of asterism and line-broadening, which was observed in the x-ray diffraction patterns of the shocked fayalite, could possibly be explained by slightly disoriented poligonization of the previous structure of the single crystal at a scale below the limit of optical resolution ($\sim$0.5 μ) and above that ($\sim$100 Å) which should be observable in the Mössbauer spectrum.

Scattering is considerably less efficient than transmission, if a thin absorber is available. The counting rates for scattering are only about 5 percent of the counting rates for transmission for the same source and for the most favorable geometries. Furthermore, a large percentage of the 6-kev radiation is caused by x-ray fluorescence after photoelectric absorption of some of the radiation from the source. This fluorescence is independent of the source velocity and merely adds to the background of the Mössbauer spectrum, decreasing the ratio of signal to noise. These problems could be considerably reduced if a stronger source were used, for example, one of the order of 100 mc. In spite of these difficulties, scattering is a sensitive method for obtaining Mössbauer spectra of thick iron-bearing samples, such as iron meteorites, for which nondestructive analysis is preferable.

L. D. LAFLEUR
C. D. GOODMAN
Department of Physics, University of Houston, Houston, Texas 77004
E. A. KING
National Aeronautics and Space Administration, Manned Spacecraft Center, Houston

References and Notes

1. R. V. Pound and G. A. Rebka, Jr., *Phys. Rev. Lett.* **3**, 554 (1959); J. P. Schiffer and W. Marshall, *ibid.*, p. 556.
2. F. Heide, *Meteorites* (Univ. of Chicago Press, Chicago, 1964), p. 88.
3. E. L. Sprenkel-Segel and S. S. Hanna, *Geochim. Cosmochim. Acta* **28**, 1913 (1964).
4. A. Gerard and M. Delmelle, *Compt. Rend. Acad. Sci. Paris* **259**, 1756 (1964).
5. G. K. Wertheim, *Mössbauer Effect: Principles and Applications* (Academic Press, New York, 1961).
6. D. Heymann, M. E. Lipschutz, B. Nielsen, E. Anders, *J. Geophys. Res.* **71**, 619 (1966).
7. N. L. Carter, C. B. Raleigh, P. S. DeCarli, *ibid.* **73**, 5439 (1968).
8. C. E. Johnson, M. S. Ridout, T. E. Cranshaw, *The Mössbauer Effect*, D. M. J. Compton and A. H. Schoen, Eds. (Wiley, New York, 1962), p. 142.
9. F. M. Bullard, *Amer. Mineral.* **25**, 497 (1940); G. P. Merill, *Amer. J. Sci.* **3**, 335 (1922).
10. H. G. Drickamer, R. L. Ingalls, C. J. Costan, *Physics of Solids at High Pressures*, C. T. Tomizuka and R. M. Emrick, Eds. (Academic Press, New York, 1965), p. 313.
11. M. Eibschütz and U. Ganiel, *Solid State Commun.* **5**, 267 (1967).
12. We thank M. E. Lipschutz for the loan of the Canyon Diablo specimens and Paul DeCarli for furnishing the fayalite samples.

19 September 1968

Milankovitch Radiation Variations: A Quantitative Evaluation

Abstract. *A quantitative determination of changes in the surface temperature caused by variations in insolation calculated by Milankovitch has been made through the use of the thermodynamic model of Adem. Under extreme conditions, mean coolings of 3.1° and 2.7°C, respectively, at latitudes 25° and 65°N are obtained for Milankovitch radiation cycles. At the sensitive latitude 65°N, a mean cooling below the present temperature for each of the times of radiation minimum is only 1.4°C. This result indicates that the Milankovitch effect is rather small to have triggered glacial climates.*

In recent years there have been a number of attempts (*1*) to correlate Pleistocene climate cycles with variations in insolation predicted by Milankovitch (*2*) in his astronomical theory of glaciation; but few quantitative temperature evaluations of the Milankovitch effect have been made, particularly on a global basis. Current knowledge and techniques now permit an approach to the solution of this problem.

We have applied Adem's thermodynamic model (*3*) to the determination of Pleistocene paleotemperatures on the basis of the insolation changes calculated by Milankovitch. Input data at 512 grid points over the Northern Hemisphere in Adem's model consist of de-

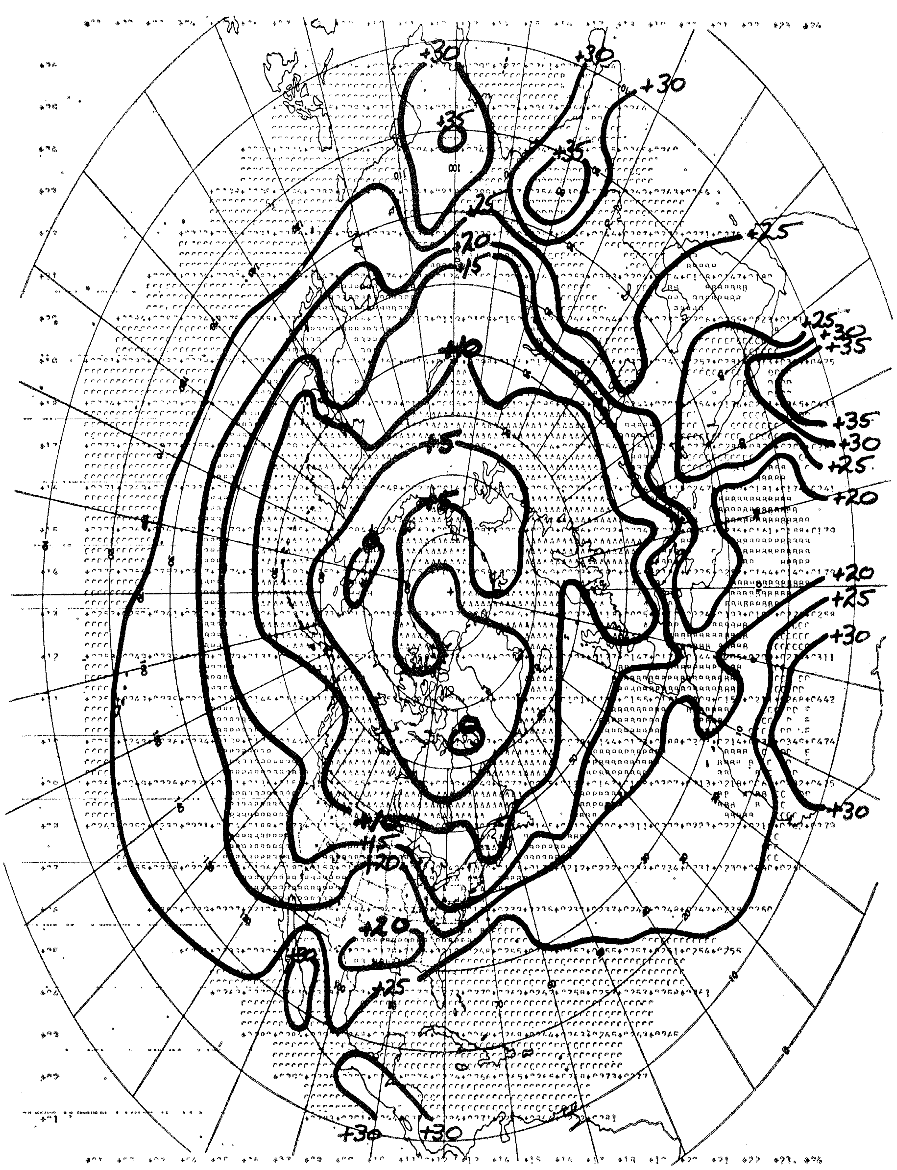

Fig. 1. Present June surface temperatures for the Northern Hemisphere computed with the use of Adem's thermodynamic model.

tails of solar radiation, surface albedo, cloudiness, latent heat lost from the surface and then released in cloud condensation, sensible heat lost from the surface, and mid-troposphere temperatures. These data are used to compute long-wave radiation loss from the surface, the mid-troposphere, and the top of the atmosphere. From these results a final surface and mid-troposphere equilibrium temperature field is computed by a relaxation method (*4*). The procedure implicitly includes the effect of horizontal heat transport.

As a test of this procedure, the present surface temperatures for the Northern Hemisphere were computed for June and January. Results of the computations for the month of June are shown in Fig. 1, where 5°-isotherms have been drawn on the machine output plotted on a distorted Northern Hemisphere grid. The isotherm distribution and the computed hemisphere mean of 20°C agree well with observations. A similar computation for January gives a hemisphere mean of 9°C. The annual computed mean of 14.5°C agrees very well with the generally accepted mean of 15°C. Also, Adem (*3*) verified the accuracy of temperatures computed by this model. We therefore feel that we can apply the model to evaluate the effect of the radiation changes predicted by Milankovitch.

Milankovitch radiation data (*2*) are given as total radiation at latitude intervals of 5° for each of the summer and winter half-years for both hemispheres. His data were computed at intervals of 5000 years, as well as at times of coincidence of perihelion with summer and winter solstices. Values for the 512 grid points used in Adem's model were interpolated from these data. In general, most correlations of paleoclimatic events with Milankovitch theory are based on the times of radiation minima and maxima at 65°N for the summer half-year, because temperature at the high latitudes must control glacial growth. We carried out computations of surface temperature distribution for all of these times to 200,000 years before the present.

The form of these results shown in Fig. 2 is computed from Milankovitch data for summer radiation at the minimum for 25,000 years before the present. In comparing these results with those in Fig. 1 for the present summer, only a little change is evident in the Arctic region and a slight cooling over the peripheral continents. Rather than attempt to present here a laborious analysis of the 57 resulting maps, we computed 10° zonal averages of surface temperatures for latitudes centered at 15°, 25°, 35°, 45°, 55°, 65°, and 75°N. These computations were carried out for continental areas only, since they would be more sensitive to changes in insolation. Results for the summer half-year are summarized in Table 1.

Before Table 1 can be interpreted, it must be noted that temperatures have been computed on the basis of the present surface and atmospheric conditions in order to estimate the effects of changes in radiation in triggering larger climatic variations. Obviously, glacial ice, once developed, made its own climate regardless of the cause of its formation.

To show representative variations in temperature for high and low latitudes, the data from Table 1 for 25° and 65°N are plotted in Fig. 3. The low-latitude curve shows a periodicity of about 24,000 years, while that for high latitudes is about 36,000 years. Variations at low latitudes are controlled primarily by precession, whose effective period is 21,000 years. Those at high latitudes are controlled mainly by tilt (obliquity of the ecliptic), whose period

Table 1. Temperature variations with time and latitude, computed from Milankovitch radiation data (B.P., before the present).

Date (10^3 years B.P.)	15°N	25°N	35°N	45°N	55°N	65°N	75°N
0.6	23.3	23.4	20.4	13.9	7.9	3.8	4.5
5.0	23.9	24.2	21.3	14.7	8.7	4.6	5.1
10.0	24.9	25.4	22.6	15.9	9.6	5.3	5.6
11.1	24.9	25.4	22.7	15.9	9.6	5.2	5.5
15.0	24.4	24.8	21.9	15.2	9.0	4.7	5.0
20.0	23.3	23.2	20.0	13.4	7.3	3.0	3.7
22.1	23.1	23.0	19.7	13.0	6.8	2.5	3.1
25.0	22.8	22.6	19.3	12.6	6.5	2.1	2.8
30.0	24.5	24.6	21.3	14.3	7.8	3.2	3.5
32.7	24.6	24.7	21.5	14.5	8.0	3.4	3.7
35.0	24.5	24.6	21.5	14.5	8.1	3.5	3.8
40.0	23.9	24.1	21.1	14.3	8.2	3.8	4.3
45.0	23.6	23.9	21.1	14.7	8.7	4.7	5.3
47.1	23.6	23.9	21.0	14.6	8.7	4.6	5.2
50.0	23.7	24.0	21.1	14.6	8.7	4.6	5.2
55.0	24.1	24.4	21.4	14.7	8.5	4.2	4.6
60.0	24.7	25.0	22.0	15.0	8.6	4.1	4.3
60.6	24.8	25.1	22.0	15.0	8.6	4.1	4.3
65.0	24.3	24.4	21.2	14.3	7.9	3.4	3.8
70.0	22.9	22.8	19.5	12.8	6.7	2.5	3.1
71.9	22.7	22.5	19.2	12.6	6.6	2.4	3.1
75.0	23.1	23.0	19.8	13.1	7.1	2.8	3.4
80.0	25.0	25.4	22.4	15.4	8.9	4.4	4.6
82.8	25.5	26.1	23.2	16.1	9.6	5.0	5.1
85.0	25.3	25.9	23.0	16.1	9.6	5.1	5.3
90.0	23.3	23.6	20.8	14.4	8.5	4.5	5.2
94.0	22.4	22.5	19.6	13.4	7.8	4.0	4.9
95.0	22.4	22.5	19.7	13.5	7.9	4.1	5.0
100.0	24.1	24.4	21.3	14.6	8.4	4.0	4.4
105.0	25.6	25.9	22.8	15.5	8.7	3.8	3.8
105.1	25.6	25.9	22.8	15.5	8.7	3.8	3.8
110.0	24.2	24.2	20.9	14.0	7.6	3.0	3.3
115.0	22.4	22.2	18.8	12.3	6.3	2.2	3.0
116.1	22.3	22.1	18.7	12.2	6.3	2.2	3.0
120.0	23.3	23.2	20.0	13.4	7.3	3.0	3.6
125.0	25.1	25.6	22.7	15.8	9.4	4.9	5.1
127.7	25.4	26.0	23.2	16.3	9.8	5.3	5.5
130.0	25.2	25.7	23.0	16.1	9.8	5.4	5.6
135.0	23.7	23.9	21.0	14.5	8.5	4.3	4.9
140.0	22.8	22.8	19.8	13.3	7.5	3.4	4.2
145.0	23.6	23.7	20.5	13.8	7.6	3.2	3.8
150.0	24.9	25.1	22.0	14.9	8.3	3.7	3.9
152.2	25.1	25.3	22.2	15.1	8.5	3.9	4.0
155.0	24.9	25.1	22.0	15.0	8.5	3.9	4.1
160.0	23.4	23.6	20.5	13.9	7.8	3.6	4.2
164.0	22.7	22.7	19.7	13.4	7.6	3.6	4.4
165.0	22.7	22.7	19.7	13.4	7.7	3.7	4.5
170.0	23.9	24.3	21.4	14.8	8.8	4.6	5.1
175.0	25.6	26.1	23.3	16.3	9.8	5.3	5.4
176.3	25.6	26.2	23.3	16.3	9.8	5.1	5.2
180.0	24.9	25.2	22.2	15.3	8.8	4.3	4.5
185.0	22.6	22.4	19.2	12.7	6.8	2.7	3.4
187.5	22.1	21.9	18.6	12.2	6.4	2.3	3.2
190.0	22.5	22.3	19.1	12.5	6.6	2.4	3.2
195.0	25.0	25.2	22.1	15.0	8.4	3.7	3.9
198.5	25.9	26.4	23.3	16.1	9.3	4.5	4.5
200.0	25.7	26.2	23.2	16.0	9.3	4.6	4.6

is about 41,000 years. Milankovitch considered the variations in the latitudes of ice-sheet growth—the high latitudes—to be the more important. Nevertheless, his precise calculations of radiation on the basis of precession, eccentricity, and tilt automatically give the correct weighting of these elements for all latitudes. The model we used then computes temperatures from these data and includes effects of horizontal heat transport. It thus seems inappropriate, in the correlation of the Milankovitch effect with empirical data (Broecker, *1*), to suppress the effect of tilt in order to obtain a better match of the 65°-curve with the observations.

The data of Table 1 and these data as plotted in Fig. 3 yield a mean cooling of 3.1°C for eight complete cycles at 25°N, and a mean cooling of 2.7°C for four complete cycles at 65°N. It may be noteworthy that the change at high latitudes is distinctly lower than that at low latitudes. Also, we must emphasize that these cooling values are extreme results, because any moderating influences of the oceans have been deliberately omitted in restricting the computations to continental grid points.

It is very difficult to assess the climatic significance of our calculations of the Milankovitch cooling effect, but some interpretation can be attempted. The horizontal lines in Fig. 3 indicate the level of computed present temperatures. Most of the low-latitude curve is above this level. In the case of the high-latitude curve, the mean trough level is 1.4°C below the present. Hence, according to the Milankovitch concept, an average decrease of only 1.4° below the present temperature must be sufficient to trigger glaciation. This is very

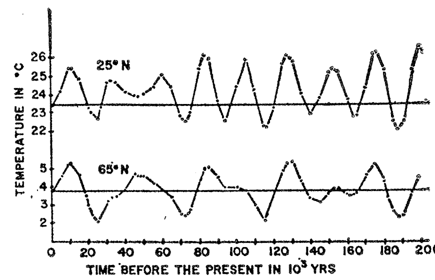

Fig. 3. Variations of temperature with time for 25° and 65° N as taken from Table 1. The horizontal line indicates computed present temperatures for the latitudes shown.

nearly the temperature decrease observed during historic times (that is, during the Little Ice Age, A.D. 1550 to 1880). Simpson (*5*), in investigating this problem earlier, considered a change of 2°C to be insignificant in causing glaciation.

A wealth of available observations show rather clearly that the temperature variations of the Pleistocene epoch were primarily controlled by the presence of continental ice sheets. Thus, the Pleistocene climatic record, essentially interpreted from marine sediments, must reflect the history of the volume of glacial ice. These must in turn significantly lag the behavior of the causative mechanism, further complicating the problem of correlation between cause and effect. However, if our calculations are valid, it does seem difficult to see how the growth of these ice sheets could have been initiated by a mechanism such as the variations in temperature of the magnitude computed from the Milankovitch theory.

DAVID M. SHAW
WILLIAM L. DONN

Lamont Geological Observatory, Columbia University, Palisades, New York 10964, and *City College of New York, New York 10031*

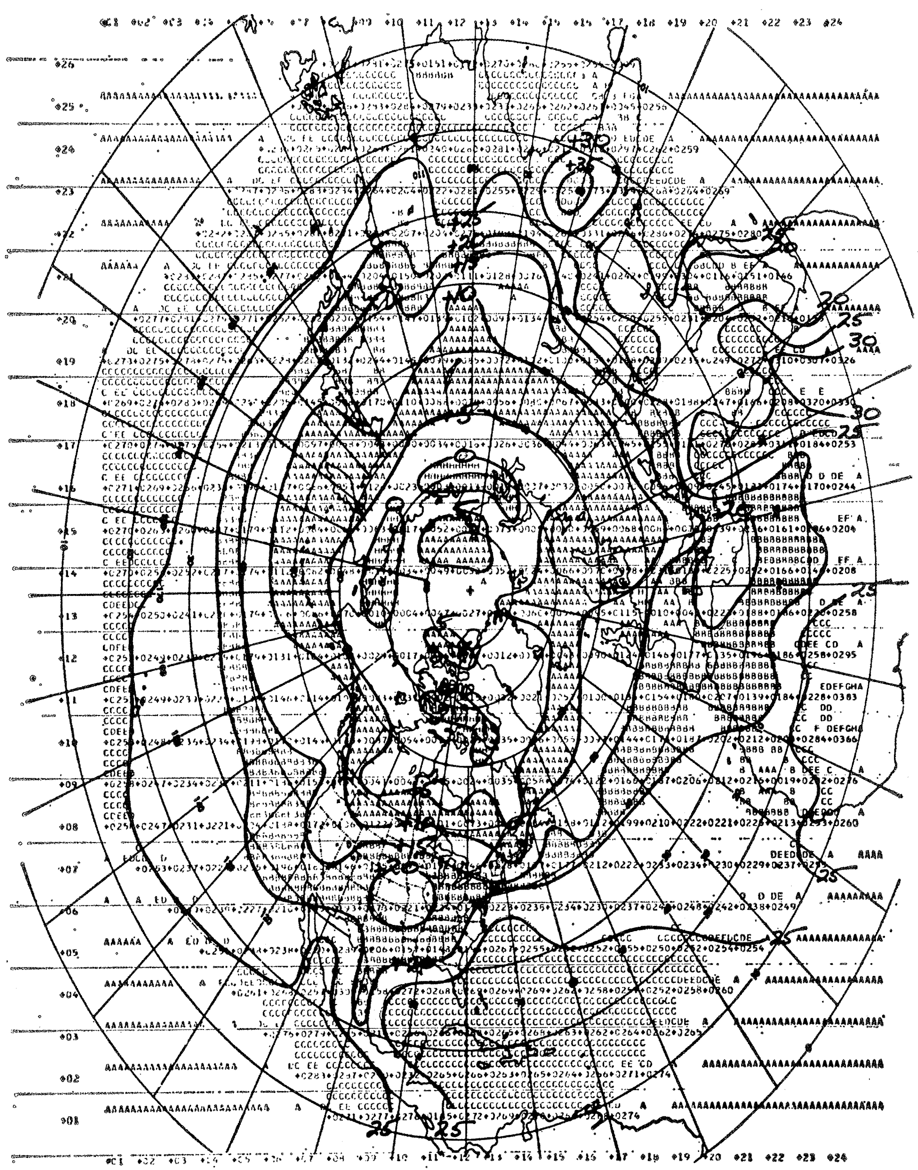

Fig. 2. Surface temperatures for the Northern Hemisphere computed for 22,000 years ago for the summer half-year.

References and Notes

1. C. Emiliani, *J. Geol.* **74**, 109 (1966); W. Broecker, *Science* **151**, 229 (1966).
2. M. Milankovitch, in *Handbuch der Klimatologie*, Koppen and Geiger, Eds. (Borntraeger, Berlin, 1930).
3. J. Adem, *Monthly Weather Review* **92**, 91 (1964); *ibid.* **93**, 495 (1965).
4. Computations were carried out on the IBM 360/95 digital computer of the Goddard Space Flight Center, Institute for Space Studies, New York City.
5. G. C. Simpson, *Proc. Linnean Soc.* **152**, 190 (1940).

6. We gratefully acknowledge the scientific help of J. Adem and J. Namias of the Extended Forecast Division of the U.S. Weather Bureau, ESSA, and the financial support of the U.S. Steel Foundation and NASA grant NSG 445 (E).
7. This is Lamont Geological Observatory (Columbia University) contribution No. 1258.

22 August 1968