5.3 Planetary Atmospheres

In the absence of an atmosphere, it is difficult to imagine an ocean of water or any other thalassogen being present on a world. It appears that both liquids and gases are required in the chemical interactions which lead to the origin of life. Discounting the occasional origin of life in the subsurface regime of its crust, a world probably cannot be suitable for living organisms unless it possesses some kind of atmosphere.[20]

While atmospheres may exist without oceans, oceans may not exist without atmospheres. More factors must be taken into account in assessing a molecule as a possible atmospheric constituent.

First, it must be reasonably abundant. Second, it must be present in either gaseous or vapor form at reasonable planetary temperatures. Third, the molecule must be neither so lightweight nor so hot as to have escaped from the world over a period of eons. Fourth, effects of planetary surface chemistry become extremely important in the evolution of atmospheres - the presence of large oceans is especially significant. Fifth, natural biological modification of the atmosphere must be considered.

As far as abundance is concerned, there are fewer restrictions on composition than when we were talking about thalassogens. While oceans may represent 0.01-0.1% of the total mass of a terrestrial planetary body, an atmosphere will run two or three orders of magnitude less. Consequently, Tables 5.3 and 5.4 are far from complete. Far less abundant molecules, rejected as thalassogens on grounds of scarcity, are welcome as constituents of the air.

Looking at the boiling points (and vapor pressures) of the molecules in Table 5.4, we note that virtually all have a gaseous phase at reasonable temperatures for some planets. (E.g., Pluto may have a neon atmosphere ![2064]) In view of the liberal temperature and abundance requirements, literally hundreds of molecules may comprise planetary atmospheres in various concentrations and pressures. An exhaustive treatment is clearly beyond the scope of this book.

The third consideration is the escape of molecules from a world by a process known as thermal evaporation. Just as rockets must achieve escape velocity to overcome Earth's insistent gravitational tug, so must atoms. Gas molecules which are traveling fast enough and are light enough can stream off into space, leaving the planet high and dry. Higher temperature means higher energy which means higher velocity. Also, the lighter a molecule is at any given temperature, the more likely it is to escape because it needs less energy to get away. Light molecules thus leak off faster than heavy ones.

Close to the surface of a world, molecules cannot travel very far before they bump into one another. Even a particle moving at ten times the escape velocity would strike several others before it had traveled one centimeter. It would distribute its energy, slow down, and not escape.

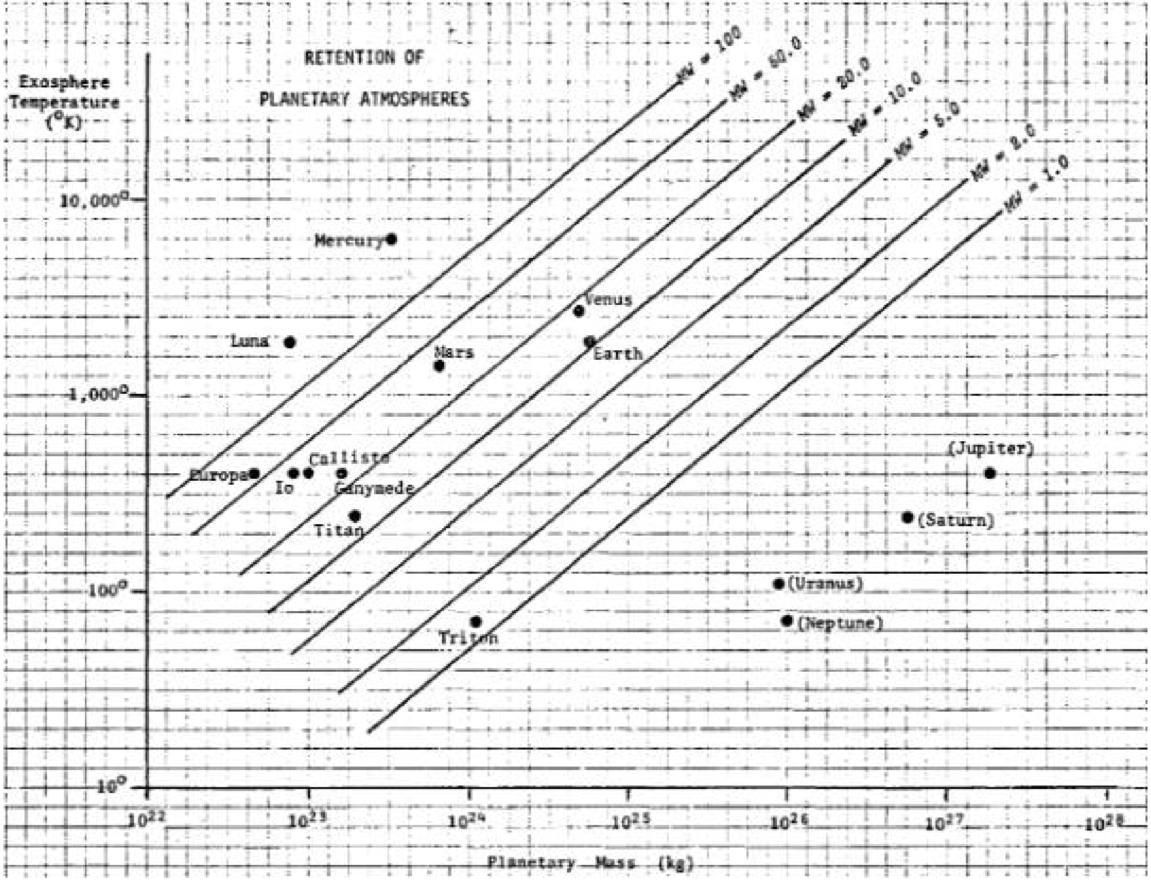
But in the exosphere (as it is called) of a planet, molecules can fly literally kilometers before a collision occurs. Only in the upper atmosphere can gas which is hot enough to escape have a reasonable chance of making it. So it is this exosphere temperature, and not the planetary surface temperature, which is relevant to the escape of atmospheric components. Earth's exosphere, to use an example, lies at roughly 600 kilometers and varies from about 1500-2000 K.[20,214,521]

From the abundances listed in Table 5.3 we might expect planets to start out with mostly hydrogen and helium, with less than 2% other elements as impurities. Jovians are massive enough (high escape velocity) and cold enough (low velocity molecules) to hold the concentrations of these two elements to within spitting distance of their primitive solar nebula abundances. On worlds as small and hot as Earth, though, hydrogen escapes in a characteristic time of perhaps 1000 years.[20] On still smaller and hotter worlds, like Mercury, the gas is retainable only for a matter of hours. (The characteristic time for hydrogen on Jupiter is estimated to be something like 10200 years.[57])

On the other hand, most average-sized terrestrial planets are quite capable of hanging on to carbon dioxide, water, nitrogen and oxygen. (These are also retained by the jovians, but the proportion is vastly smaller because of all the hydrogen and helium around.) Following Dole,[214] we may classify all planets into three general categories: Airless, light atmosphere, and heavy atmosphere.

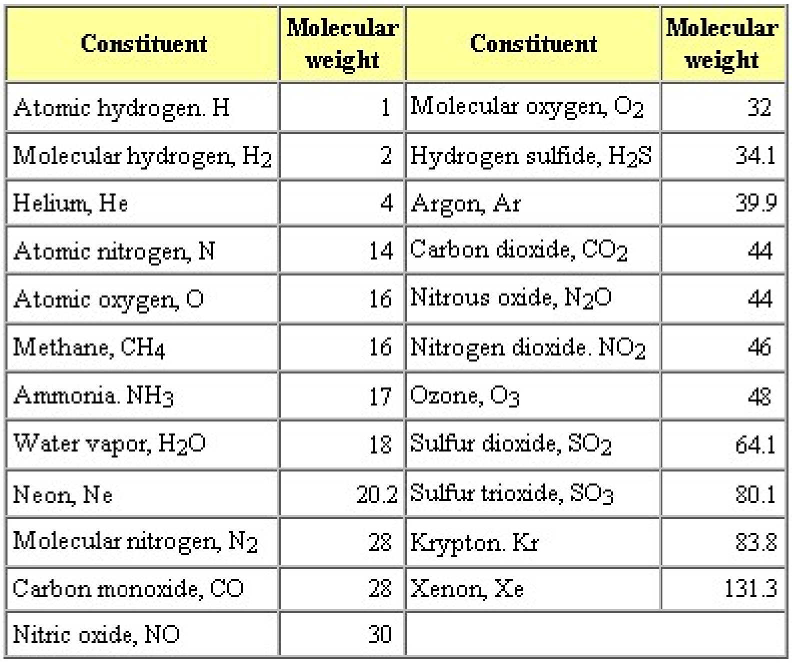
Atmospheric constituents whose molecular weight (Figure 5.5, Table 5.5) places them above a planet are retained, those below are not. The closer a planet lies to the molecular weight (MW) = 1.0 line (corresponding to molecular hydrogen), the more massive its atmosphere is likely to be. Planets lying below this line will probably be gas giants.

Figure 5.5 Retention of Planetary Atmospheres as a Function of Molecular Weight (after Dole[214])



Atmospheric constituents whose molecular weight places them above a planet are retained, those below are not. The closer a planet lies to the molecular weight (MW) = 1.0 line (corresponding to molecular hydrogen), the more massive its atmosphere is likely to be. Planets lying below this line will probably be gas giants.

Table 5.5 Potential Atmospheric Constituents (from Dole[214])



Constituent	Molecular weight	Constituent	Molecular weight
Atomic hydrogen. H	1	Molecular oxygen, O_2	32
Molecular hydrogen, H_2	2	Hydrogen sulfide, H_2S	34.1
Helium, He	4	Argon, Ar	39.9
Atomic nitrogen, N	14	Carbon dioxide, CO_2	44
Atomic oxygen, O	16	Nitrous oxide, N_2O	44
Methane, CH_4	16	Nitrogen dioxide. NO_2	46
Ammonia. NH_3	17	Ozone, O_3	48
Water vapor, H_2O	18	Sulfur dioxide, SO_2	64.1
Neon, Ne	20.2	Sulfur trioxide, SO_3	80.1
Molecular nitrogen, N_2	28	Krypton. Kr	83.8
Carbon monoxide, CO	28	Xenon, Xe	131.3
Nitric oxide, NO	30		

Airless worlds are those which lie above the molecular weight MW = 100 line on the planetary atmosphere retention graph on Figure 5.5. Mercury,[1566] Luna and the asteroids in our solar system have virtually negligible gaseous envelopes. Planets which lie between this line and the MW = 5 line will have atmospheres of small mass relative to the main rocky body. Gases, if present in the first place, will be retained according to their molecular weight and the specific surface conditions they encounter. Finally, planets lying below the MW = 5 line will possess atmospheres which represent a sizeable fraction of the total mass. Such will consist primarily of hydrogen and helium, with trace impurities of methane, ammonia, and so forth (depending on temperature).

Still, we are not yet in a position to predict the atmospheric composition of terrestrial worlds. Venus and Earth, for instance, have roughly the same mass but their atmospheres are vastly different. According to the discussion above, one might have expected the Cytherian air to be less dense than our own because it’s hotter closer to Sol (and so gas should be lost more quickly). Yet the surface pressure on Venus is ~100 atm. Clearly, other forces are at work besides simple selective leakage of gases.

Part of the mystery may be cleared up by considering the information contained in Table 5.6 below. As we expect, there is a large depletion of the lighter elements - hydrogen and helium. But why are other elements so severely dissipated as well ? Most peculiarly, why are argon, krypton, and xenon pretty well gone from Earth, despite the fact that the characteristic leakage times for these components should be 1070 years or more ?

Table 5.6. Element Abundances on Earth as Compared to the Primitive Solar Nebula[315,521]

Element	**Earth/Cosmic Abundance**	**Element**	**Earth/Cosmic Abundance**
Aluminum	1.1	Nitrogen	8.8 x 10-6
Silicon	1.0	Hydrogen	9.6 x 10-7
Magnesium	0.85	Argon-36	2.6 x 10-7

Sodium	0.73	Krypton	8.7 x 10-8
Oxygen	0.15	Xenon	7.1 x 10-8
(Water)	1.6 x 10-4	Neon	5.2 x 10-11
Carbon	1.0 x 10-4	Helium	1.7 x 10-14

If we look at what the composition of Earth should be (based on thermal evaporation considerations alone) and then compare it to the actual makeup of our planet, several very striking facts emerge. Most of the solid elements that go into rocks - silicon, aluminum, magnesium, sodium - are present in just the right amounts. Most of the oxygen around was similarly tied up. However, all the gaseous components are depleted by an average of six orders of magnitude! What's going on ?

Planetologists today believe that in primitive times Earth (and the other terrestrials in this system) lost not only H and He due to thermal evaporation but most of the rest of its atmosphere as well.[2031] The exact mechanism by which this cosmic dust broom operated is not clear, but it may be connected with the T Tauri gales associated with the early stages of evolution of Sol-like stars. The lack of noble gases is significant because they are the heaviest molecules present in any planetary atmosphere. If even they are gone, it's virtually certain that all lighter components have also been scoured away.

But then - how do we account for our present atmosphere ? If Venus started out as an almost airless globe, where did it manage to find 100 atm' worth of carbon dioxide ?

The four elements common to all terrestrial environments, C, H, O, and N, are the four least depleted of all the gaseous components. Why is this so ? It appears evident that compounds containing these elements were actually incorporated into the early Earth in both solid and gaseous form.[33] Later, they were released from their rocky vault to take up new careers as atmosphere and ocean.

When the primitive Earth contracted and began to melt, trapped gases slowly bubbled to the surface.[2042] Volcanoes today emit as much as 60% water and 20% CO2 in their eruption products,[2031] and molten rock can dissolve perhaps 5% of its weight in water. Scientists suspect that by similar processes, our air and water gradually emerged from the interior of the planet.[2031]

The early hot crustal material may have had large amounts of free iron, which would have reduced much of the water and carbon dioxide to methane and hydrogen.[57] Our secondary atmosphere thus probably began as a chemically reducing environment, rich in effluent H2, CH4, H2O, NH3, and increasing amounts of CO2 and N2.[20,57,521,1293,1645]

We arrive at the fourth important factor relating to planetary atmospheres: Surface chemistry effects. The evolution of the air of a world is closely linked to its mass, temperature, geological activity, and oceans. Most terrestrial planets destined to have light atmospheres (Table 5.7) are expected to have gone through the same processes of outgassing as described above for the Earth - though perhaps at slightly different rates.

Table 5.7. Summary of Terrestrial Planetary Atmospheric Evolution[2041,2044]

Location in Habitable Zone	Typical Surface Temperature	Typical Surface Pressure	Representative Planet	Main Constituent

Inner (hot)	700 K	100 atm	Venus	97% CO2
~~Middle (mild)~~	~~300 K~~	~~1 atm~~	~~Earth~~	~~78% N2~~
Outer (cold)	230 K	0.01 atm	Mars	95% CO2

Dr. S. Ichtiaque Rasool, Chief Scientist at the Planetary Programs Office of NASA and a specialist in planetary aeronomy, has formulated a fascinating theoretical model (Figure 5.6) for atmospheric evolutionary processes.[2065] The model predicts that terrestrial worlds relatively close to their primary (like Venus) will always be too hot for water vapor to condense at the surface into oceans. With no water in pelagic quantities to dissolve it, the CO2 disgorged into the air by volcanoes must remain aloft. A dense atmosphere soon builds up. Temperatures are further elevated by the greenhouse effect* : The carbon dioxide forms a warm blanket over the entire planet, absorbing and reemitting the infrared heat radiated by the illuminated planetary surface. This effect adds only 30 K to the temperature of Earth's atmosphere, but amounts to a whopping 500 K on Venus !

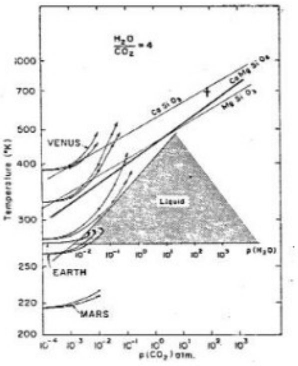
On such a hot terrestrial world, the water vapor could be split into its component atoms by the ultraviolet rays from Sol. The hydrogen would then be lost to space by thermal evaporation, and the oxygen could combine with the surface rocks and disappear from the air. The carbon dioxide level is partially buffered by chemical reactions with silicate rocks in the crust. These reactions tend to eat up CO2 and produce carbonate rocks, or limestone. Unfortunately, buffer reactions proceed at a reasonable rate only if there is plenty of water around. But as we've seen, there won't be much on a hot terrestrial. The volcanoes can go on dumping carbon dioxide into the atmosphere and the crust can do little to prevent it. This process is commonly known as a "runaway greenhouse."[2037,2065,2066]

On a world closer to the center of the habitable zone (like Earth), the chain of events is much different because things are cooler. The atmosphere begins to emerge at the time when the nearly airless surface has a temperature at or near the freezing point of water. As the CO2 comes out and the planet starts to greenhouse, the temperature rises slightly. Water sloshes together in liquid form and becomes ocean. The carbonate-producing buffer reactions begin in earnest, laying down gargantuan deposits of limestone and chalk as the carbon dioxide is removed from the air. The greenhouse does not run away.

We see that the surface temperature of the planet is of critical importance in determining the fate of its atmosphere. Rasool calculates that a change of perhaps 10 K (hotter) would be enough to have caused Earth to miss the liquid phase of water altogether and become a close replica of Venus.[2065]

Figure 5.6 Rasool's Model of Planetary Atmospheric Evolution

CO2/H2O PHASE DIAGRAM FOR TERRESTRIAL PLANETS[2065]



Atmospheric physicist S. I. Rasool assumes that atmospheres of terrestrials are the product of early "degassing" from the molten interiors of the primitive planets. Shown in the diagram at left is the triangular region of pressure and temperature in which water remains a liquid thalassogen (cross-hatched area). Also depicted are the evolutionary tracks of three typical terrestrials in our own solar system.

The theoretical development of Venus is illustrated by two curves -- one for a non-rotating world (upper curve, marked "VENUS") and one for a fast-rotating planet (curve starts at 330 K).

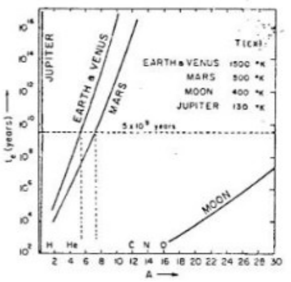
Tracks for Mars and Earth are also shown, and still another curve depicts the startling conclusion that Earth would have missed the water-liquidity triangle altogether had it started out a mere 5°C hotter,

Apparently our lush, verdant planet would have become a close duplicate of hellish Venus were it a mere 6-10 million kilometers closer to Sol.[1907]

THERMAL EVAPORATION OF PLANETARY ATMOSPHERES[2031]

The drawing at right presents the effective escape time for various gaseous components of planetary atmospheres, as a function of atomic (molecular) weight A. Various exosphere temperatures are assumed for each of the planets shown.

For a planet to be a terrestrial world capable of evolving advanced lifeforms, its retention curve must lie to the right of helium on the diagram, so that both this gas and hydrogen are lost in one "genesis time" (~5×10^9 years). At the opposite extreme, a planet must be able to retain all *other* gases for at least one genesis time. The Moon fails to fulfill this requirement by several orders of magnitude.



The model also predicts what happens to terrestrial worlds in the outlying regions of the habitable zone (like Mars). Here again we have no oceans forming, because any water emitted by volcanoes is frozen out. Carbon dioxide may build up, free from the moderating influence of silicate buffering reactions. (But Mars is a small, cold planet, so degassing from the interior proceeds much slower than for a larger body. A 1 Mearth world at Mars' orbit should eventually become quite Earthlike, though it will naturally take much more time.)

As regards Mars : After perhaps ten eons or so of slow planetary evolution, enough carbon dioxide may accumulate to produce a respectable greenhouse effect. Since the water has not been lost but is merely stored away at the poles, oceans could develop when the temperature manages to rise above 273 K - the freezing point of H2O. In this view, Mars has never had oceans and is in an earlier stage of evolution than Earth. (There are some who would disagree with this conclusion, arguing from the riverbed-like structures observed on the Martian surface by Mariner 9 and Viking.[15,2044,2074])

So the story of the gross atmospheric conditions is largely the story of water and carbon dioxide. But what about the other components of the air ? Well, much of the hydrogen is lost to space by thermal evaporation from the exosphere. Nitrogen is released by volcanism and is relatively inert -- it remains in the air relatively unchanged. The ammonia dissolves in the water, if there is any, or dissociates into hydrogen and nitrogen. Methane under goes organic reactions, again, if there is an ocean. And oxygen is produced when water is split apart in the exosphere by ultraviolet radiation. O2 can reach natural concentrations of perhaps 0.1% of the air. For example, Ganymede and Callisto are believed to have thin oxygen atmospheres (~10-3 atm), which could have arisen as fast as ten thousand years in this fashion.[2095]

Production of oxygen is a good example of what is called a "self-limiting" process. As the concentration of O2 rises, a thin ozone (O3) shield begins to form which screens out the UV rays from the water vapor below. As ozone increases, less H2 is dissociated and less free oxygen is produced.

It seems that natural mechanisms may be able to change a reducing (hydrogenating) atmosphere into a more neutral one, but apparently simple chemistry alone is incapable of creating an oxidizing atmosphere.[96] Earth is the only planet in the solar system that is oxidizing. Why ?

The answer is found in the biological modification of the air - our fifth important factor. It appears that until perhaps two eons ago, the carbon dioxide in Earth's air (say, 1%) kept the surface temperature well greenhoused to warmer levels. As the blue-green algae began to work their photosynthetic magic in our oceans, they took over from the silicate rock and carbonate buffer chemistry in the removal of CO2. After only about 500 million years, Earth's atmosphere changed from 0.1% O2 to about 20% O2. This effectively removed about an order of magnitude of carbon dioxide from the air, reducing its concentration down to about 0.1% of the total. Instead of limestone formations, carbon began to be incorporated as biomass (Figure 5.7).

Figure 5.7 Biological Modulation of Planetary Atmospheres[1293]

Atmosphere of a Lifeless Earth

Atmosphere with Life Present

This model of the Earth with no life from the start is not unlike what would be expected from interpolation to conditions lying midway between Venus and Mars, The surface pressure is still about 1 atm, but the air is perhaps 97% nitrogen and a few percent carbon dioxide.

The effects of adding life to a planet's geophysical history are striking when biological modulation of the atmosphere takes place. While the air is still mostly nitrogen, autotrophic living organisms convert perhaps 95% of the available carbon dioxide into biomass-carbon and free oxygen -- which is then utilized by animal life.

The presence of an oxidizing atmosphere is probably a good test for biology.** We know that Earth's crust is rather underoxidized and would eat up most of the abundant O2 in our air in a relatively short time. As Carl Sagan has pointed out, *"a high level of oxygen such as we have in the Earth's atmosphere can only be accounted for by vigorous biological activity."*[445] (The photosynthetic recycling time for the O2 in our atmosphere is roughly 2000 years.[1945])

But scientists today argue that more than just oxygen levels are controlled by terrestrial biota. Dr. Lynn Margulis of the Boston University Department of Biology and Dr. J. E. Lovelock, an applied physicist at the University of Reading in England, believe the Earth is a complex "entity" which could almost be described as living. They present evidence that biology not only modifies our environment but modulates it as well.[1293]

That is, the conditions in Earth's oceans, atmosphere, lithosphere and biosphere are all regulated by life on the surface in such a way as to maximize the growth of the biosphere. It gives one pause to consider that those same forces of natural selection responsible for the diversity, abundance, and efficacy of lifeforms on this world are also operative on the biospheric, global scale. As species evolve over time, so do complex feedback mechanisms seek and preserve planetary homeostasis - the optimum physical and chemical environment for life on Earth.

Let us now attempt a brief summary of our conclusions regarding terrestrial planet atmospheres generally. First, abundance and gaseous state requirements are so loose that it is difficult to exclude virtually any reasonable candidate molecule on these grounds alone. As far as thermal evaporation is concerned, a planet in the habitable zone with a mass greater than perhaps 0.1 Mearth should be able to hang onto any gas already present (other than hydrogen or helium) for geological time periods.

It appears that the typical terrestrial without oceans is most likely to carry an atmosphere consisting of more than 95% carbon dioxide through out much of its evolutionary history. Planets with oceans of liquid water should develop an equivalent predominance of nitrogen in the air, because the CO2 is returned to the crust via silicate buffer reactions. (There are no precedents in our system for nonaqueous terrestrial oceans, and unfortunately the chemical surface processes have not yet been worked out in detail for alternative thalassogens.)

We see that the total surface pressures may range from less than 0.01 atm to more than 100 atm, depending primarily upon the rate of outgassing of the secondary atmosphere from the interior of the planet. Larger, more massive worlds should tend to outgas faster and build up thicker air, as a general rule.

Finally, if life is present, thermodynamically unstable components may appear in the atmosphere -- such as oxygen on Earth. Of course, any other chemically active gaseous oxidant may equally well be found, depending on the particular modulating biochemistry of the life on the planet's surface (Table 5.8).

Table 5.8 Exotic Biological Modulation Schemes :
Theoretical Atmosphere/Thalassogen Biochemical Energy Systems,
Neglecting Abundance Problems (after Asimov[1358])

Atmosphere	Thalassogen	Allowable Temperature Range (°K)	Planet at Proper Temp.	Plant Biochemistry			Animal Biochemistry			Relative Energetic Efficiency	Likelihood and Remarks
				Take Up	Store	Transpire	Eat	Inhale	Exhale		
O_2	H_2	273 - 373	Earth	H_2O	H	O_2	H	O_2	H_2O	1.0	Very likely (Earth)
H_2	S	393 - 718	Mercury	H_2	H	S (liq)	H	S	H_2	0.08	Improbable -- too inefficient
F_2	HF	190 - 293	Mars, Ast. Belt	HF	H	F_2	H	F_2	HF	1.5	Improbable -- UV photons required for photosynthesis
HCl	Cl_2	188 - 239	Ast. Belt	HCl	H	Cl_2	H	Cl_2	HCl	0.4	Improbable -- too inefficient
HBr	Br_2	266 - 332	Earth	HBr	H	Br_2	H	Br_2	HBr	0.2	Improbable -- too inefficient
SO_2	S	393 - 718	Mercury	SO_2	O	S	O	S	SO_2	1.2	Possible
CO	CO_2	217 - 304	Earth Mars	CO_2	O	CO	O	CO	CO_2	1.6	Improbable -- CO ocean too difficult to arrange
CO	CH_2 (Formaldehyde)	181 - 252	Mars, Ast. Belt	CH_2	H	CO	H	CO	CH_2	0.5	Improbable -- chemically too complicated & non-competitive
CN	HCN	240 - 299	Earth	H + CN	HCN	null	HCN	null	H + CN	(-0.5)	Unlikely -- too complex & requires partial reversal of plant/animal roles
H_2	H_2O	273 - 373	Earth	H_2O	O	H	O	H_2	H_2	1.0	Possible, on a subjovian world within Earth-like ecosphere

* Technically this is a misnomer because it's not the way horticultural greenhouses keep warm. Rather than selective passage of visible (but not infrared) wavelengths, they work simply because a body of air is physically confined and heat cannot escape by convection. In 1908, Dr. Robert W. Wood constructed two greenhouses - one of glass and one with rock salt panes (NaCl passes infrared, unlike glass) - and both worked equally well.

** Life is quite possible (and in fact originated) in fully reducing atmospheres. However, advanced forms of life need far more energy. Hence, they appear less likely to arise in hydrogenous environments because their metabolisms would seem to be less energy-efficient.

5.4 Planetary Meteorology and Astrogeology

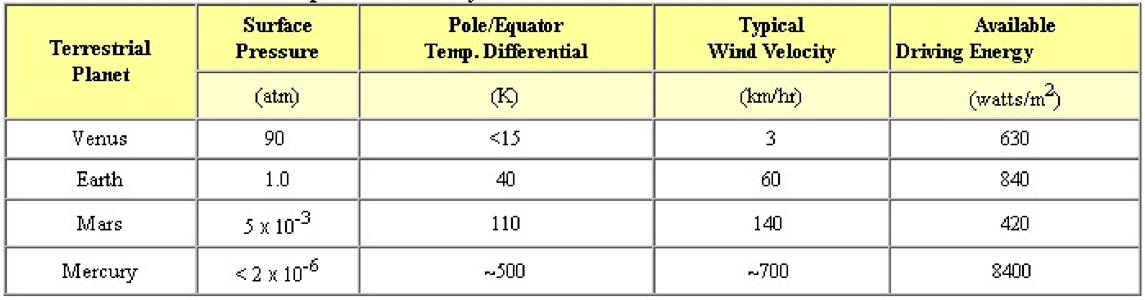
So far we have confined ourselves to an examination of the gross, bulk properties of planets, oceans and atmospheres. But xenologists are also very much interested in somewhat "smaller scale" phenomena. What kinds of climate and weather will the aliens have ? Will their world know lazy clouds, blue skies and shimmering auroras ? Are their mountains tall or short (e.g., "astrogeology"[2144]), and how fierce are their storms and quakes ? What color is their sun ?

The answers to such questions, and many others like them, are extremely hard to come by in a definitive way because the causative dements are so complex and variable. Yet they are of vital importance if we hope to comprehend alien art and culture, languages, architectural forms and lifestyles, and even ET social patterns and individual psychologies.

5.4.1 Climate and Weather

We've already hinted at the effects of evolutionary history on a planet's surface temperature. What else can be said about the overall climate ? First of all, the thinner the atmosphere the greater will be the diurnal variations in temperature. This is because a dense, massive atmosphere has more "thermal inertia." Since huge amounts of heat are stored, a brief nighttime cooling-off period has very little effect. But if the air is thin and lightweight (as on Mars), very little heat is reposited. Thus, on the night side the surface and the air above it cool rapidly, leading to large swings in temperature between the two sides of the planet. This results in faster-moving winds (Table 5.9), but because the air is less dense the energy available is actually less.

Table 5.9. Wind Speed and Planetary Surface Conditions for Terrestrial Planets[1566,2066,2087]



Terrestrial Planet	Surface Pressure	Pole/Equator Temp. Differential	Typical Wind Velocity	Available Driving Energy
	(atm)	(K)	(km/hr)	(watts/m^2)
Venus	90	<15	3	630
Earth	1.0	40	60	840
Mars	5×10^{-3}	110	140	420
Mercury	$< 2 \times 10^{-6}$	~500	~700	8400

Perhaps one of the most decisive factors in planetary meteorology is the rotation rate of the planet. On a planet such as Venus, where a single “day” lasts months, surface winds are believed to be no more than a few kilometers per hour, maximum.[1257,2041] On worlds with intermediate rotation rates like Earth and Mars, typical wind speeds range around 50-70 km/hour.[1257,2067] Fast-spinning bodies like Jupiter are known to have winds averaging 140-290 km/hour and higher near the equator.[1141,1257,2045] Naturally, faster rotation and stronger winds means larger Coriolis forces, along with more violent cyclonic disturbances such as tornadoes, hurricanes, typhoons and water-spouts. Also, slow worlds tend to have greater day/night thermal differentials than faster ones because the air is not as well stirred, Surface temperatures are less uniform as a result.[214]

The heat capacity of the molecules in the atmosphere is also important. This may be thought of as the amount of energy which must be added to a unit of air to raise its temperature a fixed amount. It can also be conceptualized in terms of energy loss: How much heat must be lost to drop the atmospheric temperature one degree ?

An atmosphere like Earth’s in every respect but comprised of hydrogen would have nearly fifteen times the heat capacity of normal air. It would thus take fifteen tithes longer to heat up or cool down, so surface temperatures on a hydrogen-atmosphere planet should be pretty much the same every where.[1257] There would be little if any “climate” as we know it on such a terrestrial.[1257]

The presence of oceans affects the climate in many ways. Largely pelagic worlds should experience smaller variations in surface temperature because the water acts as a giant thermal buffer.[286] On dry worlds, the climate is likely to be more “continental,” or desert-like.[214] With no seas, meteorology becomes more volatile - weather changes more rapidly.

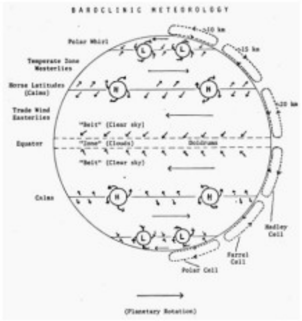
Many other factors are important too. The winds are driven by the energy supplied fun a planet’s star. Worlds near the inside edge of the habitable zone should therefore have more violent weather, because more energy is available. Unfortunately, life is more complicated than this because of the vagaries of atmospheric evolution, albedo differences, and the problem of self-heating planets (like Jupiter and Saturn).

Another factor which is extremely complicated is the effect of planetary mass and surface gravity on wind and air pressure patterns. If Dole’s empirical relation between mass and angular momentum holds up,* then it is a fair guess that worlds with high mass will have higher velocity winds, in general. And there are other, more subtle problems. For instance, the winds on Mars often blow at more than half the local speed of sound. One wonders what a “transsonic meteorology” might be like.[2037]

Some insight into comparative meteorology can perhaps be gained by looking at the peculiar manifestations of weather on other planets in the solar system. Mars has global-scale storms the likes of which have never been seen on Earth. Most every Martian year, dust storms enshroud the entire world in a dull-ochre blanket for months on end. Winds exceed 320 km/hr during this time - far in excess of most Earthly hurricanes. Yet Mars has roughly the same rotation rate as our planet, is colder and farther from Sol, and has a thinner and less massive atmosphere. How can such a magnificent storm develop ?

A small, natural cyclonic disturbance is where it all begins (Figure 5.8). Airborne particles absorb more sunlight and heat up the surrounding gas; outside of this local turbulence the air is cooler. The temperature differential causes major winds to begin to circulate. While hurricanes on Earth are caused by water vapor condensation near the eye, Martian hurricanes get their energy directly from the sun.2044

Figure 5.8 Different Patterns of Cyclonic Meteorology



Baroclinic Flow

Climate powered by large temperature differential between equator and poles (DT > 10-100°C). Vertical pressure gradient minimal.

Characteristic of:

1. Planets with low pressures.
2. Planets with slower rotation.
3. Planets with negligible internal heating, or which are heated from above (e.g. an optically thick atmosphere).
4. Planets whose atmospheric constituents have relatively low heat capacity (e.g. O_2, N_2).
5. Planets having a solid surface.

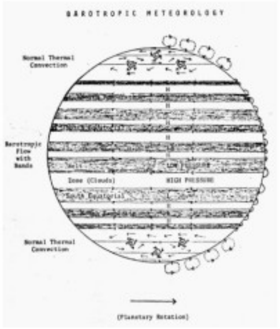
CALMS are regions of "Coriolis pileup," unstable with little wind, source of cyclonic disturbances (hurricanes). Cold, dry air falls, removes low altitude moisture, creating most of world's deserts.

DOLDRUMS -- moist, warm, rising air causes cloud cover "zone" at Equator ± 100 latitude.

Low and high PRESSURE REGIONS form into localized eddies and whorls.

FEATURES persist for weeks (Earth) or for months (Mars).

Typical examples in our solar system:
EARTH, MARS (especially in Martian autumn and spring),
VENUS (single Hadley cell, "symmetric" regime circulation)



Barotropic Flow

Climate powered by vertical pressure gradient forces. Temperature differential between equator and pole minimal (DT < 5°C).

Characteristic of:

1. Planets with high pressures.
2. Planets with fast rotation.
3. Planets with significant internal heating.
4. Planets whose atmospheric constituents have relatively large heat (e.g. capacity (e.g. H_2, He).
5. Planets with no solid surface.

ZONES contain moist, warm, rising air.

BELTS contain dry, cool, falling air.

WINDS flow around planet at zone/belt boundaries.

Low and high PRESSURE REGIONS girdle planet in a series of concentric zonal systems.

Atmospheric FEATURES can persist for centuries because there is no solid surface below the weather, and therefore no real frictional drag.

Typical example in our solar system: JUPITER, SATURN

Earth has a relatively massive atmosphere with large thermal inertia, so temperature changes occur only very slowly. Our planet thus has a long "response time" to change. Not so on Mars. The Martian air responds to changes in temperature in a matter of hours, because its thermal inertia is low. Winds can build up much faster.

The cyclonic disturbance grows larger and the winds go higher still. One planetologist has estimated that once the turbulence extends about ten kilometers vertically and perhaps 50-90 kilometers horizontally, the storm cannot be stopped,1313 A kind of "runaway weather," the Martian hurricane continues to grow until it virtually covers the globe. At this point, the thermal gradient which drives the winds lessens and finally disappears, and the storm soon begins to taper off.**

Science fiction writer Arthur C. Clarke has considered an unusual form of weather that might exist on cold terrestrials (like Titan), which are thought to possess large amounts of solid ammonia and gaseous methane. We know that the smaller the liquidity range of a thalassogen, the more volatile will be the meteorology. Sudden weather changes should be commonplace. As an example, liquid methane may be present in small pools on Titan in local cold spots on the surface. Because it has such a narrow liquidity range, the methane could abruptly flash into steam at the first gust of warmer air or if there is a momentary break in the clouds. The high winds thus generated, Clarke suggests, might be called "methane monsoons."1947

Another hard science fictioneer, Hal Clement, has written of the peculiar behavior of weather on planets with very high surface pressures. Gases -- and air -- are generally at least a thousand times less dense than liquids. But what if we have an atmosphere with a base pressure from 100-1000 times Earth-normal? The air will take on liquid-like densities, becoming thick and viscous.1936

What can we say about the presence of frozen thalassogen on the planetary surface ? It is well-known that for the greater part of its history, Earth was without polar icecaps. We have them now only because we are in the middle of an Ice Age. Ice Ages are believed by some to occur cyclically every 200 million years or so, triggered by small changes in Sol's output or by orbital and rotational resonances.[2068,3678]

(Of course, icecaps need not form only at the poles. A tidally-locked, one-face planet might have a single icecap on the night side only. Or, peculiar resonances between planetary rotation rate and orbital eccentricity could give rise to icecaps located on either side of the equator - although this remains a strictly speculative possibility.[2070])

Will all planets with open oceans have icebergs ? The answer to this deceptively simple question actually has deep climatic significance. We know that the present climate of our world is in a state of very delicate balance. Surface conditions are largely dictated by the overall energy balance. The greenhouse effect acts to hold heat in and trap energy; Earth's shiny polar caps tend toward the opposite extreme, reflecting energy back into space and cooling the planet.

Icebergs are floating chunks of frozen thalassogen. This proves to be a destabilizing factor in Earth's climate, because ice reflects energy away far better than the liquid water of the oceans. If there is a prolonged, unusually cold spell planetwide and abnormally great: amounts of ice are produced, more of Sol's life-giving warmth is cast away by the highly reflective ice floating on the surface. Our planet cools because less heat is available. The icecaps spread, and Earth cools still further. The effect is the exact opposite of the runaway greenhouse discussed earlier, and might properly be termed "runaway icecaps" - an Ice Age.

On the other hand, if the solid form of the thalassogen is less reflective (i.e. darker) than the liquid, the climate should be relatively stable. Any ice formed during a sudden cold snap must subsequently absorb more energy than the surrounding liquid - and soon melt. Icecaps would be unlikely, Ice Ages practically impossible.

Similarly, if a thalassogen cannot form floating icebergs, then even if the ice is highly reflective it still will submerge below the surface of the liquid before it can give rise to thermal instability and runaway icecaps. That is, it moves itself out of the way before it can do much damage. Of course, one man's bread is another's poison. The lack of icebergs may promote a more stable climate, but it will also make biology much less likely.

If there are no icebergs, and frozen thalassogen sinks to the ocean bottom because it's denser, then the sea may freeze from the bottom up and thaw only from the top down. Over the normal range of temperature variations, it is entirely possible that the whole body of liquid could freeze solid for various lengths of time. This is xenologically significant, as the viability of life in such an inimical environment must necessarily be greatly decreased.[47,1551]

Water is virtually unique in this respect: The frozen form, water-ice, floats atop the liquid form. Water expands slightly when it freezes, so the ice is less dense than the fluid. (Only elemental bismuth metal and a very few other rare substances display this behavior.) Hence, where water is the thalassogen, bergs will float and life is not precluded by the threat of a planetwide oceanic freezeup during cold spells.[974] (The price paid for this advantage is climatic instability - it would appear that Ice Ages are possible only if water is the thalassogen.)

Not so with all other thalassogens of interest. As we see from Table 5.10 below, no other single thalassogen has the unique property of floating iceberg production. Even if we allow for a dual thalassogen system, say of ammonia and methane,[1947] it is rather difficult to arrange for icebergs or floes of solid ice. Ammonia-ice not only sinks in liquid ammonia, but in liquid methane as well.***

But there are a few possibilities. Water icebergs should float on oceans of liquid oxygen, as should methane and ammonia bergs. Water-ice will also float on carbon dioxide seas at the right pressures. But sulfur, hydrogen, carbon dioxide and oxygen floes are probably out of the question on any kind of reasonable planet.

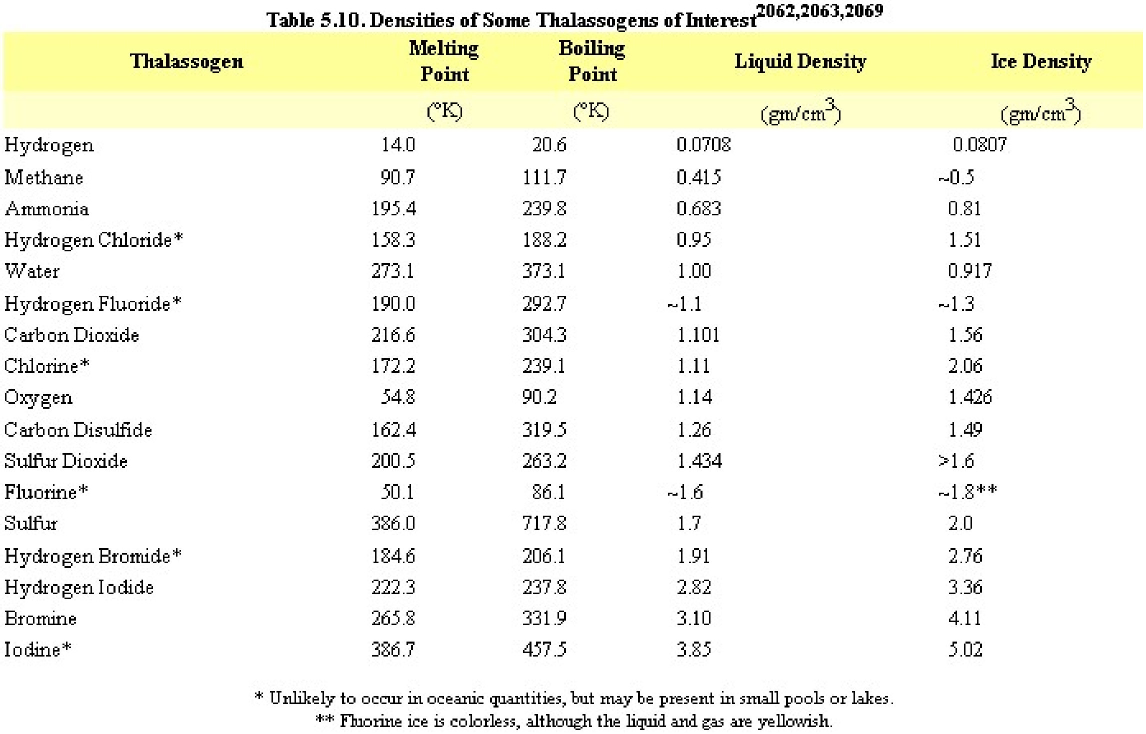


Table 5.10. Densities of Some Thalassogens of Interest[2062,2063,2069]

Thalassogen	Melting Point	Boiling Point	Liquid Density	Ice Density
	(°K)	(°K)	(gm/cm^3)	(gm/cm^3)
Hydrogen	14.0	20.6	0.0708	0.0807
Methane	90.7	111.7	0.415	~0.5
Ammonia	195.4	239.8	0.683	0.81
Hydrogen Chloride*	158.3	188.2	0.95	1.51
Water	273.1	373.1	1.00	0.917
Hydrogen Fluoride*	190.0	292.7	~1.1	~1.3
Carbon Dioxide	216.6	304.3	1.101	1.56
Chlorine*	172.2	239.1	1.11	2.06
Oxygen	54.8	90.2	1.14	1.426
Carbon Disulfide	162.4	319.5	1.26	1.49
Sulfur Dioxide	200.5	263.2	1.434	>1.6
Fluorine*	50.1	86.1	~1.6	~1.8**
Sulfur	386.0	717.8	1.7	2.0
Hydrogen Bromide*	184.6	206.1	1.91	2.76
Hydrogen Iodide	222.3	237.8	2.82	3.36
Bromine	265.8	331.9	3.10	4.11
Iodine*	386.7	457.5	3.85	5.02

* Unlikely to occur in oceanic quantities, but may be present in small pools or lakes.
** Fluorine ice is colorless, although the liquid and gas are yellowish.

Many other specific meteorological phenomena are also of major interest to xenologists. For instance, clouds and fogs should be common in any atmosphere with reasonable pressures. Condensation nuclei will always be plentiful, and most thalassogens can condense to tiny droplets around them at moderate temperatures. Rain should likewise be a regular occurrence at the surface of worlds possessing large open bodies of liquid thalassogen. (Of course, other things may rain down - such as the periodic volcanic ash “rains” in Iceland.)

The height at which clouds form is a function of humidity, thalassogen vapor pressure, atmospheric thermal lapse rate, and a score of other interrelated factors. The suggestion that more massive worlds with higher gravity must have lower-hanging clouds[2075] is simply too facile to be of much use to us.

Any planet which has clouds, rain, and sunlight reaching the surface will also have rainbows from time to time. These beautiful spectral arcs are the result of thalassogen droplets suspended in the air, acting as tiny prisms in concert to separate the incoming light into its constituent colors. The larger the droplets, the more intensely vivid the bow will appear.[2149]

Ignoring for the moment many other important factors, a larger planet with higher surface gravity will pull raindrops down before they have a chance to grow very large. Rainbows on larger worlds should tend to be rather dim, unimpressive affairs. On smaller worlds, where droplets can grow to larger sizes because they fall more slowly, rainbows should be impressive riots of color.[2059] Furthermore, if there happens to be a very bright moon overhead or more than one sun; bows might appear in several parts of the sky at the same time.[2059]

How about lightning discharges ? Electrical storms occur because molecules are split apart in the upper atmosphere to ions, which are then carried to the ground by dust and rain. This charges up the planet to at least half a million volts from ground to top of atmosphere - a process likely on any world, save for the exact details of scale height and voltage. Planets with regular and intense sand or dust storms may generate intense electrical fields that could lead to more severe or more frequent discharges.[1232]

Another important factor is the breakdown voltage of the air - the voltage at which a spark will jump a gap of unit distance. A charged cloud may be 100 million volts higher than the surface below, which is high enough for the “spark” to leap to earth. The spark gap voltage for dry air (at 1 atm) is usually listed as 11000 volts/cm, and can be corrected for variations in temperature, pressure, and humidity. Now, if the atmosphere was comprised of a more conductive gas, such as neon, the spark gap voltage would only be 800 volts/cm (at 1 atm). This means that lightning should occur more frequently in neon (hydrogen, helium, etc.) than in oxygen (nitrogen, halogens, etc.).

This prediction may perhaps claim some support from the radio observations of Jupiter in the last decade or so. Decameter radio wave outbursts lasting from seconds to hours have been detected, with an equivalent energy of trillions of terrestrial lightning strokes per event.[609] Similar outbursts have been observed on Saturn.[2097]

Will alien worlds have auroras too ? Probably. These displays appear at the north and south planetary magnetic poles, and are caused by the funneling of solar wind ions in the converging magnetic field of the planet. Rapidly rotating, massive worlds should tend to have stronger magnetic fields. Also, hotter stars most likely have more vigorous solar winds. We would guess that a 4 Mearth planet with a ten-hour day circling an F5 sun will probably have far more striking auroral displays than a tidally-locked 0.4 Mearth planet orbiting a K2 star.

Mirage physics is also rather interesting. On Earth, mirages often result when there is a layer of warm air lying close to the ground. This air, being hotter, is less dense. It acts as a giant lens. Light coming from the sky near the horizon swoops down close to the ground and is refracted back up.[2073] The mirage of water on an open highway is just a smeared-out image of blue sky.

Mirages on Earth generally appear about 100 meters away from the observer at ground level. On Mars, where the atmosphere is so thin the air is hardly heated by the ground at all, the refraction layer is thinner.[950] The mirage backs away, out to about one kilometer. (To date, no Martian mirages have been photographed by the Viking landers, possibly due to the extreme roughness of the terrain and because the camera horizon is too close.[2094])

On planets with very high density air, as on Venus, the mirage concept literally takes on new meaning. The transfer of heat from ground to near-surface air is complete, and it is believed by many that the extreme refraction near the ground will cause a kind of “fishbowl effect.”[15,2060] The horizon would appear above the observer at all times,**** appearing to bend upward at the sides.[2034] (The idea has already been used in science fiction.[2071])

Dr. Conway Snyder at the Jet Propulsion Laboratory in Pasadena, California has performed a numerical simulation of the light-bending phenomenon at the Cytherian surface.[2066] Let us imagine with him, for a moment, that we are aliens on the surface of Venus. Our eyeballs can see into the microwave region of the spectrum as well as the visible. What do we see ?

The horizon appears to be elevated upward, all around us, at 9.40 from the horizontal. (Only 5°, if visibility drops to 200 kilometers.) Since Venus rotates backwards, the sun rises in the west and sets in the east, creeping across the sky at an imperceptible eight minutes of arc per hour. We are standing at the equator at the time of the equinox, so Sol lies directly over head at noon, Cytherian daylight time.

As the sun slowly falls toward the horizon, its shape begins to change. Its vertical dimension commences to shrink, while the horizontal component remains unchanged. At 6 PM Cytherian time, Sol should just be setting - but it isn't. Instead, it lies 10.4° up, but is squashed down to a quarter of its normal size. By 7 PM the squashing has become 250:1 compared with the horizontal dimension, and by 8 PM, 30,000:1.

Sometime close to 12 PM, the tiny solar sliver suddenly increases in length dramatically, and at the stroke of midnight wraps itself around the horizon in a pencil-thin ring of light. The line then breaks in the east, the sun begins to reassemble itself in the west, and sunrise begins.

If we are more than 3/8° away from the solar latitude, however, the ring of light will not appear. Instead, we see the compressed sun-image "crawl like a worm across the horizon during the night, from the point where it has set to the place where it is planning to rise."[2086]

* Using our own solar system as his source of data, Dole finds that angular velocity is directly proportional to the square root of planetary mass for planets which are not tidally braked or locked.[214]

** Because the Martian atmosphere is only 1% as dense as that of Earth, the wind packs only about 10% as much punch, An astronaut standing in a 320 km/hour gale on the surface of the red planet would feel the equivalent of a 32 km/hour wind on Earth.[1313]

*** It should be noted that there are some six different allotropic forms of water-ice which form at various temperatures and pressures. Only one of these - "natural ice" or ice I as the chemists call it - is lighter than water. Ice II through ice VII all sink if placed on the liquid.

**** Calculations indicate the effect would be rather small, though, perhaps a few degrees inclination at most.[2068] The first pictures back from the two Russian Venera spacecraft that landed on Venus in 1975 showed no evidence of the fish bowl,[2034,2079] but since the maximum range in the photos was only a few hundred meters the issue remains unresolved.

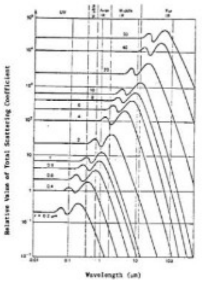
5.4.2 Sky Colors

What about the color of alien skies ? Must they always be blue ?[2059] Of course, ETs will probably have different physiological seeing equipment than ours, but we shall permit ourselves the minor anthropocentric convenience of viewing their world through human eyes.

Light that reaches our eyes from the sky is merely sunlight scattered by the atmosphere. Had the Earth no air, our sky would appear quite black. This explains where the light comes from, but not why it is blue.

In 1899, a famous Englishman by the name of Lord Rayleigh devised an explanation for the color of the sky (Figure 5.9). According to his mathematical theory, scattering from very small particles (such as air molecules) increases as the fourth power of wavelength.[1995] This means that blue light, which has a very small wavelength, is highly scattered, while red light, with a relatively long wavelength, is scattered much less - sixteen times less, in fact.[1990,1991] So the blue light is preferentially removed from sunbeams and spread out uniformly from horizon to horizon. A little red is also present, and some yellow and green too, but blue is clearly predominant.

Figure 5.9 Scattering of Light in Planetary Atmospheres



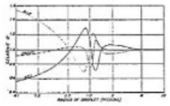
SCATTERING OF LIGHT BY AIRBORNE PARTICULATE MATTER[1993, 1994, 1995]

The family of curves at left represent the relative amount of light scattered away -- at each particular frequency of light -- by a hypothetical cloud of perfectly spherical, transparent, uniform size droplets suspended in air. However, ideal Mie monodispersions rarely occur in nature. Clouds of particles are of various shapes, textures, sizes, colors and degrees of opacity. Consequently, this graph is an abstracted, idealized version of reality and should be interpreted in that spirit.

The beginnings of Rayleigh scattering are seen in the visible portion of the spectrum, in the right-hand section of the graph, where the particle radius r falls below a tenth of a micron or so. The flat part of the curves stretching horizontally to the left indicate uniform scattering of all frequencies of light. The wavy part in the middle demonstrate the oscillatory nature of the preferential scattering by color.

EXTINCTION OF LIGHT BY PASSAGE THROUGH A CLOUD OF PARTICLES[1995]

The three curves at right are simply a slightly different way of looking at the data in the above graph. Here, we compare the relative attenuation of blue, green and red light as it passes through the same cloud of idealized haze/fog particles we considered before. Note that for small droplets in the air, blue is preferentially scattered giving a blue sky. At large particle sizes, no frequency is preferred and the sky washes out white. For intermediate scatterer radii, red and blue alternate in their supremacy. Note also that green, whenever it predominates, is accompanied by large amounts of the other two colors -- leaving a largely white sky with perhaps the faintest of greenish tinges.



Type	Radius	Concentration
	(mm)	(cm^{-3})
Air molecule	10^{-4}	10^{19}
Aitken nucleus	10^{-1} - 10^{-2}	10^{4}-10^{2}
Haze particle	10^{-2} - 1	10^{3}-10
Fog droplet	1 - 10	100-10
Cloud droplet	1 - 10	300-10
Raindrop	10^{2} - 10^{4}	10^{-2} - 10^{-4}

PARTICLES RESPONSIBLE FOR NATURAL ATMOSPHERIC SCATTERING[1994]

This table lists the approximate size (in microns) and concentration of typical scattering particles normally present in Earth's air.

Aitken nuclei are hygroscopic (water-absorbing) microscopic condensation nuclei, the result of chimney flue gases, tobacco smoke, sulfur dioxide industrial emissions, and a host of natural sources.

We can correct the Rayleigh theory for differences in planetary surface pressure and temperature. It turns out that the amount of light scattered is directly proportional to the atmospheric pressure, and inversely proportional to the temperature.[1994] So if we double the pressure we double the amount of light scattered in all colors - and the sky gets brighter generally. Doubling the temperature has the opposite effect : the intensity of scattering is cut in half. On the surface of a high pressure planet like Venus, the effect would be rather extreme. All colors would be so strongly scattered that the sky be comes a dim, featureless white.[2059]

In a perfectly clear, Earthlike atmosphere, the sky would be a rich blue hue. But we observe it to be a hazy, lighter blue. Why ?

The Rayleigh theory applies only to particles which are much smaller than the wavelength of light, say, less than 10-100 Angstroms.[1994] If the scatterers in the air are much larger than this (as with dust in the atmosphere), Rayleigh's formulation breaks down and the vastly more complicated Mie theory must be used[1995] - the details of which are beyond the scope of this book.

Rayleigh's theory tells us that particles smaller than about 0.1 micron will preferentially scatter blue light. The Mie theory explains the behavior of atmospheres containing particles larger than about 4 microns. Above this critical size all frequencies of light are equally scattered, and the result is a gray or white sky. (Since there is always plenty of particulate matter, water haze and industrial pollutants floating around in the air - perhaps 100-1000 kg over each square kilometer - the sky's sharp natural blueness is washed out unless we move to higher altitudes.)

Between 0.1 and 4 microns, the Mie theory becomes especially complex.[1995] The selection by color oscillates, sometimes preferring to scatter more blue and sometimes more red.[1993,1995] This effect is extremely sensitive to particle size. A uniform haze of 0.4 micron particles would scatter more blue (blue sky), but a similar cloud of 0.6 micron particles would produce more red (red sky).[1993,1994]

If this is true, why don't we commonly see such vivid colors in natural Earthly hazes and fogs ? The reason is the natural fogs and mists contain a mixture of all sizes of particles, from one to ten microns or larger.[1995] As a result, these interesting color effects are added together randomly and average themselves out to a bland whiteness - which we do observe. If some reasonable mechanism could be proposed to get particles of a single, specific size into the atmosphere (i.e., a “monodispersion”); quite beautiful red and blue sky colors would be possible.

Barring this fascinating alternative, as particles of increasing size are added to a “Rayleigh atmosphere” the sky color will appear to change from dark blue to powdered blue, to whitish blue, and finally to grayish white.

A third factor affects sky color besides Rayleigh and Mie scattering. The color of the particles themselves is very important. A red particle, for instance, absorbs all light but red - which it reflects. Thus, it appears red in color. A green particle tend: to absorb blue and red but reflect green. (Under red or blue light such a particle would look black, but in green light it looks green.) So an atmosphere heavily laden with, say, green dust particles should also take on a distinct greenish hue.

We are now in a position to understand why the sky of Mars is red.[1989,2035] We add up the contributions from three effects : (1) Rayleigh scattering should give blue sky light, but will only be about 1% of its intensity on Earth because the Martian air pressure is only 0.01 atm;[2035] (2) Dust motes an estimated two microns in diameter[1989] should produce a bright haze without color by Mie scattering; and (3) Particles in the Martian atmosphere are reddish surface dust, which reflect red light while preferentially absorbing blue and green. Hence, the sky of Mars is unusually bright, and appears a hazy “salmon pink” or “orange cream”[1989] (“embarrassed brick” ?[2035]). It is clear that many other sky colors are similarly possible, provided a planet can be found with fine surface dust of the desired color.

There are other ways to get non-blue skies. For instance, we have discussed the process of frequency-selective light absorption by dust particles. Molecules of gas exhibit this property too.[619,620] The sky would no longer be blue under a fluorine atmosphere, to take one example. This gas absorbs blue strongly, and appears pale yellow in color. The sky would take on this color.

Chlorine air should appear green, because it absorbs light preferentially at the blue and orange-red ends of the spectrum. Similarly, an atmosphere of nitrogen dioxide would provide an orange-brown sky. If sulfur vapor is available, the air would alter color dramatically with large temperature changes. Near the boiling point at 720 K the sulfur sky would be dark yellow; as the temperature climbed to 770 K the atmosphere would turn a deep red, returning to straw yellow at about 1120 K.

The problem with using gases such as these is that they absorb light too darned well! At one atm pressure, a few meters of pure chlorine gas would transmit no visible light.[2059] This is because even though blue and red are removed preferentially, some green is also eliminated. The sulfur vapor fares no better, sadly. At 1 atm pressure, blue light is cut to below human eye visibility in less than half a meter, and the red is gone in fifty meters.

So if the partial pressures of any of the aforementioned gaseous absorbers exceeds perhaps 0.001-0.01 atm, no light of any color will be able to reach the surface of the planet from the outside. Any inhabitants there must find their way around without the assistance of eyeballs.

If we want to use gaseous absorbers, it is better to choose weak absorbers instead of strong ones. For instance, under a deep ozone atmosphere the sky would probably appear reddish, because the gas is known to slightly absorb blue, yellow, and green sunlight rather well. Methane and ammonia, weak absorbers as they are, would provide a lovely blue-green sky (because absorption is mainly in the red) assuming the atmosphere was thick enough.[2059]

If the temperature at the surface is sufficiently high, another factor must be taken into account: blackbody radiation. Just as a stove’s heating element glows red when it is hot, so will the surface of a fried world like Venus. On Venus, red light emitted by the hot rocks could be orders of magnitude brighter than terrestrial moonlight - about like Earth on a dark, rainy day. In the blue the intensity would be about 100000 times less than in the red, roughly 10% as bright as moonlight. Since red clearly predominates, reflections off the cloud base will give the appearance of a red sky, assuming fair or good visibility.

Still another trick to get colorful skies is to arrange for permanent colored cloud covers. Arthur Clarke suggests in Imperial Earth that the skies of Titan may be white with beautiful orange and red streaks and whorls, because of the presence of hydrocarbons and other organics in the atmosphere.[1947] This is similar to what is believed to impart coloration both to the orange bands and the Red Spot of Jupiter. Unfortunately, 20th-century humans are unlikely to find photochemical smog a very attractive method of obtaining unusual sky colors.

More aesthetically appealing are the possibilities of continuous luminescence, phosphorescence, and fluorescence as an adjunct to sky color phenomena.[1991] But perhaps the most intriguing of all is the striking sunset effect called the “green flash,” which occurs just after the sun has dropped below the horizon.[1992] The red and yellow light is not refracted enough to reach the observer at this point, and the blue has all been scattered away. This leaves only green, which is experienced as a brilliant flash during optimal viewing conditions.[2059]

But flashes on other planets could appear vastly different. Even on Earth, blue and violet flashes have been seen at higher altitudes.[1992] On low-pressure worlds, where blue is scattered less (as on Mars), blue flashes may be the rule. the planet's rotation is slow enough, the “flash” could become a “glow,” lasting for seconds or even minutes.

It might be supposed that by changing stars one might be able to affect the color of the sky. After all, sky light is just scattered sunlight, and a class K sun puts out a lot more red than a class F star. However, as we see in Table 5.11 on the next page, the consequences of illuminating an Earthlike atmosphere under the light of different stars are not great. Blue will predominate in the Rayleigh sky color, even if light from the coolest, reddest class M sun is used. On the other hand, we note that a terrestrial planet circling an F5 star will have skies of much deeper blue than a world associated with, say, a K2 sun. Stellar class is at best a very fine adjustment to sky color, in capable of countermanding the dictates of the atmosphere.

Table 5.11. Rayleigh Molecular Scattering in Planetary Atmospheres as a Function of Stellar Class

Color Scattered	F0 Star	G0 Star	K0 Star	M0 Star
Blue	77%	70%	61%	44%
Green	18%	23%	28%	37%
Red	5%	7%	11%	19%
Net Sky Color	vivid blue	powdered blue	light blue	pale-whitish blue

What about the appearance of the primary itself, as viewed from the planet’s surface ? If the planet is in orbit around an orange or red star, the sun would seem bigger and redder than Sol does in our sky. Colors at the surface, illuminated by sunlight, would appear slightly different - the blues darker and the reds brighter. Shadows would have blurrier outlines than those on Earth. But an F5 star might cast sharper shadows, with a slight bluish tinge.[877]

As far as color is concerned, if the observers are beneath an atmosphere which either scatters the blue (blue sky) or absorbs blue preferentially (red sky), then light from the star will lose blueness and appear redder.[1991] This effect is most striking at sunset on Earth, when the blue in Sol's rays is so completely attenuated that fiery red alone remains.[1990] Were the surface pressure perhaps five or ten times greater, Sol would appear similarly reddish at high noon and deep crimson at sunset (but much dimmer). Wispy puffs of clouds would catch the ruddy solar rays throughout the day, streaking and mottling the luminous azure sky with magnificent ever-changing patterns of coralline and cerise.

If the observers are at the bottom of an atmosphere which absorbs the red (blue sky) or scatters the red preferentially (red sky), the sun will appear bluer than normal.[1993] This effect has been seen, albeit rather infrequently, on Earth from time to time. Owing to the presence of particles at high altitudes following the great volcanic eruption at Krakatoa in August, 1883, the Moon took on a distinct blue-green color. This phenomenon of "blue moon" was observed in Great Britain on September 26, 1950, due to widespread fires covering a quarter-million acres of forestland in northern British Columbia, and on other occasions elsewhere.[360] Blue suns and green suns are also possible in the same manner,[1993] and have been observed infrequently.[2077]

I