

Cometary impacts into ocean: thermochemical equilibrium calculations of high-temperature O₂ generation on the early Earth

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The early Earth's atmosphere apparently differed from the present atmosphere mainly in its lack of free O₂, and this absence is believed to have been indispensable for the origin of early anaerobic life forms. One of the central problems in Earth science is to explain the apparent transition from the primitive atmosphere (free of O₂) to the present atmosphere which contains 21 % of the gas. Theoretical models suggest that the initial form of O₂ in the Earth's atmosphere may have been H₂O, which was converted into atmospheric O₂ mainly through photosynthesis. We have investigated an alternative (abiotic) method for the conversion of H₂O to O₂: a high-temperature shock generated during a cometary impact into an ocean (or on land). The calculations presented here show that 1 % of the present level of O₂ could have resulted from an icy 1.3×10¹⁶ kg comet entering the early (pre-oxygenic) Earth with a velocity of between about 11 and 30 km s⁻¹.

Keywords: comet, oxygen, impact, thermochemical calculation.

INTRODUCTION

A distinctive feature of the Earth is the large amount of free O₂ (21 % by volume) in the atmosphere. As present volcanic exhalations lack free O₂, only two principal sources of atmospheric O₂ are considered plausible: a biological source localised in the ocean (O₂ generating photosynthesis) and a non-biological source localised in the atmosphere (photodissociation of H₂O vapor). (Model calculations predict that the production rate of O₂ from photodissociation of H₂O vapor would be relatively small on the early Earth but would produce an observable amount of O₂: Kasting¹ and references therein). Therefore, the origin of O₂ in the Earth's atmosphere is intimately related to the early Earth's H₂O.

H₂O appeared on the Earth very early in its history. Studies of the formation of the Earth indicate that the H₂O came from the outer solar system, carried by chondrites and

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comets colliding with the newly-formed planet.²⁻⁴ According to Morbidelli *et al.*,⁴ after the Earth's formation had ended, its surface was impacted by comets. (This was the late veneer phase, coinciding with the late heavy bombardment from 4.5 to, at least, 3.8 Ga). The definition of pre-oxygenic Earth here encompasses the time period (Archean era) in the early Earth's geologic history from about 3.8 Ga (after its main accretion phase when the core and ocean had already formed) up to 2.4 Ga (the early Proterozoic). The model of a pre-oxygenic Earth presented here is with no or little atmosphere, and with the surface temperature of the planet being *ca.* 273 K.

The following preliminary report concentrates firstly on thermochemical equilibrium calculations of thermally decomposed H₂O vapor, secondly on a specific application of these calculations to an oceanic cometary impact, and thirdly on the generation of O₂ from thermally disintegrated H₂O vapor within the expanding plume created by the impact.

Accordingly, numerical experiments with cometary impactors are beyond the scope of this paper. These matters are treated in details elsewhere.⁵⁻¹¹

THE COMETARY IMPACT RATE

The Earth has been impacted by comets and asteroids throughout its geologic history. The impact rate appears to have been relatively constant back to about 3.8 Ga when it began to rise. At times earlier than about 3.8 Ga, there appears to have been an exponential increase in the rate. Terrestrial collisions with comets > 10 km in diameter have been estimated to have occurred at a rate of about 1 per 10⁸ years¹² but occasional cometary showers could have occurred at intervals of tens of millions years.¹³ (Smaller comets with an average mass of about 10⁴–10⁵ kg also impinge on the top of the Earth's atmosphere. Their flux is about 10⁷ per year¹⁴). In the history of pre-oxygenic Earth, the high cometary impact flux was probably a significant factor in the modification of the atmosphere, hydrosphere and biosphere.

COMETARY IMPACT INTO AN OCEAN

Here the possibility that during the impact of a comet into an ocean the comet H₂O - ice could have been subjected to an impact-induced (high-temperature) decomposition, generating O₂ is explored. Previous studies of these impact have ignored this possibility and it is of interest, therefore, to estimate the amount of O₂ which could have been formed in such an event. For this purpose, theoretical calculations have been carried out using the Chemkin Collections[®] and the STANJAN method equilibrium calculations. Also a simple analytical model for the thermal generation of O₂ by the impact of a comet into an ocean has been constructed using a few basic equations derived by Melosh and Vickery,⁸ Vickery and Melosh,¹⁰ Zel'dovich and Razier,¹⁵ Melosh.¹⁶ It was hoped that this model would highlight most essential features of the process. In addition, for the purpose of the following calculations, a number of appropriate assumptions and approximations were introduced. The emphasis is placed on the impact of an ice-rich comet into an ocean because: (a) the number of Earth crossing comets is four times greater than the number of Earth crossing asteroids;¹² (b) probability arguments

indicate that *ca.* 70 % of the impact flux would land in an ocean; (c) the impact-decomposed oceanic H₂O could enhance the abundance of H₂O vapor in the initial plume (at the moment of impact); and (d) the impact-generated H₂O vapor derived from the cometary and the impacted H₂O could reach temperatures of tens of thousands of degrees or even higher.^{7,9,11,16-18}

It is assumed that the O₂ generation by the impact of the comet into the pre-oxygenic Earth ocean took place in two major steps. The first one includes the disintegration of the comet H₂O vapor at high temperatures (20,000 K) into atomic oxygen species (OS) (O and its ions) and molecular hydrogen species (HS) (H₂ and its ions), followed by the rapid diffusion of HS into the outermost (and fastest) zone of the impact-created plume. This is the basic premise of the model. (Quantitative data on the physical conditions (impact velocity, impact pressure and impact temperature) which govern the impact-induced decomposition of H₂O vapor are not yet available). The second step comprises the escape of HS into interplanetary space and the subsequent formation of O₂ molecules (within the remaining plume) through recombination of O atoms with each other.

THERMAL DECOMPOSITION OF H₂O

The chemical reactions associated with the decomposition of H₂O vapor (at temperatures < 6000 K and at pressures < 1 bar) are shown below,



along with their pressure equilibrium constants

$$K_1 = f(\text{H}_2) [P f(\text{O}_2)]^{1/2} [f(\text{H}_2\text{O})]^{-1}$$

$$K_2 = P[f(\text{H})]^2 [f(\text{H}_2)]^{-1}$$

$$K_3 = P[f(\text{O})]^2 [f(\text{O}_2)]^{-1}$$

$$K_4 = f(\text{OH}) [P f(\text{O}) f(\text{H})]^{-1}$$

and the mole fraction equation

$$f(\text{H}_2\text{O}) + f(\text{O}_2) + f(\text{O}) + f(\text{OH}) + f(\text{H}_2) + f(\text{H}) = 1$$

where P is the total pressure and $f(\text{X})$ is the mole fraction of the gaseous component X. (The mole fraction of the different gases are equal to the partial pressure of the gas divided by the total pressure. The mole fraction of O₂ in dry air is 0.21). Reaction (1) requires a substantial amount of energy (*ca.* 245 kJ) to produce gaseous H₂ and O₂ and the above process is endothermic, *i.e.*, high temperatures and low pres-

sures favor the decomposition of H₂O vapor. (H₂O vapor dissociation has an activation energy threshold of about 31 MJ kg⁻¹. The generated O and H atoms then combine to O₂ and H₂ losing about 18 MJ kg⁻¹ in the combination processes.)

Many authors have studied the decomposition of H₂O vapor (steam) by direct thermolysis (this has been reviewed by: Fletcher and Moen,¹⁹ King²⁰ and Jellinek²¹) and by shock decomposition (Bauer *et al.*²² and Lyzenga *et al.*²³ and references therein). The available experimental data indicate that at low temperatures, H₂O vapor does not decompose, but at high temperatures (>1500 K), dissociation becomes significant. These investigations also show that the most abundant species generated during the decomposition are O₂, H₂, O, H and OH and that the extent of dissociation, as expected, increases with increasing temperatures and decreasing pressure. (The decomposition of H₂O vapor resulting from high-temperature (>3000 K) heating under atmospheric pressure (1 bar) or higher pressures has not yet been studied).

THERMOCHEMICAL EQUILIBRIUM CALCULATIONS

Han and Runnegar²⁴ report finding eukaryotic microfossils, tentatively identified as *Grypania spiralis*, in 2.1 Ga old rocks. The authors claim that the atmosphere of the Earth between 2.0 and 2.5 Ga contained 0.01 to 0.1 of the present atmospheric level (PAL) of O₂. We consider that such biologically based estimates provide useful minimum values for the early Earth and, for the purpose of the following calculations, the value of 0.01 PAL O₂ has been adopted.

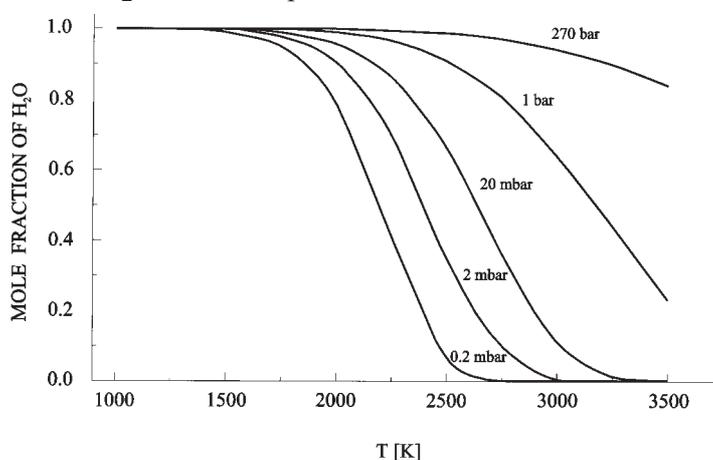


Fig. 1. Thermochemical equilibrium abundances of H₂O as a function of temperature (up to 3500 K) and a constant pressure (0.2 mbar, 2 mbar, 20 mbar, 1 bar and 270 bar).

Equilibrium thermochemical calculations show that thermal decomposition of H₂O typically occurs at temperatures above 1500 K, which agrees with expectations based on previous experimental data-results (for details, see Fletcher and Moen,¹⁹ King²⁰ and Jellinek²¹). The equilibrium abundances of H₂O at different temperatures (up to 3500 K) are illustrated in Fig. 1: at 0.2 mbar, 2 mbar and 20 mbar; and, for comparison, the mole fractions of H₂O at 1 bar (present-day atmospheric pressure) and at

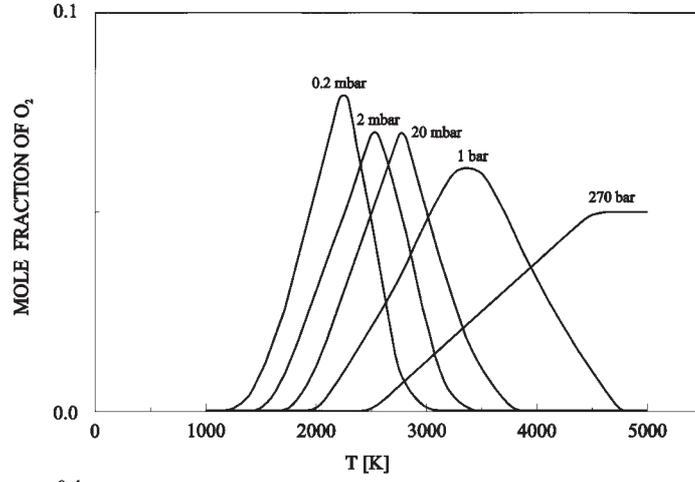


Fig. 2a

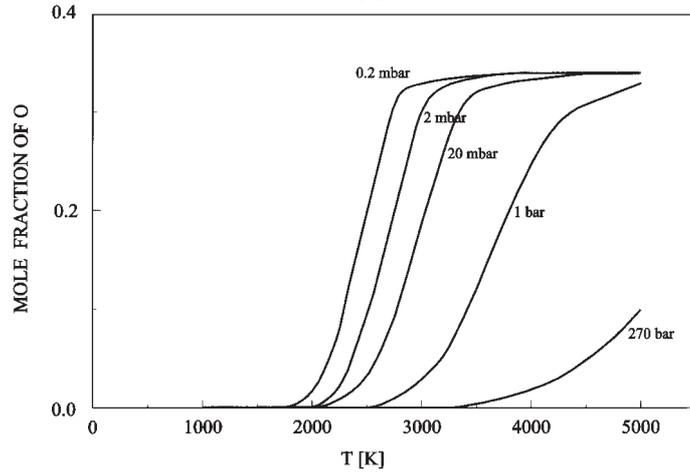


Fig. 2b

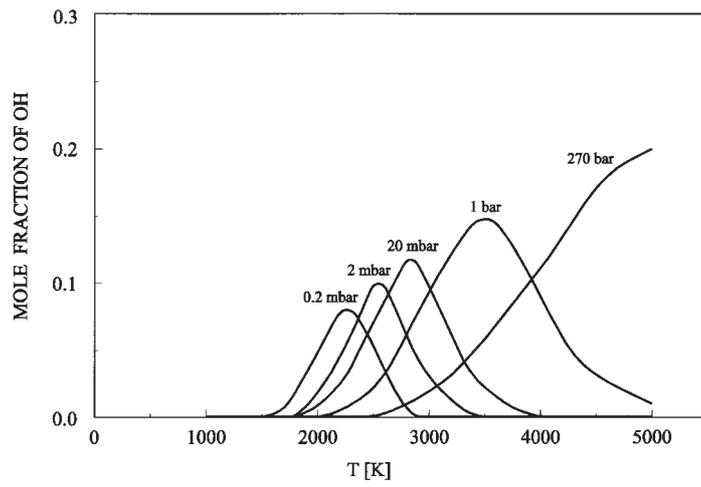


Fig. 2c

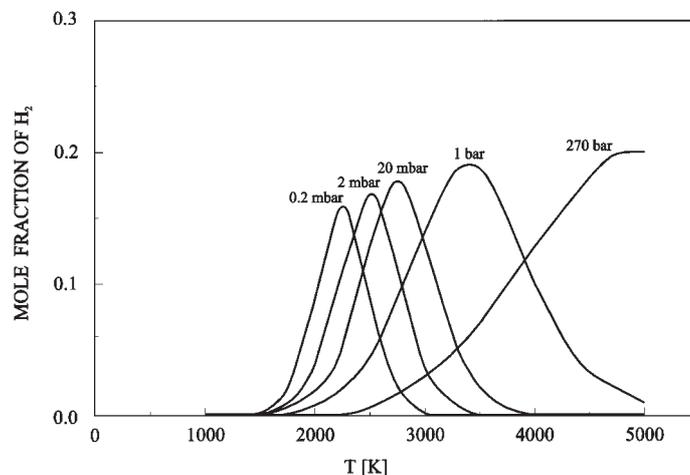


Fig. 2d

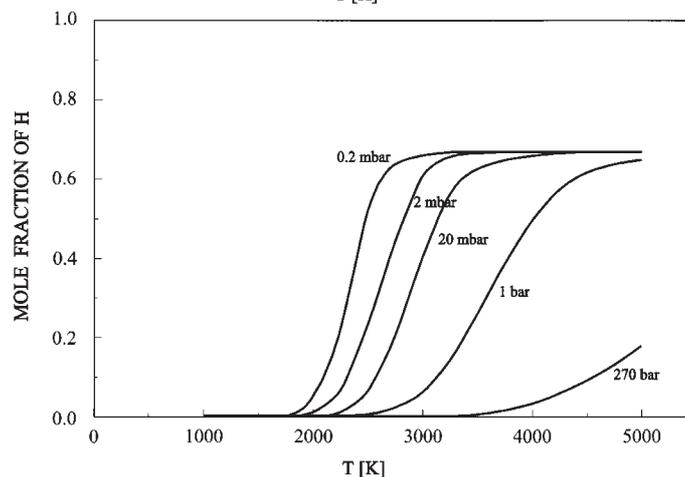


Fig. 2e

Fig. 2. Thermochemical equilibrium abundances of O_2 (a), O (b), OH (c), H_2 (d) and H (e) as a function of temperature (up to 5000 K) and a constant pressure (0.2 mbar, 2 mbar, 20 mbar, 1 bar and 270 bar).

270 bar. (The oceans contain $ca\ 1.4 \times 10^{21}$ kg of H_2O , corresponding to a globally averaged surface pressure of 270 bar). Figure 2 shows the chemical equilibrium abundances of O_2 (a), O (b), OH (c), H_2 (d) and H (e) as a function of temperature (up to 5000 K) at 0.2 mbar, 2 mbar, 20 mbar, 1 bar and 270 bar. (Similar results were obtained by a simulation based on the polarisation model for H_2O and by the reaction progress variable method). As shown in Fig. 2a, the maximum O_2 abundances ($ca.\ 7-8\%$) at 0.2 mbar, 2 mbar and 20 mbar were generated at about 2100 K, 2400 K, 2700 K, respectively. The equilibrium abundance of O_2 decreases at higher temperatures (up to 5000 K) because most of the O_2 is converted to O and OH.

It can be speculated that a source of O_2 on the pre-oxygenic Earth could have resulted from the high-temperature dissociation of H_2O vapor and the subsequent escape

of H₂ to interplanetary space. The pre-oxygenic Earth could develop a hot (>2000 K) steam-rich atmosphere by either a comet impact (into a ocean or on land), or an asteroid impact into a deep ocean.⁹ In this atmosphere, H₂O would gradually thermodynamically dissociate into O₂ and H₂. Consequently, H₂ may have been lost to interplanetary space, resulting in a build-up of O₂ in the residual atmosphere.

IMPACT-INDUCED DECOMPOSITION OF H₂O VAPOR

Let us assume that the impact of a comet into an ocean resulted in the complete conversion of the cometary and impacted H₂O vapor to O₂ species and H₂ which was afterwards removed from the impact plume. In this case, simple arithmetic reveals that 1.3×10¹⁶ kg of this H₂O vapor would create an atmosphere with 0.01 PAL of O₂ at a global averaged surface pressure of *ca.* 2 mbar. (In this connection, it is of interest to note that the present-day atmosphere contains *ca.* 1.2×10¹⁸ kg of O₂).

Using numerical data from O'Keefe and Ahrens,⁵ Croft,⁶ Pierazzo and Melosh¹¹ and Prinn and Fegley,²⁵ it can be estimated that a dense and ice-rich 14.6 km diameter comet with a mass of *ca.* 1.3×10¹⁶ kg (assuming a comet density of about 1000 kg m⁻³) and with a velocity of 25 km s⁻¹ could readily generate 1.3×10¹⁶ kg of superheated H₂O vapor, impacting into a (4 km) deep ocean (or on land). (Note, that significant oceanic depths are known to have existed during the Archean²⁶).

In general, the comet impact either into an ocean or on land would have completely disintegrated the impactor, placing most (or all) of its atoms and molecules into the plume.¹¹ For the sake of simplicity, it is assumed that the mass of superheated H₂O vapor within the initial plume is simply equal to the mass of the impacting comet. Evidently, the above value of 1.3×10¹⁶ kg is a conservative assumption since the impacted oceanic H₂O could supply an amount of steam to the cometary plume.^{5,27} A large part of this steam would be converted into superheated H₂O vapor.^{11,16,17,28} In addition, during the cratering process, oceanic H₂O immediately penetrating into the initial crater could also be rapidly converted into superheated steam because the temperature in the center of the crater cavity may reach temperatures of several thousands of degrees.^{11,16,29} (A cometary impact on land would, of course, provide a much lower amount of impacted H₂O vapor). The possible contribution of H₂O vapor of the target rock is also ignored. (This vapor could derive from impacted hydrous silicates and carbonates). This is reasonable since the amount of H₂O vapor provided by the target rock for a cometary impact into an ocean is not more than about 5 % of the total amount of the impact-related H₂O.³⁰

For the purpose of calculation, it is assumed that the cometary H₂O vapor was exposed at the moment of impact to a mean temperature of *ca.* 20,000 K and a mean pressure of *ca.* > 2 Mbar. (These two values are obtained from the Tillotson equation-of-state, adopting a constant specific heat capacity of ice-H₂O: 4 kJ kg⁻¹ K⁻¹). At the instant of impact, the shock-decomposed H₂O would probably consist mostly of ionised O₂, H₂ and their electrons. Equilibrium calculations show that at lower temperatures (< 20,000 K) and lower pressures (< 1 kbar) the cometary portion of the plume would contain mostly OS and HS immediately after the impact shock. (Molecular dis-

sociation requires *ca.* 15 MJ kg⁻¹ for O₂ and 218 MJ kg⁻¹ for H₂). Calculation (based on the ideal gas law) indicates that an initial plume (at a temperature *ca.* 20,000 K) would contain approximately 1.3×10¹⁶ kg of superheated H₂O vapor, exerting a partial pressure of *ca.* 100 kbar. (The comet is assumed to consist of 100 % H₂O. Comets are not, of course, pure H₂O-ice, but there are no still reliable data for their composition). The equilibrium calculations also indicate that the cometary plumes at initial low temperatures < 20,000 K may also generate O₂ but to a lesser extent.

THE EXPANDING PLUME AND HS

Equilibrium calculations indicate that the possibility of O₂ formation within the expanding plume at lower temperatures (< 10,000 K) is significantly affected by the abundances of H₂ and H. These calculations over a wide range of assumed plume compositions show that the speciation in a low temperature O–H plume depends on the bulk H/O ratio. In a low-temperature H-enriched plume, H₂O vapor would be the major gaseous component and in a low-temperature H-depleted plume, O₂ would be the major species. Thus, a high H/O ratio would suppress the formation of O₂ within the expanding plume and a low H/O ratio would favor this process. For this reason, of crucial importance for the generation of O₂ is the separation of OS and HS within the plume. This would prevent them from reacting with each other, ultimately forming the original H₂O vapor. HS could be separated from OS by either escape into interplanetary space or chemical reaction with some of the plume constituents. The remainder of this paper is focused on the removal of HS from the plume by the escape process.

THE HEMISPHERICAL MODEL OF THE PLUME

The initial expansion of a plume has a rather complex form but once the plume has expanded to several times the comet diameter (14.6 km), the plume expansion can be approximated as an expanding hemisphere of a high-temperature gas mixture, staying as such until the plume collapses. Here, the plume generated by an impacting comet is modelled as a hemispherical gas cloud expanding into a vacuum. For a discussion of the physics of such a model the reader is referred to Vickery and Melosh,¹⁰ Zel'dovich and Razier,¹⁵ Melosh^{16,31} and Zahnle.³² (It is assumed that the initial (post-shock) hemispherical plume had an average radius of about 5×14.6 km = 73 km). It is also assumed that the expanding gas cloud commences in uniform thermodynamic state.

THE PLUME EXPANSION AND THE HS ESCAPE

The most important properties of the impact-generated gaseous plume are the expansion velocity and the gaseous composition of its leading zone. These are closely related to the amount of gaseous products left on the Earth without escape. In the present model, OS and HS (ejected in the initial stage of the plume expansion) would concentrate predominantly in the outer (and much faster) layer of the rapidly expanding plume and so be separated from the inner part, containing most of the vaporised target rock.¹¹ Under the assumption that only cometary H₂O is decomposed by the impact, the specific energy available for the expansion of the plume is given by $(1/2)(E - H_{V+D})$,

where E is the total specific energy of the high velocity plume and H_{V+D} is the vaporisation + decomposition energy of ice-H₂O vapor (*ca.* 31 MJ kg⁻¹; complete vaporization for ice occurs at a shock pressure of < 1 Mbar). (It is also assumed that the comet and an equal mass of the target constitute the impact plume. This assumption rests on the planar impact approximation when both the impactor and target are nearly same materials: see Melosh³¹). For the purpose of simplicity, the assumption $E \gg H_{V+D}$ is adopted here. Thus, for a m kg and v km s⁻¹ comet (with a kinetic energy $KE = (1/2)mv^2$), impacting into a deep ocean, the mean (mass-averaged) bulk expansion velocity v_p of the plume is given by:

$$v_p = (KE/2m)^{1/2} = (1/2) v$$

(For the present case $v_p \approx 12.5$ km s⁻¹).

The expansion energy of the outer layer of the plume should be equally partitioned between OS and HS. (This assumption rests on an equipartition of the expansion energy of the plume among the various molecular and atomic species). Simple algebra then shows that the mean velocities of OS (v_{OS}) and HS (v_{HS}) within the plume are roughly given by:

$$v_{OS} \approx (3/8) v$$

and:

$$v_{HS} \approx (9/8)^{1/2} v$$

(Note, the atomic mass of an O atom is 8 times greater than the molecular mass of a H₂ molecule).

For the cometary impact in question, it can be roughly taken that

$$v_{OS} \approx 9 \text{ km s}^{-1} \text{ and } v_{HS} \approx 26 \text{ km s}^{-1}$$

Consequently, the HS would concentrate in the fastest zone of the plume periphery. Most of the OS, on the other hand, would reside in the slower zone of the periphery. (Obviously, the physics involved in the above consideration is complex, and a more detailed study would be required to examine it properly).

If the comet velocity is high ($v > 30$ km s⁻¹), most of the OS (and, of course, the HS) would escape the Earth. (According to hydrocode calculations performed by Vickery and Melosh,¹⁰ an impact of a $> 10^{16}$ kg comet on land with a speed of 30 km s⁻¹ would cause a complete loss of volatiles into interplanetary space). A maximum amount of O₂ could be generated if the comet velocity is low enough ($v < 30$ km s⁻¹) so that most of the OS could be retained within the plume. This velocity should be still high enough (> 11 km s⁻¹) so that most of the HS would escape into interplanetary space. (Short-period comets with periods > 20 years have impact velocities between 15–35 km s⁻¹).³³

The faster HS-rich zone would outdistance the OS-rich part of the plume by an average separation *ca.* $17 t_e$ km, where t_e is the plume expansion time ($t_e = 0$ at the moment of impact). For 10 s the HS-rich zone would be 260 km away from the impact site.

At this point the OS-rich portion of the hemispherical plume would be *ca.* 170 km behind the HS-rich front and at a temperature of about 19,000 K and at a gas pressure of *ca.* 250 bar. (The later two values were estimated using the ideal gas and Stefan-Boltzmann laws). Bearing in mind that the HS-rich outermost zone would have a mean expansion velocity (*ca.* 26 km s⁻¹), which far exceeds the Earth's escape velocity v_{esc} (11.2 km s⁻¹), it appears inevitable that most, if not all, of the initial HS would escape into interplanetary space. (The remainder of the plume would be a gas cloud, containing mostly OS). For about 300 s, calculations (based on the ideal gas and Stefan-Boltzmann laws) show that the HS-depleted cloud would further expand and cool down to a temperature of *ca.* 3000 K, reaching a pressure of *ca.* 2 mbar. Thermochemical equilibrium calculations indicate that at this point the expanding plume would contain mostly O₂, covering the entire planet until the plume collapse goes to completion. (Recently, Takata *et al.*³⁴ modelled an impact by a 2 km diameter comet with an impacting velocity of 60 km s⁻¹. Their numerical calculations indicate that such an impactor would generate a plume with initial temperatures >10,000 K and temperatures >2000 K for more than 100 s after impact). The newly-formed hot and O₂-rich atmosphere would then cool down to ambient temperature of about 273 K. Thus, assuming a 100 % impact efficiency, a *m* kg cometary (or any icy) object impacting into a deep ocean of the pre-oxygenic Earth would generate approximately *m* kg of O₂ if its speed is within the critical limits of 11 km s⁻¹ and 30 km s⁻¹. (It is reasonable to expect that a comet impact on land would provide an equal amount of O₂).

The most important omission of the present model is the absence of a pre-oxygenic Earth's atmosphere. Direct evidence of a reducing atmosphere have been claimed in the past, but this evidence is no longer regarded as conclusive. There is a growing consensus that in the Archean period for which data is available, the atmosphere was neutral, with negligible amounts of free O₂. It is considered likely that the atmosphere at this time was composed of CO₂, N₂, H₂O and CO. Such is the conclusion, for example, of Kasting.¹ The neglect of the Earth's atmosphere is at present unavoidable for practical reasons, since the chemistry inside the expansion plume would be rather complex as a result of the mixing and interaction of the gaseous components of the plume with the surrounding atmospheric gases. (Clearly, chemical reactions between N₂ and O₂/O would dominate within the plume. The high temperature chemistry within a cometary plume is deferred to a later paper).

SPECULATIONS AND IMPLICATIONS

Most researchers believe that an abrupt rise in atmospheric O₂ level occurred between 2.4 Ga and 1.8 Ga, reaching 0.015 PAL O₂ (or *ca.* 1.75 × 10¹⁶ kg). In a recent major reexamination of the paleosol evidence Ohmoto³⁵ has challenged this concept. He argues that the minimum oxygen pressure for the 3.0 – 2.2 Ga (for which paleosol data is available) is about 1.5 % of the present level. We wish to briefly speculate about a possible way of generating this level of O₂ on the pre-oxygenic Earth that would be compatible with the present scenario. It consists of *ca.* 16 km diameter comet (or a few of its tightly clustered fragments) with a speed (11 km s⁻¹ < *v* < 30 km s⁻¹) impacting

into a deep ocean (or on land). It can further be speculated that a giant 68 km diameter comet (or a few of its tightly clustered fragments) with a velocity within the above critical speed limits, smashing into a deep ocean (or on land) could have enabled the generation of 1 PAL of O₂ (or, at least, its initial O₂ amount) on the pre-oxygenic Earth. Alternatively, multiple cometary impact (within a short period of time) with a bulk mass of *ca.* 1.3×10¹⁸ kg and with a bulk speed within the same limits would be also capable to create the same level of O₂.

A large cometary impact is, however, not a necessity for the generation of O₂. Frank *et al.*³⁶ have suggested that small comets (most are thought to be in the 10⁵ kg range with a bulk speed < 20 km s⁻¹) frequently bombard the top of the Earth's atmosphere and vaporize above the Earth's surface. These authors also suggested that such comet-like "rain" could have replaced the Earth's atmospheric mass (*ca.* 5.2×10¹⁸ kg) in about 5×10⁶ years. Thus, if the present influx of small comets is assumed to be true for the pre-oxygenic Earth as well, it is not unreasonable to hypothesize that a rain of small comets (with the corresponding bulk velocity and mass) impacting into an ocean (or on land) may be ultimately responsible for the present-day atmospheric level of O₂ (*ca.* 1.2×10¹⁸ kg) or, at least, for its initial abundance. (Note, that O³⁷ and OH³⁸ were detected in the disintegrating small comets, impacting the top of the Earth's atmosphere). However, once the atmosphere had become oxygenic, HS escape to interplanetary space would cease and impacting small comets would deliver only H₂O to the Earth's hydrosphere, as originally suggested by Frank *et al.*³⁶

It should be emphasized here that even an abrupt rise of O₂ to 0.001 PAL (0.2 mbar) caused by a cometary impact would have caused a crisis for the primitive anaerobic bacterial life on the pre-oxygenic Earth. These life forms would be actually poisoned by such an excess of O₂ in their living environment, triggering their wholesale extinction. On the other hand, this O₂ crisis would create a suitable environment for a new but more advanced life form aerobic (photosynthetic) bacterial life which would permit a build up of O₂ to the present-day level (Walton³⁹ and references therein).

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ИЗВОД

УДАР КОМЕТЕ У ОКЕАН: ТЕРМОХЕМИЈСКА РАВНОТЕЖНА ИЗРАЧУНАВАЊА
ВИСОКО-ТЕМПЕРАТУРНОГ ФОРМИРАЊА O₂ НА РАНОЈ ЗЕМЉИ

ПАВЛЕ И. ПРЕМОВИЋ и КАТЈА И. ПАНОВ

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Рана Земљина атмосфера се очигледно разликовала од садашње углавном по одсуству слободног O₂, а то одсуство је, верује се, било неопходно за појаву раних анаеробних форми живота. Један од централних проблема наука о Земљи је како објаснити јасну промену од примитивне атмосфере (без O₂) до садашње атмосфере која садржи 21 % овог гаса. Теоретски модели указују на то да је почетна форма O₂ у Земљиној атмосфери могла бити H₂O, која се трансформисала у атмосферски O₂, углавном кроз процес фотосинтезе. Ми смо проучавали један алтернативни (абиотски) метод за превођење H₂O у O₂: високо температурни удар проузрокован ударом комете у океан (или копно). Прорачуни показују овде да је 1 % тренутног O₂ могао постати од једне ледене комете (1,3×10¹⁶ kg) која је ударила у рану Земљу (без кисеоника) брзином између 11 и 30 km s⁻¹.

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REFERENCES

1. J. F. Kasting, *Science* **259** (1993) 920
2. T. Owen, A. Bar-Nun, *Icarus* **116** (1995) 215
3. K. Righter, M. Drake, *Earth Planet. Sci. Lett.* **171** (1999) 383
4. A. Morbidelli, J. Chambers, J. I. Lunine, J. M. Petit, F. Robert, G. B. Valsecchi, K. E. Cyr, *Meteorit. Planet. Sci.* **35** (2000) 1309
5. J. D. O'Keefy, T. J. Ahrens, *Geological Society of America Special Paper* **190** (1982) 103
6. S. K. Croft, *Geological Society of America Special Paper* **190** (1982) 143
7. J. Lewis, H. Watkins, H. Hartmann, *Geological Society of America Special Paper* **190** (1982) 385
8. H. J. Melosh, A. M. Vickery, *Nature* **338** (1989) 487
9. N. H. Sleep, K. J. Zahnle, J. F. Kasting, H. J. Morowitz, *Nature* **342** (1989) 139
10. A. M. Vickery, H. J. Melosh, *Geological Society of America Special Paper* **190** (1990) 289
11. E. Pierazzo, H. J. Melosh, *Meteorit. Planet. Sci.* **35** (2000) 117
12. E. M. Shoemaker, R. F. Wolfe, C. S. Shoemaker, *Geological Society of America Special Paper* **247** (1990) 155
13. W. T. Holser, M. Schidlowski, F. T. Mackenzie, J. B. Maynard, in *Chemical Cycles in the Evolution of the Earth*, C. B. Gregor, R. M. Garrers, F. T. Mackenzie Eds., Wiley, New York, 1988, p. 68
14. L. A. Frank, *Eos* **68** (1987) 343
15. Y. B. Zeldovich, Y. P. Razier, *Physics of Shock Waves and High-temperature Hydrodynamics Phenomena*, Academic Press, San Diego 1967, p. 691
16. H. J. Melosh, *Geological Society of America Special Paper* **190** (1982) 121
17. E. M. Jones, J. W. Kodis, *Geological Society of America Special Paper* **190** (1982) 175
18. C. F. Chyba, P. J. Thomas, L. Brookshaw, C. Sagan, *Science* **249** (1990) 366
19. E. A. Fletcher, R. L. Moen, *Science* **197** (1977) 1050
20. E. L. King, *J. Chem. Ed.* **58** (1981) 975
21. H. H. G. Jellinek, *J. Chem. Ed.* **63** (1986) 1029
22. C. H. Bauer, G. L. Schott, R. E. Duff, *J. Chem. Phys.* **28** (1958) 1089
23. G. A. Lyzenga, T. J. Ahrens, W. J. Nellis, A. C. Mitchell, *J. Chem. Phys.* **76** (1982) 6282

24. T. M. Han, B. Runegar, *Science* **257** (1992) 232
25. R. G. Prinn, B. Fegley, *Earth Planet. Sci. Lett.* **83** (1987) 1
26. C. G. A. Harrison, *Geophys. Res. Lett.* **13** (1999) 1913
27. P. H. Schultz, D. E. Gault, *Geological Society of America Special Paper* **247** (1990) 239
28. L. F. Jansa, *Palaeogeogr. Palaeoclimatol. Palaeoecol.* **104** (1993) 271
29. C. Emiliani, E. B. Kraus, E. M. Shoemaker, *Earth Planet. Sci. Lett.* **55** (1981) 317
30. E. Pierazzo, D. A. Kring, H. J. Melosh, *J. Geophys. Res.* **103** (1998) 28,607
31. H. J. Melosh, *Impact Cratering*, Oxford Press, New York, 1989, p. 40
32. K. J. Zahnle, *Geological Society of America Special Paper* **247** (1990) 271
33. E. M. Shoemaker, P. R. Weismann, C. S. Shoemaker, in *Hazard Due to Comets and Asteroids*, T. Gehrels Ed., University of Arizona Press, Tucson, 1994, p. 23
34. T. Takata, J. D. O'Keefe, T. J. Ahrens, G. S. Orton, *Icarus* **109** (1994) 3
35. H. Ohmoto, *Geology* **24** (1996) 1135
36. L. A. Frank, J. B. Sigwarth, J. D. Craven, *Geophys. Res. Lett.* **13** (1986) 307
37. L. A. Frank, J. B. Sigwart, *Geophys. Res. Lett.* **24** (1997a) 2431
38. L. A. Frank, J. B. Sigwart, *Geophys. Res. Lett.* **24** (1997b) 2435
39. J. C. Walton, *Origins* **3** (1977) 66.