecules from which living organisms are made. Other evidence exists that the Earth may have had an oxygen poor atmosphere early in its history. Because of these similarities, the oxygen poor atmospheres of Titan, Jupiter, and other objects in the outer solar system have been viewed as possible analogs to the atmosphere of Earth at the time of the beginning of life.

Another interesting aspect of environments that may have given rise to living organisms is the possible role of lightning. Calculations and laboratory experiments show that lightning activity in planetary atmospheres causes the formation of high-temperature compounds and prebiological molecules [64]. In the atmosphere of the primordial Earth, lightning could have been the major source of many of the molecules required for the formation of life. Spacecraft observations indicate that lightning occurs in the oxygen poor atmosphere of Jupiter and possibly Saturn [65]. Lightning may also occur on Titan, where it could be forming prebiological molecules above its methane and/or ethane oceans [66]. Spacecraft instruments are being developed to further investigate the possible role of lightning in the production of prebiological molecules in primitive atmospheres.

3.3 Magnetic Field Reversals

The rock record of Earth indicates that in the past, the Earth's magnetic field went through frequent pole reversals. At those times, the dipole component of the field decreased greatly, but the higher order moments were relatively unaltered. This observation may be the explanation for the very large tilt of the field observed at Uranus; its field may be undergoing a reversal at this time [67].

3.4 Planetary Ion Escape Processes

Charged particles, or ions, escape from planetary atmospheres. These particles form in the ionosphere and flow upward to populate the magnetosphere, from which they are lost to the planet during magnetic substorms. Since Venus lacks a global magnetic field, the solar wind interacts directly with the ionosphere, causing very high ion escape rates. Early in its history, the Earth may also have lacked a global magnetic field [68]. The ion escape processes operating on Venus today may once have dominated ion escape on Earth.

3.5 Metastable Ion Chemistry

Several ion reactions that occur in the atmosphere of Earth and cannot be reproduced in existing laboratories can be studied in the special environments of other planetary atmospheres. Here are three examples of reaction rates derived in this way:

(a) $O^{++} + O \rightarrow O^{+} + O^{+}$ was measured in Venus's atmosphere, where it is the only known loss process for O^{++} [69].

(b) $O^{+}\ (^{2}D) + O \rightarrow O^{+}\ (^{4}F) + O$ was measured in Venus's atmosphere [70]. $O^{+}\ (^{2}D)$ is important in the Earth's atmosphere because it provides a rapid loss mechanism for N_2^{+}.

(c) $CO + e^{-*} \rightarrow CO\ (a^{3}\pi) + e^{-}$ was measured in the Martian airglow [71]. This reaction is responsible for the Cameron bands in the terrestrial airglow.

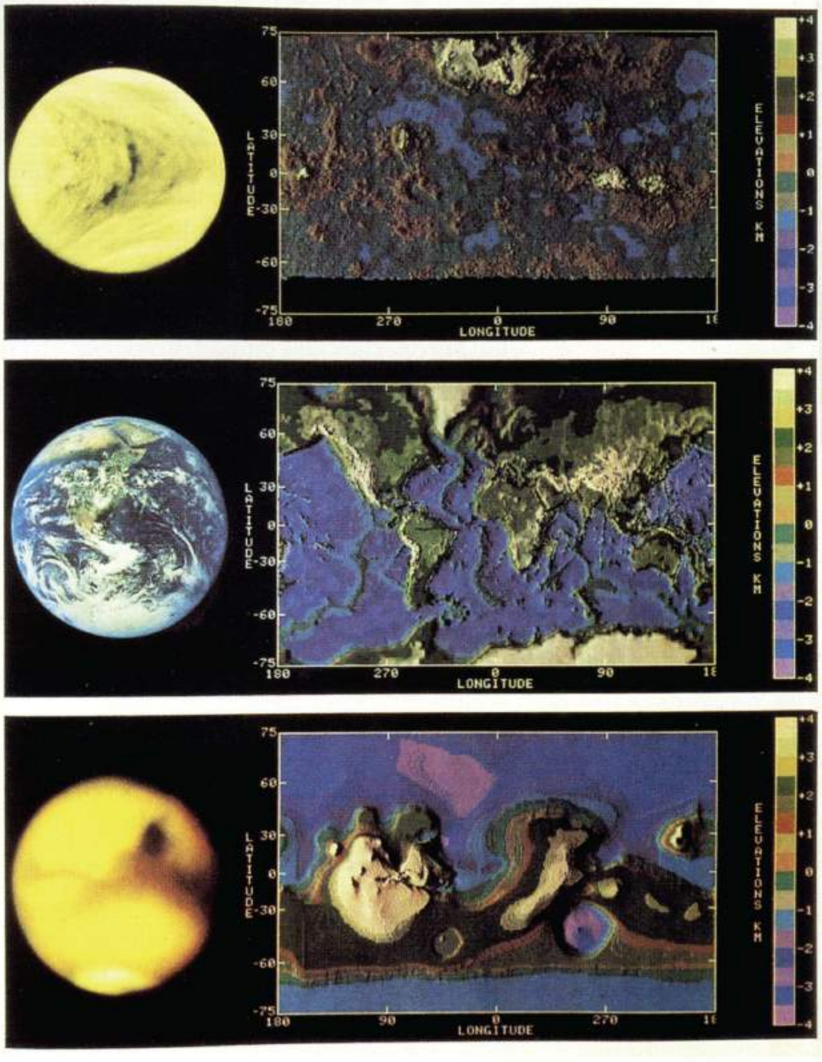
3.6 Experience from a Planetary Instrument

As a technique, polarimetry has been used to study the aerosol properties of Venus' clouds [72]. The basic theory for analyzing polarimetric data was derived at the beginning of this century; early experience in its application to obtaining global cloud properties was gained through the Venus cloud work [73]. The technique will be employed on the Galileo mission to Jupiter (scheduled for an October 1989 launch), and is now being considered as a way of supplementing other measurements of the cloud properties of Earth.

4. New Ideas

Planets are explored primarily by remote sensing instruments, from the *outside inward*. Planetary reconnaissance usually begins with relatively small data sets and large questions. This approach encourages a more global perspective on atmospheric processes than has traditionally been the case for Earth, where there is a long history of studying detailed, localized data, obtained mainly from vantage points on the surface. The global perspective has contributed in a fundamental way to our view of the planet Earth. The importance of this perspective is reflected in the current NASA plan to fly the Earth Observing System (Eos) platforms in the 1990s, as part of a *Mission to Planet Earth*.

Planetary investigations continue to produce a great many scientific insights into the properties, behavior, and history of Earth. From the data collected at each planetary encounter, new questions are raised that challenge our current views. At Venus, we observe a world with a surface that is dull red hot, an atmosphere 90 times thicker than that of Earth, a paucity of water, and 100-meter-per-second winds at cloud levels. We find the sky to be red and always full of dust on Mars. There are layers suggestive of periodic climate change, but the Viking Landers saw no evidence of life on the Martian surface — not even a few organic molecules. At Jupiter, among the long-lived cloud features, we see a cascade of rapidly varying turbulent eddies. On Titan, there is an atmosphere 1.5 times more dense than that of Earth, containing large organic molecules. Comparisons among the planets force us to think astutely about the basic physical processes that shape these diverse places, as illustrated by the examples presented in this report. We have only begun to explore the solar system, and further surprises, well beyond our present conceptions, wait to be encountered.



A comparison of the different distributions of highlands (continents) and lowlands (basins) on Venus, Earth, and Mars.

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1 Much of the work discussed in this report is supported by the Planetary Atmospheres Program, Solar System Exploration Division, NASA Headquarters. The work of R. Kahn was performed at NASA Headquarters, NASA/Goddard Space Flight Center, and the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration. The author particularly wishes to thank the following people for their participation in this effort:

W. Borucki, R. Haberle, J. Pollack, and O. B. Toon of the NASA Ames Research Center;
L. Brace, B. Conrath, F.M. Flasar, R. Hartle, H. Mayr, H. Niemann, and H. Taylor of the NASA Goddard Space Flight Center;
H. Brinton of NASA Headquarters; R. A. Brown of the Space Telescope Science Institute;
B. Buratti, J. Friedson, C. Kahn and R. Zurek of the Jet Propulsion Laboratory, California Institute of Technology;
A. Del Genio and W. Rossow of the Goddard Institute of Space Studies;
J. Fox and T. Owen of the State University of New York, Stony Brook;
K. L. Fox of the University of Tennessee, Knoxville and GSFC;
R. M. Goody of Harvard University;
A. Hou of Atmospheric and Environmental Research, Inc.;
D. M. Hunten of the University of Arizona, Tucson;
A. Ingersoll and Y. L. Yung of the California Institute of Technology;
N. Ness of the University of Delaware;
C. T. Russell of the University of California, Los Angeles;
S. Soter of the National Air and Space Museum;
C. Thompson and R. H. Weiss of Science Applications International Corporation.

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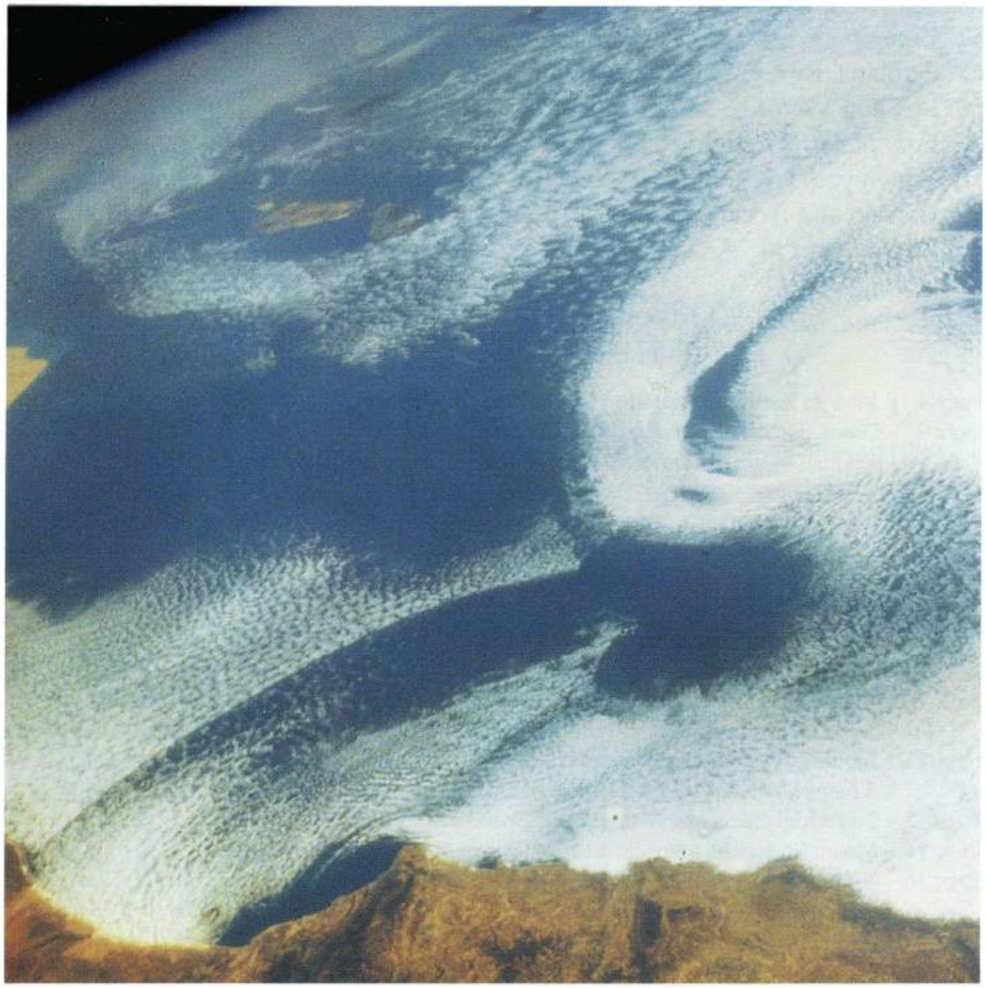

The STS-3 crew of Space Shuttle Columbia in 1982 caught sight of Earth's Canary Islands and Morocco through a slight cloud cover.