An additional planet as a model for the Pleistocene Ice Age

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Abstract

We propose a model for the Pleistocene Ice Age, assuming the following scenario: Between 3 Myr and 11.5 kyr BP a Mars-sized object existed which moved in a highly eccentric orbit. Originating from this object, gas clouds with a complex dynamics reduced Earth's insolation and caused a drop in the global temperature. In a close encounter, 11.5 kyr ago, tidal forces deformed the Earth. While the shape of the gyroscope Earth relaxed, the North Pole moved geographically from Greenland to its present position. During this close encounter, the object was torn to pieces, each of which subsequently evaporated or plunged into the sun. These events terminated the Ice Age Epoch.

1 Properties of the Pleistocene Ice Age

Earth's most recent Ice Age Epoch is characterised by unique features, which still require an explanation [1]. The Pleistocene Glaciation began approximately 2 Myr ago, after a gradual decrease of the global temperature in the Upper Plicoene from about 3 to 2 Myr BP. During the Pleistocene the general drop in temperature was interrupted by fluctuations, which augmented in proportion to the global cooling. Cold periods (Stadials) and warm periods (Interstadials) followed each other with a period of about 100 kyr during the last 1 Myr. Sometimes the temperature of the Interstadials even exceeded the average value for the Holocene [2] [Fig. 1]. The last Stadial (100 to 11.5 kyr BP) was interrupted about 20 times at irregular intervals by sudden temperature increases lasting from a few hundred to a few thousand years (Dansgaard-Oeschger events) [3] [Fig. 2]. During the Last Glacial Maximum, 20 kyr ago, the continental ice sheets reached the region around the present New York and covered Northern Germany, while Eastern Siberia and part of Alaska were ice-free and inhabited by large herbivorous mammals such as mammoths. Some of these have been excavated in a frozen state, which shows that in these areas the temperature dropped suddenly at the end of the Ice Age Epoch. During the Last Glacial Maximum, the continental ice sheets were centred in a geographically displaced position with relation to the present pole positions [4]. In the Northern Hemisphere this position was in Greenland, about 18 degrees away from the present North Pole [Fig. 3]. According to Fig. 2, the Last Glacial Maximum was suddenly terminated 11.5 kyr ago. At about the same time a catastrophic geological event occurred, the relics of which are recorded in peculiar sediments found all over the Earth [5].

2 An additional planet as the basis of the model

Usually, the Ice Age Epoch is considered to be the reaction of a highly unstable climate system to the slow insolation variations proposed by Milankovitch [6]. However, the present climate on Earth with its distribution and behaviour follows the basis of the Milankovitch model, suggesting that for the Holocene the climate does not require major nonlinearities for its explanation. In contrast, throughout the Ice Age Epoch, the climate was strongly variable, as is evident from Fig. 1. It is therefore reasonable to assume that for a limited time the main driving force of the climate was not the Milankovitch effect but an additional external agent to which Earth's climate responded linearly. In par-

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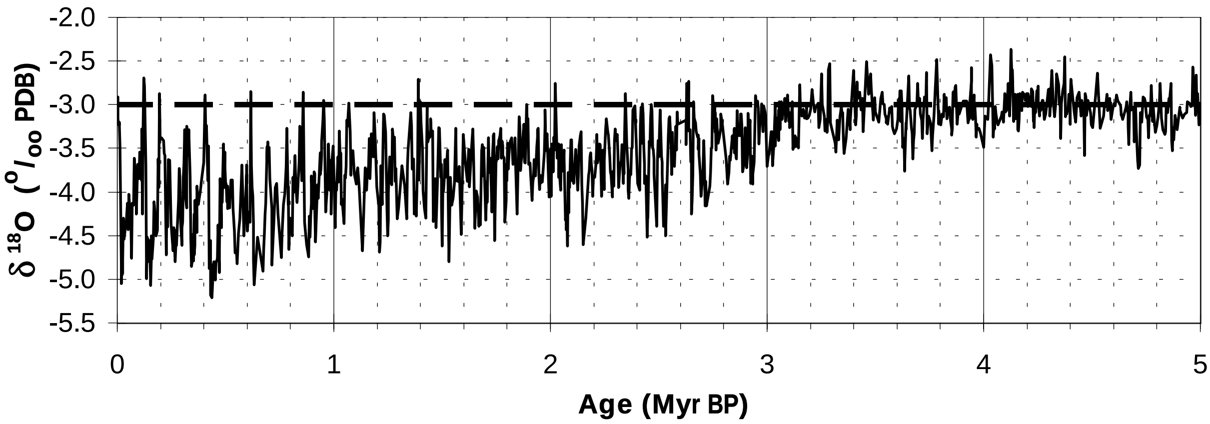

Figure 1: Variation of the $\delta^{18}0$ isotope abundance in benthic foraminifera in sea sediments from site 659 (18° N, 21° W) over the last 5.0 million years [2]. Decreasing δ^{18}O corresponds to decreasing ice caps and to warmer deep-sea temperature. The late Pliocene (before 3.2 Myr) is characterized by remarkably stable and warm climatic conditions comparable to those of the Holocene, the average temperature of which is shown by the horizontal dashed line.

ticular, the asymmetry of the ice distribution in the Northern Hemisphere as well as the presence of Mammoths in arctic Siberia during the Last Glacial Maximum suggest that the geographic position of the North Pole was located somewhere in Central Greenland. If this was the case, then, at the End of the Pleistocene, it had to move to its present position. Such a movement of the geographic position of the Earth's rotation axis, which in stellar space retains a practically fixed direction, can be induced by a transitory deformation of the Earth. This requires an extremely close passage near the Earth of a mass having at least the size of Mars. We therefore postulate that during the Ice Age Epoch and in the Upper Pliocene such an additional planet existed, henceforth called Z. Since at present Z does not exist any more, the Sun is the most likely agent to have promoted its disappearance. We therefore assume that Z moved in a highly eccentric orbit with a perihelion distance of only about 4 million km, so that during each passage near the Sun, Z was heated by both tidal forces and solar radiation. Thus planet Z was liquid and radiant.

3 Origin and fate of Z

Since Z is not a member of the present planetary system the crucial question has to be answered how in such a short time interval it could appear and subsequently disappear. Regarding the origin of Z there are several possibilities: Z may have entered into the planetary system from outside, i.e. from the Kuiper belt or the Oort cloud. Alternatively, it may have its origin in the Asteroid belt or as a moon of Jupiter. It then must have lost energy and angular momentum through resonances with other planets [7]. This requires a time of the order of a million years only. Fig. 1 suggests that Z reached an orbit with a small perihelion distance 3 million years ago, thereby creating a gas cloud resulting in the Earth's Pleistocene. Regarding the termination of Z, it is indispensable to assume that it was fragmented during the final close encounter with the Earth. This process consumed orbital energy, so that the perihelion distances of the fragments were likely to be reduced compared to the perihelion distance of Z. Most importantly, the smaller escape velocity of the fragments increased the evaporation rate. Typically, the molecular binding energy became more important than the escape energy, so that both molecules and clusters could evaporate. These were then blown away by radiation pressure. In this way, the fragments of Z could become dissolved within the Holocene. It is not unlikely that some of the fragments also dropped into the Sun.

4 Frequency of approaches to Earth

In order to obtain a measure of how often Z approached the Earth, the equations of motion of the

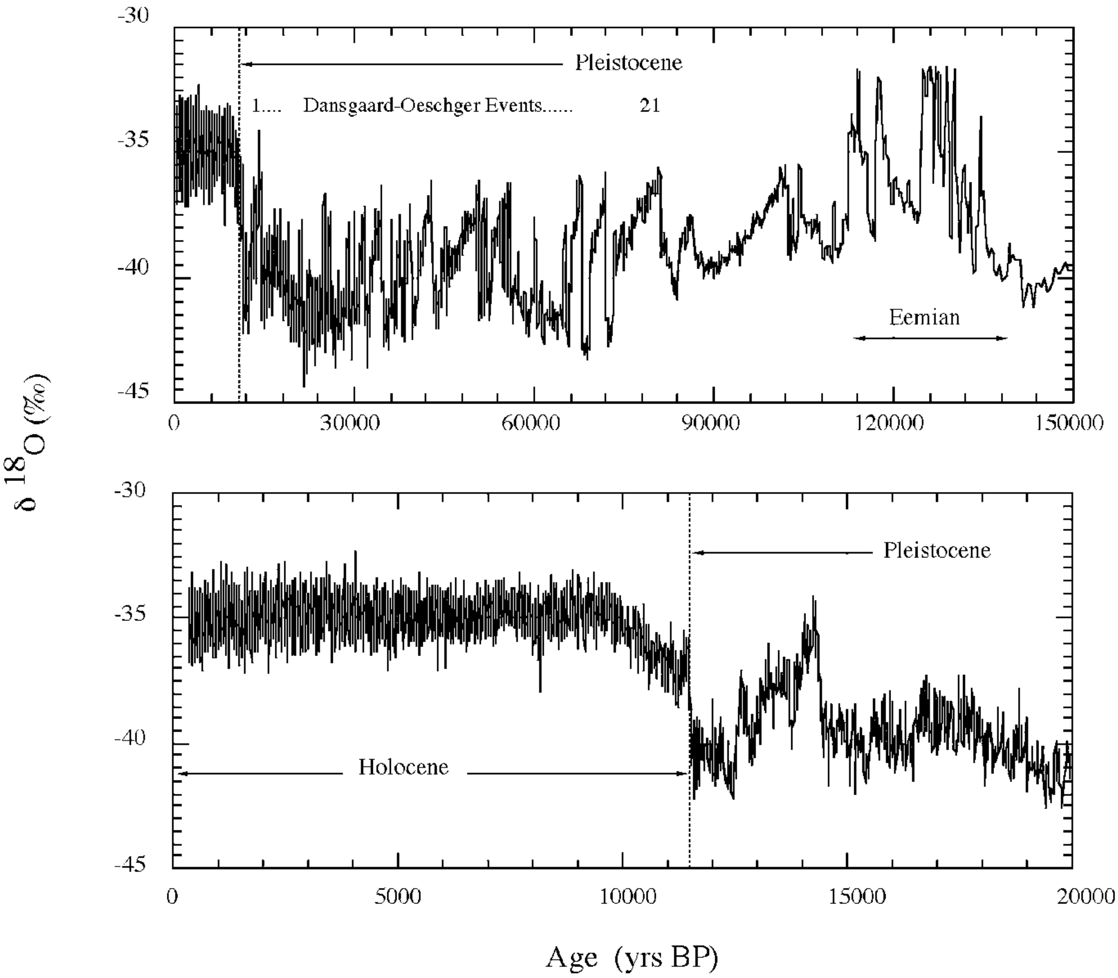

Figure 2: The upper part shows the $\delta^{18}O$ record of Greenland ice (GRIP) over 150 000 years [3]. The lower part is an expanded view of the same data over the last 20 000 years. Note the difference between the last Interstadial, the Eemian, and the Holocene. The last glacial period, 90 000 to 11 500 years ago, shows about 20 short temperature variations (Dansgaard-Oeschger events).

Figure 3: The continental ice shield of the Last Glacial Maximum was approximately centred on the central part of Greenland [4]. This suggests that this was the geographic position of the North Pole. The spiral shows the geographic migration of the North Pole for a deformed Earth as described in the Appendix. Angular momentum is conserved so that in stellar space the rotation axis remains practically fixed. The boundary of the permanent ice cover of the Arctic Ocean is uncertain.

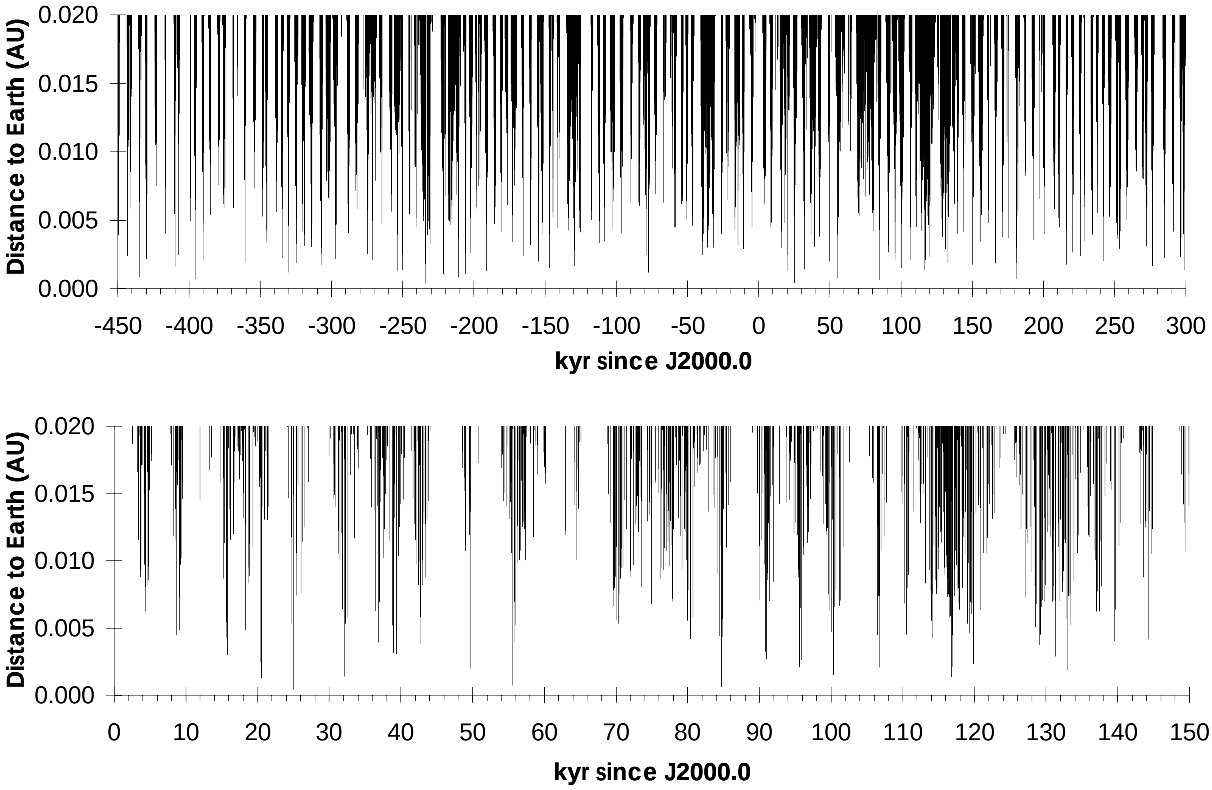

Figure 4: Upper panel: Approaches between planet Z and Earth to distances less than 0.02 AU = 3 million km as calculated over the past 750 000 years. Lower panel: Expanded view of the irregular clustering of these approaches over the last 150 000 years.

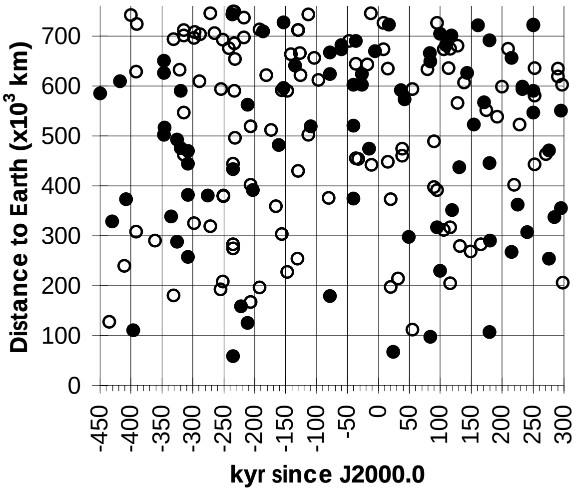

Figure 5: Closest approaches over 750 000 years below twice Moon-Earth distance. The two horizontal dashed lines indicate, respectively, Moon's distance (384 000 km) and the distance below which significant polar shifts are to be expected (30 000 km). The open (filled) circles mark encounters during which Z moves away from (towards) the Sun.

planetary system including Z were solved for various orbital parameters of Z. Tidal work and any effects from evaporation were disregarded. Earth and Moon were considered separately, and the planets beyond Saturn were omitted [8]. In the main calculation, the parameters assumed for Z at time J2000.0 were: semi-major axis 0.978 AU, numerical eccentricity 0.973, inclination 0°, longitude and argument of the perihelion both 0°. The result for a period of 750 kyr is shown in Figs. 4 and 5. The orbit of Z was found to be stable over the time range considered. The semi- major axis varied within 0.95 AU and 1.1 AU without showing a general trend. Similarly, the eccentricity remained between 0.958 and 0.977. The inclination, i.e. the angle between the orbit of Z and the invariant plane, showed an irregular variation between 0° and 13.5°, with a period of approximately 9 kyr. In Fig. 4, each approach to Earth to less than 3 million km is marked by a vertical line ending at the closest distance. The Figure shows that the encounters are irregularly clustered, somewhat resembling the pattern of temperature fluctuations of Figs. 1 and 2. In Fig. 5 calculated approaches between Z and Earth to less than twice the Earth-Moon distance are shown. Within 100 kyr there are several passages closer than Moon's distance. These must have created enormous earthquakes, and during the Ice Age Epoch must have caused ruptures of the continental ice shelves. We tentatively identify these with the Heinrich events [9]. The diagram in Fig. 5 contains no approach closer than 30 000 km, i.e., approaches which might induce a polar shift; however, additional calculations suggest that this may occur once in a few Myr.

5 Mechanics of a polar shift

The asymmetry of the glaciation in the Northern Hemisphere [Fig. 3] is the most conspicuous feature of the Ice Age Epoch. Because of this, a displaced pole position and a fast polar migration have been postulated already at the end of the 19th century [10]. This migration is a damped precession of the rotation axis on the globe, while the axis remains fixed in stellar space. This was discussed and judged as impossible. Indeed, with an Earth in either the solid or the liquid state, both of which were at that time considered, a deformation would relax too fast to allow an appreciable geographic shift of the poles. However, assuming a plastic Earth with a relaxation time of at least a few hundred days makes possible a shift of the required magnitude of ca. 18° [11]. The rotation of the unperturbed Earth is stabilised by its increased radius at the equator compared to that at the poles. If the Earth had an additional deformation in an oblique direction, it would perform a motion in which the position of the rotation axis on the globe would migrate. The deformation could result from a close passage of a planet-sized object, which would stretch the Earth by tidal forces. A 1 per mil deformation is required for the shift. We consider an initial stretching deformation of the Earth such that, at an angle of 30° with the initial rotation axis, the radius is increased by 6.5 km. In the ensuing process, the Earth relaxes into a new equilibrium shape with a displaced equatorial belt. Angular momentum is strictly conserved, and at all times the rotation axis practically points to the same star. The spiral in Fig. 3 shows the geographic path of the rotation axis. It is the solution of Euler's equations and a relaxation equation for the inertial tensor. A turn in the spiral takes about 400 days. For details of the calculation, see Appendix and [12]. A stretching force is obtained from the tidal action due to a mass near the Earth. The required deformation corresponds to the equilibrium shape of Earth when a Mars-sized mass is at 24 000 km distance. The actual deformation problem, with a mass passing near the rotating Earth, is vastly more complex. We expect that the peak tidal force has to be about an order of magnitude larger; this brings the closest distance between the centres of Earth and Z into the range of 12 000 to 15 000 km. As a result, Z enters the Roche limit of Earth. It is then likely to be torn into two or more parts. Since Z is lighter than the Earth, tidal effects are stronger on Z than on Earth: Z is torn to pieces rather than the Earth. Note that the requirements restrict the mass of Z at the end of the Pleistocene to a range of at least that of Mars and clearly smaller than Earth's. The polar shift event must have been accompanied on Earth by continental floods, earthquakes and volcanic eruptions, i.e. a world-wide catastrophe, which actually left many stratigraphic evidences and which can also be assumed to be reported in traditions in many countries all over the globe [5].

6 The gas cloud during the Ice Age Epoch

Since during the Pleistocene Z is assumed to have been at least Mars-sized, evaporation was limited by the gravitational escape energy. Only single atoms escaped from the hot surface of Z. If an atom has an optical transition from the ground state within the main solar spectrum, then radiation pressure expels it from the planetary system. However, some atoms and many ions can be excited with ultraviolet light only. Apart from the rare gas atoms, these include atoms of Oxygen and Carbon. In these cases the repulsion due to solar radiation is much weaker than the gravitational attraction to the Sun, so that atoms of these elements can remain in bound orbits. These orbits shrink due to the Poynting-Robertson drag. The continued evaporation creates an interplanetary cloud. Its material consists of single atoms and ions and is thus quite distinct from the present zodiacal dust [13]. The dynamics of the atomic cloud involves a variety of processes and is complex. We can only tentatively guess its behaviour. Collisions between atoms with planetary velocities are inelastic. They reduce the relative velocity between the colliding particles, so that their outgoing orbits become more similar. This increases the particle densities and thereby the frequency of collisions. This suggests that the range of inclinations of the orbits in the cloud can shrink with a time scale determined by the mean free time for particle collisions. Also, since collisions are inelastic, the semi-axes diminish. Particles with different ratios of repulsion by solar radiation to gravitational attraction intrinsically belong to different orbits and may become separated. If molecules form, these are expelled by radiation pressure. Atoms and molecules may become ionised. The scattering of solar radiation from any material along the line between Sun and Earth lowers the global temperature. Clearly, this screening depends on the density of the cloud and on the relative motions of cloud and Earth. Therefore, the extremely strong variations in temperature characteristic of the Pleistocene may be due to changes in the screening of the Sun. The isotopic and stratigraphic data for the last Myr of the Ice Age Epoch show a 100 kyr period [14]. Now, Earth's inclination, i.e. the angle between Earth's orbit and the invariant plane, is governed by a 100 kyr cycle. The maxima of the inclination in fact coincide with the Interstadials, except for the last maximum, where no Interstadial has been observed. This indicates that the orbits of the atoms of the cloud often had inclinations which were smaller than the maxima of Earth's inclination. Possibly at the end of the Pleistocene the width of the cloud had become too large. A similar solution to the problem of the origin of the 100 kyr cycle has previously been suggested by Muller et al [15, 16].

7 The termination of the Ice Age Epoch

The climatic fluctuations which occurred towards the end of the Pleistocene require further study. We just note here that the last rapid increase of the temperature recorded in the polar ice data occurred at 11 500±65 yr BP [Fig. 2]. All radiocarbon dates made on residue material originated during the global catastrophe point to the same age [5, 17]). However, these radiocarbon ages are not corrected for the variation of the production rate. The new dendro and U/Th calibration curves indicate that these ages have to be increased by about 1500 yr [18, 19]). Thus, it appears that the Younger Dryas, which begins at 12 700±100 yr BP [3] is younger than the polar shift event. At the beginning of the Holocene the temperature increased in two steps. The first fast step was followed by a much slower rise, which reached its maximum about 9 000 yr ago [Fig. 2]. Since then the temperature remained remarkably constant until today. The possibility should not be a priori discarded that minor, still unexplained climatic features such as the cold events at 8.2 kyr cal BP [20] and 4.166 kyr cal BP [21] as well as the so-called Little Ice Age, 300 years ago, are due to remaining traces of gaseous material.

8 Facts which become plausible or which can be explained by our model

8.1 From the displaced pole positions

- The **asymmetry** of the glaciation in North America and east Siberia; it was the main motivation for considering geographically displaced poles. At present there are no climate models which determine the optimum position of the poles and the amount of screening of the solar radiation compatible with the observed glaciation.
- The existence of **mammoths** in arctic East Siberia indicates that there was sufficient sunlight for the growth of the plants on which they lived.
- **Archaeological** objects having ages around 40 000 years BP were found close to the Arctic Circle in Siberia [22]. At the time the place had lower latitude.
- **Lake Baikal** was never frozen during the Pleistocene [23].
- The **Tibetan Plateau** was about 15° closer to the equator and not ice-domed during the last 170 kyr [25].
- The **Atacama Desert** and the **altiplano Bolivia** were humid [24]. They were then situated closer to the equator than today.
- The **Sahara desert** was covered with grass and bushes during the Pleistocene. While for the Western Sahara this may be explained by its higher latitude in the Pleistocene, other reasons such as globally lower temperature should play a role in the Eastern Sahara.

8.2 From the interplanetary gas cloud

- The **beginning** of the general temperature decrease, 3 Myr ago can be understood as the time at which the perihelion distance of Z became sufficiently small for the gas cloud to develop.
- The **coldest** Ice Age was at the **end** of the Pleistocene, since due to tidal work the perihelion distance of Z decreased. With the passing of time the cloud became denser.
- **The colder** the mean temperature, **the larger** were the **variations** of the temperature. Dense clouds throw strong shadows.
- Some Interstadials had **higher** temperatures than at present. Not only was the Earth exposed to the regular sunlight, but it also received radiation scattered from clouds or backscattered from material outside Earth's orbit.
- The form of the **Daansgard-Oeschger temperature variations**, typically a gradual decrease followed by a rapid increase, may be connected with the presently still unknown dynamics of the cloud. The observed shape of the variations may help to understand the cloud's behavior.
- During the last million years the Interstadials occur approximately every **100 kyr**, which coincides with the cycle of Earth's inclination.

8.3 From the orbit of Z

- The approaches shown in Fig. 5 produce a similar irregular pattern as the temperature variations of Fig. 2. The events marked in Fig. 5 have distances less than 3 Mio. km, which is the radius to which a gas cloud may expand by thermal motion during the passage from the perihelion of Z to Earth's distance. This suggests that a screening of the solar radiation by gases may lead to a **frequency of temperature excursions** as observed in the sequence of the Dansgaard-Oeschger events.
- Gigantic earthquakes, as listed in Fig. 5, accompanied fly-byes at less than Moon's distance. Their frequency, about 6 per 100 kyr, corresponds to the **frequency of Heinrich**

events, in which large glaciers broke away from the continent and floated into the Atlantic Ocean.

- Fig. 5 contains no fly-byes to less than 30 000 km, which might induce a polar shift. The **rarity of polar shifts**, say one event in a few Myr, is compatible with Fig. 5.

8.4 From the polar shift catastrophe

- The model explains how a **polar shift** within the time of relaxation of a global deformation, i.e. a few years, can occur.
- The **frozen mammoths** in the permafrost of arctic Siberia are a direct consequence of the geographic motion of the polar axis.
- The catastrophe produced a global **extinction of** many **species** of large animals [5, 17].
- **Frozen muck** containing broken trees and bones testify for the violence of the event [5].
- The fragmentation of Z lead to its relatively rapid disappearance. Thus the Ice Age Epoch had an **end**.
- Once the continental ice shelf was molten, the **Holocene** was **constantly warm** and distinct from the Interstadials, which were interrupted by temperature variations.
- Human **civilization reappeared** about 9 000 years ago. Notably these populations, which stem from survivors, had an elaborately structured language.
- Many **traditions** are related to Z or its fragments, such as the Chinese dragon, a flying animal that spits fire and has a long, indefinite tail [26].

9 Conclusion

At present, the climate system of the Earth is observed to react to external forcing in a plausible way. If we assume this to be generally true in the geological past the observed asymmetry of the glaciation during the Late Glacial Maximum requires a shifted pole position and a fast migration of the poles at the end of the last glaciation. A pole shift of the order of 18° requires a close encounter with a massive object, which we have here called Z. Its mass was at least Mars sized, but clearly smaller than Earth's, so that Z could be torn into fragments during the encounter. Since only the Sun can dispose of Z, we have to assume the perihelion of Z so small that Z was intensely heated. Clearly, its aphelion has to be larger than the radius of the Earth's orbit. The choice of the aphelion determines the frequency of encounters. It had several million passes near the sun and a few close encounters with the Earth as well as with the other inner Planets. The heating of the surface of Z lead to the accumulation of an interplanetary atomic gas cloud having a complex dynamics. The material between the Sun and the Earth reduced the insolation and thereby the global temperature in a time-dependent way. In particular, the increasingly cold and variable climate during the last 3 Myr, until 11.5 kyr ago, is plausibly explained by the slow decrease of the orbital energy of Z and its angular momentum. The perihelion decreases, and this enhances the density of the gas cloud. In the Holocene, after the removal of all fragments of Z, its threat for life on Earth finally ended. Note that this model has only few free parameters. On the other hand, it creates new problems that deserve a more complete treatment in future studies. It may be worthwhile to clarify the relation of our model to a claim held by I. Velikovsky [26] that a close-by passage of Venus and later of Mars had produced a polar shift on Earth. Einstein [27] in his third letter to Velikovsky resumed his recommendations by the expression "Catastrophes yes, Venus no". Our model is compatible with this directive of Einstein.

Appendix

The tidal force field $F(z)$ (for large distances R compared to the radius R_E of the Earth) is parallel to the z-direction, which points to the perturbing mass M_Z . It has the value

$$F(z) = 2M_Z G\,\frac{z}{R^3}, \tag{1}$$

where $G = 6.673 \cdot 10^{-11}$ m^3 kg^{-1} s^{-2} is the gravitational constant. Earth's induced deformation is described by an increment to the radius $H(\gamma)$, where γ is the angle with the direction z (at latitude 30°)

$$H(\gamma) = H_0 \left[\cos(2\gamma) + \frac{1}{3}\right]. \tag{2}$$

The energy for such a deformation is minimised by the amplitude

$$H_0 = \frac{R_E^2 M_Z G}{2R^3 g} \tag{3}$$

with $g = 9.8$ m/s^2, the gravitational acceleration at the surface of the Earth. For $R = 24\,000$ km, $H_0 = 6.45$ km. In a dynamic theory R will be smaller. The diagonalized inertial tensor of the equilibrium Earth Ξ_0 has matrix elements [1.0033,1,1] in units $8.01 \cdot 10^{37}$ kg m^2. For the deformed Earth the initial inertial tensor $\Xi(0)$ has diagonal elements [1.0018, 0.9995, 1] and off-diagonal elements $\Xi_{12}(0) = \Xi_{21}(0) = 0.000\,9$. Deformations are assumed to relax as

$$\frac{d\Xi}{dt} = -\frac{\Xi(t) - \Xi_0[\vec{\omega}(t)]}{\tau}, \qquad \tau = 1000 \text{ d}. \tag{4}$$

The geographic wandering of the rotation vector $\vec{\omega}$ in co-ordinates fixed to the Earth is described by the Euler equation for free motion:

$$\frac{d\,\Xi\vec{\omega}}{dt} = [\Xi\vec{\omega}, \vec{\omega}]. \tag{5}$$

Eq. (4) and (5) are solved numerically.

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