THE INTERSTELLAR MEDIUM AND THE GLACIAL ERAS DURING THE PLEISTOCENE

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Abstract. We study the hypothetical conditions for interstellar clouds dense enough to produce glaciations on the Earth. A simple differential formula (adequate to give lower limits to dust absorption) is used to relate mean temperatures and visual albedos today and during the glacial eras. For this, the geological and oceanographical records of the Pleistocene are used. The temperature decays are associated to an absorption of the solar light in visual magnitudes m_v. As the effective albedo, integrated in all wavelengths are lower than the corresponding visual value, the adoption of a visual scale leads to an underestimation of the actual amount of dust. A minimum dust absorption $\Delta m_v = 0.02$ mag, necessary to start a glacial era is then obtained. This should mean interstellar clouds with dust densities of 4100 mag. pc^{-1} and sizes of 0.3 pc or more, taking into account the time span of the glacial eras and the mean velocity of the Sun with respect to the LSR. Such clouds were never observed and are uncompatible with what is known from the interstellar medium: the 'glaciation clouds' should be clouds with densities 50–100 times above the tolerable value for gravitational stability; on the other hand, the necessary number of clouds per cubic parsec should produce the collapse of the galactic disc as a whole. From a comparative analysis of the temperatures of the other planets it seems to be that the actual thermal temperatures in their surfaces depend less than one expects from the visual albedos. From this it is raised the suspicion that the cause of the ice ages was the Sun itself.

1. Introduction

In the last years, different kinds of mechanisms have been suggested in order to explain the glacial eras during the Pleistocene. For instance, Hoyle (1984) suggested that the scattering of sunlight by particles with dimensions ~ 0.1 μm on the surface of the oceans, could produce an emergent light in the orange-blue region of the spectrum, with a resultant decay of the temperature in the water. The source for these particles should be attributed to bolid impact or to enhanced zodiacal dust. On the other hand, Hays, Imbrie, and Schakleton (1976), hereafter referred to as HIS, associated the glacial eras to the variations of Earth's orbital parameters, according to Milankovich's theory. These types of arguments could be called 'local causes' in the solar system. As a 'non-local' cause, we could consider the idea that the solar system crosses dense clouds of interstellar material. Let us remember that, for instance, the ice ages before the Pleistocene have been associated with the crossing of the solar system through the dense dust lanes of the spiral structure. At first sight, this hypothesis seems reasonable for the time span between the ice ages is some 250 millions of years (a value not far from the galactic rotation period) and each ice age spans for some millions of years. This is consistent with the width of the dust lanes (100–200 pc) and a propagation of the spiral pattern with a velocity of some 100 km s^{-1}, as it is ac-

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cepted in the density wave theory. But difficulties arise when the densities of those dust lanes are considered: they seldom exceed 1–2 mag of visual adsorption, which means dust densities of 3–7 mag/kpc if one thinks of averages. As a consequence, the mean absorption of the solar light in one astronomical unit should be less than 10^{-5} mag. We do not believe that this can produce climatic changes on Earth. It is certain that, within the dust lanes, there must be bubbles with irregular forms and higher densities, which could make more reasonable the association of the ice ages with the crossing through the spiral arms, specially if one takes into account the irregularities of these ages. Let us recapitulate what we know of the state of the interstellar material: (a) a gas density $n \approx 1-2$ atom cm^{-3} with scale size $d \sim 300$ pc representing the background in the spiral arms, which corresponds to a dust density of 1.5–3 mag/kpc in visual absorption. This is the hydrodynamical part of the spiral gas features for their velocity fields are, in a first approximation, proportional to sizes d, according to the Helmholtz theorem; (b) an intermediate state between turbulent and hydrodynamical motions which constitutes the 'vortices', $d < 300$ pc, gas with scale sizes $2 \lesssim \, < n_{\mathrm{H}} < 6$ atom cm^{-3} densities and dust densities $3 < n_d < 9$ mag/kpc; (c) the turbulent regime of clouds of sizes less than 100 pc with gas and dust densities above the range given for the vortices. For instance, a typical dark cloud of Lynd's catalogue has some 700 atoms/cm^3, dust density of 1 mag. pc^{-1} and sizes $d \sim 5-6$ pc. For more details on this classification, see Quiroga (1983).

Thus, if one takes into account the densities of the small clouds, and the property of a turbulent spectrum that the number of clouds grows with their decreasing sizes, one might be tempted to generalize the above 'non-local' hypothesis to the glaciations: the solar system, with its velocity of 20 km s^{-1} with respect to the LSR could cross a cloud of some 2–5 pc in $10^5-2.5 \times 10^5$ yr and this interval of time is of the same order of the frequency of a glaciation (10^5 to 2×10^5 yr). The main purpose of this paper is to show that, according to what is known of the turbulent spectrum of the interstellar medium, the attempt to associate the glaciations to the crossing of the solar system through dense clouds of the spiral pattern leads to inadmissible gravitational conditions for the clouds themselves and for their number per cubic parsec. If one takes into account the necessary densities in order to produce the 0.02–0.03 magnitudes of absorption of the solar light, capable to produce a glaciation, the clouds should be collapsing clouds and their number per cubic persec to explain the frequency of the glaciations should give a total mass that would produce the collapse of the galactic disc as a whole.

2. The Glaciations

Let us recall here some facts about the glaciations that will be needed in our discussion. From the geological evidences in the Pleistocene, we know that the Earth has undergone systematic oscillations of its temperature, whose amplitudes depend on the geographical latitudes L. For $L \gtrsim 45°$, fossil indications of permafrost show that temperature decays of 10°–12°C or more with respect to the mean today. As cases representing extremes and not averages of the ice caps, we can mention the Würm and Wisconsin ages, when the ices reached the latitudes $L = 46°$ and $L = 40°$ respectively. For intermediate latitudes, $45° \lesssim L \lesssim 30°$, botanical and pollen data indicate a mean in mid-european latitudes of 7–9 °C below the mean today. For $L \lesssim 30°$ a decay of 5–6 °C is estimated in Equatorial Africa and botanic and pollen data indicates that the level of vegetation in mountains of Costa Rica and Columbia was 1000 m below the level today. This should mean a decay of some 5 °C, consistent with the records of equatorial Africa. In ocean waters, the differences of temperature are lower: some 5 °C or 6 °C at latitudes $43° \mathrm{S} < L < 47° \mathrm{S}$ in the Indian Ocean, as one can see in HIS. They have studies the O^{18} isotopic composition of planktonic foraminifera and have estimated the mean temperature on the sea surface from a statistical analysis of subantartic radiolaria. Such an isotopic composition gives a measure of the level of the waters or the sizes of the ice sheets on the Earth poles. HIS have found, for the changes of the oxygen isotope and the mean temperature, a main cycle of some 100000 years and a secondary cycle of 42000 years, associating them to changes of the eccentricity of Earth's orbit in a range $0 < e < 0.04$, and to variations of the inclination of the polar axis with respect to the ecliptic ($22° < \epsilon < 24°$). As these changes in orbital parameters can produce only a change of 0.1% in total power received from the Sun, it is thought that the mechanism relating the incident solar power to the cooling of the Earth's surface is strongly nonlinear, but such mechanism remains unexplained.

The dependence on latitudes of the temperature decays with respect to the values today is obvious if we remember the dependence of the received solar power per unit area on the Earth's surface on latitutdes and the sizes of the ice caps during the glacial eras; they represented some 15% of the Earth surface whereas, today, they do not exceed 6%. Consequently, it is natural to expect that the terrestrial albedo was higher during the glacial eras. In the calculations to be made below, those facts will be taken into account.

In order to estimate the increasing of the terrestrial albedo during the glacial eras, let us compare first the following meteorological data from the standard manuals (*see also* Lamb, 1972): (a) The distribution with geographical latitudes of the mean temperatures today and during the glacial eras: the curve for the glacial eras is based and the above mentioned data. For instance, the records of HIS give a mean decay of 5–6° in ocean waters al $L \sim 42°$ S. There the water temperature today is some 2 °C higher than the atmospherical mean. We took into account these differences. This is illustrated in Figure 1a.

The permanent snows are today at $L \gtrsim 70°$, a mean for both poles. The mean atmospherical temperature in these zones are at least −10 °C and −15 °C (for the northern and southern hemispheres, respectively), and the temperatures of the oceanic waters becomes $T < 0$ °C. This mean that in order to have a permanent layer of ice and snow we need to be below those limits (−10 °C for the atmosphere and 0 °C for waters). From the comparison with the curve of temperature of the glacial eras $T(L)$ we arrive to the conclusion that it is very difficult to bring ice and snow caps

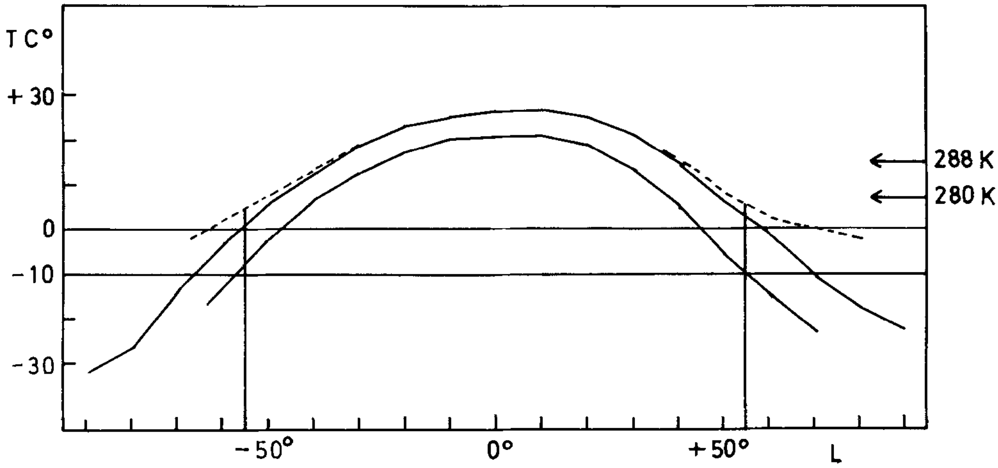

Fig. 1a. Mean annual temperatures at sea level vs. geographic latitudes – upper curve: atmospheric temperatures today, the broken line refers to oceanic temperatures today – lower curve: most probable curve for the atmosphere during the glacial eras according to geological records. For permanent ices, at least – 10 °C in the atmosphere and – 2 °C in waters are necessary. The limits at $L = \pm 55°$ mark the maximum possible advance of the ice caps at the glacial eras.

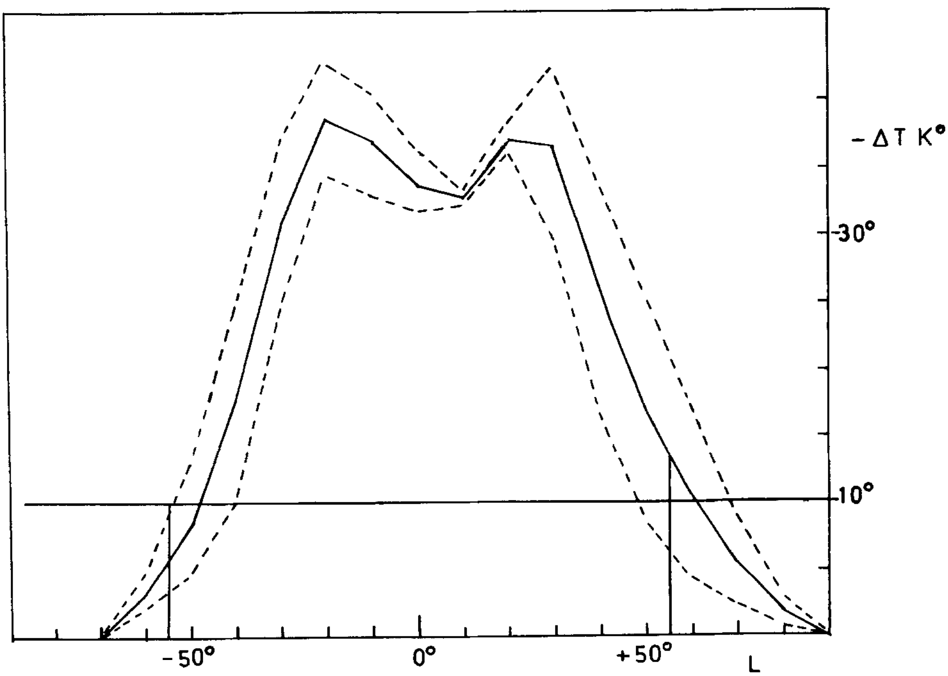

Fig. 1b. Necessary mean decay of the atmospheric temperatures in order to bring permanent ices and snow to the sea level; upper and lower curves: decays for dry and moist climates. Middle curve: adopted mean. We also plotted the limits for permanent ices up to $L = +55°$. Explanations in the text.

at latitudes below $L \sim 55° - 60°$ (see Figure 1a). (b) The altitudes above the sea level of the permanent snows h(L): they can be converted in a scale of celsius degrees as $\Delta T = \text{C.h}(L)$. Valid for the lower troposphere $h < 10$ km. The constant C oscillates between 10 °C/km for dry air and 5 °C/km for saturated water vapor. The usual adopted mean for dry and moist climates is 7 °C/km. We have used this factor to convert in ΔT the levels for dry and moist climates (Figure 1b). If one takes the extreme values for C, the scale ΔT should be multiplied by 1.43 for dry and by 0.71 for moist climates, leading to a mean decay in ΔT somewhat larger than the 7 °C/km. The resultant effect should be that the necessary temperature decay of 10 °C in order to have permanent ices and snows at sea level should be shifted to even higher latitudes. But this would exagerate the statistical weight of the dry climate zones. Thus, we have taken the more conservative curve $T(L)$ for a gradient of 7 °C/km, which indicates stable ice caps for temperature decays $\Delta T \gtrsim 10$ °C at $L \gtrsim 55°-60°$.

The curves $\Delta T(L)$ and $T(L)$ are referred to the sea level, let us see the irregularities of the northern and southern hemisphere. Let us remember first, that the glacial eras in the Pleistocene were mainly a North Atlantic phenomena. The center of the northern ice caps was somewhere between North Canada and North Greenland ($L \sim 80°$), as it is known from the difference between the geological records in Siberia, North America, and Europe. For this hemisphere and in the regions of our interest ($L > 55-60°$), the curve in Figure 1b should be corrected for the altitudes above the sea level in the continents, but taking into account the percentual areas of the ocean and land masses, as well as the altitudes above the sea level of those land masses, this should mean a correction $T \sim 3-4$ °C. The only resultant effect should be a curve $\Delta T(L)$ more symmetrical with respect to the equator than the given in Figure 1b*.

The southern hemisphere ice cap was more symmetrical than the northern one with respect to the pole. The land covered by the ice, excluding Antarctica, was some 10^6 km^2 and certainly, some minor irregularities are to be expected. For instance, there are glacier indicators on the mountains of South Argentine, Chile and New Zealand but not in the Falklands. The predominantly oceanic character of the southern hemisphere restricted severely the advance of the ice, certainly above the lower limit $L = 55°$. A those latitudes, we have today a mean oceanic temperature of 5 °C, while permanent ice requires $T = -2$ °C at least. Temperature decays of more than 7 °C is unlikely in those regions since the records of HIS give 5–6 °C at $L = 45°$ S.

Thus, in the glacial eras, the Earth had ice caps whose area are was certainly below the 18% of the total Earth surface and 9% of the terrestrial disk, corresponding to

* In order to see just what happens, we evaluate the mean Earth's temperature during the glaciations using the curve $T(L)$ of Figure 1a. The mean today (288 K) is usually obtained by giving the proper statistical weight to the areas within each isotherm on the maps. As the isotherms do not run as constant latitudes and did not run as such in the glacial eras, we had to project $T(L)$ on the Earth's surface and introduce arbitrary fluctuations to those isotherms running as L = constant, given the proper weight to the covered areas. For instance, one can consider as a fluctuation the asymmetric northern ice cap in the glacial eras, whose center was, as said above, at $L \sim 80°$. The obtained mean is $T = 281 \pm 1$ K, some 7 °C less than the mean today, coherent again with the geological records.

the upper limit of $L = 55°$. If we take $L = 60°$ for this limit, as an average for both hemispheres, we get some 14% and 5.8% for whole surface and disc. These small percentual areas are not substantially changed when seen by the sun, taking into account the polar tilt of 23°.

We can estimate the terrestrial visual albedo during the glacial eras by

$$A_v = A_{v1}S_1 + A_{v2}(1 - S_1) \tag{1}$$

where $A_{v1} = 0.61$ is the usual accepted albedo for ices, $A_{v2} = 0.39$ is the today Earth's visual albedo and S_1 is the above mentioned percentual disc area of the polar caps. We accept here that the albedo below the ice caps during the glacial eras was the same as today: this is to overestimate the factor $A_{2v}(1 - S_1)$ for in the modern albedo is included the effect of the ice caps. The factor $A_{1v}S_1$ is also overestimated, for the ice caps are near the limb of the terrestrial disk and the percentual radiation absorbed in the atmosphere before to reach the surface is larger than the corresponding percentual in the zones below the polar latitudes. The overestimation of the total value A_v produces an underestimation of the necessary amount of interstellar dust in order to produce a decay in the received solar power, compatible with the glaciations. This favours our purpose to show that the necessary sizes and densities of the interstellar clouds to produce glaciations are excessively high and uncompatible with the typical interstellar clouds known.

3. Discussion

The temperature of a planet in radiative equilibrium with the received solar power, averaged by rapid rotation is given (cf. Landolt–Börnstein, 1965) by

$$T_v^4 = \frac{T_{vR}^4}{4} = \frac{1}{4}(1 - A_v)\, T_\odot^4 \left(\frac{R_\odot}{r}\right)^2, \tag{2}$$

where T_{vR} is the temperature of the sub-solar point, A_v is the visual albedo, $T_\odot = 5770$ K is the effective temperature of the Sun, $R_\odot$ is the solar radius and r is the distance of the planet to the Sun. If we use adequate units, we can write

$$T_v = 279 \text{ K } (1 - A_v)^{1/4}\, r^{-1/2}, \tag{3}$$

where the distance r are in astronomical units. There are differences between the actual and calculated temperatures: $T(\text{actual}) > T_v$ is a common fact in all bodies with atmospheres. For instance, for the Earth surface one has $T(\text{actual}) = 288$ K where Equation (3) give $T_v = 247$ K. The difference is usually attributed to the greenhouse effect. The planetary temperatures are discussed in the Appendix. Thus, it should be more realistic to define an effective temperature as

$$T(\text{actual}) \gtrsim T_{\text{eff}} = \left(\frac{1}{4\sigma}\int_{-\infty}^{+\infty} I(\lambda)\, \alpha(\lambda)\, d\lambda\right)^{1/4} \gtrsim T_v, \tag{4}$$

where $\alpha(\lambda) = 1 - A(\lambda)$ and the integrand represents the solar power absorbed by the Earth. The greenhouse effect could be more conveniently measured by $T - T_{\text{eff}}$ and not by $T - T_v$ as usually.

The function $A(\lambda)$ is known to vary from 0.3 in the ultraviolet to 0.1 at $\lambda > 8000$ Å in the case of the Earth (see Frederick (1981) and Figure 1 in the Appendix). It has a maximum in the visual region not only for the case of the Earth but also for the other planets (see for instance, the data for Jupiter given by Petropoulos and Banos (1984). The factor within the integral in (4) can be estimated from the Figure 1 in the Appendix, this gives an approximate effective albedo $A_{\text{eff}} \sim 0.24$ and $T_{\text{eff}} \sim 260$ K. Let us call also to the actual temperature of the Earth today $T_{oi} = 288$ K and to the visual temperature today $T_{ov} = 247$ K, with this we have $T_{oi} > T_{\text{eff}} > T_{ov}$ as expected from (4). These values T_{oi}, T_{ov} represent an upper and lower limit in the simple differential form

$$\frac{1}{4}\left(\frac{\alpha_v - \alpha_{ov}}{\alpha_{ov}} + \frac{I - I_o}{I_o}\right) \approx \frac{\Delta T}{T_{oi.\,v}} \quad \text{with} \quad \frac{I}{I_o} = 10^{-0.4 m_v}, \tag{5}$$

obtained from Equations (3) and (4) for $r = 1$ AU, here $\alpha_{ov} = 1 - A_{ov} = 0.61$, $I_o = 1.36$ kw/m^2 are simply the terrestrial absorption, albedo and solar constants today; α, I and T are the values of these quantities in the glaciar eras and ΔT the mean temperature decay in these epochs.

The difference in visual magnitudes Δm can be associated to: (a) a change in the absolute magnitude of the Sun; (b) a change in Sun's distance modulus; or (c) to the presence of interstellar dust whose densities are given in units of visual magnitudes. In this paper we analyse only case (c). For a detailed calculation we should need the function $\alpha(\lambda)$ or $A(\lambda)$ for ices and snow. But this will not be necessary because: (a) ice and snow are more opaque in the infrared than in the visual, consequently, $\alpha_{\text{eff}} > \alpha_v$ for such materials. The same is valid for the clouds in the atmosphere; (b) from the data given in the Appendix, one has that near one half of the solar power lies above 7000 Å and the visual absorption in dust (in percent of power units) exceeds 2.4 times the absorption above 7000 Å (Johnson's filter R). This is to say that when we use a scale m_v, A_v in Equation (5), we are underestimating the necessary amount of dust in order to produce a given percentual decay of the solar power absorbed by the Earth.

In Figure 2a we have plotted the decay in temperatures ΔT, adopting Equation (5) with $T_{\text{oi}} = 288$ K and calculating the terrestrial albedos for ice caps up to latitudes $L = 45°$. We can see that if we ignore the correction for the increase of ice caps, we get a decay $\Delta T \simeq 7$ K (a reasonable mean for all the Earth during the glaciation) and the classical value $\Delta m_v = 0.1$ magnitudes due to dust absorption with which the glaciations are associated. Increasing the size of the ice caps, the necessary amount of dust decreases as expected. Obviously, the curves below $A_v = 0.41$ (ice caps at $L = 55°$ are completely unrealistic from what we know from the geological records and from Figures 1a and 1b.

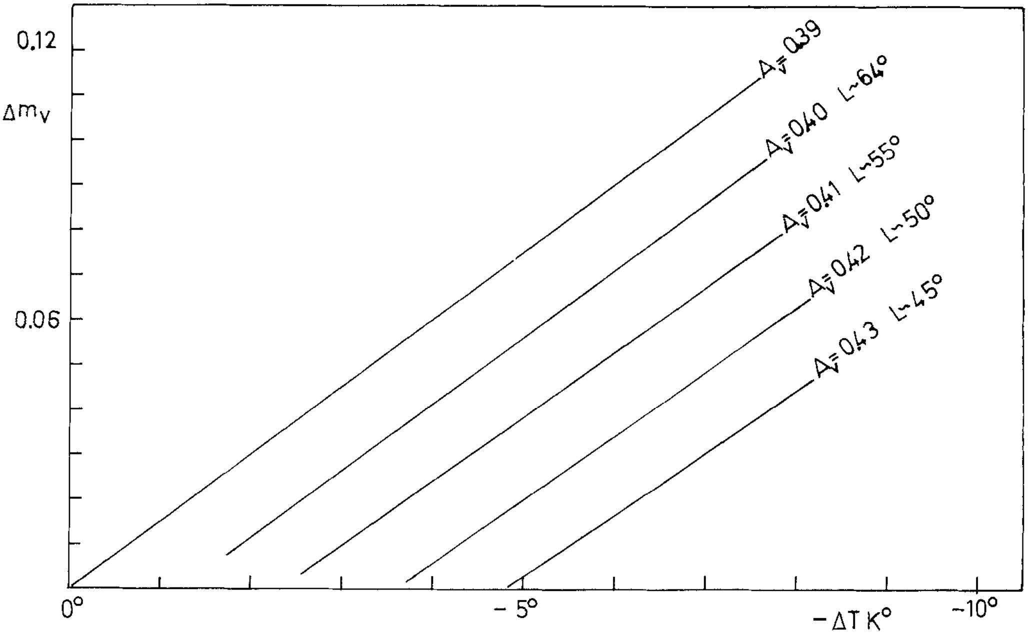

Fig. 2a. Mean decay of the atmospheric temperature associated to the glacial eras, given by the decay of the received solar power (in magnitudes) and by the increase of the terrestrial albedo A_v due to the increase of the ice caps up to latitudes L. The zero is given by the means today: $T = 288$ K, $A_v = 0.39$. The decay of the solar power is associated to interstellar material.

We have plotted these curves simply to illustrate that, from Equation (5), the relations $\Delta m(\Delta T)$ is practically linear for the small percentual decays $\Delta T/T$ of less than 3% that the Earth underwent during the glacial eras. This is not substantially modified for any value $T_{ov} < T < T_{oi}$ in formulae 5: in Figure 2b we did the same as in Figure 2a for the limits of these interval of temperatures and for a more realistic range of albedos $0.39 < A_v < 0.41$. The only effect is an additional amount of dust of 0.02 mag for $\Delta T = 7$ K if one adopts the lower limit $T_{ov} = 247$ K. Thus we conclude that in order to have a glacial configuration in the Earth with the linear form (5) we need at least 0.06 mag of visual absorption in dust.

In several theories a non linear mechanism between the fluctuations of the solar power and the thermal response of the Earth is invoked for the glaciations. One of the reasons of such non-linearity is the increase of the terrestrial albedo in a slow and gradual form: the snows did not melt in summer before turning to their usual previous levels in altitudes h above the sea or in geographical latitudes L. This idea is often in the literature. Thus, let us suppose that the process started with only 0.02 mg of absorption. This can produce a decay of 1.3 °C in the Earth's mean according to the relation between the scales Δm_v, ΔT, A_v (L). This lower limit is also suggested from the result of Lockwood (1975), who observed photometric variations of $\Delta m \approx 0.02$ or more in Uranus, Neptune and Titan between 1972 and 1976. Morrison and Morri-

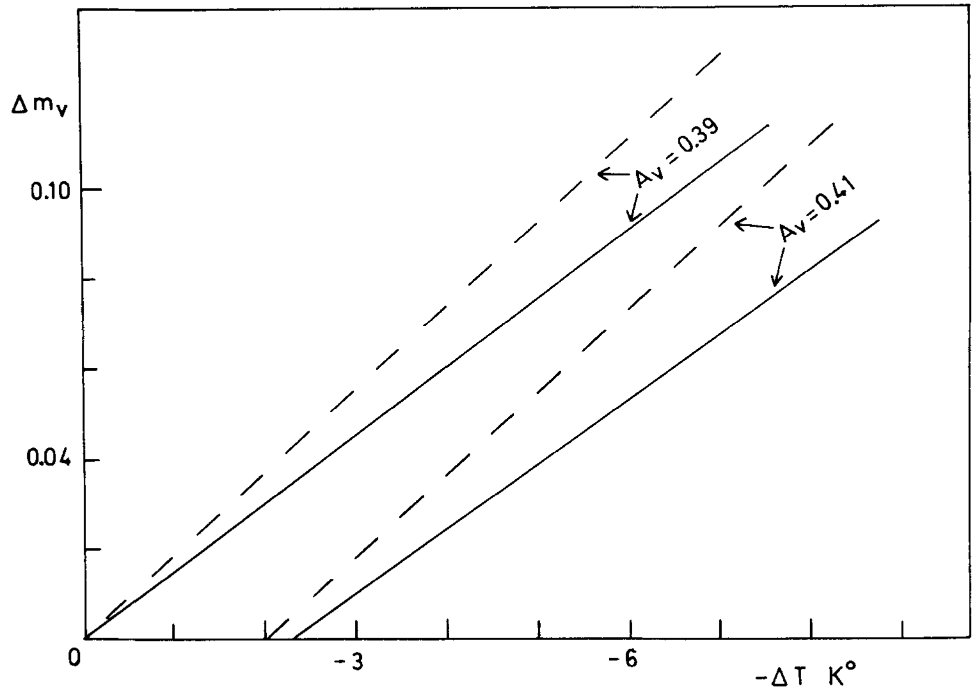

Fig. 2b. Extreme cases of application of the relationships in the text: the full line is for the mean Earth's temperature at sea level today (including greenhouse effect) $T = 288$ K. The broken line is the for Earth's visual temperature $T_v = 247$ K. Two limit cases are plotted: the albedo today $A_v = 0.39$ and the albedo $A_v = 0.41$ for the limit of ice caps at $L = 55°$.

son (1976) suggested that if these variations are associated to the Sun, there would be serious complications in the Earth's climate. In order to see these effects on the Earth we believe we must wait ~ 30 years (the thermal scale time of the oceans). If nothing special happens, this will be more an argument on favour of our purpose here. Let us suppose then that with $\Delta m_v = 0.02$ mag and a cummulative mechanism a glacial era can be set on. It is not important here to which is this mechanism; we suppose it only to reduce even more the necessary amount of dust. A visual absorption of 0.02 mag in a astronomical unit means a dust density $n_D = 4.100$ mag pc^{-1}. If we take the mean gas to dust relation (Bohlin, Savage, and Drake, 1981; Quiroga, 1983), $n_H/n_D = 0.65$ atom cm^{-3} mag^{-1} kpc we get $n_H = 2.7 \times 10^6$ atom cm^{-3}. We can have a information about the sizes of the interstellar clouds from the O^{18} diagrams (HIS and Shackleton *et al.*, 1984) for the oceanic waters during the Pleistocene era. The widths of the peaks in those diagrams have a range in time between 2×10^4 to 10^5 yr. Taken with the mean solar motion with respect to the LSR ($V_{\odot} \sim 20$ km s^{-1}), this gives a minimum size of 0.4 pc to a maximum of 2 pc. But if we want to generalize, let us take the mean interval of 250000 yr, obtained from continental data, based mainly on mountain glaciers, for seven eras since the begin-

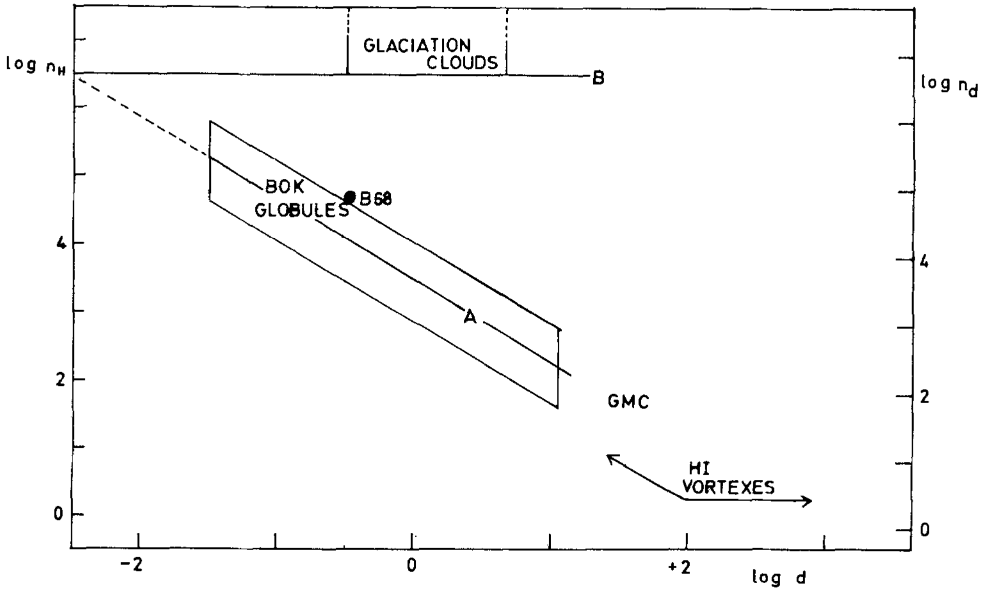

Fig. 3. Schematic diagram synthetizing the modern data in molecular lines and HI (21 cm). The scales are, gas densities n_H (atom cm^{-3}), diameters d(pc) and dust densities n_d (mag Kpc^{-1}). The parallelogram contains practically all the observed molecular clouds. Also, are shown the neutral hydrogen vortices (intermediate state between the spiral arms and turbulent clouds), the giant molecular clouds (GMC) and Bok globules usually observed in NH_3 line; the black circle is the object Barnard 68. The mean line A crossing the parallelogram is the gravitational stability line including magnetic fields in the clouds (Pellegatti-Franco *et al.*, 1985). If there is no magnetic field, the stability line must be shifted to lower densities by log 2. The line B is the minimum necessary dust density for glaciation clouds. For dust alone (without gas) the stability line runs parallelt two decades above the traced stability line.

ning of the Pleistocene. We have, therefore, a cloud size of 5 pc which we shall take as a maximum value.

Let us see now what we know from the interstellar medium to see where, in the observational data, we can find this type of clouds. Figure 3 shows the data, taken from Pellegatti–Franco *et al.* (1985), hereafter called FTQ. It represents CO, H_2O, NH_3, and HI data (see also Quiroga, 1984). The typical sizes and densities of the mentioned 'vortices' are plotted in Figure 3. These vortices are an intermediate state between the typical molecular clouds and the hydrodynamic regimen, characteristic of the spiral arms. The mean line in the diagram at $d < 10$ pc is the stability line of the turbulent clouds as already described in FTQ. It is obtained combining the relation between the observed velocity dispersion and diameters of the clouds – $\sigma \propto d^{0.38}$ – which is a modified form of Kolmogorov's law, with the Jeans criterium for stability $d \propto n_H^{-1/2}$. This given $n_H \propto d^{-1.24}$ which is very much coherent with the mean line of the observed clouds. In the line of Figure 3 it was included the $\sqrt{2}$ factor in σ, in order to take into account the contribution of the eventual magnetic field to the internal energy of the cloud. According to the argument given in FTQ, the magnetic contribution must be $B^2/8\pi \leq$ turbulent kinetic pressure, which means an Alfvén velocity $V_A \lesssim \sigma$ or a total maximum equivalent pressure twice the corresponding to the observed line dispersion σ. As seen in FTQ, the observed Zeemann splitting in some clouds is an argument in favor of such a condition, but it has not been confirmed yet as a general rule for the clouds. At any rate, the effect of this is to put the glaciation clouds closer to the stability line making their existence more probable than really they are. The fact that such a line is practically the same as a mean for the observed molecular clouds is an indication that the hypothesis given in FTQ is correct. Here we will consider the question of the gravitational stability of a cloud as an statistical concept: it is known that the clouds have very irregular forms and it is not easy to calculate the virial of a given cloud. Let us accept simply that a cloud with a density, say, 2 to 3 times higher than the corresponding to its size, when compared with the stability line, has more chance to collapse than a cloud in the stability line itself. When one reaches densities $n_H > 2.7 \times 10^6$ atom cm^{-3} and sizes $d < 0.4$ pc, typical of a glaciation cloud, one can be sure than a collapse will occur because these clouds are at least 2 decades above the stability line. On the other hand, from the frequency of glaciations given by HIS (100000 y and 250000 y from mountain records), the solar system should pick a cloud each 2 to 5 pc at its velocity of 20 km s^{-1}. Thus, for such type and abundance of clouds, we should have, in the galactic disk, 2.0 to 15 $M_\odot$/pc^3 of gas and dust alone. From the K_z force, we know that the total mass must be 0.2 $M_\odot$/pc^3 or less. In order to stabilize the galactic disk, we should need a stellar velocity dispersion σ_z from 3 to 10 times larger than the mean observed.

These results were obtained with the usual gas to dust ratio in masses of 100. This parameter, of course, is not a constant for the whole galaxy and fluctuates in different regions. A maximum unrealistic extreme is that of clouds of dust alone. In this case, the mass should be reduced by a factor of 100 and we should be in the limit of tolerance of the galactic disk. The glaciation clouds, then, should be 2 decades below in the diagram of Figure 3 and stable. In other words, we could rise the stability line by 2 decades in the scale of n_D. But, as a matter of fact, clouds with dust densities of more than 4000 mag/pc and sizes greater than 0.4 pc have never been observed, with or without gas. The clouds compiled in *F, T, Q,* have densities $n_H \lesssim 10^6$ atom cm^{-3} and sizes $d \gtrsim 0.05$ pc (NH_3 data). It could exist smaller and denser clouds scaping to detection with $n_H \gtrsim 10^6$: with this we should be in the range required for glaciations (the required range of sizes is an additional problem), but, what is the chance that the solar system encounters one of such a clouds?

As an example of an observable cloud that could be associated to a glaciation, let us see the interesting object Barnard 68, observed by Bok. From its calculated absorption and size of 0.3 pc, it has a dust density of 66 mag pc^{-1} (Valdez, 1983). This object is rather denser than other Bok globules seen in NH_3 line, whose ranges of densities and sizes are plotted in Figure 3. But it is 50 times less denser than the necessary to produce a glaciar era on the Earth. Let us suppose, then, an unknown strongly non-linear mechanism starting a glacial era with dust absorption like that of Barnard 68. Suggestions of the same nature were made by HIS in order to associate their 0^{18} diagrams with Milankowich's theory. Converting adequately the units, the decay of the solar power produced is of 4×10^{-4}. This is even below the normal variations of the solar power seen by the satellite Helios. We believe that such an hypothesis is in a worse situation than those of HIS, because the Earth's excentricity fluctuations according to Milankovich theory represent at least a regular available phenomenon, no matter whether the resultant fluctuations of the received solar pwoer can start a glacial era or not. Concerning those received solar power fluctuations (~ 0.1%), the difficulties in HIS and our case are comparable. But we are still facing the problem of putting the solar system into an object like Barnard 68 each 100000 yr and it is hard to imagine a regular mechanism for that.

4. Conclusion

We arrive thus to the conclusion that it is impossible to associate glaciar eras to the influence of the interstellar medium from what we know today. It is really very difficult to suppose a cumulative mechanism with a variation of 10^{-3} or less of the received solar power producing variations on the Earth's climate, when the time scale of the thermal reservoir of the ocean is some 30 years, no matter the origin of that decay (interstellar medium or changes in Earth's excentricity). The same type of argument was used by Hoyle (1984) with respect to Milankovich's theory. Hoyle supposed that the glaciations are due to submicron dust producing a preferential scattering in the blue-orange region of the spectrum, with a net power decay consistent with the temperature of the glaciar eras. The source of such a dust should be enhanced zodiacal dust or bolid impact. If this second hypothesis is correct, the curves for O^{18} and temperatures for the pleistocene given by HIS and Shackleton *et al* (1984) represent rather a random and not a periodical phenomena but this remains to be confirmed (or rejected) by the oceanologists. The features of O^{18} and temperature diagrams could be reproduced by turbulent bubbles of the interstellar medium if it did not exist unavoidable problems of the necessary dust densities and frequency of encounters of those bubbles with the solar system (mean free path ~ 2 pc). As said above such type of material was never observed and if it existed, it should mean clouds collapsing themselves in a collapsing galactic disk as a whole.

It is interesting to see that the necessary amount of dust in the oceanic waters calculated by Hoyle is 10^{17} g. This is more or less the amount of dust that the Earth could collect if the solar system remained some 15000 years within a glaciation cloud of some 0.3 pc in diameter. For longer time-spans (100000–150000 yr, say) this amount of dust could be collected in clouds that should be located in Figure 3 in a density range between 'glaciation clouds' and Bok globules. Thus, an hypothesis of interstellar dust precipitated in oceanic waters could be more interesting than that of dust absorbing the solar power. But it is still far from the observed values in dust clouds.

In what concerns the major glaciar eras of 2.5×10^8 yr, as for instance the Permian Carboniferous, they have been associated to the dust lanes in spiral arms, with

1–2 mag and width of 100–200 pc. These dust lanes are better observed in other near galaxies with spiral patterns more regular than the ours. In our Galaxy, this range can be found in the vortexes illustrated in Figure 3, representing an intermediate state between the hydrodynamic regime of the spiral arms and the turbulent regime. But the situation here is worse due to the fact that these dust lanes have densities at least 10^2 times lower than in the turbulent clouds. We conclude thus, that *no matter what caused the glacial eras, it can be taken for sure that the interstellar medium played no role in the process.*

If future geological records confirm the regularity of the glacial eras, it will be difficult to explain by bolid impact the dust in the oceans. If more detailed studies confirm the regularity of the atmospherical temperatures in the other planets and their weak dependency on the albedos as discussed in the Appendix, *this shall mean that the only remaining suspect is the Sun.*

From Figure 2 one can obtain a reasonable glacial configuration for the Earth with an increasing of 0.06 mag in the absolute magnitude of the Sun and with ice caps up to latitudes $L \sim 60°$. Fluctuations of 0.06 mag with a scale time of 100000 yr are impossible to be mesured. Unfortunately we know from the Sun less than we wish as to put the blame on it for the glacial eras, let us remember the problem of the neutrinos. We mentioned above that Lockwood and Morrison and Morrison raised the suspicion than the Sun have smaller fluctuations of 0.02 mag in a time-scale of some 10 years. Intuitively one can think that the larger the fluctuations the larger the scale time: turning again to Figure 2, a fluctuation of 0.02 mag should produce $\Delta T \approx 1$ K or less taking into account the attenuation of the oceans. The most probable is that this remains hidden below the usual fluctuations of the Earth climate.

Finally, in order to illustrate the up to date knowledge of the Sun, let us remember that the adopted solar constant and its error when given in a scale of temperature for rapid rotating bodies is (284 ± 4) K (see Hanel *et al.*, 1986, for instance). An actual fluctuation of 8 K of amplitude should be indeed a 'typical' value for a glacial era.

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Appendix: The Solar Spectrum and the Question of Planetary Atmospheres

Figure 1 in this Appendix shows the received solar power outside the Earth according to Allen (1973). $F(\lambda)$ is the intensity of the mean solar disk; $F\ (\lambda)$ is the same as $F(\lambda)$ but refers to the continuum between the lines. $I'(\lambda)$ and $I\ (\lambda)$ are *analogue to* $F'(\lambda)$ *and* $F(\lambda$ *but taken* at the center of the solar disk. $I(\lambda)/I'(\lambda)$ represents the observed line blanketing and the integral of $F(\lambda)$ over all wavelengths is proportional to the effective temperature of the Sun $T_{\mathrm{eff}} = 5770$ K); $f(\lambda)$ is simply what is received outside the Earth and its integral over all wavelengths is the solar constant I_0 used in Equation (5).

In this figure we can see that in the range $8000 < \lambda < 25000$ Å, the brightness temperature of the Sun can be well represented by a color temperature of 5970 ± 30 K, while the color temperatures outside this range are $T \lesssim 5500$ K at $\lambda > 25000$ Å and

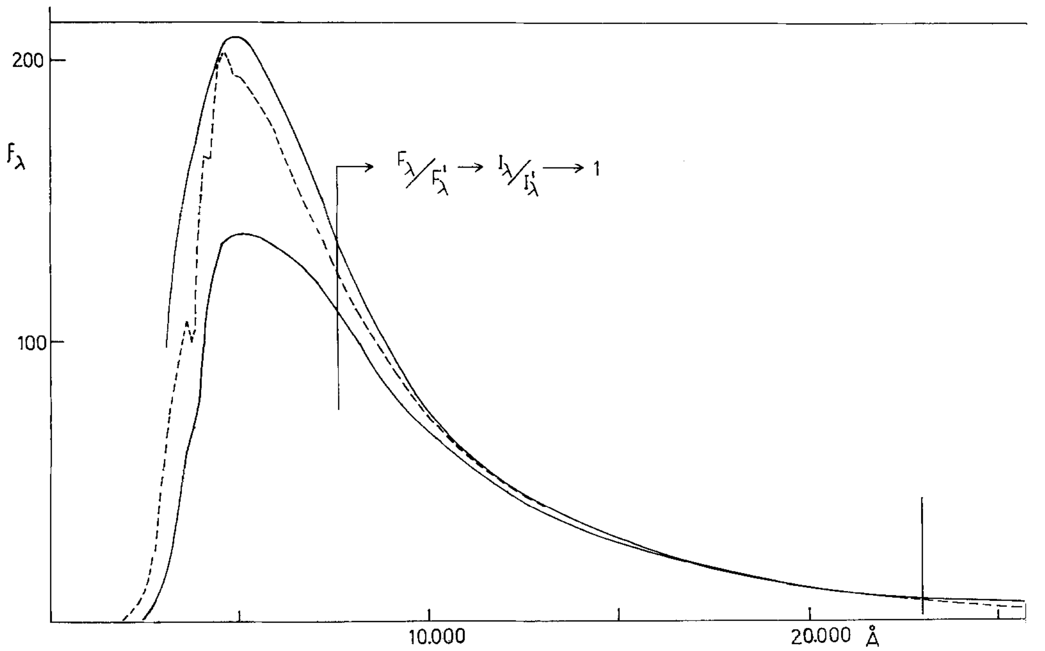

Fig. 1. Schematic diagram of received solar radiation outside the Earth's atmosphere. The upper curve is a black-body with $T = 5970 \pm 30$ K. The broken curve is the observed solar radiation (small details ignored). The lower curve is the total received radiation in the atmosphere and soils. In the near infrared, the sun tends to be a 'well-behaved' blackbody. Nearly 60% of the absorbed power is at $\lambda > 7000$ Å.

$T \simeq 5850$ K in the blue-visual (Allen, 1973). The 5970 K temperature was obtained testing numerically Planck functions with the observed $F(\lambda)$. The best consistency between those functions is in a range $5940 \lesssim T \lesssim 6000$ K. In this infrared region, the line blanketing becomes negligible; in the visual the ratios $I'(\lambda)/I(\lambda)$ and $F'(\lambda)/F(\lambda)$ are $\lesssim 0.9$, reaching a minimum of 0.5–0.6 between the blue and the near ultraviolet. On the other hand, the terrestrial albedo decays to 0.1 or less in the near infrared as is shown by Figure 1. There, we have plotted simply all the energy received in the terrestrial atmosphere. It is no matter for our purposes if such radiation is absorbed in the atmosphere (as for instance CO_2 absorption at $\lambda > 20000$ Å or the vapor's at 11000 and 14000 Å), or if radiation of shorter wavelengths, after reaching the soil, is re-irradiated to be absorbed by the CO and water vapor. As a result for all that, we have simply that the average thermal temperature of the Earth at sea level, 288 K, corresponds exactly to that given by Equation (2) for rapidly rotating bodies, but taking a 'black body', near infrared sun of 5970 K, illuminating a 'black-body Earth' with $A(\lambda) \rightarrow 0$. In these limits, for the infrared, such a formula gives $T_i = 288$ K $r^{-1/2}$ (r in AU) when one should expect, discounting the greenhouse effect, $T = (1 - A_{\text{eff}})$ 279 K $r^{-1/2}$, after averaging adequately $A(\lambda)$ in all spectrum and taking $T_{\text{eff}} = 5770$ K. Thus, the question that remains open is that if the thermal temperature of the Earth tends to the limit T_i or if this happens just by mere chance. Here we will restrict ourselves to a brief description of the planetary atmospheres and to some systematic effect seen in their temperatures similar to these seen in the Earth. All this is topic of other studies to be published later. (Reis, Cordeiro, Master's Thesis, 1987). By the moment one has that thermal emission of Jupiter and Saturn according to the data of the Pioneer and Voyager I are 124 K and 95 K respectively. (see Hanel *et al.*, 1983; and Petropoulos and Barros, 1984). In Uranus, from the Voyager II one has that the latitudinal temperatures associated mainly to the annual insolation are $T \lesssim 65$ K (see Hanel *et al.*, 1986). The coincidences of these temperatures with $T = 288$ K $r^{-1/2}$ are suggestive although nothing conclusive can be said by the moment. If, for comparison, one takes the atmospherical temperatures at the level $P = 1$ atm according to the data given in these works, one has values higher than the corresponding to such a relation. But in these massive gaseous planets there are additional complications when compared with the tellurical planets: undefined surfaces, inner thermal sources in Jupiter and Saturn, and in Uranus today a South pole near the sub solar point. All this requires a detailed analysis out of our purpose here. In the tellurical planets for obvious reasons the comparisons with the Earth are easier. From the results to be discussed below, there are coherences with a limit temperature 288 K $r^{-1/2}$ valid for a relatively transparent atmosphere and a rapidly rotating body (see the cases Venus and Mars). These coherences suggest that the atmospherical temperatures of the planets depend on the albedos and in the chemical compositions much less than one should expect. This is the main purpose of this Appendix: to justify the simple linear differential form (5) used to calculate the temperature decays during the Pleistocene in a planet whose atmosphere remained practically invariant and probably whose albedo varied less than the usual errors in modern measurements.

If one remembers the relation between life and water, the temperature decays are very important when seen in the natural biological scale of degrees Celsius. But in the natural thermodynamic scale of Kelvin degrees they are simply small fluctuations of some 3%. Let us see now what happens with Venus, Mars, and Titan.

A. Venus

It is known that there is a considerable greenhouse effect below the dense cloud layer at 25 to 50 km of altitude, reaching 750 K and 90 atmospheres of pressure at the surface. Below this opaque layer, the atmosphere is relatively transparent, resulting in the trapping of radiation and raising the temperature. Above the cloud layer, the atmosphere is transparent again, and there, for altitudes $h > 50$ km and pressures $P < 1$ atm, we have $T \lesssim 340$ K (Mulheman *et al.*, 1979); this level of pressure is taken for comparison with the Earth. The adiabatic gradient in Venus is 10 K km^{-1}, quite similar to that of the Earth, for dry air in its troposphere. It is suggestive that the curve $T(h)$ of Venus, above the cloud layer, is quite similar to that of the Earth in its troposphere, if one reduces the temperature by a scale factor $r^{-1/2} = 1.176$ in order to normalize the distance to the Sun. Thus, we have that the Venus temperature at 1 atm is $T \approx 288$ K $r^{-1/2}$, the limit infrared temperature for a rapidly rotating

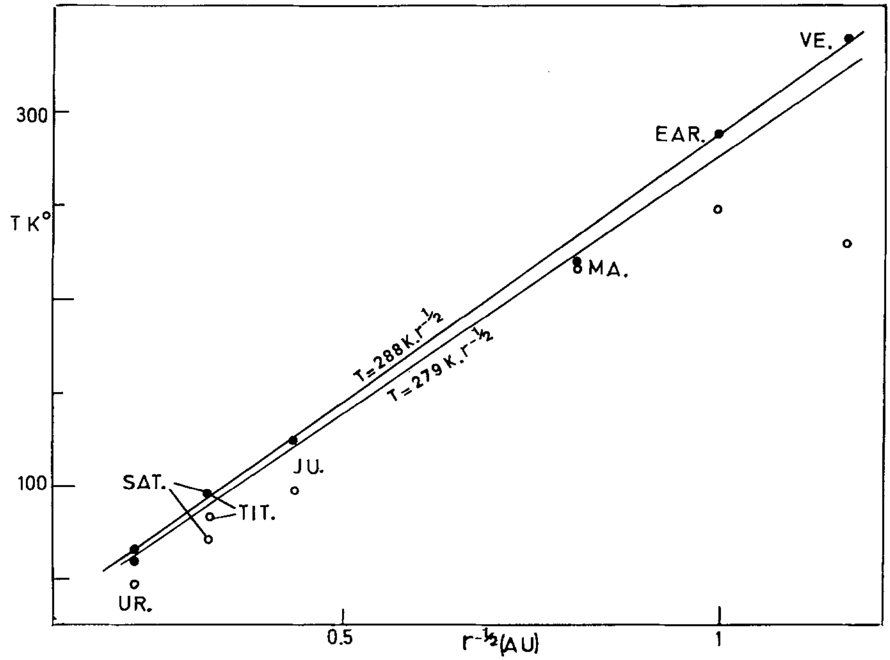

Fig. 2. Open circles: Expected planetary visual temperatures from the received solar power. Full circles: The mean thermal temperatures for the surfaces of the Earth, Mars, and Titan. For Venus, the temperature at the level $P = 1$ atm above the opaque cloud layer. For Uranus are given the latitudinal temperatures $T \lesssim 65$ K and the effective temperature $T_{eff} \lesssim 60$ K according to Hanes *et al.* For comparison is also given the equivalent emission temperatures in the infrared for Jupiter and Saturn. The upper and lower lines are the limit temperatures for zero albedo for the near infrared Sun of 5970 K and for the effective Sun of 5770 K see the text.

body. Let us remember that Venus, with its day of 2×10^7 s and thermal scale time of its atmosphere of 10^9s is also a rapidly rotating body. (The thermal scale time is the time required for the solar radiation to rise the temperature of the whole atmosphere from 0 K to the emission temperature as defined by Goody (1974)). For the Earth, this time-scale is $\sim 10^7$ s or 120 days and this is the reason why we have seasons on Earth.

B. Mars

With its thermal time scale of some 2 Martian days and with its mean atmospheric pressure of 10 milibars, this planet cannot be considered as a rapid rotating body. Thus, an agreement with $T_i = 288 \text{ K } r^{-1/2} = 233$ K is not expected. Its thermal mean is some 220 K, a value rather near the visual temperature $T_v = 217$ K.

C. Titan

The expected value is $T_i = 93$ K while from Voyager data one has 95 ± 1 K on the surface, with a pressure of 1.6 atm. From Morisson and Gregory (1985), one has that Titan has an earthlike atmosphere when compared to the other telluric bodies. The molecular weight of its atmosphere ranges between 27.5 to 30.0, indicating that nitrogen (weight = 28) is the main component. The Earth has 29 units for its standard mixture while Mars and Venus have values near 44 for their predominant CO_2. The thermal gradient in the curve $T(h)$ for the troposphere is some 1 K km^{-1} or less, while for the Earth, we have 7 K km^{-1}. The top of Titan's troposphere is at ~ 50 km and its thermosphere begins at 750 km (these values for the Earth are 10 and 85 km). These differences are expected for a body whose acceleration of gravity is 7.5 times less than that of the Earth.

In Figure 2 of this Appendix we have plotted the mean temperatures of the Earth, Titan, and Venus at 1 atm of pressure, together with the limit temperatures for rapid rotation 288 $Kr^{-1/2}$ and 279 $Kr^{-1/2}$ corresponding to the near infrared Sun of 5970 K and the effective Sun 5770 K. We have seen above that the Earth's temperature of 16 °C coincides with the limit temperature $T_l = 288$ K $r^{-1/2}$, within ± 1 K of accuracy. This alone could be a mere chance for we have taken arbitrarily, as a level for comparison, $P = 1$ atm. The same can be said about Venus: the zone on which the atmosphere becomes transparent and one can compare with the limit temperature associated to the near infrared Sun is indeed $P \lesssim 1$ atm. But, independent of the level of pressures adopted, such a limit is also seen in bodies withouth atmospheres. In the Moon, other satellites and asteroids, as one can see in Saari *et al.* (1972) and Hanel *et al.* (1986), infrared measurements gave a maximum for the subsolar points $T(r) = 408$ K $r^{-1/2}$, as T (sub solar point) $= \sqrt{2}\ T$ (rapid rotation) this is coherent with the near infrared Sun of 5970 K while for the effective Sun one expects 395 K $r^{-1/2}$.

It is accepted that re-irradiation from soils heats the lower layers of an atmosphere, producing temperatures somewhat higher than the expected from the solar radiation and the planetary albedos. On Earth, it is associated to the carbon dioxide and, in a lesser degree, to the water with their absorbing ranges in the infrared. In Venus, the radiation trapping is due to the opaque cloud layer at 25–50 km of altitude and there we have the greenhouse effect in the usual sense of the word. But in case of the Earth, we believe that the association of the difference 40 K to the greenhouse effect, is an exaggeration because: (a) this difference is with respect to the visual temperature, realistic in all the planets; (b) the percentual water vapor is in the range 10^{-2}–10^{-3}, depending on the local climate and the CO_2 percentual concentration is 5×10^{-4}. Thus, the question which remains open is why the thermal temperatures of the planets, when averaged in the whole surface tend to the limit $T = 288$ K $r^{-1/2}$ and why these analogies between the curves $T(h)$, despite of their different chemical compositions.

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