A Penetrating

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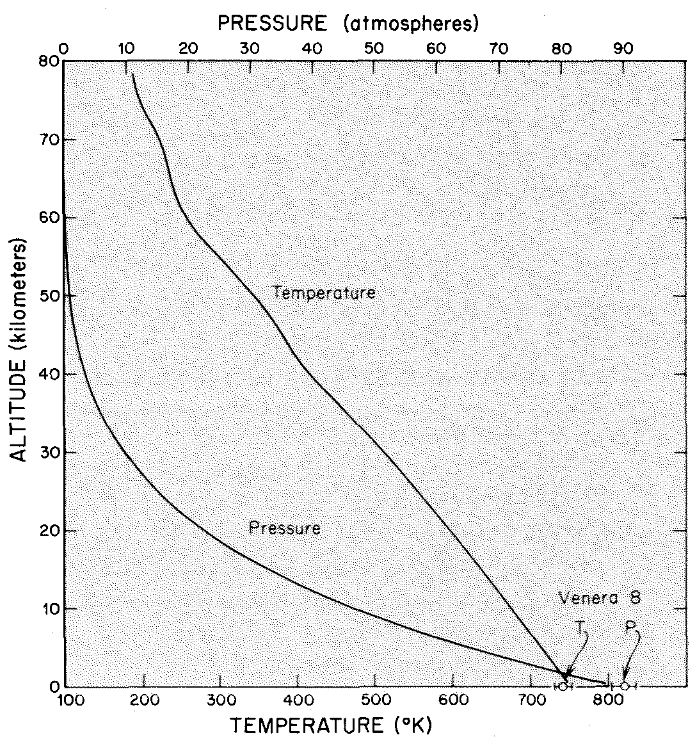
Earth-based radio observations are a powerful tool in our investigation of the solar system. Here's what a radio astronomer "sees" when he looks at Venus



These curves show the temperature and pressure profiles of the Venus model atmosphere. The earth's atmosphere is very crudely similar to Venus's at about the 50-km level. The Russian (Venera 8) surface measurements are indicated by the circles.

All objects in the solar system emit radio noise. The primary mechanism is simply blackbody radiation that depends on the absolute temperature of the object, although other emission mechanisms have been discovered, particularly for Jupiter. Since the temperatures of solar system bodies range from about 50 to 800 degrees Kelvin, most of the blackbody radiation is in infrared, rather than radio emissions. Thus, radio astronomers must be contented to work with much weaker radiation fields.

The primary advantage in studying the radio emission of objects is that long-wavelength radiation has great penetrating power, which is well demonstrated by the fact that your pocket radio works rather well in the sub-basement of a concrete Caltech building. For example, when we detect the radio emission from the moon at a wavelength of 50 centimeters, the effective emitting layer in the moon's soil is about 7 meters beneath the surface.

The importance of this phenomenon is more dramatically illustrated when we consider a planet such as Venus, which has a thick atmosphere. At a wavelength of 50 cm, nearly all of the emission from Venus arises in the first few meters of the planet's surface; but at much shorter wavelengths—say in the infrared—all of the emission arises from altitude levels greater than 50 kilometers. Thus, for Venus we can select a particular atmospheric layer for study by choosing a particular radio wavelength of observation.

Radio emission from all of the planets (except Pluto), the moon, the sun, and one of the major satellites of Jupiter has been studied at Caltech's Owens Valley Radio Observatory since the founding of the Observatory in 1959. In the last 10 years most of the investigations of the solar system objects have been carried out by Glenn Berge,

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senior research fellow in planetary science and radio astronomy, and myself, with the aid of numerous graduate students. The facilities of the Owens Valley Radio Observatory have been of major importance because of the interferometer, consisting of the 130-foot antenna and two 90-foot antennas that can be moved on tracks. We achieve east/west spacings of over 1 kilometer and north/south spacings up to half a kilometer.

One of the obvious disadvantages in working in the radio spectrum is that the beam widths of antennas become very large at relatively long wavelengths. No single antenna in existence has a beam size smaller than Venus—the largest planet in the sky. Therefore, spatial resolution must be achieved by some trick such as interferometry. Stated crudely, an interferometer operates as though it consists of two (or more) pieces of a giant antenna whose diameter would equal the antenna spacing. It isn't sufficient to just have two spaced antennas; they must be wired together so that they operate coherently. In this case the analogy to a giant antenna is complete.

Rather than listing Caltech's contributions to our knowledge of each solar system body, I will restrict my remarks to Venus—the radio astronomer's ideal target. Venus, of course, has received major attention in the space program during the last decade as well as from earth-based observers. I will not attempt to review all of this history, but will concentrate on the intimate relationship between all of these efforts and the contributions from radio science.

Modern investigations of Venus began with the measurement of radio flux from Venus at 3 cm by workers at the Naval Research Laboratory in the middle 1950's. They reported that if the emission was blackbody radiation then the temperature of Venus must be about 600°K! This result was very hard to understand, taking into consideration the similarities beween the earth and Venus and the fact that Venus is really not much closer to the sun than the earth is.

Since a measurement at a single wavelength cannot tell you the physical mechanism behind the radiation (it could have been lightning discharges, a hot ionosphere, or many other things), a second measurement at a longer wavelength was quickly made. The result was the same, about 600°K, which strongly supported the blackbody hypothesis. By 1960 enough of the Venus spectrum had been measured to convince most radio astronomers that Venus was indeed that hot. However, many people remained skeptical until the Russians actually flew a thermometer to the surface of Venus.

In 1960 Alan Barrett of MIT studied several widely different models of Venus and its atmosphere—one of which we now know is essentially correct. The model assumed that Venus had a pure CO_2 atmosphere and, in order for the numbers to agree with the measurements, the surface pressure must be about 100 atmospheres. Unfortunately, no one knew which of Professor Barrett's models was correct at that time.

Great strides at settling the issue were made in 1962 at Owens Valley by Barry Clark, then a Caltech graduate student and now at the National Radio Astronomy Observatory. The difficulty was in being sure that the equivalent blackbody temperature of the radiation corresponded to the true temperature of the atmosphere and surface. Radiation flowing through a surface interface has its polarization altered. In particular, for emission at the Brewster angle (about 50 degrees from vertical for Venus), the emerging radiation is nearly plane polarized even though the blackbody emission under the surface has random polarization. Furthermore, emission from the gases in the atmosphere is completely unpolarized. Barry Clark's measurements with the interferometer showed that the 10-cm radiation was polarized in this manner, proving that this radiation was coming from the subsurface of Venus and that Venus was indeed hot—about 700°K after correcting for the surface emissivity.

I should point out that before radar echoes were obtained from Venus by a group at JPL (including myself) it was not certain that Venus even had a solid surface. The radar measurements showed that the atmosphere, while thick, was still partially transparent at a 12.5-cm wavelength and that the surface material was probably ordinary rocks and soils (as opposed to a universal sea of oil or whatever). To this day I don't understand why so many people had to wait for a spacecraft landing on the surface before becoming convinced about the unusual properties of Venus.

During the last seven or eight years Glenn Berge and I, joined more recently by a graduate student in planetary science, Glenn Orton, have made high-resolution observations of Venus at many wavelengths. Our goal is to develop a model of the atmosphere and surface that is consistent with all available observations of Venus. Our measurements are primarily determinations of the radii of the effective emitting layers in the atmosphere, as well as the brightness temperatures both as a function of wavelength and the surface polarization.

We have combined our observations with radar measurements of the reflecting power of Venus, which is also a function of wavelength due to the varying atmospheric absorption. We have also used measurements of the refractive index of the atmosphere as a function of altitude made during the passage of Mariner 5 behind the Venus atmosphere.

In this experiment, investigators at JPL measured the alteration of the Doppler shift of the Mariner communications signal as the ray path moved deeper into the Venus atmosphere. These measurements reached down to an altitude of 35 km, at which point the signal was cut off by critical refraction; i.e., the density gradient is so great in the Venus atmosphere that the curvature of the ray approaches the radius of Venus, and no signal can pass through the atmosphere from the spacecraft to the earth. These measurements are sensitive measures of the atmospheric density (if the chemical composition is known).

We know very little about the composition other than that more than 90 percent of the atmospheric gas is CO_2 and that there are *traces* of water vapor, HF, and HCL. In our model calculations we assumed that the main thermodynamic structure of the atmosphere is controlled by the CO_2 and the nitrogen that surely must be present.

In order that our model fit all of the diverse observations, we find that the atmosphere must consist of 96 ± 3 percent CO_2 with the remainder essentially all nitrogen. Perhaps more importantly, we find that, without the trace gases present, this atmosphere would be deficient by almost a factor of two (1.95) in its ability to absorb radio waves. Thus, the trace gases may not be very important in determining the physical structure of the atmosphere, but their presence is very important in controlling the planet's emissions. Undoubtedly, the complete list of trace gaseous compounds is much larger than that given above; e.g., there is rather strong evidence that the clouds of Venus contain considerable quantities of sulfuric acid. The immediate goals of new research on Venus are centered on the detection of the remaining chemical constituents of the atmosphere and surface.

How does our latest model compare to "ground truth"? The Russian Venera 8 measured the temperature and pressure for a few minutes while it sat on the Venus surface. These values are shown in the drawing on page 38, along with our temperature and pressure profiles. Since no one knows whether the Venera 8 was parked on a mountain or in a deep valley, we had to assume that the measurements were made at the mean surface of Venus. (We have determined this surface to have a radius of 6051.2 ± 1.0 km.) The agreement with the model is very good.

We have learned a great deal about Venus. We understand the gross structure of the atmosphere and surface. Recent measurements of the radio occultation by Venus of Mariner 10 have found several cloud layers formed by unknown substances high in the atmosphere. It is the investigation of the chemistry and thermodynamics of these structures that lies ahead. Perhaps when this step has been accomplished we will be able to understand why Venus is so hot and why enormous quantities of CO_2 are in the atmosphere instead of being tied up in the surface materials as on the earth. And finally, perhaps we can solve the biggest puzzle of all—why Venus is so deficient of water in comparison to the earth.

I have told the story of Venus from the standpoint of a radio astronomer. Many equally interesting and complex objects exist in the solar system for us to study. We must improve our equipment and build new systems that can investigate the millimeter spectrum where the emission is stronger and many atmospheric gases have a rich microwave spectrum. Earth-based radio observations will remain a powerful tool in the investigation of the solar system. □