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Astronomy

Climatic Conditions on the Surface of the Ancient Earth

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ABSTRACT. Taking into account the greenhouse effect and contemporary surface temperature of Venus, for the ancient Earth's surface temperature 352°C is received. The model of the atmosphere is constructed; its principal components are CO_2 and H_2O. The obtained results radically change the traditional notions on the climatic conditions dominating on Earth in the epoch of the origin of life on it. The fact, pointed above, should be taken into consideration while investigating the problem of the appearance of life on the planet. *© 2009 Bull. Georg. Natl. Acad. Sci.*

Key words: *Ancient Earth, climate.*

1. Introduction

In solving the problem of the origin of life on the Earth an important problem arises of the climate condition on its surface in the archaic epoch, when there was no life at all.

It is traditionally believed that life originated in the warm ocean of the primeval Earth but, as far as we know, there were no attempts to estimate its true temperature before [1]. It was demonstrated in [1] that on the primeval earth surface in the early Archaic (Katarcheic) period there might have been a rather high temperature (~350°C) and the primeval ocean could not be called otherwise than boiling.

The cause of such a high temperature was a greenhouse effect' which is also the cause of a high temperature of the Venus' surface.

Only after the cleaning of the atmosphere from carbon dioxide, due to photosynthesis and other processes, leading to the formation of carbonates, the greenhouse effect ceased to play a determining role and the Earth's surface temperature fell to the contemporary level.

The process of escaping of CO_2 from the Earth's depths could have occurred so slowly that its concentration would have always remained small. In such a case the Earth's surface temperature would always have been moderate; nevertheless, at the origin of life in the late Archaean the Earth's surface temperature was rather high, up to 150°C [2, 3].

In solving this problem contemporary Venus serves as a good model of the ancient Earth. The existence of ocean on the ancient Earth could only have intensified the greenhouse effect. That is why we shall begin constructing the model of the ancient Earth atmosphere by comparing the chemical composition of atmospheres of these two planets in our days.

At the same time it should be kept in mind that simultaneous existence of water and CO_2 contributes to the development of nonstability in the atmosphere. With the rise of temperature both the increase of partial pressure of saturated vapor and the escape of carbon dioxide from aqueous solution, as well as from carbonates occurs, as carbon dioxide strives for the wollastonite equilibrium, which in its turn increases the greenhouse effect and leads to the further rise of temperature. Thus the system has a positive feedback.

As all the above-mentioned processes have a reversible character, two limit equilibrium states are probable: the one with a comparatively rarefied atmosphere under a minimum greenhouse effect (let us call it a "cold" equilibrium) and the other with a dense atmosphere under a great greenhouse effect (a "hot" equilibrium).

Table 1.

Pressure, temperature, percentage of gases and equilibrium temperatures

Planet	P	T	A (content in %)			T_e
			CO_2	N_2	Ar	
Venus	90	735K	96.5	3.5	0.015	327K
Earth	1	287K	0.03	78.1	0.93	278K

Because of the positive feedback transition from one equilibrium state into the other may be abrupt. The first version was repeatedly studied in literature, so we shall study the second ("hot") version.

2. Chemical composition of the ancient Earth's atmosphere

In Table 1 information on the atmospheres of Venus and Earth [4] are presented. There are given: pressure in atmospheres (P) and mean temperature (T) near the surface, percentage content of the most important gases (A) and also an equilibrium,- for absolutely black sphere moving on planets' orbits,- temperature (T_e).

At first sight the chemical composition of these two atmospheres has nothing in common.

Nevertheless, calculating the value of a relative (in units of the mass of planet) number of substances, given in Table 1, we receive:

$$m = \frac{PSA}{Mg}, \qquad (1)$$

where M is the mass of planet, S - its surface square and g - surface gravity on it, we shall obtain the results presented in Table 2.

Table 2.

Relative existence of gases

Planet	In millions of parts		
	CO_2	N_2	Ar
Venus	93.5	3.4	0.014
Earth	0.0003	0.69	0.008

It is evident from the data of Table 2 that the relative content of argon in the atmospheres of both planets is almost identical and a certain moderate deficit of nitrogen in the Earth's atmosphere is observed. A great carbon dioxide deficit is probably due to the living activity of plants on Earth and its dissolving in the ocean with further sedimentation. The deficit of nitrogen in the Earth's atmosphere may be explained also by the activity of bacteria, binding this not very active element. As to argon, among rather abundant elements of the atmosphere it is the most stable as regards both chemical activity and (owing to great atomic weight) dissipation from the atmosphere.

The mentioned consideration enables us to conclude that in chemical composition the atmospheres of the ancient Earth and contemporary Venus must be similar.

Under such an assumption it is easily calculated that partial pressure (in atmospheres) for each gas on the surface of ancient Earth equaled:

$$P = \frac{90Mr'^2A}{M'r^2}, \qquad (2)$$

where M and r are the Earth mass and radius respectively; the same values for Venus are marked by hachure.

With the aid of the expression (2) for partial pressure of carbon dioxide and nitrogen we obtain the value 106 and 4 atmospheres respectively.

The following reason can be given to support our viewpoint: for the creation of a pressure of 106 atmospheres the mean mass of carbon dioxide contained in atmosphere should be $550\text{x}10^{21}$G, which corresponds to $150\text{x}10^{21}$G of carbon. This value correlates with the quantity of carbon in the Earth's sedimentary shell, which, according to evaluation [5] equals $100\text{x}10^{21}$G. As a result of the escape of organic carbon from the living cycle and its fossilization, accumulation in the biosphere of a considerable mass of free oxygen became possible [6].

As it will be illustrated below, the third most important component of our planet's ancient atmosphere was saturated vapor.

3. Temperature on the surface of the primeval Earth

Above we have assumed that by carbon dioxide content the primeval Earth's atmosphere was comparative with Venus' atmosphere. The existence of the primeval ocean provided for a considerable amount of vapor. Thus, there were on the primeval Earth all conditions for the formation of the greenhouse effect, not less than those observable at present on Venus.

In calculating the surface temperature of the ancient Earth we shall be guided by the hypothesis that in the case of the greenhouse effect heat radiation occurs according to Stefan-Boltzmann law:

$$E = aT^4, \quad (3)$$

where coefficient a may differ from Stefan-Boltzmann constant.

Proceeding from (3) we shall have for the Earth surface temperature:

$$T_0 = T_0' \sqrt{R_V}, \quad (4)$$

where Venus' surface temperature and radius of its orbit (in astronomical units) are designated by T_0' and $\sqrt{R_V}$.

It is easy to calculate with the aid of (4) that T_0 turns out to be equal to 625K (352°C), i. e. as distinct from Venus the Earth's surface temperature happens to be lower than water's critical point.

At such high temperature water as a liquid can exist only under the pressure of 167 atmospheres.

We have shown above that partial pressure of carbon dioxide and nitrogen totals 110 atmospheres. Consequently, if our previous assumptions are correct, part of the ocean should have been intensively evaporating until the vapor's partial pressure reached 57 atmospheres. Equilibrium was gained under the total pressure of 167 atmospheres.

Thus we obtain the following chemical composition for the primeval Earth atmosphere at the surface: carbon dioxide, vapor and nitrogen constituted (in volume) 38, 60 and 2% respectively.

The temperature and vapor pressure values, given here, are in reality overstated as according to our notions of stellar evolution luminosity of the Sun after Archaic period has increased by 20-60%, according to different evaluations [7-10]. So as the second (minimum) variant let us take solar luminosity equal to half of the present luminosity. In this case Earth's surface temperature must be equal to 525K (252°C) and the pressure of saturated vapor - to 41 atmospheres, respectively.

Consequently, CO_2, H_2O and N_2 will constitute 70, 27 and 3% respectively.

4. Atmosphere model

As it usually turns out while constructing atmosphere models in the lower layers (troposphere) the following condition takes place:

$$\frac{d(\ln T)}{d(\ln P)} \geq \frac{\gamma - 1}{\gamma}, \quad (5)$$

The right part of (5) may acquire values from 0.25 (for polyatomic molecules) to 0.4 (for atomic gas). The condition (5) describes convective or, in the case of equality, adiabatic atmosphere.

Below we shall see that existence of a large amount of saturated vapor in the considered cases leads to an inequality, adverse relative to (5), i. e. the ancient Earth's atmosphere was super-adiabatic, which means that no vertical movements took place in it.

In such an atmosphere mixing up does not matter and the components' diffuse division by height turns out to be the main physical process, resulting in the change of density of each (regardless of other components) by barometric law (in accordance with each component's molecular weight):

$$dP = g\rho dh, \quad (6)$$

where the density of the given gas is designated by ρ.

For carbon dioxide and nitrogen density is defined by the equation of ideal gas:

$$\rho = \frac{\mu P}{RT}, \quad (7)$$

where m is molecular weight, R - gas constant.

Saturated water, however, should not be considered an ideal gas and for it the expression (7) is unfair. In this case dependence between ρ, P and T is established with the aid of respective tables [11].

Existence of a large quantity of saturated vapor in such atmospheres leads to the fact that at each height temperature is established (similar for all components) not lower than the one to which water boiling temperature corresponds at a given pressure.

In fact, if temperature at some point falls lower than this value, part of the vapor is condensed and at the expense of a latent evaporation heat the temperature will rise up to the primary value. Thus the temperature, obtained in our model, should be considered as the lower limit.

As we have found out, the dependence between P' and ρ' for the saturated vapor given in [11] can be expressed by the interpolation formula:

$$\rho' = \frac{P'(u^3 - 0.71326u^2 + 2.07222u + 4.40052)}{0.24363u^3 + 0.83888u^2 + 8.69651u + 3.14222}, \quad (8)$$

where the designation is introduced:

$$u = \sqrt{\ln \frac{P_k}{P'}} \quad (9)$$

and P_k means critical pressure of vapor, which we have assumed to be equal to 225.6 atmospheres.

By introducing (8) into (6) and integrating we obtain:

$$\begin{aligned} g(h-h_0) &= 0.24363u^2 + 2.02530u + \\ &+ 1.71431\ln(u+1.08991) + \\ &+ 8.05678\ln(u^2 - 1.80317u + 4.03751), \end{aligned} \quad (10)$$

where the integration constant is designated by h_0.

In Table 3 atmosphere models are given, constructed on the basis of (6) in keeping with the conditions enumerated above. Their height above the ocean level (in kms), temperature (in Kelvins), components' partial pressure and total pressure P (in atmospheres) are presented. All the data are given for two cases: for the contemporary Sun and the "ancient" Sun with luminosity equal to half of the contemporary.

As is evident from Table 3 in both cases temperature and pressure slowly decrease with height: simultaneously the relative content of vapor increases, which at the height of 70 km becomes practically the single component of the atmosphere.

As the value $\frac{d(\ln T)}{d(\ln P)}$ nowhere exceeds 0.13, at all heights the atmosphere remains super-adiabatic.

The atmosphere corresponding to our model could have appeared in case if decontamination of the depths of the young Earth which occurred sufficiently intensively. At a slower decontamination rate pressure (together with the greenhouse effect and surface temperature) might have attained the least possible values even up to negative global temperature.

The realization of a "cold" equilibrium might have led to the formation of a "white Earth" - global freezing which, as is known, could not nave been melted by solar radiation.

Some existing theories attempt to eliminate this discrepancy with the reality by introducing of some hypothetical components into the atmosphere - ammonia or hydrogen [12, 13] or by supposing such a rate of volcanic activity on Earth that would have constantly kept the concentration of CO_2 in the atmosphere near to contemporary, thus maintaining temperature propitious for contemporary life forms.

Our models do not face such problem; that is why they have similar rights to exist, though the atmosphere, corresponding to it, would have been unfavorable for the contemporary life forms.

Table 3

Atmosphere models of the Earth for contemporary and "ancient" Sun

	Contemporary Sun					"Ancient" Sun				
H	T(K)	Partial pressure			P	T(K)	Partial pressure			P
		CO_2	H_2O	N_2			CO_2	H_2O	N_2	
0	625	106	167	4	277	525	106	41	4	151
10	579	45	92	2	139	498	39	25	2	66
20	544	17.8	55.2	1.2	74.2	473	13.2	15.2	1.0	29.4
30	514	6.7	33.6	0.7	41.0	450	4.3	9.2	0.5	14.0
40	488	2.4	20.6	0.3	23.3	429	1.3	5.5	0.2	7.0
50	464	0.79	12.55	0.17	13.51	410	0.38	3.26	0.11	3.75
60	442	0.25	7.57	0.08	7.90	392	0.10	1.89	0.05	2.04
70	422	0.07	4.51	0.04	4.62	375	0.03	1.07	0.02	1.12
80	403	0.02	2.64	0.02	2.68	359	0.01	0.59	0.01	0.61
90	385	0,01	1.52	0.01	1.53	344	-	0.33	-	0.33
100	369	-	0.86	-	0.86	330	-	0.17	-	0.17
110	353	-	0.47	-	0.47	317	-	0.09	-	0.09
120	339	-	0.25	-	0.25	304	-	0.04	-	0.04
130	325	-	0.13	-	0.13	292	-	0.02	-	0.02

The obtained results radically change the traditional notions on the climatic conditions dominating on Earth in the epoch of the origin of life on it. The fact, pointed out above, should be taken into consideration while investigating the problem of the appearance of life on the planet.

This, nevertheless, does not mean that life could not have originated on such Earth. It is quite probable that anaerobic bacteria, living nowadays in Iceland geysers at the temperature of 90°C, or sulfate reconstructing bacteria, which have developed in a medium with the temperature of 104°C and pressure of 1000 atmospheres [14], are direct descendants of the first creatures inhabiting the Earth.

The results obtained should be considered as preliminary, as during calculations we have not taken into account the role of radiation transfer in atmosphere in a heat energy balance, due to which expression (3) can turn out to be wrong.

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რ. კილაძე

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სათბურის ეფექტისა და ვენერას ზედაპირის ამჟამინდელი ტემპერატურის გათვალისწინებით, ადრინდელი დედამიწის ზედაპირის ტემპერატურისთვის მიღებულია მნიშვნელობა 352°C. აგებულია ატმოსფეროს მოდელი; მისი ძირითადი ქიმიური კომპონენტებია CO_2 და H_2O. მიღებული შედეგები რადიკალურად განსხვავდება დედამიწაზე სიცოცხლის ჩასახვის ეპოქაში გაბატონებული კლიმატური პირობების შესახებ არსებული ტრადიციული შეხედულებებისაგან. აღნიშნული გარემოება მხედველობაშია მისაღები პლანეტაზე სიცოცხლის წარმოშობის საკითხის განხილვისას.

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