that the general scheme is plausible in order-of-magnitude terms. The following types of observation are, however, relevant. (1) Background spectrum: although the spectrum should be essentially thermal, deviations from the Planck law might arise if energy were injected at epochs when thermalisation was no longer fully effective at all wavelengths. Also, if some volatile contributor to the opacity with a spectral feature at some wavelength λ_1 were to condense out at a well-defined temperature T_1, then the background spectrum might now display a feature at wavelength $\lambda_1(T_1/2.7\text{ K})$. (2) Small-scale isotropy: the effective source of the microwave photons reaching us would lie at $z \gtrsim 100$, when they were emitted by a grain or molecule, or scattered by a free electron. The expected amplitude of the temperature anisotropies due to inhomogeneities would be similar to those predicted by the 'hot big bang' picture. An interesting difference in the present scheme, however, stems from the fact that various wavelength-dependent opacities (and not just electron scattering) are important: this means that the angular fluctuations observed at different wavelengths need not be correlated, as the location of the 'cosmic photosphere' depends on wavelength. (3) Galaxy formation and 'missing mass': any observations bearing on galaxy formation, the value of Ω, and the nature of the 'dark' mass in galactic haloes and clusters are relevant to the ideas discussed here.

In conclusion, there are astrophysical reasons for expecting a large radiative output from pregalactic events when $t \lesssim 10^7$ yr. This radiation could be thermalised, and would now be comparable in temperature to the observed microwave background. It is thus tempting to suppose that essentially all this background originated in this way rather than being a vestige of a hot 'primordial fireball'. The general argument leading to equation (6) then allows us to understand why the parameter $\mathcal{S}$—whose value is unexplained by the 'hot big bang' theory—is $\sim 10^8$. The arguments pertaining to helium and deuterium are thus our only real clues to the entropy and dynamics at much earlier eras; and the options of non-zero lepton numbers or non-Friedmannian dynamics complicate this issue (as do the uncertainties about nucleosynthesis in the pregalactic objects themselves). The very early Universe thus seems a topic for conjecture rather than consensus while such obscurity veils the first 3 Myr.

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Venus' rotation and atmospheric tides

VENUS rotates with a period of 243.00 ± 0.04 d retrograde[1]. The obliquity, or angle between the spin vector and orbit vector is $178 \pm 1°$ (ref. 1). Both the long period and the near 180° obliquity suggest that the spin has evolved under the influence of tidal torques. Tides raised by the Sun in the body of Venus would de-spin the planet in $\sim 10^8$ yr if no other torques were acting[2]. The final state would be one of synchronous rotation (one side always facing the Sun). So either we are living during the final stages of Venus' tidal evolution, an unlikely circumstance, or else Venus has already reached a stable equilibrium in which other influences balance the solar body tide. It is possible that the Earth has 'captured' Venus into a resonance in which the spin period is 243.165 d. However, for this resonance to be a stable equilibrium, either Venus must have a gravitational field that is ~ 10 times 'rougher' than the Earth's[2], a possibility that is largely ruled out by direct observation[3], or a third torque must balance the body torque due to the Sun. Tides in the atmosphere driven by periodic solar heating could supply the necessary third torque[4–6], but no quantitative theory has previously been published. Such a theory[7] is presented here, in which we argue that the current rotation is a stable balance between atmospheric and solar body tides.

Because the atmosphere is thin compared with the radius, tidal torques on the atmosphere depend only on lateral variations of atmospheric column density, which is proportional to surface pressure. Although less energy is absorbed at the surface than in the clouds (100 W m^{-2} compared with 500 W m^{-2} at normal incidence)[8], heating at the ground is the dominant source of surface pressure variations. This follows from the 25-fold decrease in solar diurnal period, from 117 d at the surface to 4 d in the clouds[8], and the fact that surface pressure oscillations vary roughly as $(\text{period})^2 \times (\text{pressure})^{-1/2}$ at the level of absorption.

It is not difficult to show that the power absorbed by the ground is quickly exchanged with the lower atmosphere. A simple model, representative of more distributed forcing, treats this heating as being confined to a thin layer above the surface. Because of the rigid lower boundary condition, such heating does not excite significant tidal oscillations in the atmosphere above, and fluid parcels within the heated layer remain approximately at constant pressure. The rate of change of column density is therefore

$$\frac{\mathrm{d}}{\mathrm{d}t}\int_0^\infty \rho\,\mathrm{d}z = -\int_0^{z_0} \frac{\rho}{T}\frac{\mathrm{d}T}{\mathrm{d}t}\,\mathrm{d}z = -\frac{F}{c_\mathrm{p}T_0} \tag{1}$$

where z_0 is the thickness of the heated layer, t is time, ρ is atmospheric density, T_0 is surface temperature, c_p is specific heat at constant pressure, and F is the heat flux (in $\mathrm{W\,m^{-2}}$) absorbed by the layer. To simulate the finite residence time of a heat pulse in the lower atmosphere we replace $\mathrm{d}/\mathrm{d}t$ by $\mathrm{d}/\mathrm{d}t + 1/\tau$ where τ is a thermal time constant associated with boundary layer processes and is in general a function of the forcing frequency.

Equation (1) is solved for the column density as a function of planetocentric latitude, longitude, and time, assuming the lower atmosphere rotates with the solid body. The heat flux F is expressed as a function of these variables by assuming $F = 0$ on the night side and $F = F_0 \cos\zeta$ on the day side, where ζ is the solar zenith angle. The column density is then multiplied by the gradient of the tidal potential, crossed with the planetary radius vector and integrated over the spherical surface to give the net torque on the atmosphere. In a steady state, this torque must be transmitted to the crust. The torque may be resolved into a component parallel to the spin axis, which affects the magnitude ω of the spin angular velocity, and a perpendicular component which affects the obliquity. Defining the angle β as

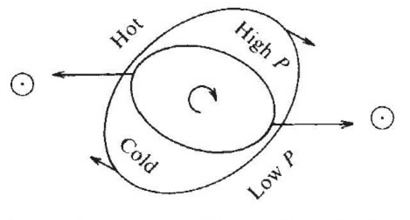

Fig. 1 Balance of torques on Venus. As only the semidiurnal components of the tides produce a torque, an 'image Sun' is shown diametrically opposite the true Sun, to make the picture symmetrical and to aid visualisation. The Sun is held fixed in this sketch so that Venus is rotating clockwise as seen from north of its orbit plane. The inner oval represents the tidally distorted figure of Venus, while the outer oval represents a surface of constant atmospheric pressure; the outer oval may also be regarded as the surface of an ocean of equivalent mass. Solar radiation raises the air temperature in the afternoon and causes mass to flow to the colder morning region. The high-pressure areas as well as the tidal bulges in the body of Venus are fixed with respect to the Sun (but not with respect to the surface). The gravitational attraction of the Sun, represented by arrows in the diagram, thus exerts contrary torques on the atmosphere and body of Venus.

the supplement of the obliquity, for $\beta \ll 1$ (as at present) one obtains

$$\frac{d\omega}{dt} = \left[\frac{3\pi n^2 r_0^4 F_0}{8c_p T_0 C}\right]\delta(2\omega+2n) \tag{2}$$

$$\frac{1}{\beta}\frac{d\beta}{dt} = \left[\frac{3\pi n^2 r_0^4 F_0}{8c_p T_0 C\omega}\right]\frac{1}{2}[-\delta(2\omega+2n)-\delta(\omega+2n)+\delta(\omega)] \tag{3}$$

where

$$\delta(\sigma) = \sigma(\sigma^2+\tau^{-2})^{-1} \tag{4}$$

Here n is the orbital angular speed, r_0 is the planetary radius, and C is the planet's greatest moment of inertia.

Equations (1)–(3) have a simple physical interpretation. Heating at the ground causes temperature to rise and column density to fall (equation (1)). Hence there is a mass concentration at the coldest time just after sunrise and a mass deficit at the hottest time just before sunset. The Sun's gravity acting on the sunrise side leads to a torque that tends to speed up the atmosphere (Fig. 1). The relevant frequency $2\omega+2n$ is that of the solar semi-diurnal tide (equation (2)). The obliquity is affected first by the component of the semi-diurnal tidal torque that acts perpendicular to the spin axis (frequency $2\omega+2n$), and second by the tides at frequencies ω and $\omega+2n$ that result from the annual migration (at frequency n) of the sub-solar point across the equator, modulated (at frequency $\omega+n$) by the motion of the Sun relative to the surface (equation (3)).

The gravitationally induced tide that acts on the solid planet leads to expressions of form similar to those above[2]:

$$\frac{d\omega}{dt} = \left[\frac{3k_2 G M_\odot^2 r_0^5}{2a^6 C}\right][-\varepsilon(2\omega+2n)] \tag{5}$$

$$\frac{1}{\beta}\frac{d\beta}{dt} = \left[\frac{3k_2 G M_\odot^2 r_0^5}{2a^6 C\omega}\right]\frac{1}{2}[\varepsilon(2\omega+2n)+\varepsilon(\omega+2n)-\varepsilon(\omega)] \tag{6}$$

(Symbols are defined in ref. 2.) The $\varepsilon(\sigma) \approx Q^{-1}$ are phase lags with the same sign as σ that depend on dissipation in the solid planet. $Q(\sigma)$ is the quality factor for oscillations at frequency σ. Values of Q for Venus are unknown, but analogy with the Earth suggests $30 \lesssim Q \lesssim 100$ (ref. 9).

According to equations (2) and (5), atmospheric tides tend to increase ω away from synchronous rotation, while solar body tides tend to drive the spin toward synchronism. For $\tau \to \infty$ (long thermal response time), balance at the current diurnal period of 117 d requires $Q \approx 30$, as shown in Fig. 2. For smaller τ, balance at the current period requires larger Q. Equations (3) and (6) indicate that the current state is stable to obliquity perturbations provided τ is less than about 2 weeks. The Earth resonance is also stable provided atmospheric and solar body tides balance at a period sufficiently close to the resonant period.

We have shown in which conditions the current rotation might be a stable equilibrium. As shown in Fig. 2, there is also a prograde equilibrium state with a diurnal period of 117 d (spin period $\approx$ 77 d). The stability of this state may be analysed by substituting $\pi-\beta$ for β and $-n$ for n in equations (2)–(6). Our analysis shows that when one of the two equilibrium states in Fig. 2 is stable to obliquity perturbations, the other is unstable.

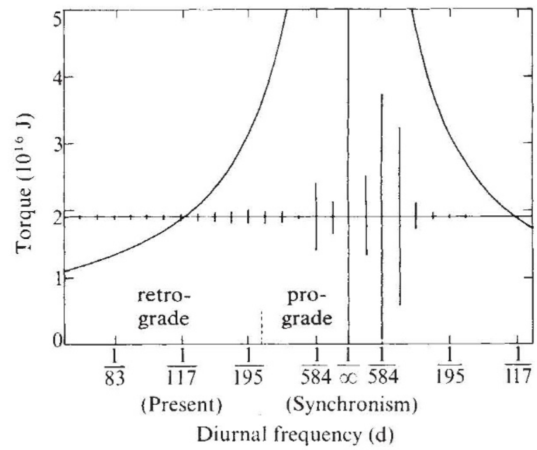

Fig. 2 Tidal torques plotted against the diurnal frequency $(\omega+n)(2\pi)^{-1}$ for spin vector parallel to the orbit vector. Atmospheric torques (curved lines) tend to drive the spin away from synchronism, and are shown for values of the thermal time constant $\tau \to \infty$. The solar tidal torque on the solid body (horizontal line) tends to drive the spin toward synchronism, and is shown for a value of the quality factor Q = constant $\approx$ 30. This choice of Q ensures that atmospheric and solid body torques together drive the spin toward the current diurnal period of 117 d. Torques due to Earth resonances (vertical lines) tend to hold the spin period at the resonant frequencies, and are shown for a value of $(B-A)C^{-1} = 2.2\times10^{-5}$, similar to that for the Earth. Here A, B, C are the three principal moments of inertia of Venus, with $A<B<C$. For this amount of gravitational roughness, the Earth torques are too small by an order of magnitude to overcome the solar solid body torques, unless the solar torques and atmospheric torques balance near a resonant frequency. A recent analysis[1] of radar data suggests that the spin period is very close but not equal to that required for resonance with the Earth.

However, in general, other equilibria (both stable and unstable) can occur with obliquities between 0° and 180°. A more complete theory to be presented later indicates that Venus probably originated with a retrograde rotation in order to have evolved to the current retrograde state.

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