Chapter 4

Venus Unmasked

Venus was the mysterious planet only radar could unmask. As fast as lunar radar techniques developed, they were tried out on Venus.

At closest approach to earth, Venus is over 100 times further away than the moon, so the results sometimes were problematic. In 1958 Gordon Pettengill and others attempted to bounce a radar wave off Venus using the MIT Lincoln Lab Millstone antenna. They claimed to have successfully detected the return echo. In September 1959, the experiment was repeated at both Jodrell Bank and Millstone. Jodrell bank claimed to replicate Millstone's 1958 results, but Millstone failed to and they withdrew their 1958 detection claim. The Jodrell Bank data was erroneous–as reflected in the fact that it yielded a Cytherian rotation period of 20 days. On March 10-16, 1961 using the JPL Goldstone antenna Richard Goldstein and others finally did unambiguously detect radar waves returned from Venus. MIT's Millstone, Jodrell Bank, and a Soviet installation in the Crimea obtained corroborating results. In 1963 reanalysis of the MIT data tapes would show that Millstone in fact had made radar echo detections on September 14, 1959, and March 6, 1961.

Before any of this happened, however, *passive radar* signals had been obtained from Venus. The radar systems we have been examining are *active radar systems*. If you remove the transmitter portions from them you have left a passive radar system. Passive radar is limited to detecting electromagnetic waves emitted from the surface of the planet and solar waves reflected back from the surface. Because of its dense cloud cover, there is little reflected solar energy on Venus. Thus the energy radiated from Venus is mostly *emissivity*. For the moment assume the energy emitted is heat.

A planet has three main realms: An atmosphere, a surface, and an interior. Each of these parts has heat associated with it, and there can be heat transfers both between and within the parts. Thus, for example, air circulation is a heat transfer process and on earth the formation of rain clouds and precipitation involve transfer of heat between surface and atmosphere. Inside the earth itself there are various heat transfers between and within the core, mantle, and crust.

There are three main kinds of mechanisms for energy transfer. The most common is *conduction* –a relatively slow process where the kinetic energy of molecules is transferred from hotter regions to colder ones. This includes both redistribution of a planet's internal heat and *absorption* of that component of solar radiation which is not reflected back. In *convection*, heat is transferred by bodily transport of the heated material from one place to another. *Radiation* involves no material transfer by either convection or conduction. The least amount of the Earth's energy transfer is by radiation.

Energy radiated from the surface of the planet is known as emissivity. And it is an important indicator what is going on geologically within a planet. Since it can be detected by even passive microwave systems, emissivity data was among the first information obtained about the surface of Venus. To understand what emissivity can tell us geophysically about a planet, we need to look more closely at heat transfer within live planets. Earth is our prime example.

In addition to transfers of existing energy and absorption of solar energy, a planet's thermal budget may include new heat produced by natural radioactivity. The surface of the earth is about 300° Kelvin or about 27° C. As one goes towards the center of the Earth, radioactivity causes temperatures to increase. As one goes deeper the temperatures increase initially at a rate of about 30° C/km and physical properties of the interior material change. Whether a region is liquid, solid, or plastic is a function of temperature and pressure.

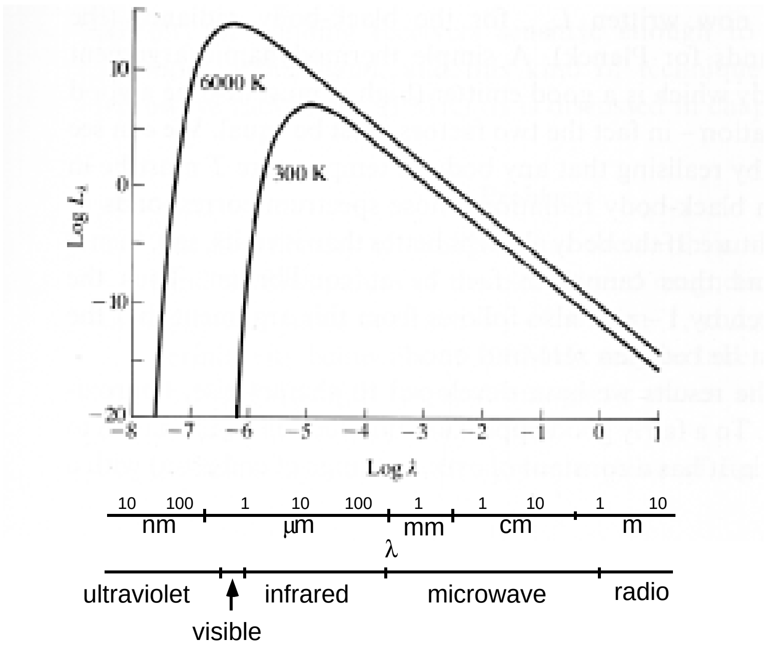
The upper region of high rock strength, known as the *lithosphere*, is topped by a brittle *crust* 5-40 km thick. On Earth the lithosphere is about 600°C at a depth of 20 km and 900°C at 30 km. In the temperature range of 600°-900° the lithosphere becomes soft and increasingly plastic. The Earth's lithosphere is about 100 km thick on average, though at places such as beneath large mountain ranges it reaches around 300 km. The *asthenosphere* is the plastic upper region of the mantle beneath the lithosphere. It reaches to about 640 km deep. Beneath is the *lower mantle*, approximately 2245 km thick, then the 2,270 km thick liquid *outer core* and finally the 1220 km solid *inner core*. At the bottom of the mantle the temperature perhaps reaches 5000° C and perhaps 6000° C in the core. If the 30° C/km rate of heat transfer were continued to the core, its temperature would be 191,340° C. Obviously the rate of increase is smaller lower down. This largely is because the bulk of radioactive material is located in crustal regions.

The amount of convective heat transfer in the lithosphere and asthenosphere is much greater than once was thought. Mantle *plumes* bring molten material from the deep mantle up to the surface as *volcanism* or *hotspots*. Especially in volcanoes that molten magma spreads out over existing crust, resulting in *resurfacing* and *crustal thickening*. The Earth's crust consists of around 20 semi-rigid crustal blocks or *plates* that move relative to each other. Plate motions are a surprisingly effective means of heat transfer. Under sea-floor spreading new material is brought up resulting in horizontal plate flows. Sometimes the clash of plates causes *subduction* where one plate is forced under the other being deflected down into the asthenosphere. The result is a kind of convective cycle where hot material rises to the crust, and cooler crustal material is forced back into the mantle. The consequence is an overturn or "recycling" of the crust.

Resurfacing brings significant amounts of heat to the surface that are radiated. Horizontal plate motions of a few centimeters a year are sufficient to overturn the entire surface of the Earth in about 100 million years (my). This is roughly the period of time on Earth since the extinction of dinosaurs. The present geological era, the *Cenozoic*, only began about 65 million years ago (mya).

A *geologically alive planet* is one that has a high rate of resurfacing due to volcanism, plate movements, and subduction. The main surface signatures of resurfacing are volcanic lava flows embaying existing surface and tectonism–deformation within the crust and associated structural effects. Answering the question whether Venus is alive comes down to determining whether there presently are active volcanism and/or tectonism on Venus, and if so how much and what forms? Is there active volcanism? Are there presently active tectonics? If so, are the crustal deformations due to plate motions? Is there subduction?

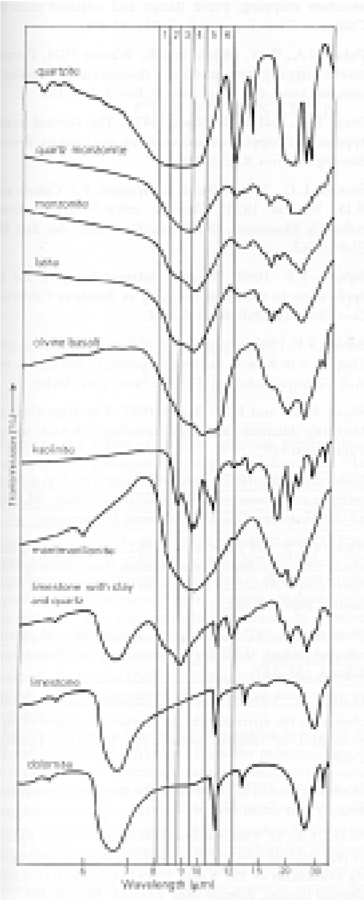
The non-solar energy radiated from the Earth's surface comes from two sources: Most of the Earth's radioactivity is concentrated in the crust, hence a substantial portion reaches the surface. Volcanism and tectonism bring heat up to the surface where it cools in the process. The geological activity of a live planet like the Earth is evidenced in the heat radiated from the surface. Hotter, radiating planets have thin lithospheres which make resurfacing by volcanism and tectonics possible. Dead or moribund planets such as the moon, Mars, and Mercury are cold, tectonically and volcanically inactive, and have thick lithospheres. The interior and surface of a geologically active planet have a relatively large negative heat balance. Thus by measuring emissivity we get some idea of the geological state of a planet including estimates of lithospheric thickness. Emissivity data also will impose heat-transfer boundary conditions on geophysical attempts to model the internal activity of the planet.

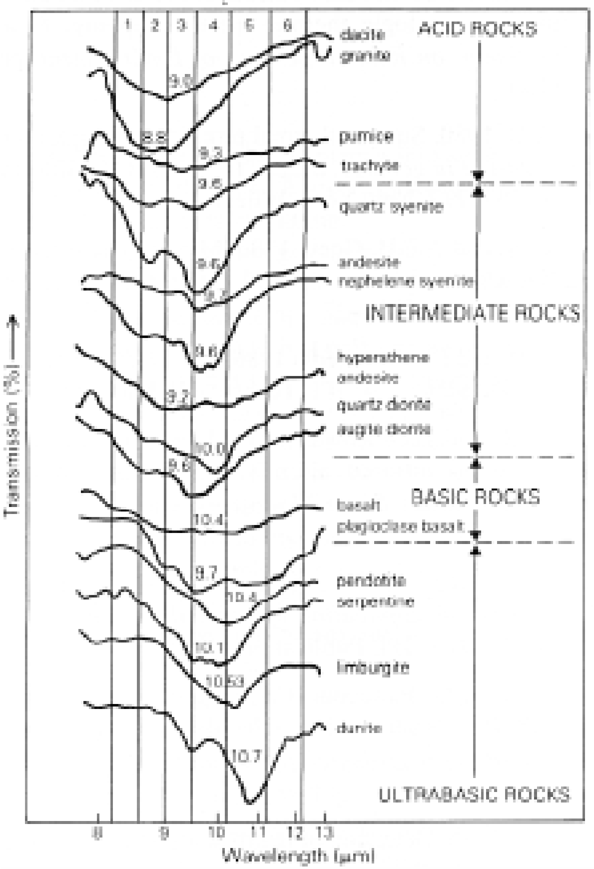


The intensity of emitted or reflected power from a planet's surface is a function of surface *brightness temperature* and wavelength. Brightness temperatures always are given in absolute temperature (°K). The brightness temperature for Venus is about 725-797°K and so falls slightly to the left of the 300° curve shown. Passive microwave apparatus is used to detect energy in the long "tails" of the distributions. In order to make these tails visible intensity is represented logarithmically here. In the microwave frequencies virtually all of the intensity is due to emittance. [Diagram modified from W. G. Rees, *Physical Principles of Remote Sensing* (Cambridge: Cambridge University Press, 1990), p. 39.]

Heat is a form of electromagnetic radiation. The basic properties of electromagnetic waves are their *wavelength*, *frequency*, and *intensity*. The wavelength is the distance between peaks in the wave, and the frequency is the number of vibrations or wave crests passing a point in one second. The shorter the wavelength the higher the frequency. For visible light the intensity is a measure of its *brightness*, but we use the latter term more generally to refer to the intensity of energy reflected or emitted from a planetary surface. The intensity or *power* of the wave is measured in *watts* or *joules per second*. *Emittence* is simply a measure of the intensity of electromagnetic radiation leaving a unit area of surface and is measured in *watts per square meter*. That intensity varies with the surface temperature and wavelength. Thus we tend to indicate emissivity as intensity at a given surface *brightness temperature* measured in degrees Kelvin (absolute temperature where 0° K = -273.15° C). At a given brightness temperature there are systematic relationships between wavelength and emittence intensity. For remote celestial bodies only some ranges of emittence feasibly can be measured. These are the visible, infrared, and microwave frequencies (40 nm to 1 m–or 10^{15}–10^{9} *Hertz* [Hz]). Emittence intensity is a function of the surface temperature of the body and wavelength. For a given planet the relative proportions of reflected and radiated energy vary with frequency. At microwave frequencies reflected solar radiation is scant, so the passive detection of microwave energy at the surface of a planet is a measure of its emissivity.

The measure of emittence at microwave frequencies involves a fair degree of modeling. We begin with a model of an idealized perfect *blackbody emitter.* Then we use the Stefan-Boltzman law which defines the emitted intensity in a wavelength range as a function of the wave frequencies, speed of light, and two constants (Planck’s and Boltzmann’s). This gives us a model of a *perfect emitter*. Next we develop an equation which relates the black-body radiation to the power received by an antenna of specified antenna temperature, aperture, and wavelength. Using several approximations including the Rayleigh-Jeans one, these two models are combined into a composite model in which the power at wavelength received at the antenna is a function of the planet’s brightness temperature. The brightness temperature thus can be derived from the power at wavelength received by the antenna. If the antenna has high-enough resolution





Passive radar emissivity measurements are made at a given wavelength. The power received at the antenna can be converted to an estimate of the surface or brightness temperature for a perfectly radiating *blackbody*. Of planetary surface materials only water approximates the emissivity behavior of a blackbody. When other surface materials are present, they deviate from the blackbody ideal. For most minerals the % deviation from perfect blackbody emissivity (=1) varies with wavelength. Thus different kinds of rocks have characteristic

[continued on next page]

emissivity patterns of deviation from the blackbody model. On the left the relative spectral shapes of a number of igneous and sedimentary rocks are shown. On the right, we see systematic relations between the emissivity profiles of igneous and metamorphic rocks as a function of falling silicone dioxide content. Through modeling these characteristic emissivity patterns can be used to estimate surface compositions of a planet's surface. [Diagrams from S. A. Drury, *Image Interpretation in Geology*, second Edition (London: Chapman and Hall, 1993), p. 173][£]

to have only portions of the target fill its aperture, brightness temperature measures can be made for different portions of the planetary surface.

However, such measures are at best an upper-bound on actual emissivity. For on planetary surfaces only water approximates perfect emittence (= 1). Rocks and other crustal features are much poorer emitters. How poor depends on their composition. Actual emissivity is measured as the proportion of actual radiance of a body at temperature to the blackbody values. Measurements thus are model-dependent: The measurements are obtained by comparing the actual radiated energy at wavelength with the value provided by the ideal black-body model. Emissivity values are reported as percentages of black-body emittance.

Emissivity values typically vary with frequency and different minerals have characteristic patterns of low and high emissivity wavelengths. If a planet were entirely covered by water, then the received power would provide a direct measure of surface brightness temperature at receiver wavelength. But Venus is a mysterious planet shrouded in dense clouds. Prior to penetrating her atmosphere with satellite probes one of the important unanswered scientific questions was whether her surface did contain oceans.

Since we cannot presume Venus is a perfect blackbody emitter, we resort to further modeling to convert the power at frequency to a measure of brightness temperature. Essentially we produce plausible

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[£] This is not an optimal diagram. If only covers the infrared portion of the spectrum. What is needed is an analogous set of profiles for the microwave portion where reflectivity does not affect the curves or compound interpretation.

models of the distribution of minerals on the planetary surface. Then using known wave-length emissivity dependencies for minerals, we can convert the blackbody upper-bound estimates into closer estimates. Typically we would produce *end-member models* that supposed, for example, there was no water and the surface was essentially basaltic, or essentially granitic. Another end-member model might be a planet that was completely water covered. If we gradually assemble measurements at different wavelengths, we will find that the patterns of variations in received power do not conform to the expectations of a particular model (say the granitic one) but that they conform well to that of the basaltic end-member model. Similarly, the presence of water can be estimated from detailed examination of the emittence spectrum.

Alternatively, we can produce a model of the distribution of surface temperatures over the planet which will yield blackbody predictions of antenna power returns at frequency. We then can use this as a baseline for noting disparities in actual received powers. If we do that over a range of frequencies, we now will get a wavelength intensity profile, which can then be compared with the profiles characteristic of various likely mineral types such as basalt or granite. We also can do a fair bit of bootstrapping–using initial upperbound estimates of brightness temperatures at wavelength to constrain plausible surface distribution models, which are used to obtain wavelength intensity profiles, which can then be used to improve the accuracy of brightness temperature estimates, and so on.

There are certain complications to emissivity detection. For example, the polarization of waves affects measurements and modeling. The surface emissivity itself is in heat transfer with the atmosphere, and such interactions may affect the intensity of detected emissivity. Finally at visual and near-visual wavelengths solar absorption and reflectivity will mix with emissivity, compounding determination of the emissivity component. (To correct for this we will obtain measures of surface *albedo* or ability of the surface to reflect radiation over the whole visible and near-visible range, and then use these and brightness temperature estimates to allocate detected power at wavelength.) But we will refrain from pursuing such complexities here.[1]

Early attempts to observe Venus using passive radar were not terribly impressive. In 1956 J. F. Kraus attempted to measure emissions from Venus at the quite long 11 meters wavelength. (Today radar astronomy uses 1 m to 1 mm wavelengths.) In three reports published in *Nature* he claimed to detect short burst-like emissions resembling thunderstorm atmospherics, lasting only fractions of a second, which he suggested were indicative of thunderstorms on Venus; a second type of signal resembling signals from an Earth radio station; and made a radio estimate of 22 hours, 17 minutes with an uncertainty of ±10 minutes for Venus's rotational period–which was off by over eight months. He further claimed there was a definite relationship between solar outbursts, the signals detected from Venus, and radar echoes from the moon. In every important respect his claims were incorrect and later examination disclosed serious misinterpretations in his work.[2]

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[1] For further discussion see the following works which were consulted in writing the above discussion of emissivity and its passive detection: F. T. Ulaby, R. K. Moore, and A. K. Fury, *Microwave Remote Sensing*, 3 vols. (Reading, MA: Addison-Wesley, 1981, 1982, 1986); R. N. Colwell (ed.), *Manual of Remote Sensing*, second edition (Falls Church, VA: American Society of Photogrammetry, 1983); W. G. Rees, *Physical Principles of Remote Sensing* (Cambridge: Cambridge University Press, 1990), chapters 2, 6; S. A. Drury, *A Guide to Remote Sensing: Interpreting Images of the Earth* (New York: Oxford, 1990), Section 2.2; S. A. Drury, *Image Interpretation in Geology* (London: Chapman and hall, 1993), Chapters 1, 6; A. P. Crackwell and L. W. B. Hayes, *Introduction to Remote Sensing* (London: Taylor and Francis, w991), Chapter 2; Allan Cox and Robert Brian Hart, *Plate Tectonics: How it Works* (Boston: Blackwell Scientific Publications, 1986), pp. 180-181; Bruce A. Bolt, *Inside the Earth: Evidence from Earthquakes* (San Francisco: W. H. Freeman, 1982), pp. 156-164; David Gubbins, *Seismology and Plate Tectonics* (Cambridge: Cambridge University Press, 1990), Sections 1.4, 1.5, 2.8, chapter 7; John Suppe, *Principles of Structural Geology* (Englewood Cliffs: Prentice-Hall, 1985), Chapter 1.

[2] J. D. Kraus, " " *Nature* 178(1956): 33, 106; " " *Nature* 178(1956): 159; " "*Nature* 178(1956): 687. An account is given in Hunt and Moore, *The Planet Venus*, *op. cit.*, pp. 80-81.

Fortunately passive radar observation got better. But doing so was hampered in two respects: First, the fact that available antenna apertures did not have sufficient angular resolution to measure the distribution of radar brightness over the surface. Second, we did not know whether the received signals were emitted from the surface of Venus. In 1956 signals were detected at the 3.2 cm wavelength–a wavelength capable of passing through most materials and thus the signal presumably originated from the surface. The intensity of signals suggested a brightness temperature of about 600° K at 3.2 cm. Others interpreted this finding differently, offering a "cool surface" hypothesis wherein the microwaves actually came from a Cytherean ionosphere far richer than the Earth's and that the true surface temperatures were closer to 348° K (76° C = 170° F).[3]

On August 27, 1962, the Mariner 2 spacecraft was launched on a fly-by mission to Venus, passing within about 35,000 km of Venus on December 14, 1962. It's navigational success was due in large part to the improved estimates of the AU and better ephemerides made via active radar determination. Indeed, it was a stunning confirmation of the accuracy of these determinations and became radar astronomy's first important achievement. Had earlier values for the AU been used, Mariner would have been to far off course to gather useful data.[4]

On board Mariner 2 were passive microwave and infrared detectors capable of making measurements directly to the Venusian surface and obliquely through her atmosphere. The "cool-surface" hypothesis implied that the oblique path would produce the bulk of the radiation detected. The opposite was the case. These findings refuted the cool Venus hypothesis. More importantly it established Venus

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[3] D. E. Jones, "The microwave temperature of Venus" *Planetary and Space Science* 5/2(1961): 166-167.

[4] Butrica, *To See the Unseen, op. cit.*, p 2-130.

had an insignificant ionosphere, and thus it's surface could be detected directly by microwaves without having to correct for Faraday rotation effects.[5]

In 1967 Mariner 5 and the Soviet Venera 4 gave further confirmation to a very hot surface temperature on Venus. Eventually it would be determined that Venus is uniformly hot over its surface, varying by only about 25°C between the nightside and the dayside. By comparison, Mercury, which is closer to the Sun, ranges from a low of -100° K (-173° C) to a high of about 700° K (427° C)–slightly lower than Venus's 725-747° K (452-474° C) average. The difference is that Mercury has insignificant atmosphere and Venus has one 90 times more dense that the Earth's. The Cytherian atmosphere holds in Venus's internal heat–the prototype greenhouse effect.

By late 1965, the brightness temperature of Venus had been well established on the basis of many measurements at a variety of wavelengths between 0.4-10 cm. The results tended to be in good agreement and showed brightness temperature emissions of around 600° K in the 3-10 cm range and 350°-400° K in the 0.4-0.8 cm range. One needs the distribution of temperature over the planetary surface to estimate actual surface temperatures from these radar brightness measures. Lacking data, distribution models were developed instead. Models employed typically led to an estimate of 630° K for the center of the disk, 690° K for the equatorial region, and 440° K for the polar regions. (Later we will learn there is no such large variation between equatorial and polar regions.) Another concern was attempting to detect the presence of water on the surface by detailed analysis of the spectrum.[6]

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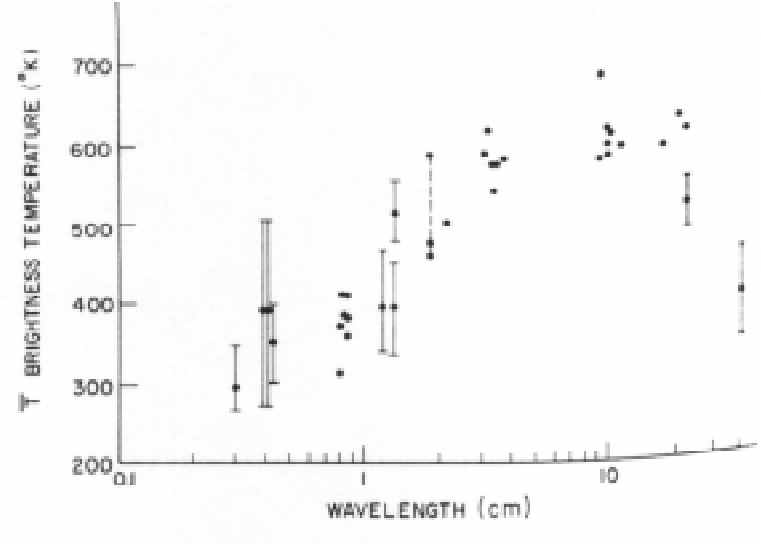
[5] F. T. Barath, A. H. Barrett, J. Copeland, D. E. Jones, and A. E. Lilley "Mariner 2 microwave radiometer experiment and results" *Astronomical Journal* 69/1(1964): 49-58.

[6] A review of passive radar observations of Venus before 1964 is given by A. H. Barrett and D. H. Staelin, "Radio Observations of Venus and the Interpretations" *Space Science Reviews* 3/1(1964): 109-135. Much of the above discussion is based on Alan H. Barrett, "Passive Observations of Mercury, Venus, Mars Saturn, and Uranus" *Journal of Research National Bureau of Standards, Section D, Radio Science* 69D/12(December, 1965): 1565-1573, and other papers in the same Session III



A summary of passive radar detections through 1964 of brightness temperature on the surface of Venus at different wavelengths. Mariner 2 had established that such measurements were from the surface of Venus rather than postulated ionospheric effects. (Mariner 2 also established the lack of a significant ionosphere.) From these brightness measurements further modeling enabled estimates of surface temperatures. These were estimated to range from an equatorial high of 690° K to a polar low of 440° K. Later determinations would show the entire surface is remarkably uniform, ranging from 725-747° K (452-474° C). Active radar detection would prove far more important in the investigation of Venus than passive detection. [Figure from p. 1568 of Alan H. Barrett, "Passive Observations of Mercury, Venus, Mars Saturn, and Uranus" *Journal of Research National Bureau of Standards, Section D,* Radio Science 69D/12(December, 1965): 1565-1573.]

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on passive radio observations of planets. See also discussion by G. H. Pettengill on pp. 294-295 of his "Radar Studies of the Planets", Ch 6 in Hagfors and Evans (eds.), *Radar Astronomy, op. cit.*

Because Venus lacks a significant ionosphere, radar had little potential for investigating the Venusian atmosphere. To do that probes would be sent by the Soviets and the U.S. These probes also would give improved (albeit sometimes controversial) data about surface temperature conditions. Eventually landers would be sent that would give more definitive results. But for the present, radar remained the primary instrument for investigating surface conditions. However passive radar lacked the resolution needed, and so active radar investigations would dominate. Nevertheless, Magellan would have the capability to detect emissivity and would produce a fairly fine-grained determination of emittance variations over the surface. For now we will concentrate on active radar investigations of Venus.

Once radar signals had been bounced off Venus and unambiguously detected, radar astronomers proceeded to determine the radar cross-section at various wavelengths. Daily variations in value suggested significant variations in the type of surface at the sub-radar point. Average values for the Venusian radar cross section of 15–16% were obtained at wavelengths above 20 cm–which is far higher than values obtained for the moon, Mercury, or Mars. By 1968 it has been postulated that the cross section values correspond to the reflection coefficients for solid rocks, and thus that Venus seems to have quite limited erosion or decomposition on its surface. A variety of scenarios are compatible with the cross section measurements and their variations over time–including variations in altitude of the planetary surface, water vapor, and meteorological changes in the atmosphere. Each of these scenarios is model based, and at least five different models had been produced which were consistent with the cross-section data at various wavelengths.[7]

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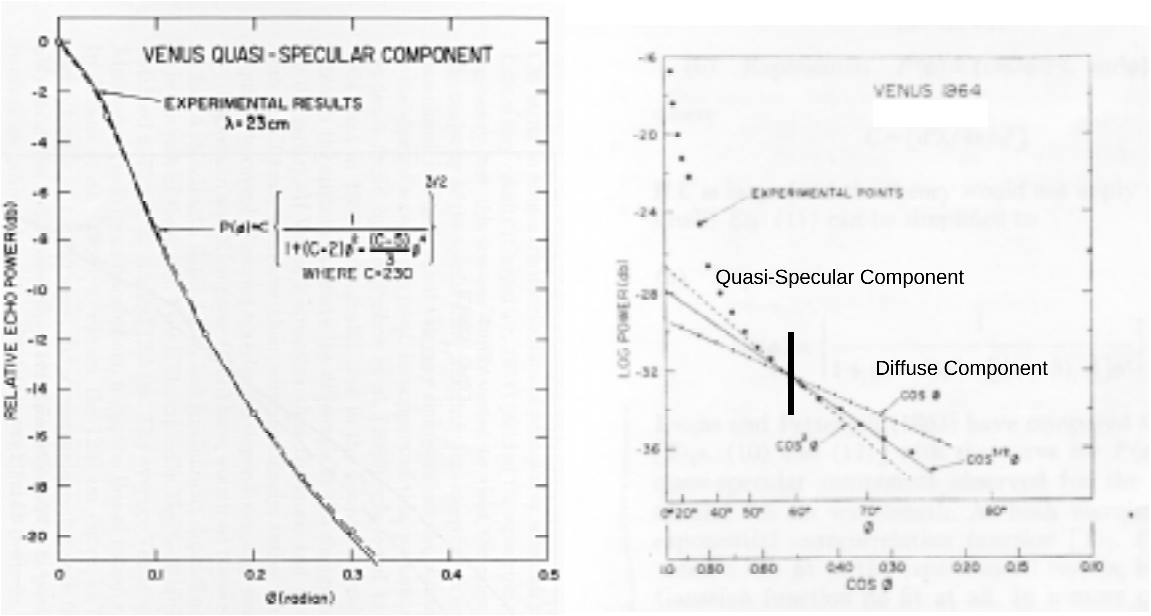
[7] Pettengill, *ibid.*, Section 6.3, 6.4A.



Quasi-specular and Diffuse components of the echo power distribution for Venus at 23 cm. The break between the two components comes at $\phi = 60°$ whereas it is at $\phi = 45°$ on the moon. The quasi-specular component obeys an exponential law and the diffuse component a $\cos^{3/2}\phi$ law. [Left diagram from p. 306 of Pettengill, "Radar Studies of the Planets", chapter 6 in Hagfors and Evans *Radar Astronomy, op. cit.*; the right diagram is modified from p. 497 of J. V. Evans, R. A. Brockman, J. C. Henry, G. M. Hyde, L. G. Kraft, W. A. Reid, and W. W. Smith, "Radio Echo Observations of Venus and Mercury at 23 cm Wavelength" *Astronomical Journal* 70/7 (Sept. 1965): 486-501.]

Echo power distributions were measured at various wavelengths and compared to lunar ones. Scattering laws were fit to the data, though not as precisely as for the moon because echo power could not be determined past 30 milliseconds out to the limbs. At 23 cm the break between the quasi-specular and diffuse components is at $\phi = 60°$, not the lunar 45°. As with the moon, the quasi-specular component is best fit by an exponential distribution. However, in the Venusian case power drops off more rapidly than the moon, thus indicating there is less surface roughness as one moves away from the sub-radar point. Again, this is evidence that Venus is smoother than the moon. The diffuse component best fits a $\cos^{3/2}\phi$ law.

Probability distributions for slopes were calculated, and from this average surface angle measurements were made. As noted last chapter, there was great variability in these but Venusian measurements consistently were lower than lunar ones made in the same manner. Thus radar provided fairly compelling evidence that Venus was smoother than the moon.

Where radar really proved its superiority was determining the rotational period of Venus–a problem that had proved intractable since the 17th C. (Recall the Table from Chapter 2 summarizing these attempts.) However, some early radar attempts were noteworthy failures. Using their erroneous 1959 data (which had claimed to confirm the Millstone 1958 radar detection of Venus), Evans and Taylor at Jodrell Bank published an estimate of 20 days rotation. Then using 1964 Jodrell data John Thompson calculated both a forward and a retrograde period of about 225 days, but dismissed retrograde motion as extremely unlikely. In 1961 a Soviet team working in the Crimea got an estimate of 11 days, perhaps 9-10 days, and missed the retrograde motion. Their estimates were based on the same data that produced an estimate of the AU that was at odds with other 1961 radar determinations. (Later, reevaluation of the same data in light of new 1962 observations would lead them to produce a revised estimate of 200-300 days retrograde.).[8] [§]

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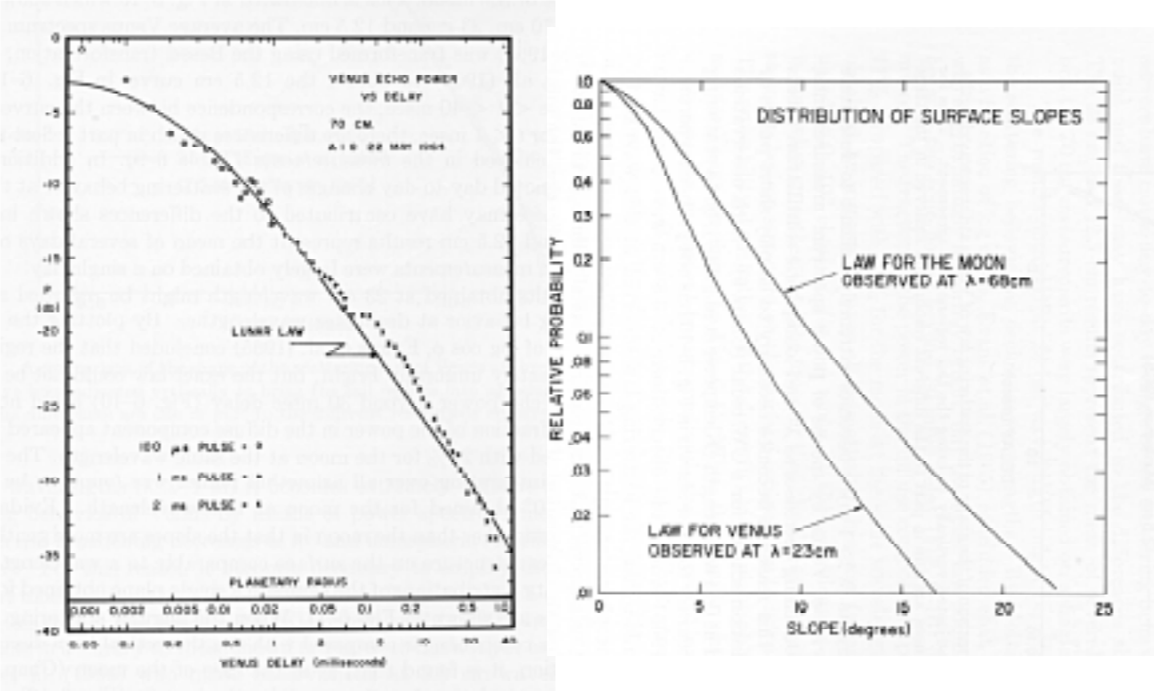
[8] Evans and G. N. Taylor, "Radio Echo Observations of Venus" *Nature* 184(1959): 1358-1359.p. 1359. Ponsonby,, J. E. B., J. H. Thomson, and K. S. Imre, "Rotation Rate of Venus Measured by Radar Observations" *Nature* 204(1964): 63-64; V. A. Kotelnikov et al, "Radio Contact with Venus" *Journal of the British Institution of Radio Engineers* 22 (1961): 295.

[§] These observations need to be added to the table in Chapter 2.



On the left a typical mid-1960s echo power distribution for Venus at 70 cm wavelength. It conforms to the same general pattern as the moon. The right graph displays the distribution of surface slopes compared to lunar slopes. It is clear that Venus on average has lower slopes, hence is smoother. Although there is great variation between slope estimates, the pattern of Venus having a lower average slope than the moon is a robust effect. [From pp. 303, 306 of Pettengill “Radar Studies of the Planets” in Hagfors and Evans (eds.), *Radar Astronomy, op. cit.*]

Between April 2 and June 8, 1961 William B. Smith observed Venus using the Millstone antenna, then subjected the observations to sophisticated computer analyses of signal spectra. He concluded the signal bandwidth change over time could only be explained by retrograde motion and wrote up his results for publication. His supervisor, Paul Green, prevented him from publishing the retrograde result, though the remainder of his findings eventually were published. The only mention of retrograde motion was a statement in the abstract, corresponding to nothing in the text, that the spectral analysis "implies a very slow or possibly retrograde motion of the planet".[9] Green's caution was rooted in the relatively low power and sensitivity of Millstone and concern not to repeat the embarrassment of 1958 when Millstone announced radar detection of Venus which it failed to confirm the following year. Also, the result was quite amazing and without adequate explanation. Virtually every other planet and planetoid in our solar system has a forward motion (Uranus and Titan being two notable exceptions), and typical axial rotation periods range from a day to a couple dozen days. No other body has a rotational period slower than its synodic period. If the results were correct, Venus was a very strange planet indeed. One wanted to be very sure if one was going to publish that anomalous a result.

In July 1961, based on 1961 Goldstone observations Pettengill and others at JPL announced a 225 (+275,-110) day rotational period but failed to note Venus's retrograde motion.[10] A period of 225 days is a rotation in synchrony with the Venusian year or synodic period. Then, later, based on further analysis of the same 1961 data, Roland L. Carpenter announced discovery of the retrograde motion in a May 1, 1962, JPL internal memo. He improved his determination during the October 1-17, 1962 observations. The Goldstone antenna was far more sensitive than Millstone and he found a persistent irregularity slowly changing position day by day. He took it to be a surface feature that was a source of particularly strong echoes. From the movement of this irregularity, Carpenter calculated it could be due to

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[9] W. B. Smith, "Radar Observations of Venus, 1961, and 1959." *Astronomical Journal* 68(1963): 15-21

[10] G. Pettengill, et. al. "A Radar Investigation of Venus" *Astronomical Journal* 67(1962): 181-190. The first announcement was in a paper read by Solomon Golomb and Leonard R. Malling at a convention on radio techniques held at Oxford in July 1961.

either a forward rotation of 1200 days or a retrograde motion of 230 days. However, spectral bandwidths were incompatible with the 1200 day forward rotation. He refined the estimate to 250 ± 40 days retrograde. With Richard Goldstein, Carpenter published his convincing results in the March 8, 1963 issue of *Science*. Later determinations using various radar facilities and data analysis techniques would further refine the rate down to 243 days.[11]

Venus has a 243 day retrograde rotational period, longer than its 225 day synodic period (orbital year). Indeed, its rotation and orbit are in such close synchrony with the Earth's orbit that Venus presents nearly the same face to Earth observation each inferior conjunction. Just how did radar enable determination of these facts?

One constraint was that radar antennas of the early 1960s could only detect Venus at times of inferior conjunction where Venus comes closer to the Earth than any other planet–to within about 40 million miles. Observations tended to be restricted to a brief period surrounding the time of closest approach. This fact would prove important in determining rotation was retrograde. It also meant all of the radar telescopes observed Venus during roughly the same periods. Thus it was possible to compare data gathered simultaneously at different frequencies using pulse and CW systems and processed using different procedures. Robustness of detected effects could be evaluated.

Basic Newtonian and General Relativity theory also played an important role. From the perspective of the radar antenna, the detected angular velocity of Venus decomposes into two components: First, there is the intrinsic or internal rotation ω_s of Venus herself. Second, there is the relative motion ω_o of the earth-

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[11] Carpenter, "An Analysis of the Narrow-Band Spectra of Venus," in *JPL Research Summary No. 36-14 for the Period February 1, 1962 to April 1, 1962* (Pasadena: JPL, 1 May 1962), pp. 56-59; R. Goldstein and R. Carpenter, "Rotation of Venus: Period Estimated From Radar Measurements" *Science* 139(1963): 910. The account in these last three paragraphs is based in large part on Butrica, *To See the Unseen*, op cit., pp. 2-130 to 2-138.

based radar site and the center of Venus. The composite $\omega_s + \omega_o$ of these two motions relative to the Earth and Venus determines the *angular velocity* ω *of Venus relative to the radar site.* When we send a CW signal to Venus, the return echoes will be Doppler-shifted with characteristic bandwidth B. That Doppler-shift bandwidth is a function of the relative angular velocity ω, an angle formed by the target's angular velocity vector relative to the planet-antenna line, the delay relative to the sub-radar point, and the antenna transmitter's frequency.

Doppler detection enables us to determine the bandwidths *B*: we simply measure the distance between the peaks at the limbs of the Doppler-broadened spectrum. Because the relative angular velocity ω changes over time, so too will the bandwidths B change. By making multiple observations of *B* in sufficient quantity over an adequate period and plugging in other known or estimated values, we can mathematically produce unambiguous determinations for every variable involved in determining ω and ω_o except for ω_s. Thus we can calculate the actual angular velocity ω_s of Venus since $\omega = \omega_s + \omega_o$. Results typically were calculated once using Newtonian theory and again using General Relativity theory. Discrepancies for Venus proved to be quite small (divergences occurring only in the fifth to seventh decimal place).

If one has sufficient power and resolution to detect a recurring and recognizable surface feature, then one can trace the associated anomaly in the Doppler returns and estimate the angular velocity. This simpler method is essentially what Carpenter did. The method was briefly described last chapter. It utilizes many of the same theoretical relations as were just sketched.

After Carpenter made his 1961-1962 determination of a 250 ± 40 days rotation period, his determinations were replicated many times at later inferior conjunctions, resulting in an eventual refinement of the estimate to 243.1 days. It is instructive to look at these subsequent determinations of Venus's rotation rate from the perspective of hypothesis testing. Irving Shapiro describes how hypothesis testing is done in radar astronomy:

> If we adjust the parameters and initial conditions of the theory so that the observations are best represented (in a weighted-least-squares sense), then we find that the a posteriori residuals (observed minus computed values) are less than, or at least not significantly greater than, the estimated measurement errors. Since all physical theories involve unspecified parameters, the comparison with observations consists essentially of two steps: (1) determining the most likely values of the unspecified parameters and initial conditions, and (2) determining how well the resultant theory agrees with observations. For such a comparison to be meaningful, redundant data are almost always required (i.e., the measurements must be of more than sufficient number and variety to allow the space of adjustable parameters and initial conditions to be spanned.)[12]

Compare this to standard philosophy of science text-book accounts of hypothesis testing. The most common versions go like this: One makes a prediction, tests it against observations obtained independently of the prediction, compares prediction and observation, and counts it as a confirming instance if there is agreement and a disconfirmation or falsification otherwise. Confirmation of the hypothesis results from successful replication of the test using a variety of separate observations.

Shapiro's account conflicts on every point: First, prediction independent of observational data is not involved; theoretical determinations typically are not made prior to observations. Second, the data used to determine most likely values of unspecified parameters and initial conditions typically include the

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[12] Shapiro, “”Spin and Orbital Motions of the Planets” *op. cit., p. 146.*