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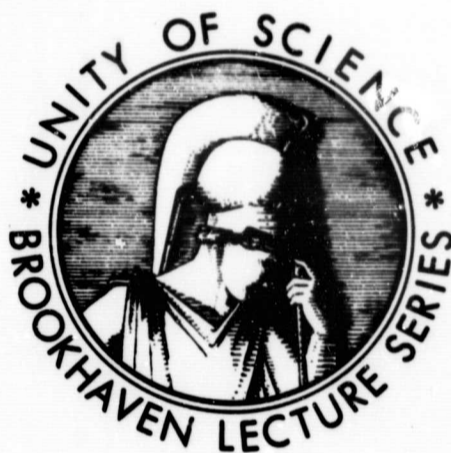
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BROOKHAVEN LECTURE SERIES

The Rise and Stability of the Earth's Atmosphere

LLOYD V. BERKNER AND LAURISTON C. MARSHALL

MASTER



Number 64

March 8, 1967
(Revised June 1968)

BROOKHAVEN NATIONAL LABORATORY

Associated Universities, Inc.

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FOREWORD

The Brookhaven Lectures, held by and for the Brookhaven staff, are meant to provide an intellectual meeting ground for all scientists of the Laboratory. In this role they serve a double purpose: they are to acquaint the listeners with new developments and ideas not only in their own field, but also in other important fields of science, and to give them a heightened awareness of the aims and potentialities of Brookhaven National Laboratory.

Before describing some recent research or the novel design and possible uses of a machine or apparatus, the lecturers attempt to familiarize the audience with the background of the topic to be treated and to define unfamiliar terms as far as possible.

Of course we are fully conscious of the numerous hurdles and pitfalls which necessarily beset such a venture. In particular, the difference in outlook and method between physical and biological sciences presents formidable difficulties. However, if we wish to be aware of progress in other fields of science, we have to consider each obstacle as a challenge which can be met.

The lectures are found to yield some incidental rewards which heighten their spell: In order to organize his talk the lecturer has to look at his work with a new, wider perspective, which provides a satisfying contrast to the often very specialized point of view from which he usually approaches his theoretical or experimental research. Conversely, during the discussion period after his talk, he may derive valuable stimulation from searching questions or technical advice received from listeners with different scientific backgrounds. The audience, on the other hand, has an opportunity to see a colleague who may have long been a friend or acquaintance in a new and interesting light.

The lectures are being organized by a committee which consists of representatives of all departments of the Laboratory. A list of the lectures that have been given and of those which are now scheduled appears on the back of this report.

Gertrude Scharff-Goldhaber

The drawing on the cover is taken from a 5th Century B.C. relief on the Acropolis in Athens, the "Dreaming Athena," by an unknown sculptor.

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*The Rise and Stability of the Earth's Atmosphere**

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and

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INTRODUCTION

It gives me particular pleasure to introduce tonight's speaker. You know that these Brookhaven Lectures are by Brookhaven people for Brookhaven people, but we didn't have to bend the rules very much to invite Lloyd Berkner to speak to us tonight because we still consider him as one of us.

As you may recall, Lloyd Berkner was the President of Associated Universities, Inc. for about ten years, from 1951 to 1960, and it was during this time that Brookhaven had its most important growth. But Lloyd is a man of many, many interests which he has pursued during all his life, not only while he was President of AUI, but also before and after. I have a very efficient staff - they prepared three pages of honors and achievements of Lloyd's. I am not going to read them all to you. I would only like to tell you that he was the driving force, the man who initiated the International Geophysical Year, which was one of the great international achievements and which is a model for many more such enterprises which we hope will come in time. At present he is Chairman of the Board of the Southwest Center for Advanced Studies, and he has found in his new position more time for research. Tonight we shall hear about his ideas in which he has been interested for nearly a third of a century, and which he has brought to fruition in the last few years, on the Life and Stability of the Earth's Atmosphere.

MAURICE GOLDHABER

Lloyd V. Berkner died on June 4, 1967, at the age of 62. In his honor the Brookhaven Lecture Committee sought to publish this lecture, despite the loss of the original manuscript. Because the work discussed by Dr. Berkner represented the fruits of many years of collaboration with Professor L.C. Marshall, the Committee invited Professor Marshall to appear as co-author of the final paper, which he carefully amplified and revised from Miss Jean Corwith's able transcription of a tape recording made during Dr. Berkner's delivery.

The Rise and Stability of the Earth's Atmosphere

The start of the work presented here, about 35 years ago, while one of the authors (Berkner) was at the Carnegie Institution of Washington, led to a problem that could not be solved at that time. A great deal of observational work had to be done in many fields, and during the interim many other people have accomplished some of the research that was necessary to get the problem in hand.

The current project was initiated with Dr. L.C. Marshall in 1962, and the purpose of this lecture is to describe progress of the work that may lead to a general theory of planetary atmospheres of the terrestrial-type planets: Mars, the Earth, Venus, and, to the extent it has an atmosphere, of course, Mercury. It is very important to understand such a general theory because the stability of Earth's own atmosphere can then be predicted with a great deal more precision. The first step, therefore, was to look at the Earth from the standpoint of the history and development of its atmosphere.

In all probability, the Earth was agglomerated out of either a gas or a group of planetesimals (themselves the result of the collapse of a gas), and was without a primordial atmosphere. Absence of atmosphere appears well supported by the very high fractionation ratios of the noble gases. For instance, the present ratio of atmospheric neon to silicon for the Earth is less by a factor of 10^{10} than for the solar system as a whole, and on Earth the ratios of hydrogen and helium to silicon are deficient by factors of 10^6 and 10^{14} compared with the solar system. The nitrogen/neon ratio taken for the universe as a whole is very close to one – about 6.6/8.6. The same abundance ratio taken for the Sun is also nearly unity; but for the Earth, the nitrogen/neon ratio is $\approx 10^6$, making nitrogen more plentiful than expected by several orders of magnitude. Other elemental ratios (e.g., Mg/Si) indicate that atmospheric constituents not bound chemically in solids of the planetesimals forming the Earth were lost during a regime of low gravitational fields prior to final agglomeration.

About 1950, Latimer,¹ at the University of California, did a very nice piece of work in studying the collapse of the dust cloud that would form Earth or its planetesimals. What he discovered was

that the viscosity of the gas during the course of collapse would be so high that the energy of collapse would be radiated away before the Earth or its planetesimals were agglomerated. Consequently, the heat of gravitational collapse would be lost, and the Earth would be agglomerated in a relatively cool state. The evidence indicates that the temperature of agglomeration was about 400°C , and that there was no primordial atmosphere.

Where then does the atmosphere come from? As nearly as can be determined at the present time, it comes entirely from secondary sources. With the exception of one gas, namely oxygen, all components of the atmosphere come from the interior of the Earth: through thermal springs and volcanoes. Note that oxygen is always bound chemically at volcano temperature. These sources, therefore, yield nitrogen, water, carbon dioxide, and a series of trace elements, notably ^{40}K . The last is the source of ^{40}Ar , the principal isotope of argon and a significant component of Earth's atmosphere. This atmosphere contains, at the present time, in column, about 210 g cm^{-2} of oxygen, about 780 g cm^{-2} of nitrogen, $2.8 \times 10^5\text{ g cm}^{-2}$ of water, and about 13 g cm^{-2} of argon. For carbon dioxide, it has been calculated that the total amount released into the Earth's atmosphere is on the order of 5×10^4 , or $50,000\text{ g cm}^{-2}$. The amount of CO_2 actually present in the atmosphere is considerably less. This is due largely to the deposition of carbonates (limestones), and here the oceans are an important factor. During the early history of the Earth, the blue-green algae were probably the most important users of carbonates in solution. Later a wide variety of shell-bearing organisms, of which the Foraminifera are only one example, continued the process of carbonate utilization and final deposition. It is from these records of fossil deposition that the total release of CO_2 can be calculated.

Now one might ask, what caused the Earth to be heated to the point of out-gassing by thermal phenomena if it was originally cool? There are at least four sources of heating: first, there is radioactivity, which at present is only $\frac{1}{10}$ of the original amount available; $\frac{1}{10}$ of the radioactivity has al-

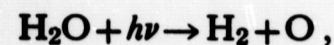
ready been dissipated, largely by decay of ^{40}K . This source, and the next two mentioned, each yield a total of on the order of 10^{37} ergs of heat energy, a very large amount. The second source may be surprising: it is earthquakes. The Earth has apparently slowed in rotation from its original 4 hr per revolution to the present 24. With this, oblateness has also changed; and because the Earth has strength, the hydrodynamic symmetry lags the centrifugal force. Consequently, there are large forces set up in the crust of the Earth that are released by earthquakes. Such local earthquakes can release on the order of 10^{23} ergs during each occurrence, and this energy superimposed on the radioactive heating melts large amounts of magma.

The third source of heat was the separation of the Earth's core. When the Earth was agglomerated, it presumably had a composition very much like that of a chondritic meteorite, but with internal heating, the iron - actually iron-nickel - settled toward the center because of its greater density. This migration, which has been studied at great length, during its course would release energy on the order mentioned above. The core was in all probability formed within the first billion years of Earth's existence, and probably in a much shorter time.

The fourth source of heat energy is much smaller in magnitude. It is the shrinking of the Earth, which is going on at the present time. The first three sources of heat caused the Earth to swell during its early history, but at present the heating is reduced since the core has been formed and the radioactivity has largely decayed. As a consequence, the Earth has shrunk appreciably; but in this shrinking, a new source of heating is derived from the energy released.

These are the four sources of heating. The release of this heat went on largely during the first billion years of the Earth's existence. This means that in all probability the gases mentioned, H_2O , CO_2 , N_2 , and most of the argon, were released in this span. The Earth is about 4.7 billion years old, and very probably the level of these gases has changed little during the past 3.7 billion years. Indeed, a gas like nitrogen may actually have decreased in level because of the deposition of nitrates by nitrogen-fixing bacteria. The most important of the latter appeared only about 200 million years ago. It may well be that nitrogen reached a peak earlier, and is on the downswing at the present time.

But what about oxygen? To modern evolutionary forms, oxygen in proper proportions, of course, is one of the most important of gases. It was thought for many years that oxygen appeared in the Earth's atmosphere primarily because of the photodissociation of H_2O by the solar ultraviolet. The latter process gives rise to a series of reactions that may be summarized in part:



M represents a third molecule; N_2 is the most likely candidate in Earth's atmosphere. The above are well-known reactions, and it was felt that the balance of oxygen in the Earth's atmosphere may originally have been a consequence of such processes.

In 1959, Urey, in a very interesting paper for the *Handbuch der Physik*,² pointed out that the water vapor in the atmosphere was distributed far from exponentially. Figure 1 shows the actual distribution of water vapor in the atmosphere. The integrated path length is plotted from the top of the atmosphere down to zero altitude, a range of 40 km. It is clear that the troposphere contains most of the water vapor in a range of about 0 to 10 km. Beyond this range there is very little; about 1 cm total STP path. Urey; in a qualitative way, estimates that the upper atmosphere of Earth is as dry as the atmosphere of Mars. Photodissociation of H_2O , moreover, is going to produce oxygen. The oxygen in turn will be distributed exponentially in the atmosphere, as shown in Figure 1. Dissociation limits, moreover, for both H_2O and O_2 are very close together, at 2400 and 2420 Å respectively. Inspection of absorption curves of these gases (Figure 2) shows an overlap for oxygen and water vapor in the photodissociative range between 1500 and 2100 Å. The wavelengths below 1500 Å can be eliminated from consideration because of the low amounts of energy in the uv of the solar flux, amounting to $\sim 2 \text{ erg cm}^{-2} \text{ sec}^{-1} (50 \text{ Å})^{-1}$. Urey pointed out that there would be shielding of the main body of water vapor, in the troposphere, because of the relative distribution with altitude shown in Figure 1. This mechanism would result in a self-regulated level of oxygen produced in a primitive atmosphere, a condition that is found to be exceedingly stable.

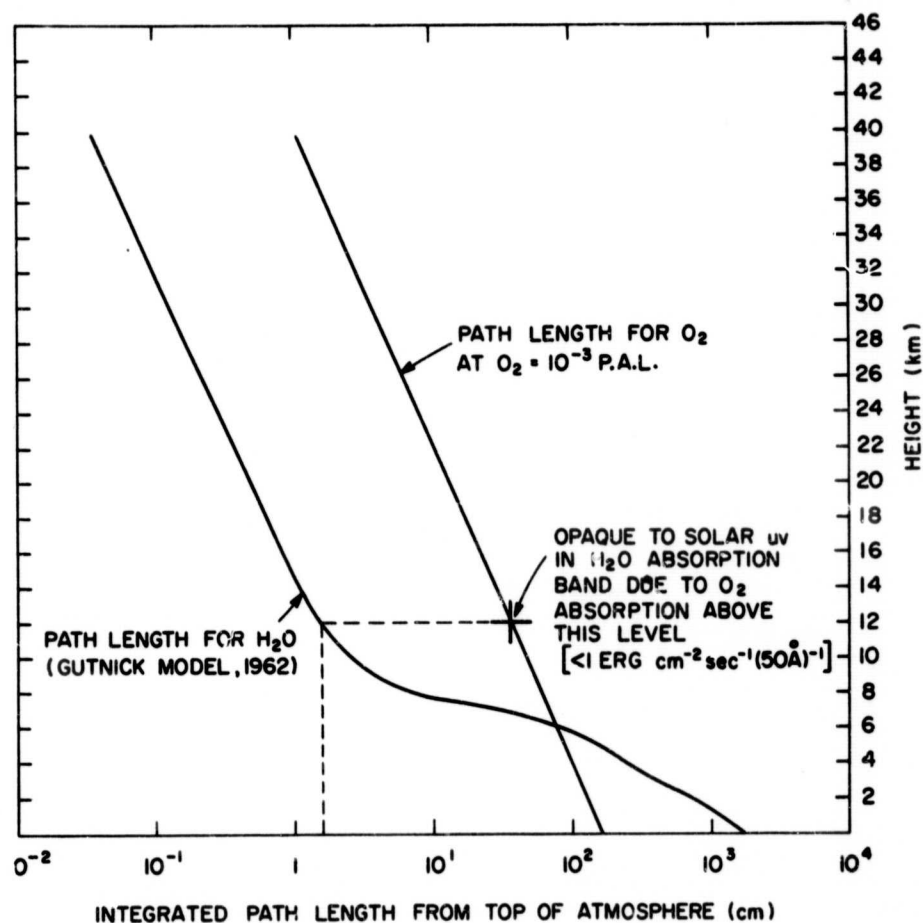


Figure 1. Shielding from photodissociation of atmospheric H_2O by O_2 . (P.A.L. = present atmospheric level.)

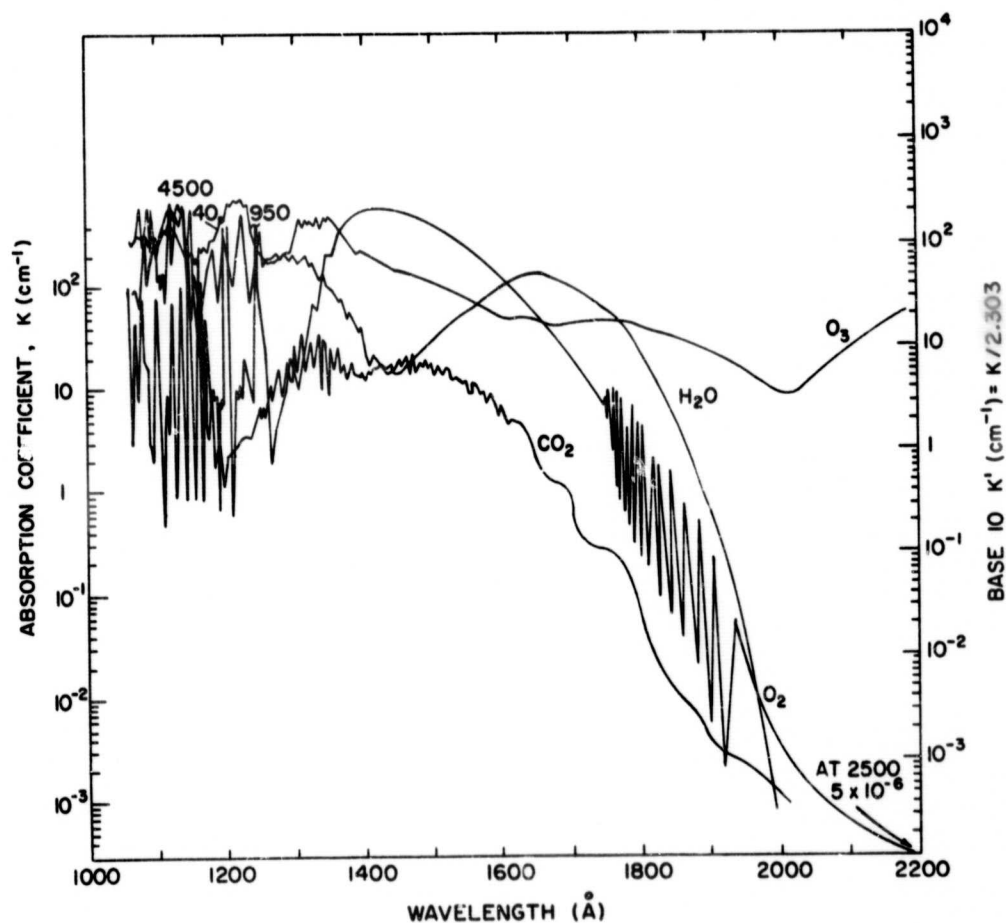


Figure 2. Composite of uv absorption in atmospheric gases.

Berkner and Marshall³ calculated this self-regulated level; it turns out that in a primitive atmosphere the partial pressure of oxygen must be about 0.001, or less, of the present atmospheric concentration, or level. In other words, only $\frac{1}{1000}$ of the present total amount of oxygen in the atmosphere is sufficient to shield ultraviolet radiation from the main body of water vapor below 10 km, and photodissociation would not take place in the troposphere. This shows very clearly that very little oxygen can be produced in the atmosphere of any planet by photodissociation of water vapor. This is a most interesting result because it is generally assumed that all oxygen in a planetary atmosphere must come from water. Photosynthetic life must therefore exist on a planet to build an oxygenic atmosphere. Furthermore, such life must be on a scale sufficient to override the stable Urey equilibrium.

Calculations were made of the scale at which photosynthetic life had to exist. These indicated that modern densities would require photosynthetic activity in a range of 1 to 10% of the present continental area if the effect of the Urey equilibrium were to be broken. What happens is this: the Urey limitation on oxygen is 0.001 present atmospheric level (P.A.L.). If some kind of photosynthetic organism starts producing oxygen, the latter merely *substitutes* for the photodissociated oxygen, so that the total level of the gas will not change. The partial pressure of oxygen will remain at the equilibrium point unless and until there is sufficient photosynthesis to override this limitation. The problem is, therefore, by what mechanism, on any planet, does a large enough area of photosynthesis become established to counteract the Urey equilibrium? In particular, this is the problem for the Earth.

This kind of thinking was not at first very popular with geologists, since Hutton, more than 200 years ago, pronounced the principle of uniformitarianism – a very sensible proposition, by the way. This states that if there is no reason to believe otherwise, one should always assume that what happened in the past is the same as what is happening now. Unfortunately, the principle is deceptively simple; as a result, there is a tendency to believe that nothing has *ever* happened in the past that is not happening now. Some curious geological theories were constructed on this premise that do not face up to the realities of physics. For the past 4 or 5 years this has been debated, but

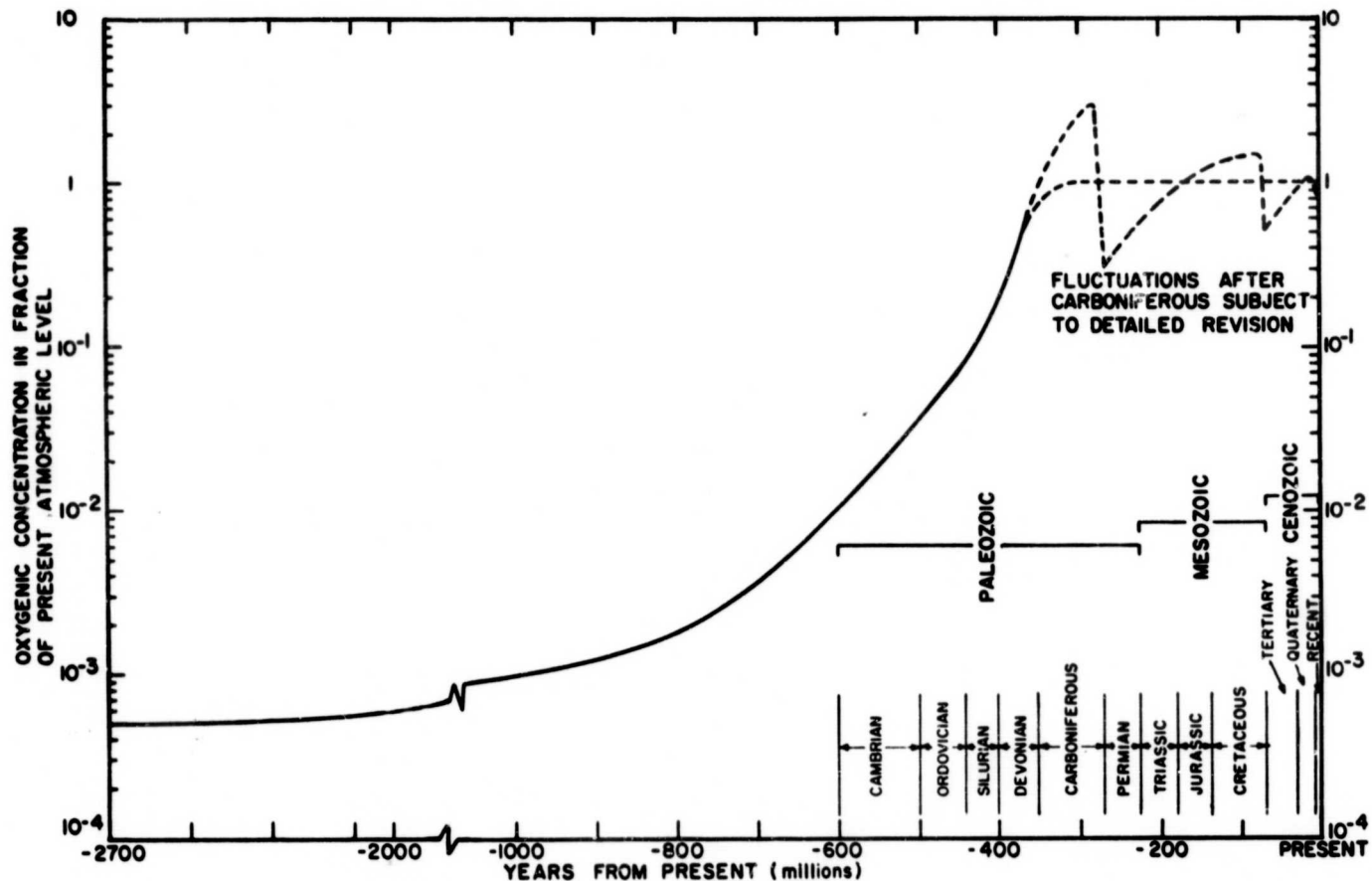


Figure 3. Model of terrestrial oxygen evolution.

most geologists are now willing to accept the views of physicists on these points. These views will now be used to consider the question: what is the way in which oxygen was built up in the atmosphere, and what were the consequences of that build-up?

Figure 3 is a tentative model of the evolution of oxygen on Earth. Starting 4.7 billion years ago, there was some H_2O , in the form of water vapor, available for photodissociation; this produced the Urey equilibrium in the primitive atmosphere at 0.001 of the present amount of oxygen. This amount did not change over a long span, i.e., 3 billion years, 2 billion, to one billion. At points around 620 million years ago, 420 million years ago, 250 million years ago and then down to the present, there are some interesting features. First, it seems quite clear that for about 2.7 billion years the Urey equilibrium was in effect, and that only 0.001 of the present amount of oxygen was present in the atmosphere of the Earth. Here are some of the reasons for the changes indicated in Figure 3.

The oldest known sedimentary rocks on Earth yield signs of life as early as 3.3 billion years ago. Some of these rocks are found in Africa,⁴ and modern electron micrography produces rather good pictures of the form that life took at the time. It appears that from this period right up to the

beginning of the Paleozoic, about 620 million years ago, all life was what is called procaryotic. This term includes many species of nonphotosynthetic life (i.e., bacteria) but it also includes the blue-green algae. Procaryotic life is unicellular and the cells have no nuclei. They are not mitotic and there are no distinct organelles. In a way it appears that such cells are just messy inside. The blue-green algae have green pigments, but no distinct chloroplasts; with the DNA scattered around the interior of such a cell, there must be tremendous redundancy to permit reproduction in anything like a continuous form; for there is no meiosis, no diploidy, in a procaryotic cell.

As biologists know, there is just one other type of cell; the eucaryotic. This does have a nucleus, displays mitotic splitting, and has all the basic characteristics of advanced forms of life. Bacteria and blue-green algae, the latter simply a bacterium with a green pigment to provide for photosynthesis, were probably the rulers of Earth from the beginning of life to about 620 million years ago. It seems likely that no eucaryotic organisms existed much before that time. There is a recent discovery in Central Australia that resembles a nucleated green alga, and this is tentatively dated about 800 million years ago; but the dating is quite probably

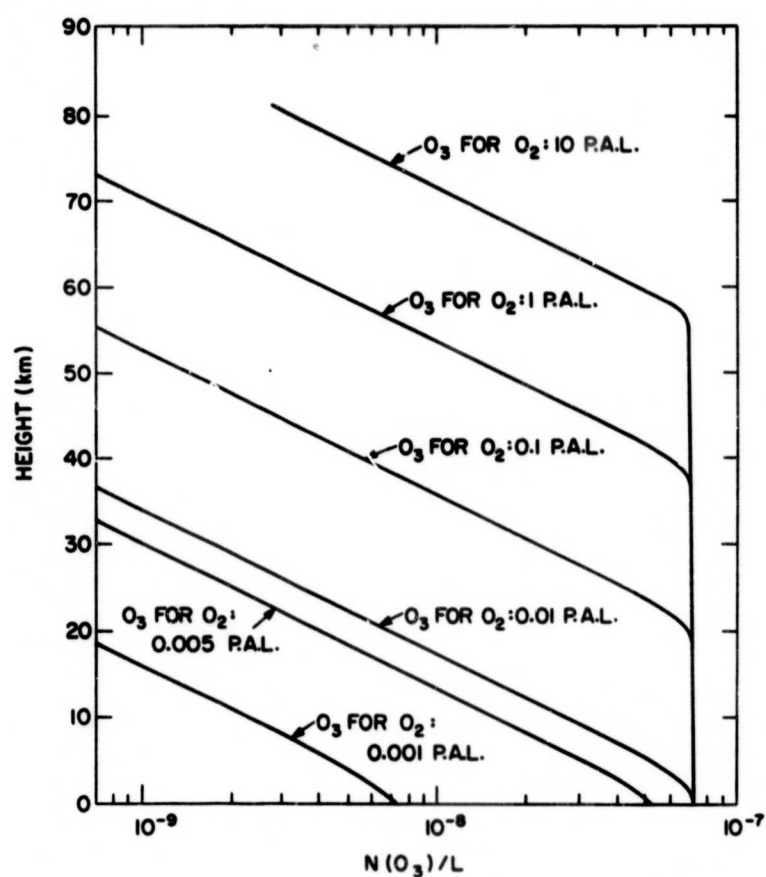


Figure 4. Estimated idealized distribution of ozone for various levels of oxygen. [$N(O_3)$ = number of molecules of ozone per cm^2 ; L = Loschmidt's number.]

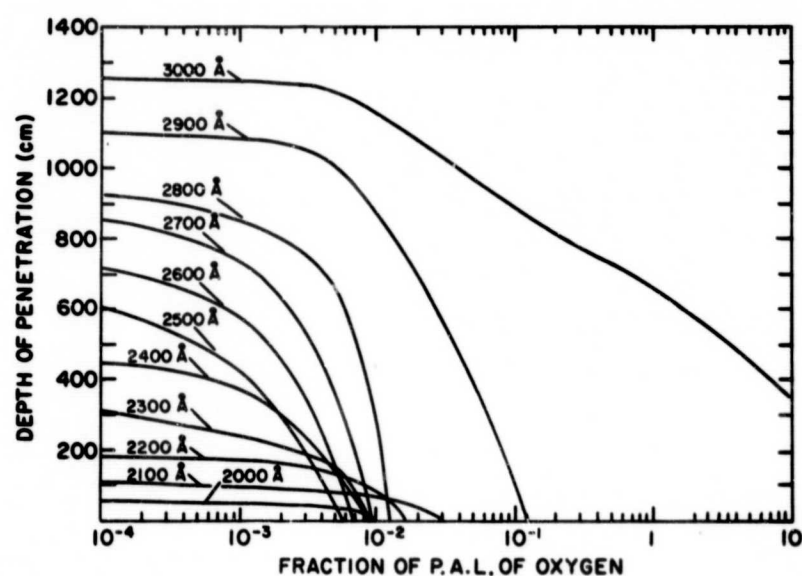


Figure 5. Penetration of uv radiation in liquid water with various combinations of oxygen and ozone atmospheres. Intensity at extinction = $1 \text{ erg cm}^{-2} \text{ sec}^{-1} (50 \text{ \AA})^{-1}$.

in error according to the latest information. This leads to the belief that procaryotic organisms were the chief, if not the only, forms of life until at least 620 million years ago.

Some have argued, on the basis of geological evidence such as the banding of iron structures and the amount of surface oxidation, that the

Urey equilibrium was broken around 2 billion years ago. The stability of this equilibrium suggests, however, that the oxygen level increased very, very slowly. It is possible to make a case for the idea that oxygen reached $\frac{1}{100}$ of its present atmospheric level about 620 million years ago. No multicellular organism is known to exist unless the oxygenic level is above what is called the Pasteur point. This is the point at which the organism can enjoy respiratory metabolism. Below this point, for example, green plants can ferment; but fermentation yields only two ATP units whereas respiratory metabolism yields 38 ATP units. In simpler terms, this means that at a level below the Pasteur point an organism can use its food only partially, for it cannot acquire enough energy to utilize nutrients completely. Only with respiratory metabolism can an organism fully utilize organic food, reducing it directly to carbon dioxide and water – the most elementary and lowest-energy states. This process of reduction, by the way, yields precisely the same amount of energy from food that would result from an explosion of hydrogen and oxygen. It is only at the level of respiratory metabolism that this energy release is possible, and no multicellular organism is known to exist below this level. If one asks, at just what level do organisms begin to enjoy respiratory metabolism, and if one studies a large number of organisms, it appears that some of these do just begin to have oxidative respiration at the oxygenic level of $\frac{1}{100}$ of the present atmosphere. From this Berkner and Marshall have constructed what might be termed an heuristic argument; namely, that since respiratory metabolism appears at this level, multicellular organisms should begin to appear in evolutionary history at this point. What happens when respiratory metabolism and multicellular organisms appear is most interesting. It turns out – and this is an accident of physics, perhaps – that at 1% of the present level of oxygen, ozone also reaches a maximum just at the surface of the Earth, as shown in Figure 4. When the oxygen level reaches $\frac{1}{10}$ the present atmospheric level, moreover, the altitude of the ozone maximum also rises. As a consequence, there is a thicker ozone layer; and this is just enough ozone to protect the oceans from lethal ultraviolet radiation previously experienced at the surface of the Earth. (See also Figure 5.)

To illustrate the situation, assume a pond with blue-green algae. The pond would have to be

about 10 meters deep (Figure 5) to protect the algae from lethal ultraviolet (in the range 2100 to 3000 Å) before the shielding described could become effective. In this situation, there could be no pelagic organisms (that is, free-swimmers), because these would swim into the lethal zone and be destroyed by the uv flux. During the whole period, therefore, prior to the evolution of oxygen to $\frac{1}{10}$ of the present level, there would be only benthic organisms, living on the bottom of rather small, deep ponds, to continue the build-up of oxygen. Turbulent waters would be unsuitable since here the organisms would be carried to the surface and eliminated. This gives some idea of the difficulty of building an oxygenic atmosphere. Ozone protection is badly needed. Figure 4 shows a rather idealized distribution of ozone for various levels of oxygen and shows that maximum production of ozone changes approximately one decimal scale height with each order of magnitude change in the level of O_2 . It should be noted that ozone is the only molecule that could have existed in sufficient quantity in the primitive atmosphere to provide the required protection from lethal radi-

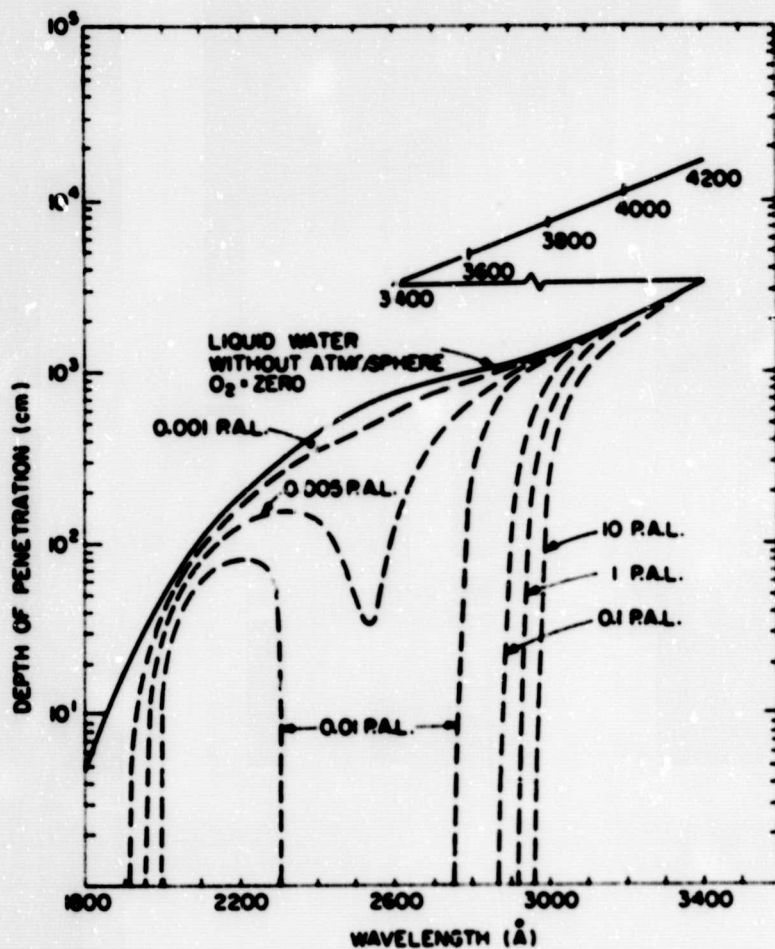


Figure 6. Path length in liquid water in the presence of O_2 and O_3 for various concentrations of O to absorb available uv to "extinction," $1 \text{ erg cm}^{-2} \text{ sec}^{-1} (50 \text{ Å})^{-1}$.

tion. This is why it was only when oxygen rose to the point permitting an increase in ozone that the surfaces of the oceans were shielded and, for the first time, pelagic organisms could appear.

This highlights an interesting correspondence: (1) at the oxygenic level 0.01 present atmospheric (Pasteur point), multicellular organisms became possible; and (2) at this same level there is just sufficient ozone present to shield pelagic life-forms from radiation (Figure 5). It is also important for rapid evolution that a situation prevail in which not only mutations are prevalent, but also isolation permitting weak species to propagate. The opening of the oceans by the process just described provides such isolation – all because ozone was able to reach a level high enough to protect pelagic organisms from lethal ultraviolet.

On such assumptions, supported by the fossil record, the most striking evolutionary events of all history took place about 620 million years ago. Up to that time it appears that only procaryotic life existed. Within the next 30 million years, 1200 different advanced species of organisms appeared. This change may have taken place in as little as 10 million years; 30 million is probably a maximum. One interesting example is the trilobites; these became very complex multicellular organisms up to 50 cm across in the time from 620 to 590 million years ago. Geologists had always assumed that there must have been a long precedent evolution, but now there seems good reason to change this opinion. Consider the organisms in a pond. The probability for a mutation is proportional to the number of individuals multiplied by the time. To put this in orders of magnitude, note that rate of mutation should vary as

Number of individuals in a pond	10^{15} to 10^{21}
Multiplied by number of generations per day	10 to 10^4
Multiplied by number of days/year	3.6×10^2
Multiplied by number of years	10^6 to 10^9
Total	3.6×10^{24} to 10^{36}

In comparing these numbers, the mutational opportunities are very large whether the span is 10^6 or 10^9 years.

The point is that there are going to be a tremendous number of mutations in any case. Isolation is also a requirement, and in the small ponds suitable for life before shielding from lethal radiation, this isolation was not available. The number of species was, therefore, restricted. It was only when the shielding opened up the oceans to life

that multicellular organisms and protozoa could evolve. At this point there evidently occurred the evolutionary explosion that produced the above 1200 multicellular species in a range of 10 to 20 million years.

Next consider the growth of oxygen beyond this stage. Before taking up this question, it might be well to study Figure 6, which shows the penetration of lethal radiation into water. Without oxygen or ozone, lethal radiation is still effective at depths as great as 10 m. As oxygen and ozone begin to accumulate, the penetration changes. At the point where oxygen is 1% of its present level, there is a notable change; i.e., ultraviolet in the range 2300 to 2800 Å is completely absorbed. The maximum absorption of the nucleotides occurs at 2650 Å, and for proteins near 2800 Å. The ozone protection indicated by this curve happens to come just in the range of this maximum absorption. Note that the curves in Figure 6 are calculated strictly from the physics of the absorption of ultraviolet light and water; yet there is this biological coincidence. It is interesting to question whether different nucleotides might have evolved had nature set the absorption somewhere else. This is, of course, speculative, but may have significance. Note also (Figure 6) that at the 0.01 level of oxygen, the relatively shallow waters are protected and organisms can live there. When oxygen reaches 1/10 of its present level, practically every wavelength of radiation is shielded at the surface. Only 2900 and 3000 Å, which are not particularly damaging, are still unprotected.

Inspection of the geological record moving forward in time highlights a very important fact. At the end of the Silurian, geologically 420 million years ago, every species in the water seems to have migrated ashore about the same time. This is very clear evidence that there must have been environmental change permitting life on shore rather than a mutational accident. It then becomes important to know the ozone level at that time. As noted above, the land is protected up to 2900 Å at 0.1 of present oxygen level. This is sufficient protection to allow life to go ashore. It may be no accident that the first species of formerly marine life to evolve ashore were, in almost every case, those with shells, since radiation in the 2900 to 3000 Å range is, if not lethal, quite uncomfortable (any form of life would get quite a sunburn). In any case, life did go ashore about 420 million years ago, and the other data cited show that oxygen

must be at or near the 10% level to make this possible. This provides another milestone in the estimate of accumulation of oxygen in Earth's atmosphere.

Finally, there is another significant point in the evolution of oxygen; but acceptable evidence is difficult to locate, and present statements are largely guesses. This point would be the time of arrival at the present oxygenic level. Best estimates place this stage at the end of the Permian, because only then did really large creatures evolve, requiring a high level of oxygen. There is some indication that the level of oxygen has fluctuated even in recent time, but more work is needed to determine the factors involved.

Present knowledge can serve as a basis for a general theory describing the composition and development of the atmospheres of the inner planets. Such a theory rests upon hypotheses widely discussed by various authors, and may be summarized under seven headings as follows:

1. The terrestrial-type planets, or the major planetesimals from which they were formed, agglomerated in a relatively cool state without significant primordial atmosphere. Notable contributions to this point have been made by, among others, Hans Suess,⁵ Harrison Brown,⁶ and Wendell Latimer.⁷

2. The basic atmospheric gases, with the exception of oxygen, were released chemically as a consequence of internal heating with proportionate differentiation of their components. William Rubey,⁸ Harold Urey,⁹ and A.E. Ringwood¹⁰ have made significant observations on this aspect.

3. Quantities of such secondary gases released on different planets, as discussed earlier, should be in relative proportion to the degree of internal heating and associated differentiation, since the bulk composition of the terrestrial-type planets appears essentially the same. If, therefore, one can ascertain the total release of a particular atmospheric gas on each of two planets, corresponding secondary release of other gases can be calculated proportionally. For example, from recently measured amounts of carbon dioxide on Mars and the total amount present on Earth, it should be possible to calculate the levels of other gases in the atmosphere of Mars.

4. Oxygen is not released from thermal or volcanic sources. In the absence of autotrophic life providing photosynthetic activity on a scale sufficient to override the Urey equilibrium, oxygen

will appear only in very small quantities (i.e., 0.001 present atmosphere).

5. Build-up of a significant oxygen atmosphere depends on biosynthetic activity of green pigmented autotrophic organisms on a relatively large scale. This provides for development of higher oxygen levels together with production of ozone necessary for screening of lethal ultraviolet over both land and water, thus encouraging the spread of life forms and the development of multicellularity at the appropriate oxygen levels.

6. The ultimate oxygenic atmosphere is thus seen to arise from a series of building steps to oxygenic levels that open the appropriate evolutionary opportunities. Hence, the presence of an oxygenic atmosphere at significant concentration is *prima facie* evidence of widespread evolutionary opportunity for life forms.

7. The concentration of an atmospheric constituent at any time represents the difference between total production and total loss through chemical interactions, organic or inorganic, on the surface and in the atmosphere, or through escape from a planet. These include processes that will profoundly affect the surface features of the planet.

In the light of the general theory, it is particularly interesting to note (Figure 7) the comparison of the fossil record with the half-loading range, or P_{50} , of the organisms appearing at specified times. P_{50} represents the partial pressure at which the pigment of any organism is 50% saturated with oxygen. There is a remarkable coincidence between the times of evolution of various life-forms and the half-loading figures. Protozoa and a few Metazoans have a half-loading at about 0.01 present atmospheric level, and it appears that

these forms evolved around 620 million years ago. It is important to remember that species may appear below the half-loading level but do not survive because reproduction below this level is impossible. The survival of varied life-forms beginning about 620 million years ago is strong evidence for dating the appearance of a significant oxygenic atmosphere on Earth at this point. Other critical levels in oxygen accumulation may also be suggested, although much remains to be done in this area. The data shown in Figure 7 and the above conclusions are dependent on the degree to which the assumptions stated are correct. There is, of course, the statistical possibility of an accidental correlation of this kind. Obviously, more data are needed.

Turning to the atmosphere of Mars, calculations of the amount of carbon dioxide in the atmosphere appear to be sufficiently reliable to serve as a basis for application of the technique of proportional calculation of other gases. Data on the Martian atmosphere based on the observations of Mariner IV¹¹ and the work of Owen,¹² Spinrad,¹³ and Kaplan¹⁴ indicate that the ambient temperature is low – about 85°K – which implies that CO₂ escape would be negligible; that is, most of the CO₂ ever produced on Mars is still there. If there are life-forms of the blue-green algal type on this planet, a small amount of CO₂ may have been deposited as fossil carbonate. The currently accepted value of atmospheric pressure on Mars, 9.5 mb, with more than 95% CO₂ content, corresponds to about 25 g cm⁻² of CO₂ in column. Another 25 g cm⁻² may have been deposited in the form of carbonates, making a total of 50 g cm⁻².

This yields the ratio of 1/1000 for the amount of CO₂ on Mars to that on Earth. (Total CO₂ released on Earth is about 5 × 10⁴ g cm⁻², as discussed earlier.)

On the basis of the general theory as described, the composition of the Martian atmosphere as compared with that of Earth may be tabulated (Table 1). Note there is little nitrogen on Mars, as is to be expected in the light of the theory. The estimate of water on Mars, 2.8 × 10² g cm⁻², appears surprising because most authorities agree that the Martian atmosphere is very dry. This water is probably mainly present as permafrost. It should also be possible to demonstrate by calculations that on as much as 400 km² of Mars (a very small area compared with the total of 1.5 × 10¹² km²), there may be hot springs. These could be

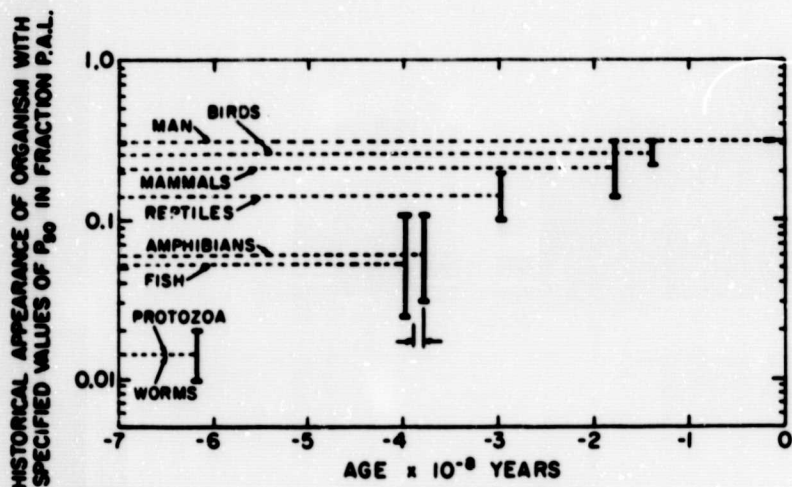


Figure 7. Range of P_{50} for phyla which appeared at specified geologic periods in accordance with the fossil record.

Table 1
Estimated Atmosphere of Mars

Gas	Mass on Earth, g cm ⁻²			Mass on Mars, g cm ⁻²			Pressure on Mars, dynes cm ⁻²
	Atmosphere	Fossil or stored	Total	Atmosphere	Fossil or stored	Total	
CO ₂	0.5	5.0 × 10 ⁴	5.0 × 10 ⁴	25.0 × 10 ⁰	25.0 × 10 ⁰	50.0 × 10 ⁰	9.25 × 10 ³
N ₂	772.0	8.0 × 10 ¹	8.52 × 10 ²	8.5 × 10 ⁻¹	—	8.5 × 10 ⁻¹	3.1 × 10 ²
A	13.4	—	1.34 × 10 ¹	1.3 × 10 ⁻²	—	1.3 × 10 ⁻²	5.0 × 10 ⁰
H ₂ O	1.5	2.8 × 10 ⁵	2.8 × 10 ⁵	1.15 × 10 ^{-4*}	2.8 × 10 ²	2.8 × 10 ²	4.25 × 10 ^{-2*}
O ₂	240.0	*	not applicable	< 2.0 × 10 ⁻¹	> 1.75 × 10 ⁰	—	< 7.4 × 10 ⁻¹
Total	~1016.4			~26.0 × 10 ⁰			~9.5 × 10 ³

*See discussion and earlier text.

present for one very important reason: Mars has a flattening due to centrifugal force in the largest ratio of all the planets. Incidentally, this ratio is just at the limit of strength of a homogeneous planet. The result is that Mars must have some intense earthquakes, since a homogeneous planet is very strong. Each earthquake must produce energy on the order of 10²⁴ ergs. The release of that much energy added to the existing radioactive energy should cause thermal activity. The latter thus far may have escaped observation because existing telescopes have insufficient resolving power. Present telescopes would not see this activity any more clearly than the steam whistle of a train a million miles away. The large earthquakes on Mars specified above would result in large amounts of lava in concentrated areas. In turn, water should be given off at the rate of about 10⁵ metric tons per year, a considerable amount. There could, therefore, be some hot springs on Mars, possibly widely scattered and difficult to observe.

It therefore seems reasonable to believe that there may be blue-green algae on Mars. Such algae have been found in some of the oldest rocks on Earth; and the algae themselves are most likely a phenomenon similar to other chemical events that appear rapidly in favorable environments. As early as 1942, Wildt¹⁵ suggested that the reddish hue of the Martian surface might be due to oxidation of iron and sulphur by ozone. This hypothesis, which appears to be reasonable, has been strengthened by more recent work¹⁶ supporting the conclusion that the bands of red coloring may be

caused by the oxidation of iron to Fe₂O₃. It is, however, unlikely that the required oxygen was produced by photodissociation of water vapor in the Martian atmosphere, as simple calculations will show¹⁷ that there is not sufficient energy available for the process. This suggests the hypothesis of some form of primitive life, probably existing in thermal oases provided by hot springs, as an oxygen source on Mars. It should be noted that even the <0.2 g cm⁻² of oxygen calculated for the Martian atmosphere is sufficient to provide the ozone needed for surface oxidation. Small, widely scattered areas of photosynthetic life would, therefore, be adequate as an oxygen source. Calculations indicate that from 10 to 100 km² of thermal oasis area would be sufficient to support life producing the oxygen required.

This brief summary of characteristic features of Mars derivable from present data by application of the general theory here described is especially remarkable for the fact that a coherent and apparently reasonable portrait of the planet may be drawn from studies conducted mainly on Earth.

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