ICARUS 5, 214–220 (1966)

LETTERS TO THE EDITORS

On Climatic Change in Cosmic Perspective

Öpik (1965) strongly criticized Milankovitch's astronomical theory (Milankovitch, 1941) of climatic changes but his arguments do not look very convincing. He uses as the main arguments that the coincidences in time between the glaciations and the minima of Milankovitch's insolation curve are uncertain and that the magnitudes of the temperature oscillations caused by the variations of the elements of the Earth's orbit are too small to cause glaciations. However, the first argument does not hold since recent geological temperature and time determinations (Emiliani, 1961, 1964) have shown that the coincidences in time are good. Also Öpik's second argument is questionable. He computed with the help of a rough atmospheric model how the temperatures on Earth may change by variations in insolation, taking variations of the Earth's albedo into account. From these computations he concluded that the variations in insolation due to changes in the elements of the Earth's orbit are much too small to cause glaciations. He neglected, however, the effects of mountain building. As has already often been pointed out by various authors (for example, Emiliani and Geiss, 1957) mountain building may have been the main reason for the slow decrease in temperature on Earth since the beginning of the Miocene. The reason why mountain building and continental uplift are very probably important is that the formation of large glaciers is highly promoted by the occurrence of high mountains and large continental areas on Earth (Emiliani and Geiss, 1957). The fact that also the Permo-Carboniferous glaciation coincided with an epoch of strong orogenic activity supports the idea that mountain building seems to be a major cause of the reduction in temperature on Earth during time intervals of the order of 10^7 years. Emiliani and Geiss pointed out that it is very easily understandable that in times in which the temperatures on Earth are reduced by strong mountain building, small variations in insolation may play an important part, and may *trigger* the onset of large glaciations by means of some relaxation mechanism. A similar idea has been put forward by Wilson (1964) who also suggested that *small* variations in insolation may set in action *large* glaciations. Since Öpik does not account for these possibilities the results of his computations do not furnish important arguments against Milankovitch's theory. Öpik's suggestion that solar variations would be the cause of glaciations might be right. However, no reliable computation on this subject can be done at present, for the following reasons:

(*a*) The methods of energy generation in the solar interior are not yet completely known. Recently Pochoda and Reeves (1964) introduced two new proton–proton reaction chains which provide more than 40% of the Sun's energy generation, but still other similar chains might be discovered.

(*b*) The theory of convection in stellar interiors is only poorly known. The mixing-length theory (Vitense, 1953; Böhm-Vitense, 1958) cannot yield correct results (Schwarzschild, 1958). Although progress has been made in the theory of convection (Spiegel, 1965) no computations with the aid of refined theories have up till now been carried out.

(*c*) The opacity laws in stellar interiors are insufficiently known. For these reasons all models for the solar interior computed so far are only very rough approximations of the real situation in the interior of the Sun. The error in the central temperatures derived from various models may very well amount as much as 10% to 20% (Pochoda and Reeves, 1964).

Until the present the only theory for glaciations that makes possible precise computations and quantitative checking is that of Milankovitch (1941). None of the objections made against it have been able to diminish its value, though, according to Emiliani's (1961, 1964) measurements the variations of the obliquity ϵ of the ecliptic seem to have been more important for the occurrence of glaciations than the precession. However, this is only a minor point, and recently van den

Heuvel (1966) has shown that very probably the precession exerted a still measurable influence.

Only if one would be able to demonstrate, by computing refined solar models, and by testing their stability, that the interior of the Sun may show instabilities with a period of some 100 or 200 million years, will there be cogent arguments in favor of Öpik's theory. This, provided that the instabilities would have just the effect suggested by Öpik, i.e., to decrease the temperatures on Earth. Until then the variations of the elements of the Earth's orbit in combination with geological events like mountain building should certainly not be ruled out as a cause of glaciations.

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Received December 28, 1965

More on Climatic Change

I wish to add a few notes to van den Heuvel's letter (van den Heuvel, 1966, preceding paper). First of all, a climatic theory which "makes possible precise computations and quantitative checking" must allow at least for all important causes. Milankovitch (1941) calculates precisely the relative amounts of solar heat falling outside the atmosphere per unit area in different latitudes in summer which is a straightforward exercise in integral calculus. Here the precision ends. He completely disregards transport and storage of heat, albedo and radiation conditions, as well as the winter half of the year, and converts his variations of geometrical summer insolation into artificially defined displacements in equivalent latitude which then are supposed to represent changes in climate. Now, convective transport in circumpolar latitudes supplies an amount comparable to insolation and acts as a stabilizer—when insolation decreases and temperature falls, the transport increases and partly compensates for loss of insolation. As a consequence, the actual temperature response to local insolation is but a fraction of the black-body response in radiative equilibrium, while Milankovitch's symbolic equivalent latitudes are translated into fictitious changes several times the blackbody equivalent. There is no theoretical reason for this procedure—it is a mere arbitrary assumption. The "precision" of the theory consists in disregarding important, even dominant factors which cannot be precisely calculated but which are the most tangible reality; the climatic difference between Eastern Siberia and the British Isles is of their making. Milankovitch's approach disregards all the realities of climate and is thus not a "climatic theory" at all; a Hamlet without the prince of Denmark. It is but a formal numerical rule which cannot be justified on first princi-