could have come from the disintegration of pumice that was either waterborne or deliberately brought to the mainland by ship. There is still no evidence of an ash-fall on the mainland from the Thera eruption.

Results reported here indicate that the 1400 ± 100 B.C. date from ^{14}C analyses given by Ninkovich and Heezen (*3*) as the best date for the eruption must be narrowed to 1400 + 100 B.C to be consistent with the pottery chronology at Nichoria and at the Thera excavation (*1*). Further excavation at Nichoria may provide additional time-stratigraphic information concerning the Thera eruption, although it is to be hoped that more refinement in the dating will be realized from the archeological finds being made by Marinatos at Thera itself.

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Venus: Radar Determination of Gravity Potential

Abstract. *We describe a method for the determination of the gravity potential of Venus from multiple-frequency radar measurements. The method is based on the strong frequency dependence of the absorption of radio waves in Venus' atmosphere. Comparison of the differing radar reflection intensities at several frequencies yields the height of the surface relative to a reference pressure contour; combination with measurements of round-trip echo delays allows the pressure, and hence the gravity potential contour, to be mapped relative to the mean planet radius. Since calibration data from other frequencies are unavailable, the absorption-sensitive Haystack Observatory data have been analyzed under the assumption of uniform surface reflectivity to yield a gravity equipotential contour for the equatorial region and a tentative upper bound of* 6×10^{-4} *on the fractional difference of Venus' principal equatorial moments of inertia. The minima in the equipotential contours appear to be associated with topographic minima.*

Present knowledge of the surface of Venus rests largely on the results of radar observations. Perhaps the most striking fact to emerge has been the retrograde direction of Venus' spin and its apparent resonance with the relative orbital motions of the earth and Venus (*1*). The earth could have captured Venus' spin in this resonance only through the action of a gravitational torque on a substantial axial asymmetry in Venus' mass distribution (*2*). Heretofore, no measurement of this asymmetry has been possible. The main purpose of this report is to demonstrate that future radar observations can be used to determine equipotential contours of Venus' gravity field and, hence, to estimate the axial asymmetry of its mass distribution. A preliminary contour for the equatorial region and a concomitant bound on the axial mass asymmetry—based on past radar observations not made explicitly for this purpose—is also included.

How can radar data be sensitive to the gravity field of Venus? A direct sensitivity seems almost unthinkable. But an indirect intermediary exists, namely, the thick, carbon-dioxide-dominated atmosphere of Venus. Because this atmosphere absorbs X-band (approximately 8000 Mhz) radio radiation strongly and, for example, S-band (approximately 2000 Mhz) radiation hardly at all, we can infer surface heights relative to a particular pressure contour from a comparison of radar cross sections measured at the two frequencies, since the intrinsic reflectivity of the surface itself should not, in general, vary sharply with frequency (*3*). The use of a third frequency would allow a more precise separation of atmospheric from surface reflectivity effects on cross section. The pressure contours can then be related to the mean planet radius with the aid of measurements of round-trip radar echo time-delays, which allow the absolute surface heights to be determined (*4*). Gravity equipotential contours will coincide with pressure contours under conditions of hydrostatic equilibrium in the atmosphere (*5*). From such a contour, the gravitational torque exerted by the earth can be estimated.

Now we develop this basic idea quantitatively. Since at present its application is restricted to the equatorial regions traversed by the subradar point of earth-based observations, we confine our analysis to that situation. The possibilities for extension to high latitudes and for the use of radars on Venus orbiters are discussed briefly in the last part of the report.

The radar cross section $\sigma(\lambda,\phi)$ per unit surface area at the subradar point can be written as

$$\sigma(\lambda,\phi) = \sigma_0(\lambda,\phi)\exp[-2\tau(\lambda,\phi)] \quad (1)$$

where

$$\tau(\lambda,\phi) = \int_{h(\phi)}^{h_{\max}} \kappa(h,\lambda)\,dh \quad (2)$$

with λ being the wavelength of the radar signals, ϕ the longitude of the subradar point (we suppress θ, the latitude dependence), σ_0 the intrinsic cross section per unit area of the observed region of the surface, τ the opacity (optical depth) of the atmosphere, κ the absorption coefficient for radio waves, h the height of the reflecting region relative to a reference pressure contour, and h_{max} the altitude above which absorption can be neglected. We define the reference contour in terms of a reference longitude ϕ_0 such that $h(\phi_0) \equiv 0$. The factor of 2 multiplying τ in Eq. 1 accounts for the two-way passage of the radio waves through Venus' atmosphere. The coefficient, κ, is given approximately by the semi-empirical formula (6)

$$\kappa(h,\lambda) \simeq \frac{1.57 \times 10^{-2} P^2(h)}{\lambda^2[T(h)/273]^5} \text{km}^{-1} \quad (3)$$

where P is the pressure in atmospheres, T the temperature in degrees Kelvin, and λ the wavelength in centimeters. Since the absorption is important only in the lower atmosphere, we may use the approximate temperature-pressure relation (7)

$$\frac{P(h)}{P(0)} \simeq \left[\frac{T(0) - Lh}{T(0)}\right]^k \quad (4)$$

in the evaluation of τ. Here $h = 0$ refers to the reference pressure contour; $L \simeq 9°$K per kilometer is the lapse rate, assumed constant and $k = \mu g/RL \simeq 5.3$ is the polytropic index, with μ the mean molecular weight of the atmosphere, g the acceleration of gravity, and R the gas constant. From Eqs. 1 through 4 we obtain

$$\frac{\sigma(\lambda,\phi)}{\sigma(\lambda,\phi_0)} \frac{\sigma_0(\lambda,\phi_0)}{\sigma_0(\lambda,\phi)} \simeq$$
$$\exp\left(-\frac{\kappa(0,\lambda)T(0)}{(k-2)L}[(1-\frac{Lh}{T(0)})^{2(k-2)} - 1]\right)$$
$$\simeq \exp[2\kappa(0,\lambda)h] \quad (5)$$

where the last relation is valid only for $h << [T(0)/L] \simeq 90$ km. Since h does not seem to vary by more than about ± 4 km (4, 8), the expansion used in the last part of Eq. 5 will be in error by less than 15 percent. Hence, for expository purposes, we confine discussion to the simplified form. Solving for h then yields

$$h(\phi) \quad \frac{1}{2\kappa(0,\lambda)} \ln\left[\frac{\sigma(\lambda,\phi)}{\sigma(\lambda,\phi_0)} \frac{\sigma_0(\lambda,\phi_0)}{\sigma_0(\lambda,\phi)}\right] \quad (6)$$

Assuming that the multiple-frequency observations provide the ratios σ/σ_0, how may we use the resultant values of $h(\phi)$ to determine the height variation of the reference contour with respect to the mean surface radius, ρ? From the value of the echo time-delay, measured simultaneously with the cross section, we can infer the height, h', of the reflecting region above the mean radius (4). Thus, the height, h'', of the reference pressure contour above the mean radius is given by

$$h'' = h' - h \quad (7)$$

The function $h''(\phi)$ defines a gravity equipotential contour over the equatorial region under conditions of atmospheric hydrostatic equilibrium (5). If the contribution of the centrifugal acceleration to the gravity field were neglected (9) and if h'' were known over the entire planet, then the unknown coefficients in the expression for gravitational potential energy, U, could be obtained from inversion of

$$U[\rho + h''(\theta,\phi),\theta,\phi] = -\frac{GM_♀}{\rho + h''} \times$$
$$\left(1 + \sum_{n=1}^{\infty} \sum_{m=0}^{n} \left(\frac{\rho}{\rho + h''}\right)^n P_n^m(\sin\theta) \times\right.$$
$$\left.[C_{nm}\cos m\phi + S_{nm}\sin m\phi]\right) = U_0 \quad (8)$$

where G is the gravitational constant, $M_♀$ the mass of Venus, $P_n^m(\sin\theta)$ the associated Legendre function of degree n and order m, C_{nm} and S_{nm} the sought-for coefficients, and U_0 the value of the potential on the reference contour. For data confined to the equatorial regions, as here, Eq. 8 can be recast as

$$\sum_{m=0}^{\infty} (C_m\cos m\phi + S_m\sin m\phi) \simeq \frac{h''(\phi)}{\rho} \quad (9)$$

where

$$\begin{bmatrix} C_m \\ S_m \end{bmatrix} \equiv \sum_{n=m}^{\infty} P_n^m(0) \begin{bmatrix} C_{nm} \\ S_{nm} \end{bmatrix} \quad (10)$$

and where we set $U_0 \simeq -GM_♀/\rho$ (10) and dropped terms of second order and higher in h''. The coefficients C_m and S_m are given by

$$\begin{bmatrix} C_m \\ S_m \end{bmatrix} = \frac{1}{\pi\rho} \int_0^{2\pi} h''(\phi) \begin{bmatrix} \cos m\phi \\ \sin m\phi \end{bmatrix} d\phi;$$
$$m = 1,2,\ldots \quad (11)$$

with $C_0 \simeq C_{00} = 1$ and $S_0 \equiv 0$. No useful information on the coefficients of the zonal harmonics (C_{n0}; $n \geqslant 2$) is contained in the equatorial portion of the equipotential contour, since the zonals have no longitude dependence and their bulk equatorial effect is not easily separable from that of $M_♀$.

How may we use these results to estimate the gravitational torque exerted on Venus by the earth? For study of the putative spin-orbit resonance (2), the relevant torque is proportional to $(B - A)/C$ where $A < B < C$ are the principal moments of inertia of Venus, with C assumed to be the moment about the spin axis. Unless either (i) Venus is now a very elastic body (high "Q") with respect to the diurnal stresses of 100-day periodicity, or (ii) there exists a very delicate balance between the torques exerted by the sun on Venus' tidal bulge and on a possible atmospheric bulge (11), it appears that control of Venus' spin by the earth requires $(B - A)/C > 10^{-4}$ (2). If the tesseral harmonics for Venus fall off with degree as do those for the moon and Mars, then the approximation

$$[(C_2)^2 + (S_2)^2]^{1/2} \simeq$$
$$3[(C_{22})^2 + (S_{22})^2]^{1/2} = 0.3\frac{B - A}{C} \quad (12)$$

should yield a reasonable estimate for $(B - A)/C$.

Unfortunately, data necessary to determine an accurate equipotential contour in the equatorial region of Venus do not now exist. The lack of both accurate values for $\kappa(h,\lambda)$ and properly calibrated radar cross-section data are the major limitations; in particular, there have been no coordinated observations of cross section at more than one radar frequency. If the variations with longitude of the intrinsic surface reflectivity are small and if the effects of the differences between total radar cross sections and cross sections per unit surface area at the subradar point are also small, we may use the limited data from the Haystack Observatory on the total cross sections (8) at $\lambda = 3.8$ cm, coupled with the surface-height variations recently determined (4), to obtain an approximate equipotential contour. The result is presented in Fig. 1 for $\kappa = 0.07$ km^{-1}. This choice for κ is based on Eq. 3 and the "nominal" values $P(0) = 100$ atm and $T(0) = 750°$K (12). A comparison with the surface-height variation (see Fig. 1) seems to indicate that minima in the equipotential contour are associated with topographic minima. But one must remember that the uncertainties are large; it is even difficult to place reliable bounds on the accuracy of the equipotential contour, in view of the lack of accurate and suitable data.

We can assess analytically the relative sensitivity of h'' to the various relevant factors. From Eqs. 1 through 7 we find, under conditions validating the last part of Eq. 5,

$$\delta h'' = \delta h' + \frac{1}{2\kappa(0,\lambda)} \frac{\delta\sigma}{\sigma} - h\frac{\delta\kappa(0,\lambda)}{\kappa(0,\lambda)} \quad (13)$$

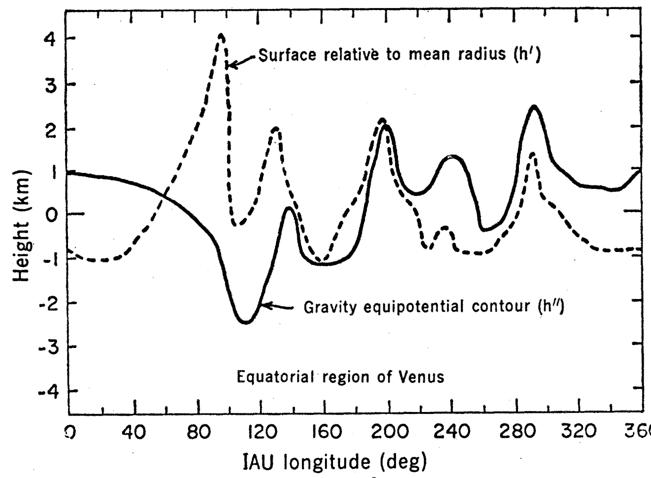

Fig. 1. Comparison of the surface heights on Venus with a gravity equipotential contour. The surface heights are based on round-trip radar echo delays from published (*4*) and recent, unpublished data. The gravity potential contour is derived from data on radar cross sections obtained at the Haystack Observatory (*8*); the uncertainties in both the scale and variations of this latter curve are large (see text). Latitude variations have been suppressed, with both curves referring to averages along a narrow ($\pm 10°$) band centered on the equator of Venus.

The last term, through Eq. 3, can be separated into components due to errors in $T(0)$, $P(0)$, and numerical factors. On the basis of experimental and theoretical evidence relating to these components, we estimate that $|\delta\kappa/\kappa| < 0.6$. This contribution to h'' is proportional to h and may therefore be as much as several kilometers. For our nominal value of $\kappa(0,\lambda = 3.8 \text{ cm}) \simeq 0.07$ km^{-1}, fractional errors in cross section of 10 percent will contribute errors of under 1 km to h''. The contribution of $\delta h'$ (*4*) should be nowhere greater than about 0.5 km.

Unless the intrinsic surface reflectivity is well correlated with the surface altitude—unfortunately a not unlikely possibility—the solutions for C_2 and S_2, and hence the estimate for $(B - A)/C$, may be relatively immune to the effects of variations in intrinsic reflectivity. Under this assumption, we find from Fig. 1 and Eqs. 11 through 13 that

$$\frac{B-A}{C} \simeq (3 \pm 3) \times 10^{-4} \qquad (14)$$

where the error reflects our estimates of the uncertainties in κ, $c(\phi)$, and $h'(\phi)$. No allowance was made for the contributions of the higher-degree terms to C_2 and S_2 (*13*). We also find that the axis of minimum moment of inertia passes through longitude 30 ± 60 degrees [International Astronomical Union (IAU) coordinate system], which is too uncertain to allow meaningful deductions about torque balance.

The prospects for improvement in this very crude estimate of the gravity equipotential are good. Results from Venera 8, for example, should tighten the bounds on atmospheric composition, $T(0)$, and $P(0)$, and hence on κ (after laboratory confirmation or correction of Eq. 3). The radar systems at Arecibo, Puerto Rico ($\lambda = 70$ cm), Goldstone, California ($\lambda = 12.5$ cm), and at Haystack ($\lambda = 3.8$ cm) could be used to reduce the uncertainties in surface-height variations to the 150-m level or slightly below. With careful calibration of the radars, cross section measurements—for the same surface regions to which the height measurements apply—should have relative errors of no more than about 2 percent (*8*). Haystack's contribution is essential here, because there is no appreciable atmospheric absorption at the wavelengths used at the other observatories. Thus, earth-based measurements could yield gravity equipotential contours in the equatorial regions of Venus with a lateral surface resolution of about 100 km, corresponding to information on spherical harmonics up to the 360th degree, and an altitude resolution of about 200 m. The decrease in the uncertainty of the estimate of $(B - A)/C$ should be at least fourfold if the higher harmonics do not contribute too much to C_2 and S_2.

Can the determination of Venus' gravity equipotential contour be extended beyond the equatorial regions traversed by the subearth point? Two approaches are possible. (i) With more powerful earth-based radar systems, such as the proposed improved Arecibo facility, it will be possible to determine surface heights and reflectivities over most of the planet with high resolution by use of the new technique of delay-Doppler interferometry (*14*) at the 12.5-cm wavelength at which this radar would operate. If a similar capability existed for shorter radar wavelengths, such as with a Haystack-Goldstone bistatic configuration, then the atmospheric absorption could be determined as well. Of course, in the analysis of these data—for which the incident and reflected waves would not be in the zenith direction on Venus—atmospheric refraction effects must be considered (*7*) as well as possible variations of the intrinsic angular scattering law with frequency (*3*). (ii) A spacecraft placed in a polar, or near-polar, orbit about Venus and equipped with a suitable dual-frequency radar, could determine surface heights, reflectivities, and the corresponding atmospheric absorptions over virtually the entire planet. Repeated polar passages would offer the possibility for continual calibration. The resultant high-resolution equipotential contours would not only yield the gravitational torque exerted by the earth but would have other scientific applications as well: these contours bear, for example, on questions of the origin and evolution of Venus, its deep interior, the extent of isostatic compensation near its surface, and the processes of surface erosion (*15*).

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12. These values are closer to the Venera findings than those used in (*8*); the reference longitude (see text) was chosen such that the values apply to the mean radius of 6050 km (*4*).
13. The analysis of the Mariner 5 radio tracking data [J. D. Anderson and L. Efron, *Bull. Amer. Astron. Soc.* **1**, 231 (1969)] yielded an upper bound on $[C-(A+B)/2]/M_e\rho^2$ of 10^{-5}, which is difficult to reconcile with a value of $(B-A)/C$ of the order of 10^{-4}. Aside from (remote) possibilities, such as Venus not spinning about its axis of maximum moment of inertia, the discrepancy may be explained by errors in the values used for κ and $\sigma(\phi)$ or by an unrealistic bound for the tracking data, or by a combination.
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16. Research at the Haystack Observatory is supported by NSF grant GP-25865 and NASA grant NGR 22-174-003, contract NAS 9-7830.

12 October 1972

2,3,7,8-Tetrachlorodibenzo-p-dioxin: A Potent Inducer of δ-Aminolevulinic Acid Synthetase

Abstract. *2,3,7,8-Tetrachlorodibenzo-*p*-dioxin, a toxic contaminant frequently formed during the synthesis of the herbicide 2,4,5-trichlorophenoxyacetic acid, was shown to be a potent inducer of hepatic δ-aminolevulinic acid synthetase in the chick embryo. As little as 4.66×10^{-12} mole of the contaminant per egg produces a significant increase in the activity of the enzyme. Induction of the enzyme is related to the dose of 2,3,7,8-tetrachlorodibenzo-*p*-dioxin and, in contrast to that produced with other drugs, is prolonged in time, with 70 percent of the maximum induced activity present 5 days after a single dose. This contaminant is implicated as the likely causative agent in an outbreak of porphyria cutanea tarda in workers in a factory where 2,4,5-trichlorophenoxyacetic acid was being synthesized.*

2,3,7,8-Tetrachlorodibenzo-*p*-dioxin (TCDD) is an unwanted contaminant formed during the synthesis of the herbicide 2,4,5-trichlorophenoxyacetic acid (2,4,5-T) (*1*) (Fig. 1). This contaminant, TCDD, is perhaps the most potent small-molecule toxin known; the oral LD_{50} (mean lethal dose) in guinea pigs is 1 μg per kilogram of body weight (3×10^{-9} mole/kg) (*2*). The widespread use of 2,4,5-T as a defoliant in Vietnam (*1, 2*) and the discovery of the teratogenic potency of TCDD (*3*) have caused concern about the potential public health hazard created by contamination of the environment with TCDD. The chemistry of the toxin has been extensively investigated, but little is known about its biological actions (*1, 4*).

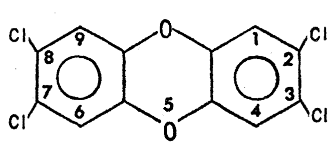

Fig. 1. Structure of 2,3,7,8-tetrachlorodibenzo-*p*-dioxin.

In 1964, Bleiberg *et al.* (*5*) reported an outbreak of occupationally related acne and porphyria cutanea tarda (PCT) among workers in a factory where 2,4,5-T was being produced. The acne was shown to be directly attributable to TCDD (*6*). Porphyria cutanea tarda is an acquired defect in hepatic porphyrin metabolism characterized by uroporphyrinuria, photosensitivity as manifested by blisters, and mechanical fragility of the skin (*7*). The etiology of PCT in these factory workers is unclear, but upon reinvestigation of the factory in 1969, we discovered that the PCT had disappeared in all workers following the institution of procedures to reduce TCDD contamination (*8*). Hepatic porphyria can be produced experimentally by a number of drugs, all of which have the ability to stimulate the activity of the initial enzyme in heme synthesis, δ-aminolevulinic acid synthetase (ALA synthetase) (*9, 10*). Stimulation of this enzyme is thought to represent induction, that is, enhanced protein synthesis (*9*).

We report here that TCDD is an inducer of ALA synthetase, and is at least three orders of magnitude more potent than any other compound known to produce experimental porphyria.

The chick embryo was chosen as the experimental animal because (i) it is highly sensitive to the toxic effects of TCDD (*11*), (ii) induction of ALA synthetase in the liver is well characterized in the chick embryo (*12*), and (iii) the egg is a closed system, which reduces the risk of laboratory contamination.

Halogenated dibenzo-*p*-dioxins were dissolved in *p*-dioxane. Fertile chicken eggs, 15 to 20 days of gestation, were injected with 25 μl of the chemical solution or of solvent alone, through a small hole punched into the shell over the air sac. After the appropriate time interval, the animals were killed, and the activity of hepatic ALA synthetase was assayed (*13*). The TCDD produced a dose-related increase in ALA synthetase activity (Fig. 2). Even at the lowest dose tested, 4.66×10^{-12} mole per egg (1.5 ng), there was significant ($P < .05$) doubling of enzyme activity. Enzyme activity increased more than 35-fold at the highest dose tested, 1.55×10^{-9} mole per egg (0.5 μg). The in vitro addition of TCDD to a reaction mixture containing control liver did not increase enzyme activity. The stimulation of ALA synthetase in

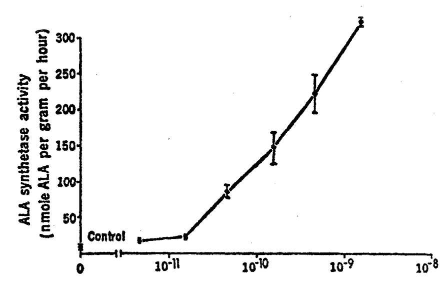

Fig. 2. The induction by TCDD of ALA synthetase: dose-response relationship. Chicken eggs of 17 days' gestation were injected with 25 μl of solvent (control), or of solvent containing various doses of TCDD. The embryos were killed 48 hours later and assayed for hepatic ALA synthetase activity (*13*). The points represent the mean ± standard error of three or four groups of pooled livers.