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About the age of the Earth

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ABSTRACT

The author presents the first attempts of eminent specialists, such as Leibniz, Buffon and Kelvin to specify the age of the Earth through different itineraries.

Buffon infers the age of the Earth from the time a cannonball takes to cool down.

Leibniz was the first to clearly propose in his book Protogaea (1680) that the Earth had initially been a molten sphere (see Leibniz, 1993).

In the introduction of his work *Introduction à l'histoire des minéraux* (1775), Buffon attempted to infer the age of the Earth through experiments aiming at measuring the time taken by the cannonball to cool down. Buffon wrote in the chapter *Experiment*: "I have made ten wrought iron cannonballs, the first one half an inch in diameter, the second one inch in diameter, [. . .] the tenth one five inches in diameter (about 13 cm)". He had them heated to bring the metal to a white heat.

"I aimed at determining two moments during cooling: the first one when the balls stopped burning anymore, i.e. when one could touch them and held them in one's hand during a second without being burned. The second one when the balls were cooled down to room temperature, i.e. ten degrees above the freezing temperature. To determine the time when the ball reached room temperature, we compared it with other cannonballs with the same diameter, but which had not been heated and could be touched at the same time as those that had been heated. Through this simultaneous and instantaneous touching on two balls with one hand or both hands, we could determine the moment when both balls were equally cold. This simple method was not only more simple than measuring with a thermometer, which would have been difficult to carry out in this case, but it was also more accurate because it was only a matter of estimating when temperatures are equal and not comparing between two different temperatures because our senses are better judges than instruments when it comes to estimate which things are absolutely equal or perfectly similar.

Given the fact that the same metal surface can appear more or less polished or rough by the touch, and that a polished object appears to be colder than it actually is, and warmer when it is warm, than a rough object even though they are made of the same material, I took care that the cold cannonballs were unpolished and similar to those which had been heated and whose surface was scattered with tiny specks generated by the fire."

Buffon then reports the results of his experiments: times called t_1 and t_2 for balls with different sizes.

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He reports: "A passage in Newton originated these experiments. Newton wanted the above experiments to be carried out."

Buffon noticed that t_1 and t_2 were proportional to the balls' diameters and boldly extrapolated the linear relationship to the Earth diameter. He concluded: "Now if we wanted to infer with Newton how much time was needed for a sphere as big as the Earth to cool down, one would find according to the above experiments that instead of the fifty thousand years he had estimated for the Earth's cooling time to be down to its present-day temperature, one needed forty-two thousand nine hundred sixty-four years and two hundred twenty-one days to cool it down to a temperature where it would not burn, and ninety-six thousand and six hundred seventy years and one hundred thirty-two days to cool it to room temperature." Illusory precision!

Buffon did not fail to notice that in order to apply to the Earth experimental results and calculations, one would have to assume that the latter is made up of "materials that would require as much time as iron to cool down, whereas the main materials making up the Earth, such as clays, sandstones, stones, etc., should cool off much more rapidly than iron does." It is true because such materials store less heat. Buffon had balls two inches in diameter made from clay and sandstone that he had brought to a white heat. He found out "that the clay ball does not need half the cooling time of the iron one." Conversely, he noticed that "the cooling of the sandstone ball requires more than half the time needed for iron." Nevertheless, Buffon does not directly draw any conclusion from his last observation with respect to the age of the Earth, and he proceeds with "experiments on heat progress in various mineral materials" using spheres one inch in diameter made of twenty-four different matters, either metallic ones such as gold, copper, iron, etc., or mineral ones such as marble, sandstone, chalk, etc.

Buffon considered again the cooling of the Earth and planets in the chapter *Hypothetical.*

"Assuming, as all the phenomena seem to indicate, that the Earth had been once liquid because of the fire, our experiments demonstrated that if the sphere had been completely composed of iron or ferruginous matters it would have solidified down to its core only in 4026 years, cooled to be touched without burning the fingers in 46,991 years only, and reached room temperature only in 100,696 years; however, as the Earth, according to all we know, seems to be made up of vitrifiable matters and limestones that cool faster than the ferruginous ones, one must consider, in order to get near the truth as must as possible, the respective cooling times of the various materials as we measured them through our experiments in our second *Mémoire*, and infer the ratio with the iron cooling time. By using in this sum only glass, sandstone, hard limestone, marble, and the ferruginous matter, one finds that the Earth sphere solidified down to its center in about 2905 years, that it cooled enough to be touched in ca. 33,911 years, and to room temperature in ca. 74,047 years."

Buffon does not mention the proportions he chose among the various materials forming the Earth. Buffon's calculations do not exceed the rule of three.

Let us consider now why Buffon's estimates are so far from truth. He implicitly assumed that the cannonballs had a uniform temperature, from their surface to the core, and that this temperature decreased through time.

In such conditions, one can admit that the amount of accumulated heat ($\rho \cdot C_p$) is transmitted from the surface with a transfer coefficient h, and one can calculate the temperature decrease through time. One finds, as Buffon did, a linear relationship between the cooling times and the radius R of the cannonballs.

However, this calculation is only valid if the temperature is assumed to be uniform, i.e. if the difference between the center of the balls and their surface is smaller than 5% T. One defines a dimensionless number, called the Biot number, $Bi = hRT/k$, where k is the thermal conductivity coefficient. $Bi < 0.1$ is the condition for Buffon's hypothesis to be valid. One can infer the transfer coefficient h from Buffon's experimental values and one finds out that the radius beyond which the approximation is not valid is about 17 cm. Now, the maximum radius of the balls was 6.5 cm. The estimate was thus valid for Buffon's experimental conditions, but the extrapolation of the Earth's radius was completely wrong: for the Earth, Bi should be ca. $4 \cdot 10^6$.

A dt/dz temperature gradient exists, which is strong enough from the surface down to a depth of about 100 km: it is the geothermal gradient measured by Cordier in 1827 and which averages 30° per km, but the temperature remains higher inside, with a much smaller gradient.

Kelvin and the earth cooling through conduction: Kelvin inferred the Earth's age by calculating the lowering of the geothermal gradient through time. He assumed, as Fourier did, that the Earth cooled by conduction starting from the surface. The heat flow is equal to the gradient multiplied by the thermal conductivity.

By measuring the starting temperature T_0 and assuming the surface temperature to be 0°, and solving the Fourier equation for diffusion, one finds that the surface temperature gradient is: $G = dT/dz = T_0/\sqrt{\pi \kappa t}$, where κ is the thermal diffusivity, i.e. $\kappa = k/\rho C_p$. Heat diffuses during a given time t over a distance $\sqrt{\pi k t}$. At smaller depths, the temperature varies like G; at greater depths, it did not have time to decrease much from its initial value T_0. The temperature gradient near the surface decreases like the reciprocal of the square root of time.

With these hypotheses, Kelvin was able to calculate the time needed for the gradient G to decrease to its present-day value and, thereafter, to infer the Earth's age: $t = (T_0/G)^2/\pi\kappa$. Kelvin proposed, in 1863, an age ranging from 24 and $400 \cdot 10^6$ years, keeping in mind the uncertainties on the k and G values. It was much larger than Buffon's estimate, which was already much too large for the tenants of the biblical age, but much too small for the tenants of the evolution theory, such as Darwin, or the geologists who considered with Hutton: "No vestige of a beginning, no prospect of an end".

One generally thought with Rutherford and Barnes (1904), and many still think so today, that if Kelvin had found a too small age, this was due to the fact that he did not know at the time that radioactivity could supply additional heat. Frank Richter demonstrated in 1986 that this explanation does not hold.

To get a greater age, and therefore slow down the temperature gradient decrease near the surface, one should supply more heat from inside the Earth. However, one should also keep in mind that the heat supplied by radioactivity inside the Earth does not matter much because conduction can only transfer a very small heat flow from the Earth interior to its surface. Therefore, conduction cannot exploit all the inner heat to slow down the decrease in the surface temperature gradient. The real problem was with Kelvin's hypothesis that the Earth cooled through conduction.

John Perry, one of his assistants, understood that if one would assume a higher thermal conductivity inside the Earth, the heat flow feeding the superficial conductive layer would be larger, and one would infer an age of a few billion years (Perry, 1895). One would get a very large "quasi-conductivity" assuming that the inner part of the Earth were fluid or partly fluid, and therefore could be driven by convection currents. Convection transfers heat along with matter, and therefore is much more efficient for supplying internal heat than conduction, because the latter only results from propagating thermal vibrations, without matter.

Perry did not succeed in convincing Kelvin.

One now knows that convection drives the interior of the Earth, which behaves as a fluid for very large time scales.

Radioactivity allowed the determination of the age of the Earth, as we will see, but it was not in a calculation based on conductivity such as Kelvin did.

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