Possible Influence of an Absorbing Cloud upon the Terrestrial Climate

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Geological research indicates irregular variations in the past climate of the earth. Warm periods during which tropic vegetation is known to have been growing near the present poles were succeeded by noticeably cooler epochs, which often developed into the so-called ice ages. At least for the last quarternary ice age it seems to be established by accurate astronomical observations that the migration of the poles or of the continents cannot be made responsible for the observed changes in the climate, and it seems to be probable that for more remote epochs the same is true; we have to admit variations in the mean temperature, most probably of the whole earth, at least of a whole hemisphere of the earth. To explain these fluctuations in the mean terrestrial temperature, different astronomical and geophysical hypotheses have been suggested; hitherto none of these has been generally accepted. In the present note we shall concern ourselves with only one particular astronomical hypothesis, namely the one which attributes the variations in our climate to the influence of interstellar absorbing clouds. For the present we assume that the intensity of solar radiation remains constant: an arbitrarily variable rate of the radiation may itself explain all or most of the climatic changes, making other hypotheses superfluous; the hypothesis of an absorbing cloud loses all possibility of proof when the solar radiation is assumed arbitrarily variable at the same time.

There exist two opposite opinions of how an absorbing cloud surrounding the solar system may influence the terrestrial climate: it may cause an increase of the mean temperature through the shielding effect with respect to radiation toward space, and through the conversion of the kinetic energy of its particles into heat; on the other hand, a decrease of the mean temperature of the earth may follow as a consequence of the absorption of solar radiation by the cloud.

I.

At first we will consider the conditions under which an absorbing cloud may cause the cooling of the terrestrial climate. The diminution of the effective insolation at the earth's surface is by no means identical with the absorption of solar radiation along its path from the sun toward the earth. As soon as the particles reach the temperature required by the local radiative equilibrium, they send out as much energy as they absorb, and no loss of insolation occurs. Thus an absorbing cloud which as a whole is at rest relative to the sun cannot cause any diminution of the mean temperature of the earth, because the temperature of the particles has time enough to settle itself at the equilibrium value. The only way how an absorbing medium might produce a loss of radiation incident upon the earth is represented by the case when the matter as a whole possesses some translational motion with respect to the sun, carrying thus a certain amount of heat away from the solar system. Nevertheless, from the following computations it appears that any conceivable absorbing cloud is qualitatively unable to produce an effect comparable to an ice age.

The maximum dimming of the insolation may be estimated by the following simplified scheme. The absorbing matter which just enters the spherical space within the radius 1 A. U. around the sun has a lower temperature than the matter which, after penetrating the sphere, moves just out. The rise of temperature of the matter takes place at the expense of the solar radiation absorbed inside the given sphere, which is thus partially transported outside the earth's orbit. In the first approximation, the upper limit to the loss of solar energy for the earth may be taken to be equal to the absorbed heat as defined just before. The actual diminution of the energy is smaller because a fraction of the energy transported outside the earth's orbit is later radiated from outside back to the earth, and thus in the present case the influence of the absorbing matter is overestimated. The amount per unit of time of the absorbed energy is

$$E_1 = M\, l\, \Delta T \quad . \; . \; . \; . \; . \; . \; . \; . \; . \quad (1),$$

where M is the total mass which flows through the sphere in unit of time, l — the specific heat of the matter, and ΔT — the mean effective increase of temperature during the passage of the particles through the space inside the earth's orbit.

Let the sun be moving in an interstellar dust cloud with the relative velocity v_∞, and let us neglect the internal motions of the cloud and the perturbations of the particles upon each other; in such a case the mass M that flows in unit of time through the sphere with the radius R around the sun (in the particular case, R is the distance of earth from sun) is determined by the formula

$$M = \pi \varrho_\infty R^2 \left(1 + \frac{v_R^2}{v_\infty^2}\right) v_\infty \quad . \quad . \quad . \quad . \quad . \quad . \quad (2);$$

here ϱ_∞ is the initial density of the cloud, at infinite distance; v_R — the parabolic velocity at the distance R from the sun. This formula can be derived easily from Kepler's second law applied to the single particles. The maximum diminution of the insolation per surface unit of the earth is obtained from formulae (1) and (2) as

$$e_1 = \frac{E_1}{4\pi R^2 \cdot 4} = \Delta T \frac{l}{16} \varrho_\infty \frac{v_\infty^2 + v_R^2}{v_\infty} \quad . \quad . \quad . \quad . \quad (3).$$

On the other hand, the energy income at the surface of the earth is increased by the kinetic energy of meteors of the absorbing cloud which fall upon the sun (stimulating its radiation) and directly upon the earth. The kinetic energy of a given meteoric mass is $E = \frac{Mv^2}{2}$. The total diffuse mass M that falls upon the sun in unit of time is found from formula (2) by setting $R = R_\odot$ and $v_R = v_0$, where $R_\odot$ is the radius of the sun and v_0 — the parabolic velocity at the surface of the sun:

$$M_\odot = \pi \varrho_\infty R_\odot^2 \frac{v_\infty^2 + v_0^2}{v_\infty}.$$

The velocity of meteoric particles relative to the sun is evidently $v = \sqrt{v_\infty^2 + v_0^2}$. Taking into account these equations, the kinetic energy of the meteoric mass falling in unit of time upon the sun is found equal to

$$E_\odot = \frac{1}{2} \pi \varrho_\infty R_\odot^2 \frac{(v_\infty^2 + v_0^2)^2}{v_\infty}.$$

We may assume with confidence that this amount of energy is immediately radiated outwards, without any noticeable influence upon the internal energy production of the sun; the equivalent increase of the insolation per surface unit of the earth is

$$e_2 = \frac{E_{\odot}}{4\pi R^2 \cdot 4} = \frac{1}{32} \varrho_\infty \left(\frac{R_{\odot}}{R}\right)^2 \frac{(v_\infty^2 + v_0^2)^2}{v_\infty} \quad . \; . \; . \quad (4).$$

The gravitational condensing effect of the earth upon the meteoric particles may be neglected, whereas the solar condensing effect is more conspicuous even at the earth's distance. For the average density around the earth's orbit we take (unpublished paper by Kusmin)

$$\varrho = \varrho_\infty \frac{\sqrt{v_\infty^2 + v_R^2}}{v_\infty} \quad . \; . \; . \; . \; . \; . \; . \quad (5).$$

The velocity of the earth relative to the absorbing cloud is variable. Also, the average relative velocity of the earth depends upon the orientation of its orbit, but has certain limits :

$$v_\infty^2 + v_R^2 \leqslant v_{\oplus}^2 \leqslant v_\infty^2 + v_R^2 + v^2 \quad . \; . \; . \; . \; . \quad (6);$$

v is the orbital velocity of the earth, $v_{\oplus}$ — the average velocity of the earth relative to the impinging cloud particles. Now, the amount of meteoric mass that falls upon unit of the earth's surface in unit of time equals $\varrho \frac{v_{\oplus}}{4}$ and hence its kinetic energy is $\varrho \frac{v_{\oplus}^3}{8}$. Only one half of this energy may be assumed to reach the earth's surface, while the other half is radiated into space ; thus

$$e_3 = \frac{\varrho \, v_{\oplus}^3}{16} \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \quad (7).$$

For the absorbing cloud to cause a cooling effect upon the earth the condition $e_1 > e_2 + e_3$ must be fulfilled, which means that the amount of heat carried away by the cloud must exceed the extra heat generated by impact; taking for $v_{\oplus}$ its minimum value $v_{\oplus}^2 = v_\infty^2 + v_R^2$, with the aid of formulae (3) to (7) the inequality becomes

$$\Delta T \frac{l}{16} \varrho_\infty \frac{v_\infty^2 + v_R^2}{v_\infty} > \frac{1}{a} \frac{1}{16} \varrho_\infty \left[\frac{1}{2} \left(\frac{R_\odot}{R} \right)^2 \frac{(v_\infty^2 + v_0^2)^2}{v_\infty} + \frac{(v_\infty^2 + v_R^2)^2}{v_\infty} \right],$$

$$\text{or} \quad \Delta T > \frac{1}{al} \left[\frac{1}{2} \left(\frac{R_\odot}{R} \right)^2 \frac{(v_\infty^2 + v_0^2)^2}{v_\infty^2 + v_R^2} + (v_\infty^2 + v_R^2) \right] \quad . \quad . \quad (8);$$

here a is the mechanical heat equivalent. This inequality determines at a given v_∞ the lower limit required for ΔT. Its smallest value we get if $v_\infty = 0$. In this case

$$\Delta T > \frac{1}{al} \left[\frac{1}{2} \left(\frac{R_\odot}{R} \right)^2 \frac{v_0^4}{v_R^2} + v_R^2 \right] = \frac{3}{2} \frac{1}{al} v_R^2 \quad . \quad . \quad (8a).$$

Adopting the values for $v_R = 4.2 \times 10^6$ cm/sec, $l = 0.3$ cal/deg.gr, $a = 4.2 \times 10^7$, we find $\Delta T > 2 . 10^6$. This means that a cooling effect from an absorbing cloud may be expected when the temperature increase of the matter during its passage through the space inside the earth's orbit is as great as 2.10^6 degrees. Surely such an increase of temperature cannot really exist. By this computation it is definitely shown that no interstellar cloud is to be taken into account as a possible cause of the terrestrial ice ages, or of other similar depressions in the mean temperature. Our conclusions are the more valid because formula (3) exaggerates the possible amount of heat carried away by the medium. Thus, a cosmic cloud cannot have a cooling influence; only warming effects can be taken into account.

II.

The warming effects to be considered are those due to the kinetic energy of impact and to the shielding of radiation into space. The maximum shielding effect is obtained on the assumption that the state of the cloud is very near to local radiative equilibrium.

The surplus energy produced by the cloud and received at the surface of the earth consists of the following components :

1) The heat generated by the kinetic energy of matter which falls upon the sun and upon the earth as considered above; 2) the energy radiated back from the absorbing envelope. Although both components exist at the same time, it is necessary to consider both only when they are of the same order of magnitude.

The formulae for the calculation of the kinetic energy of meteors are given above, equations (4) to (7). Adopting now for $v_{\circlearrowleft}$ its maximum value and denoting by ϱ the average density of the envelope at the earth's distance from the sun, the increase of insolation per surface unit of the earth is

$$e_{23} = \frac{\varrho}{16}\left[\left(\frac{R_\odot}{R}\right)^2 \frac{1}{2}\frac{(v_\infty^2 + v_0^2)^2}{\sqrt{v_\infty^2 + v_R^2}} + (v_\infty^2 + v_R^2 + v^2)^{3/2}\right] \ldots (9).$$

To estimate the amount of energy radiated back by the diffuse matter we make use of the following scheme. The density of the absorbing medium is taken as constant. This assumption is quite plausible because the mean density should actually vary with a small negative exponent of the distance from the sun (the maximum negative value of the exponent is $-\frac{1}{2}$ as appears from formula (5) with $v_\infty \to 0$, and with $v_R \sim R^{-\frac{1}{2}}$). Further, we limit ourselves to the case of an incipient shielding effect when the radiation of the cloud is small as compared with the direct solar radiation; the actual palaeoclimatic changes do not require more than 10 per cent of a warming effect. The energy flux that passes outward the element of volume $du = ds\,dR$ may in the first approximation be assumed equal to $\frac{q_0}{R^2}\,ds$, where R is the distance from the sun and q_0 the solar constant, if R is measured in astronomical units. Here the secondary radiation of the cloud is neglected because upon our assumption it is small as compared with the net energy flux. Of this energy the fraction $\tau\,dR$ is absorbed by the cloud; τ is the absorption coefficient of the medium. While the matter is assumed to be in local radiative equilibrium, an amount equal to the absorbed energy $di = \tau\,dR\frac{q_0}{R^2}\,ds$ is radiated out again; we suppose that the re-radiation takes place uniformly in all directions. On this assumption the differential increase of radiation due to the cloud per surface unit of the earth is

$$de_4 = \frac{di}{4\pi R_1^2 \cdot 4} = \frac{\tau\, q_0}{16\pi R_1^2 \cdot R^2}\, dR ds\,;$$

R_1 is the distance of the volume element from the earth. Introducing the angle α between the directions from the sun toward earth and volume element, we have: $ds = 2\pi R^2 \sin a\, da$ and $R_1 = R^2 - 2R \cos a + 1 = (R - \cos a)^2 + \sin^2 a$; the distances are measured in astronomical units. Thus

$$de_4 = \frac{1}{8} \tau q_0 \frac{\sin a}{(R - \cos a)^2 + \sin^2 a} da\, dR, \text{ and}$$

$$e_4 = \frac{1}{8} \tau q_0 \int_0^{\pi} da \int_0^{\infty} dR \frac{\sin a}{(R - \cos a)^2 + \sin^2 a} = \frac{1}{16} \pi^2 q_0 \tau \,.\,. \quad (10).$$

τ is the absorption coefficient of the diffuse matter per astronomical unit and q_0 is the solar constant. The integration over R is carried through to infinity, which offers a convenient analytical simplicity; the procedure is also quite plausible, because R appears under an arctan function which is very insensible to large values of the argument.

Thus finally we have formulae (9) and (10) as determining the warming effects of the kinetic energy and of the absorption upon the terrestrial climate. To judge which of the two warming components is more efficient at given conditions, we try to find first in what conditions their influence would be equal, $e_{23} = e_4$. Assuming that the absorbing particles possess spherical shape and that they absorb the energy in proportion to their geometric cross-section, the mass-absorption coefficient becomes $\sigma = \frac{3}{2 d \Delta}$ when d is the diameter of the particles and Δ — the density of the matter inside a particle. The absorption coefficient in formula (10) is found hence as follows:

$$\tau = \sigma \varrho \,.\, 1.5 \,.\, 10^{13} = 2.25 \frac{\varrho}{d\Delta} \cdot 10^{13} \,.\quad .\quad .\quad .\quad (11),$$

where ϱ, d and Δ are in CGS units. Though ϱ is the effective density of the cloud, in the first approximation it may be taken to be identical with the density of meteoric matter around the earth as used in formula (9). Making use of equations (9), (10) and (11), the condition $e_{23} = e_4$ may be written as follows:

$$\frac{1}{2} \left(\frac{R_\odot}{R}\right)^2 \frac{(v_\infty^2 + v_0^2)^2}{\sqrt{v_\infty^2 + v_R^2}} + (v_\infty^2 + v_0^2 + v^2)^{3/2} = 2.25 \times 10^{13} \frac{\pi^2 q_0}{d\Delta} \,.\,. \quad (12).$$

This equation determines the diameter of the particles, if the initial velocity of the absorbing cloud relative to the sun, v_∞ is given. To the minimum value of d corresponds the largest value of v_∞. The probable upper limit of v_∞ may be estimated upon the assumption that the relative velocity of a dark cloud does not exceed the largest stellar velocities. Adopting $v_\infty = 10^7$ cm/sec as a maximum value, the lower limit of $d = 0.07$ cm is found; for $v_\infty = 3.10^6$, $d = 0.4$ cm. The other data used in the above computation are as follows:

$$\frac{R_\odot}{R} = \frac{1}{214}\,; \quad v_0 = 6.2 \times 10^7 \text{cm/sec}\,; \quad v_R = 4.2 \cdot 10^6 \text{ cm/sec}\,;$$

$$v = 3.10^6 \text{ cm/sec}; \quad q_0 = \frac{2}{60} \cdot 4{,}2.10^7 \text{ erg cm}^{-2} \text{ sec}^{-1} \text{ and } \Delta = 3 \text{ g/cm}^3.$$

The influence of the kinetic energy upon the earth's climate would be greater than the absorbing effect only when the size of the particles is comparatively large ($d > 0.07$ cm). It is known that the absorption by interstellar clouds is produced mainy by much smaller particles which are more efficient with respect to absorption. Thus the density of a shielding cloud containing a sufficient proportion of fine dust may be much smaller than the density of a cloud of an equal warming effect caused by the kinetic energy of the meteors falling upon the sun and earth. As smaller masses, or smaller densities of the absorbing clouds appear to be more probable, it is also much more probable that, when a diffuse cloud has any influence upon our climate, the influence is mainly caused by the absorbing or shielding effect.

Formula (10) enables us to estimate the average absorption coefficient of a cloud which is able to produce a noticeable warming effect upon the terrestrial climate. Making use of the black body radiation law we estimate that an increase of the insolation by one per cent would raise terrestrial temperatures by about $0^\circ.7$. The fluctuations in the geological climate may have amounted to a tenfold of the above. An one-per cent equivalent change in the insolation corresponds to $e_4 = 0.01 \frac{q_0}{4}$, which by formula (10) gives the absorption coefficient equal to $\tau = 0.004$ per astronomical unit, or 880 stellar magnitudes per parsec. The absorption coefficient τ of the total energy may not be identical with the absorption coefficient with respect to visible light, but this circumstance is of minor importance here. In any case, anything like an absorbing power of 880^m per parsec has not yet been observed in the galactic dark clouds and a tenfold of it required by the geological data appears to be impossible in the case of v_∞ of the same order as stellar velocities; different may be the case when v_∞ is very near zero, or the case of a cloud nearly at rest with respect to the sun; in such a case the density in solar surroundings may become very great, without a great original density of the cloud (formula (5)). Disregarding the last possibility, we may state that no observed dark cloud would be dense enough for having any influence upon our climate. For that the density of a cloud with sufficient effect must be 10^4—10^6 times greater than the estimated densities of observed clouds. In any case it does not mean that such clouds cannot exist at all. They might be so small that they escape our present observations. For instance, a cloud of 40 *AU* diameter and of the sufficient density has a moderate total absorption of only about 2^m, thus within observed limits. However, such a limited cloud could not produce warm periods lasting for tens or hundreds of millions of years, unless its velocity with respect to the sun is small, $v_\infty \rightarrow 0$. Thus, although the possibility that an absorbing envelope has been the cause of the earth's climatic variations cannot be absolutely denied, it must be taken into account that such a possibility depends upon assumptions which are widely different from the actually observed data. Thus this hypothesis has no real foundation.

That at the present time the terrestrial climate is not under the influence of an absorbing cloud like the zodiacal cloud, is also certain. The surface brightness of the zodiacal light indicates an absorption coefficient not widely differing in order of magnitude from the absorption coefficient of the interstellar matter (G. Kusmin, unpublished results), which is utterly inadequate to account for the climatic variations of the earth.

The results of the preceding note may be summarized briefly as follows:

1. It is certain that a cosmic cloud enclosing the solar system cannot produce any diminution of the mean temperature of the earth, nor can it be advocated as the cause of the ice age: the kinetic energy generated by the cloud always exceeds the possible loss from absorption; a warming effect is thus the only possible.

2. A warming effect upon the terrestrial climate produced by the kinetic energy of the meteoric matter that falls upon the earth and sun requires much greater densities of the medium as

compared with the warming effect caused by the absorption, or the shielding effect of a dust cloud; therefore it is probable that the shielding effect is in most cases greater than the kinetic energy effect.

3. Observational data referring to cosmic dark clouds indicate that such clouds are unable to produce a perceptible influence upon the mean temperature of the earth.

In concluding it may be said that it seems to be quite improbable that the variations in the climate of the earth could be in connection with the interstellar absorbing clouds which the solar system might have been passing through.

A special case which is not directly comprised in the above negative conclusion is the case of $v_{\infty} \rightarrow 0$, or of a "solar" meteoric cloud of considerable extent and density, practically at rest with respect to the sun (except for the perturbing effect of mutual gravitation); however, the case appears to be extremely improbable.

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