Ecological Aspects of Planetary Atmospheres With Special Reference to Mars

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CURRENT KNOWLEDGE as to the composition of the planetary atmospheres is reviewed in *The Atmospheres of the Earth and Planets*, a book edited by P. Kuiper and published in 1947.[25] This comparative astronomical study indicates that only the atmospheres of Mars and perhaps Venus justify a comparative physiological and ecological study. Of special interest are the findings that CO_2 and H_2O are present in the Martian atmosphere and that the infra-red spectrum of the so-called green areas on Mars is compatible with the spectrum of lower plants (lichens and mosses).

The publication of the above-mentioned monograph certainly gives new impetus to the discussion of the possibility of life on other planets. It is inspiring for biologists to join such discussions originated by the astronomers: Schiaparelli, and especially P. Lowell[28] (see further, W. H. Pickering,[36] E. H. Mounder,[34] H. S. Jones,[21] G. T. Kuiper,[25] and G. deVaucouleur.[48]

Today physiological and ecological considerations to this end can be derived from a rather broad background of knowledge, since during the last few decades biology has made great progress in the study of the limits and stages of life as a function of environmental conditions.[10,37,38] In particular, cold and hypoxia have been the subject of intense research in aviation medicine.[4,5,7,15,27,35,41] On the basis of this present physiological experience we are able to exclude some manifestations of life and to consider others as possible on other planets.

This undertaking presupposes the assumption that the laws of biological processes are the same throughout the universe, and that the structure of living matter is based on the carbon atom and its unique chemical properties. Certain other assumptions — taking silicon to be the base atom, for instance—would trespass the bounds of sound speculation.

In this study we shall confine ourselves to the manifestations of life as we know them, and to apply to the physical environment on other planets, the yardsticks of physiology and ecology as they are valid on earth.[2] In doing so we can estimate the extent to which life on other planets is possible. At the same time we arrive at a better understanding of the limitations and abundance of life on our own planet.

In addition to being of general scientific and human interest, this subject is of special interest to aviation medicine and space medicine, two fields of study vitally concerned with the question of life under very extreme environmental conditions. No planet offers a better stage for such physiological and ecological considerations than does the planet Mars. In this respect it is interesting to note that the Martian surface atmosphere has some properties in common with the terrestrial atmosphere at an altitude of about 10 miles.

According to common usage in terrestrial ecology, we shall study the question concerning life on planets from the viewpoint of the "law of the minimum" (J. von Liebig[26]) and the "principle of limiting factors" as has been elaborated by F. F. Blackman.[8] In their simplest form these laws state that the environmental factors—such as temperature, light, water, and chemical components of soil and air—impose limits to life by being either excessively strong and abundant or too weak and sparse. A certain minimum must be reached and a certain maximum must not be exceeded; only within these limits can life exist and develop. Between these two cardinal points lies a third one, representing the optimum of an environmental condition or of a combination of such conditions, which is distinguished by being particularly favorable for the flourishing of life. Although these cardinal points, as was found later,[8] are fluctuating greatly in relation to each other ("relatively limiting factors"), in the following study these principles will be applied in their simplest form to the planets and especially to Mars. We shall confine ourselves to two environmental factors, namely, temperature and oxygen.*

*A study including all environmental factors (Radiation, H_2O, CO_2, O_3 and some unusual constituents of planetary atmosphere such as NH_3, CH_4) will be published soon.

OVERALL ECOLOGICAL VIEW OF THE PLANETS FROM THE STANDPOINT OF TEMPERATURE

Active processes of life such as growth, metabolism, activity, reproduction, etc., take place only within

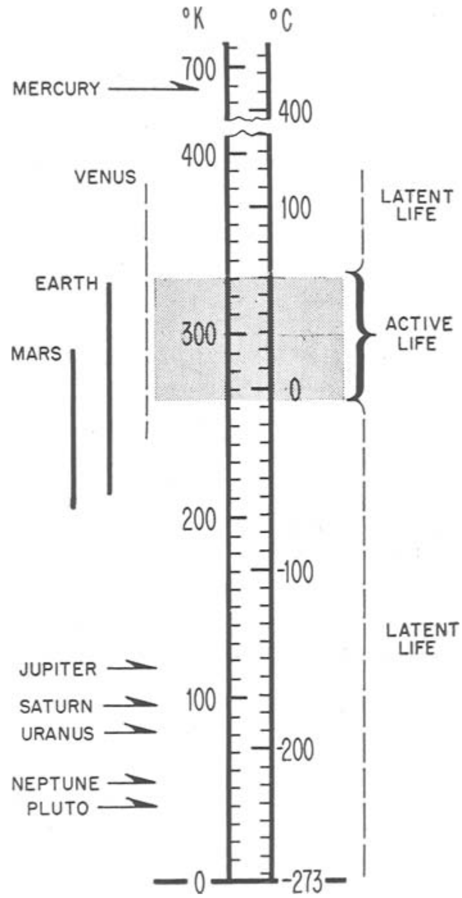

Fig. 1. *(Left Side)* Surface temperature of the planets. *(Right Side)* Temperature scale of life.

a temperature range (prevailing in the tissue) between a few degrees below the freezing point of water and about +55° to 60° C. (Fig. 1). Above this temperature living matter is transposed into the state of "heat rigor" and soon perishes (dehydration, enzyme inactivation, protein coagulation). Only the thermophilic bacteria are still capable of growing at temperatures up to 75° C. Spores of bacteria and certain seeds can survive if exposed to temperatures of +120° C. for several hours. Below the minimum temperature required for active life lies the beginning of the lethal range for most organisms; yet, as is known, arctic plants survive temperatures down to —60° C. Thus it was found experimentally, by immersing the specimens in liquid nitrogen, oxygen, hydrogen, and even helium, that certain lower organisms such as algae, bacteria, lichens, and mosses are capable, for weeks, of withstanding temperatures closely approaching absolute zero. The living matter is hereby transposed into the state of "cold rigor" which also can be designated as the state of latent or dormant life. Summarizing, we can state that there is no decrease of temperature capable of destroying, unconditionally, every form of living matter, provided the onset of cold follows certain temporal patterns.[16,18,23]

If we now consider the temperatures found on the surface and in the atmospheres of the planets,[43] we see that Mercury's temperature lies far above the maximum cardinal point, within the lethal range (Fig. 1). Venus with more than 100° C. in its lower atmospheric layers and about —25° C. in its outermost stratum approaches biological temperatures only in certain higher strata. The temperatures found on earth ranging from —60° to +50° C. cover the entire range of active life with its upper half, while they also cover about 60 centigrades of the cold range of latent life. The Martian temperature range with its upper quarter coincides with the lower part of the biothermal band and covers more than 60 centigrades of the cold range of latent life. The larger planets lie deep in the temperature range of latent life, in other words 150 to 200 centigrades below the temperature minimum for active life.

It may be added that the temperature of the moon varies between —150° and 100° C.

In conclusion the following may be said: From the standpoint of temperature, Mars and possibly Venus* are the only planets, aside from the Earth, which at present possess the prerequisites of life, in our sense. In this connection, it must be considered that in view of the large diurnal amplitudes of temperatures only eurythermal liv-

*In regard to Venus, H. Haber (personal communication) presumes that life in the form of a biological aerosol may exist in certain strata of the Venusian atmosphere, where the temperature conditions for the existence of life are fulfilled. Haber further thinks it possible that life attempts to gain a first foothold on planets within their atmospheres in the form of these biological aerosols. There, life becomes a major factor in the development of the chemical constitution of planetary atmospheres. As a consequence, the living matter alters gradually its chemical and thermal environment by changing the atmosphere's constitution, its absorptive qualities regarding solar energy, and its proper radiation, until life may finally succeed in developing explosively. According to this concept, life does not depend entirely on the chances of the creation of a suitable environment effected through inorganic processes on the surface and within the atmosphere of a planet; instead, life itself invades a planet and attempts to form an environment favorable for extensive development. In the light of this concept, Venus and Earth can be considered as presently being in different stages of development.

ing beings can exist on Mars, i.e., those which can resist changes of temperature within a wide range. This physiological requirement also points toward certain lower organisms, such as algae, lichens, and mosses, which are characterized by pronounced eurythermia.

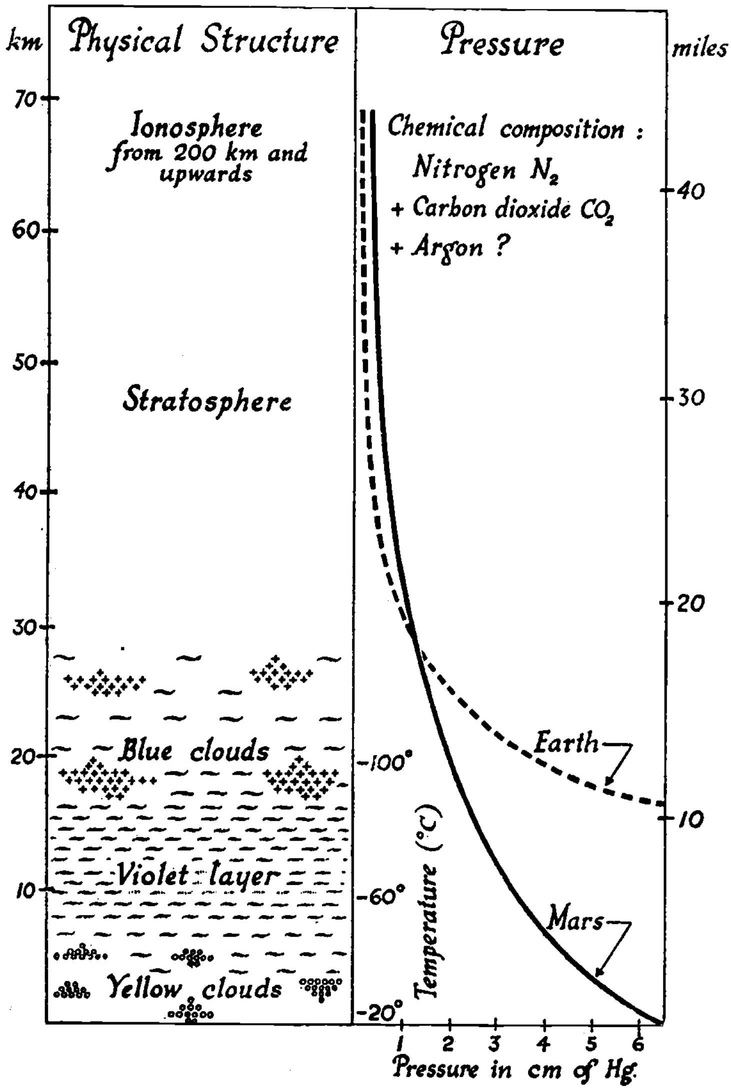

Fig. 2. Summary of the present state of knowledge concerning the atmosphere of Mars. (After G. de Vaucouleurs, The Planet Mars. London: Faber and Faber, Ltd., 1950).

POSSIBILITY OF LIFE ON MARS AND THE PROBLEM OF OXYGEN

Mars might actually be considered a biophilic planet, in regard to temperature, but its combination of ecological

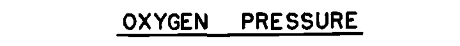

Fig. 3. *(Left side)* Oxygen pressure on Earth and Mars. *(Right side)* Minimum oxygen pressure required for man, animals, and plants.

conditions† (Fig. 2)[43,50] shows a very weak point: Oxygen cannot be found in the Martian atmosphere.[1,25]

†Physiologically Important Astronomical Data of Mars

Period of Rotation	: 24 Hrs. 37 Min. 23 Sec.
Period of Revolution	: 780 days
Acceleration of Gravity	: 0.37 g
Solar Constant	: 0.84 g cal/cm² minute
Temperature Range	: -60 to+30° C.
Atmospheric Pressure	: 60 to 80 millibar
Oxygen Pressure	: Below 0.5 millibar, if any
Carbon Dioxide Pressure	: Equal or even exceeding the terrestrial value.

Oxygen, apart from carbon, is the bioelement par excellence because (1) on the average, oxygen makes up 60 per cent of the living matter (water included); and (2) the most important energy source of the organisms is biological oxidation (aerobic respiration). Another source of energy, though less significant, is anaerobic respiration which requires no oxygen. However, the substances undergoing anaerobic respiration consist of oxygen, to a rather large part.

THE VITAL OXYGEN MINIMUM

The production of energy which is based on biological oxidation consumes large amounts of oxygen and requires a certain concentration of oxygen in the medium surrounding the organisms. For man, for instance, this concentration must be of the order of 5.5×10^{18} oxygen molecules per $cm.^3$ of air. Physiologically, this concentration or the corresponding pressure is likewise limited by a maximum and a minimum; exceeding these limits is incompatible with life. In the following we are mainly interested in the oxygen minimum which is just sufficient to permit a "vita minima."

For man the minimum oxygen pressure is about 65 mm. Hg (corresponding to an altitude of 7,000 m.) (see Fig. 3). Acclimatization to altitudes of about 7,000 m. is possible for some time, as shown by experiments in low pressure chambers and various Himalayan expeditions,[3,4,7,8,9,13,16,17,29,41] but permanent settlements are found up to 5,000 m. only (Andes). Thus, we can conclude that the presence of manlike creatures on Mars belongs to the realm of fantasy, since the minimum oxygen pressure required for man is at the least 100 times larger than the O_2-pressure which may at best be present on Mars.

It was found in decompression chamber experiments that the vital minimum oxygen pressure of homoiothermic animals (monkeys, dogs, cats, rabbits, guinea pigs, rats, pigeons) corresponds to an altitude of 8,000 to 12,000 m., i.e., barely less than 50 mm. Hg (Fig. 3). Poikilothermic animals (reptiles, amphibians, fishes, worms, etc.) withstood pressures below 50 mm. Hg down to 5 mm. Hg and less.[9,12,32] We know that a number of animals of the lowest species can live without oxygen for quite some time, e.g., in deep layers of stagnant lakes.[22,37,38] Oxygen-free habitats are likely to develop in ice-covered ponds and lakes, if there is a high oxygen consumption by organisms. It is necessary that systematic investigations on the oxygen-pressure demand of poikilothermic animals be performed, since many of the experiments and observations made so far are only informative. Be that as it may, so far as the animal kingdom is concerned, the presence of homoiothermic and higher poikilothermic animals on Mars must be negated in view of the prevailing oxygen pressure. Arguing about the presence of lower species is futile because of the lack of clues to justify such argumentation.

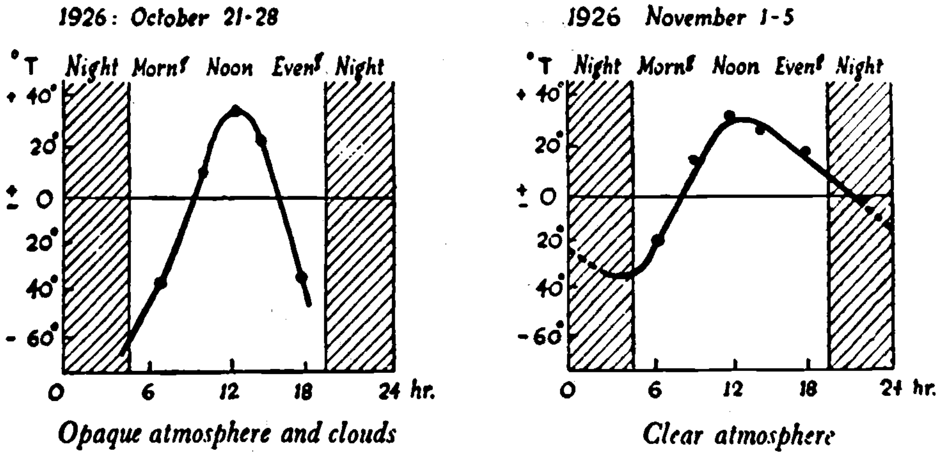

Fig. 4. Diurnal temperature variations in the southern tropical regions of Mars near midsummer of the southern hemisphere, according to the radiometric measurements of W. W. Coblentz at the Lowell Observatory in 1926. (From G. de Vaucouleurs, The Planet Mars. London: Faber and Faber, Ltd., 1950).

There are clues, however—namely, visible ones—that suggest the possible existence of vegetation on Mars. These clues are the seasonal discolorations of the green Martian areas (Lowell[28]) and the spectroscopic finding made by Kuiper.[25] Accepting this vegetation hypothesis,[28,36] we are confronted with the problem of how to view it from the standpoint of physiology, since we must consider the apparent lack of oxygen in the Martian atmosphere.

It is true that plants also respire and require oxygen, though they are able to switch to anaerobic respiration at any time.[24] There are plants which stop respiration as soon as the oxygen pressure of the air falls below 1.5 mm. Hg. This point is designated as the physiological zero point of plant respiration.[20,40] For growth and development, plants generally need a higher oxygen pressure. Notwithstanding, plants can overcome this difficulty by their ability to produce oxygen through the process of photosynthesis; in this respect, plants are superior to animals. They have their own oxygen generators in the chlorophyll-containing chloroplasts.[30,42] As is well known, photosynthesis requires carbon dioxide and water as raw materials, as well as light and a certain temperature.[33] Do these factors reach or exceed the physiological minimum for the process of photosynthesis on Mars?

First of all, the temperature minimum for photosynthesis lies generally some degrees around the freezing point of water. Yet, in some arctic plants (lichens) a minimum of –20° C. has been observed. During daytime on Mars, these temperatures are exceeded by 20 to 40°.[11] (Fig. 4).

Second, the minimum of light is certainly exceeded, since the solar constant on Mars averages 0.84 g cal/cm.^{2} min. (40 per cent of the terrestrial solar constant).

Third, the amount of carbon dioxide in the Martian atmosphere is, according to Kuiper, higher than that found in the terrestrial atmosphere.

Fourth, the presence of H_2O on Mars can be taken for granted. Still, the water question is possibly the weakest point in the combination of conditions for photosynthesis on Mars.

In short, if this last factor should not be definitely below the minimum (see J. Franck[14]), photosynthesis (as we know it) should be possible on Mars, since all other factors are adequate. Moreover, the combination of conditions for photosynthesis on Mars is, on the average, farther away from the optimum than is that on Earth. It is, therefore, improbable, that plants of higher order—such as vascular plants—can exist on Mars because of their higher demands as to temperature and humidity. Only lower plants which are very cold-resistant and drought-enduring (xerophytes) would be able to stand up against such climatic conditions. Kuiper's spectroscopic observations suggest the presence of lichens and mosses.[25] Lichens and mosses belong to the two lowest subdivisions in the plant kingdom, the thallophytes and bryophytes. The lichens have some very peculiar characteristics (see monographs[44,46]). They consist of two dissimilar organisms, a fungus and a number of algae (conidia), living in symbiosis. The fungal component offers protection from cold and supplies inorganic substances including water (because of the hygroscopic nature of most fungi). The algal component builds up organic substances and supplies oxygen through photosynthesis. On account of this ideal symbiosis, lichens are very resistant to a dry and cold environment; they have hardly any demands as to the substratum upon which they live. We find them growing on barks of trees, and even on the surface of rocks and monuments. In the subarctic zones they represent the chief vegetation (reindeer "moss"). In the Himalayan mountains they can be found at altitudes up to 5,000 m. In short, they are the "last outposts" of plant life in every direction. They can exist on bare rocks because of their ability to decompose rock by producing organic acids. In this way they are "pioneer plants," preparing the humus for more demanding plants.[16] In the course of the Earth's history they may well have made the first start for vegetation that developed on barren volcanic rocks. This phenomenon can be observed, for instance, on the lava masses of the Sunset Crater in Arizona.

Liverworts, the more primitive types of the bryophytes, are almost as resistant as the lichens.

In fact, from the biological point of view, it is tempting to assume—even if there is no oxygen as on Mars, for instance—that plants similar to lichens and mosses may also be the last outpost of life and the pioneer plants on other planets.

INTERNAL ATMOSPHERE

Terrestrial plants have developed a mechanism which aids in the process of respiration, transpiration and photosynthesis. This mechanism, when applied to an oxygen- and water-poor environment like that on Mars, affords a further support for the hypothesis of Martian vegetation. It is the phenomenon of the "internal atmosphere." As is well known, the microscopic picture of the thallus of lichens (Fig. 5) and liverworts and that of the leaves of higher plants show intercellular air spaces. Especially pronounced is this manifestation in the leaves of plants submerged in water. This system of intercellular air

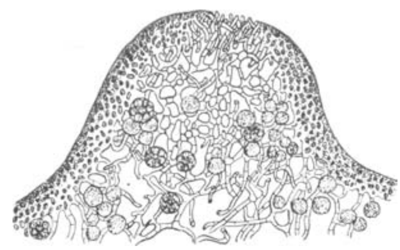

Fig. 5. Cross section through the thallus of a lichen; 175 times. (After Rosendahl, from Fr Tobler. Berlin: Verlag Borntraeger, 1925).

spaces is also called "aerenchyma." The maze of intercellular air passages is so widely spread that practically each cell of the parenchyma is in contact with the internal air. On account of this spongy structure, the inner surface of a leaf is much larger than the outer one. The ratio of inner to outer surface of leaves of different species ranges between 10 and 30.[47] The intercellular air spaces are in contact with the ambient air through pores or stomata. There are several hundreds of such pores per square millimeter of the upper or under leaf surface, respectively. Referring to lichens, some of these plants are equipped mainly with primitive openings called "cyphellae," (Fig. 5).

The physiological significance of this intercellular airing system is obvious. Not only is the area of exchange between leaf and environment increased enormously—a fact reminding us of the surface area of the pulmonary alveoli (= 100 square meters)

—there has also been created a kind of endoatmosphere, or *internal atmosphere.* It is this "private atmosphere," not the ambient air, with which the cells are in direct gas exchange. The microclimate with which the plants supply themselves is more apt to meet the requirements in regard to environmental conditions (for instance, water vapor and oxygen). Analyses of the intercellular air revealed that their oxygen content may amount to 30 to 60 volumes per cent.[33] Hence the air space serves to store the surplus oxygen produced by photosynthesis. In this way the system of intercellular air spaces facilitates the existence of plants in an oxygen-poor or oxygen-free environment (submerged water plants). Suppose the micromorphological structure of the hypothetical Martian plants had developed according to similar lines, then the objection that can be advanced against the existence of vegetation in an oxygen-free Martian atmosphere would lose weight. The picture of Martian plant life could be visioned as follows:

Active plant life on Mars could be possible only on that side of the planet exposed to sunlight, as soon as—after sunrise—the combination of environmental conditions within the internal atmosphere becomes adequate. After sunset the plants would return to a dormant state. Plant life would then be photorhythmic—without light, no active life.

Perhaps, during the Proterozoic era on Earth, the first primitive life was intermittent in a similar way. Today, the terrestrial plants have an oxygen reservoir of $1.2 \cdot 10^{21}$ g within the atmosphere, so they can continue breathing during the night. However, plants existing in an oxygen-free atmosphere, such as on Mars, are forced to live on the "current production" of oxygen. They consume the oxygen in "statu nascendi," or take it from the small stores of their microclimate. After sundown, the plants return to a state of latent life on account of the cold. In an oxygen-poor or oxygen-free milieu, the combination of dark plus cold seems to be more adequate from the physiological viewpoint than darkness plus higher temperatures. In the latter case plants can develop, in general, only if the ambient atmosphere—like that on the Earth — contains oxygen in amounts sufficient for respiration at night. Vegetation on Mars absolutely requires cold nights in view of the hypoxia—or better even, anoxia—existing on this planet.

From the physiological standpoint, therefore, the assumption of a Martian vegetation does not create insurmountable difficulties. This is particularly so if due consideration is given to the relativity of the physiological combination of environmental factors, as well as to morphological and functional adjustments of the living organisms to extreme environmental conditions, as are found in great variety in terrestrial biology. When considering these facts, the oxygen problem offers fewer difficulties than is frequently assumed. It is not oxygen, but carbon dioxide, that is the "conditio sine qua non" for vegetation.

The problem of the presence of oxygen in the Martian atmosphere might be formulated from the physiological point of view as follows:

Although, according to the findings

in astronomy, Mars practically does not have any atmospheric oxygen, from the aspect of physiology there might be an oxygen layer within the vegetative substrate which, at adequate temperature and humidity, moves around the planet together with the sunlight.

In regard to Haber's hypothesis concerning the possibility of life in the Venusian atmosphere, the biological aerosol within the proper layers of the atmosphere of this planet also could benefit from a similar morphological structure that permits formation of an internal atmosphere by drawing oxygen from the ambient carbon dioxide through the process of photosynthesis.

In concluding this subject, I want to thank Dr. Heinz Haber for his advice in pertinent astronomical questions and for very informative discussions.

SUMMARY

The question of the possibility of life on other planets has been approached under the aspect of principles of physical and physiological ecology such as the principle of limiting factors, adaptive processes, et cetera. The discussion has been confined chiefly to temperature and oxygen as ecological factors.

Comparing the scale of bio-temperatures with the temperatures found on the surfaces and within the atmospheres of the planets we find that only Mars and, possibly, Venus are left as ecological spaces since their range of temperatures partially covers the "thermo-band of active life."

Further discussions concern the ecological properties of the Martian atmosphere emphasizing the oxygen question in terms of the minimum pressure of O_2 required for living beings. So far as plant life on Mars is concerned the minimum of environmental factors required for respiration and photosynthesis has been discussed at some length. Emphasis is given to the importance of certain manifestations of adaptation of the microscopical structure of plant tissue such as intercellular air spaces, which —providing an "internal atmosphere" —could considerably facilitate the existence of plant life within a milieu free of oxygen such as on Mars. The assumption of such adaptive morphoses to have taken place in the hypothetical Martian vegetation would diminish physiological objections that can be advanced against its existence.

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