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VLA Observations of Venus at 1.4 GHz

Abstract

We present observation of Venus made with the Very Large Array (VLA) interferometer in the L band (1.4 GHz). We find a diameter of 11879 ± 190 km, which is about 1.9% smaller than the known diameter. The measured total flux density was 1.122 ± 0.022 Jy using the IMEAN routine. We calculate a brightness temperature of 607 ±12.75 K from our measured flux density, which is in good agreement with previous studies.

Introduction

Venus is one of the most well-studied objects in our solar system. It is the third brightest object in the sky, behind the Sun and the Moon. Ancient astronomers from nearly every culture around the world documented its movements relative to the stars. Modern astronomers still look to Venus, using both home-made telescopes and million-dollar instruments, like the Hubble Space Telescope. Radio astronomers are also interested in Venus. It was one of the first targets of the VLA, before it was officially operational (Muhleman, 1980).

This paper presents modern observations of Venus using the VLA at 1.4 GHz. The presentation is broken into several parts. First, we discuss the historical and modern observations of Venus and their impact on society and scientific knowledge. Second, we discuss our observations and the difficulties we encountered. Third, we present the results of our measurements and calculations and discuss their implications. Finally, we summarize our results and propose future observations.

Historical and Modern Observations of Venus

Nearly every ancient civilization recorded observations of Venus. It is easy to understand why. Venus is the brightest point-like object in the night sky and it moves relative to the background stars. Early cultures watched Venus and the other planets and used them in their myths and religions. Obviously, the name Venus is taken from the Roman goddess of beauty. The Chinese called it “Tai-pe,” which means “Beautiful White One.” To the Egyptians, it was known as “Bonou,” or “The Bird.” The Phoeniceans named it “Astarte” (Moore, p.28). There is also evidence that the Aztecs, Mayans, Inca, and many other indigenous North American cultures kept a close eye on Venus.

The first recorded observations of Venus are on the "Venus Tablet" discovered by Sir Henry Layard at Konyunjik archeological site near Mosul, Iraq. The tablet contains details of weather events, which are chronologically tied to observations of Venus. We know it was written between 1646 and 1626 BCE because it makes references to King Amisaduqa, whose reign was well-documented (Moore, p.28).

Venus was one of the first astronomical objects ever seen through a telescope. In 1609, barely one year after the invention of the telescope, Galileo Galilei pointed his at Venus. What he saw would change the world forever. To his surprise, Venus was not just another little dot in his view. Instead, it was a crescent shape. Even more surprising was the fact that the shape changed over time, much like the moon. The only logical explanation for this was that the Earth and Venus were both orbiting the Sun, but Venus was closer to the Sun. In other words, Copernicus was right! The Earth was not at the center of the universe. In fact, it was not even at the center of the solar system.

Since Galileo's first observations of Venus, nearly every astronomer in the world has looked through a telescope at Venus. The planet has been photographed more times than Paris Hilton (well, maybe not quite as many, but it's probably pretty close).

Venus has also been studied with several radio telescopes from Earth. Radio observations can give us more information about the planet than optical because optical observations only see the planet's thick atmosphere. Some radio wavelengths are able to penetrate this soupy mixture of carbon dioxide and sulfuric acid. According to optical observations, the temperature at the top of Venus' atmosphere is about 230 K (Morrison & Owen, p.232). Astronomers expected that the surface temperature of Venus would be warmer than Earths because the planet was nearer to the Sun. Initial estimates were around 280 K, about 15 K warmer than Earth. However, when radio astronomers looked at Venus in 1958, they calculated a surface temperature of more than 600 K (Morrison & Owen, p.233).

Observations of Venus are not limited to ground-based or even orbital-based instruments. Many of our unmanned spacecraft have paid a visit to Venus. Some were sent there specifically, and others were just passing by on their way to other planets. The Venera, Pioneer, Magellan, missions were all dedicated to observing Venus. The Voyager, Galileo, and Cassini missions tested some instruments on Venus before heading to the outer planets.

One interesting phenomenon to look for on Venus is lightning. Despite some evidence, the existence of lightning on Venus is still somewhat controversial (Russell, 2007). Unfortunately for us, the only evidence for lightning events on Venus comes from visiting spacecraft and in much lower frequencies than we were using. It is also unfortunate that most of these probes found their evidence in the VLF band (around 100 Hz). The most compelling evidence in the radio band came from the Galileo probe during its flyby of Venus in 1990. During this brief observation, the spacecraft recorded nine events in the radio band from 100 kHz to 5.6 MHz (Russell, 1993). The Cassini probe also looked for lightning on Venus during its two flybys in 1998 and 1999. The probe looked for events in the 0.125 to 16 MHz range, but did not see any (Gurnett *et al*, 2001). The only instrument with sensitivity in the same basic range as our observations was the Magellan radiometer at 2.65 GHz. The device did not record any lightning events during its lifetime, although this frequency is significantly higher than would be useful for lightning detection (Russell, 1993). Therefore, we would not expect to see any lightning events in our data. One of the stated science goals for the Low Frequency Array (LOFAR) is to look for lightning events from Venus and other planets (Zarka *et al*, 2004). The Long Wavelength Array (LWA) may also see extraterrestrial lightning events.

Observations

Our observations of Venus were scheduled for February 21, 2009 by Laura Zschaechner and Justin Linford (with help from Greg Taylor and Bryan Butler) using the VLA's JObserve program. The times are summarized in Table I below. There are some difficulties in observing Venus with the VLA. One must take into consideration the orbital motion of the planet as well as the rotational motion of the Earth. Also, Venus tends to be very close to the Sun, getting only about 48 degrees away at maximum elongation. During our observations, Venus was approximately 39.3 degrees from the Sun, according to the HORIZONS program from the Jet Propulsion Laboratory (http://ssd.jpl.nasa.gov/horizons.html). We believe this was far enough away to avoid any major interference, but still close enough to contribute to background noise.

For our absolute flux calibrator, we used 3C48 (0137+331). For our phase calibrator, we chose 0022+002.

TABLE 1

All observations on February 21, 2009 at the VLA in Configuration B in L Band (1.4 GHz)			
Target	Start Time (UT)	End Time (UT)	Notes
0137+331	21:19:45	21:21:45	Absolute Flux Calibrator (3C48)
0022+002	21:24:05	21:25:15	Nearby Phase Calibrator
VENUS	21:25:55	21:51:05	
0022+002	21:51:45	21:52:45	
0022+002	22:10:05	22:12:25	
VENUS	22:13:05	22:33:15	
0022+002	22:33:55	22:35:05	
0022+002	22:50:35	22:51:45	
VENUS	22:52:25	23:12:25	
0022+002	23:12:45	23:14:15	

Results and Discussion

All of our data was calibrated with the AIPS software package (http://www.cv.nrao.edu/aips/). The figures were created using Matlab® (R2006b, The Mathworks, Natick, Massachusetts).

Calibration and Imaging

We experienced some problems with several antennas during our observation of 3C48. This is very unfortunate as any error in flux calibration leads to errors in brightness temperature calculations. We used the TVFLG routine to remove as much bad data as we could. The results are that only 19 of the 27 antennas were used in the absolute flux calibration. The task SETJY set the flux densities for 3C48 (16.384 in IF 1, 15.748 in IF 2). The current best estimates of uncertainties in flux density calibration at the VLA for 1.4 GHZ is about 2% (Butler, 2001).

Because 3C48 is not completely point-like in B configuration, we applied a band-appropriate model using CALRD. We used the CALIB routine on the flux calibrator and our gain calibrator. Using GETJY, we derived the fluxes for the gain calibrator. The results were promising, with an average gain of 3.22 with a range of 2.12 to 4.99 and a standard deviation of 0.589. Only one antenna was down for all observations, but a second antenna did not come online until after half-way through the observing run. See Figure 1 for UV coverage and calibrated visibilities for venus and Figure 2 for visibilities of 3C48 and 0022+002.

After the gains were calibrated, we applied the calibration to Venus using CLCAL. We ran IMAGR to clean the image and found that our noise (off source) was higher than we had hoped. We decided to try self-calibration. After one run of phase self-calibration, our noise (off-source) decreased by a factor of ~2, from 835 μJy/beam to 470 μJy/beam. The second iteration of phase self-calibration led to a further reduction in noise, but only by a factor of 1.18, going from 470 μJy/beam to 398 μJy/beam. Further iterations of self-calibration, including both amplitude and phase, did not lead to any decrease in noise, but they did result in increased flux on the source. Figure 3 shows a contour map of our Venus data. Figure 4 shows our final image. Figure 5 shows a 3D surface map of the disk region.

The final total flux density was 1.122 Jy, using the IMEAN routine to find the total flux in a box drawn around Venus using TVWIN. The final off-source noise was 418 μJy/beam, again using TVWIN and IMEAN. The peak flux was 31.054 mJy/beam. This gives us a dynamic range of only 74.29. Using the 2% uncertainty for absolute flux calibration gives us an error of ± 0.022 Jy.

We used the VLA sensitivity calculator (http://www.vla.nrao.edu/astro/exposure/calc.html) to find our expected thermal noise for our observations. Our inputs for the calculation were: 26 antennas, total bandwidth = 172 MHz, observing frequency = 1.5 GHz, and configuration B. Recall that antenna 8 was not usable for our any of our observations, thus leading to 26 antennas instead of the maximum 27. The bandwidth stated in the observing logs was 50 MHz per IF per polarization. This should lead to a total bandwidth of 200 MHz. However, the sensitivity calculator stated that the true bandwidth for the VLA at 1.5 GHZ was 43 MHz. Therefore, the total bandwidth was really 4x43MHz = 172 MHz. Using these inputs, the calculator estimated a thermal noise of about 23 μJy/beam.

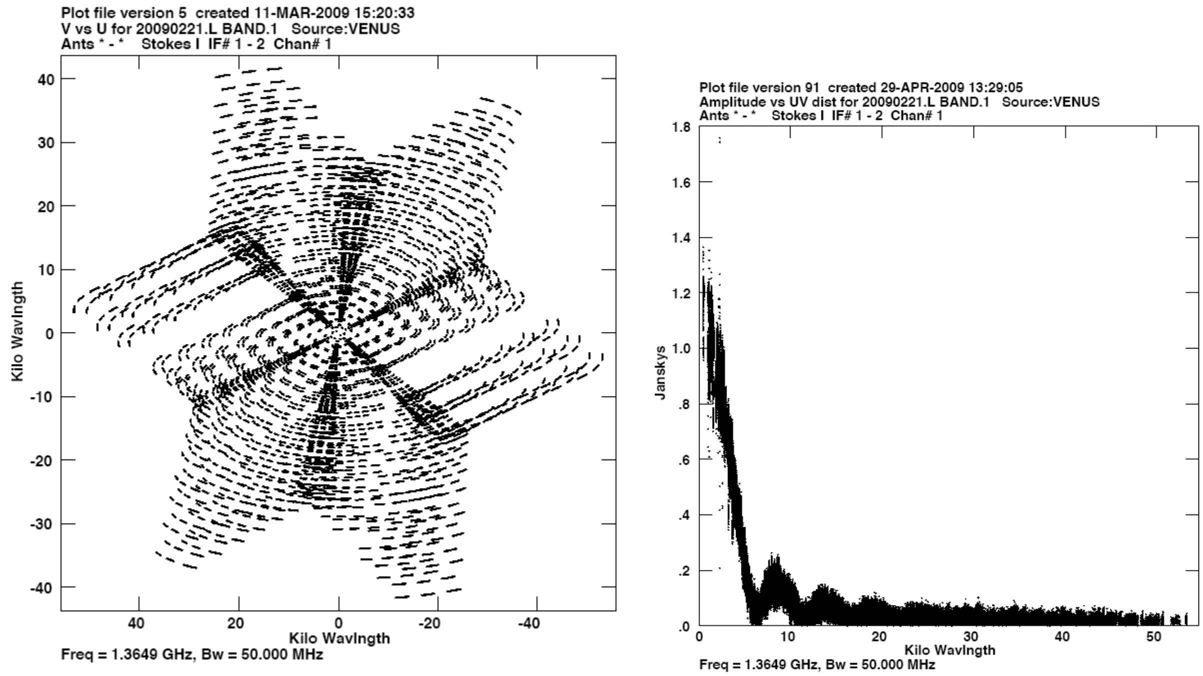

Figure 1: UV coverage and calibrated visibilities for Venus

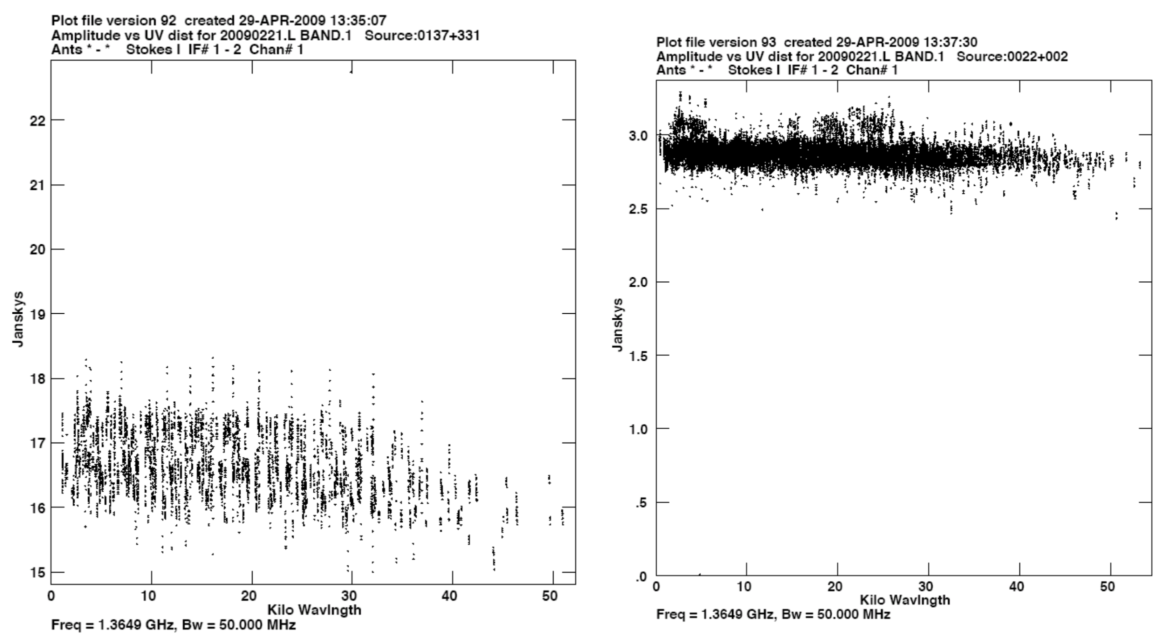

Figure 2: Calibrated visibilities of the primary flux calibrator 3C48 (right) andthe phase calibrator 0022+002 (left)

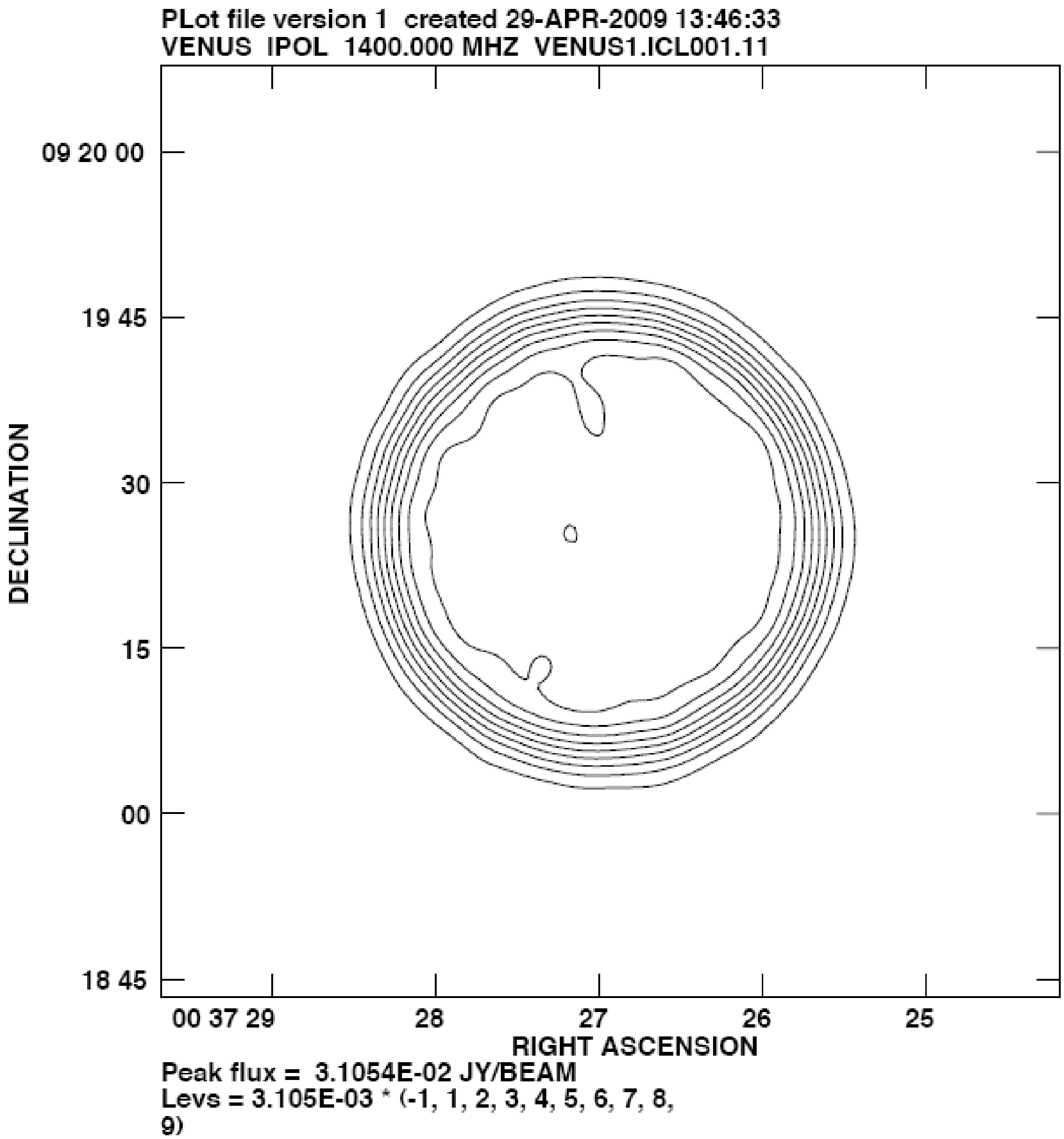

Figure 3: Contour map of Venus at 1.4 GHz. Our beam size was about 4 arcseconds.

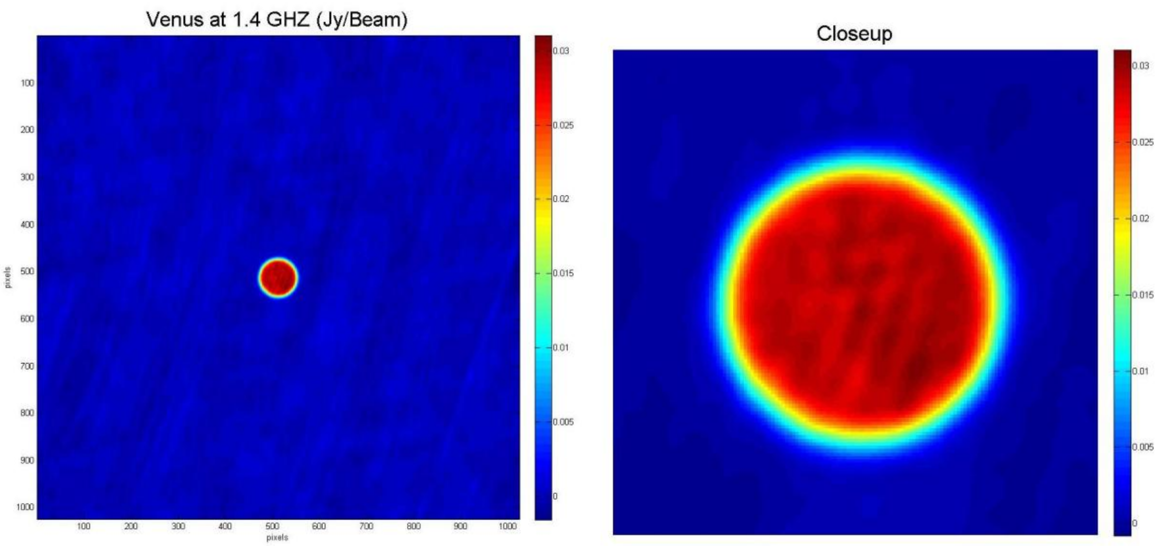

Figure 4: Venus image and closeup

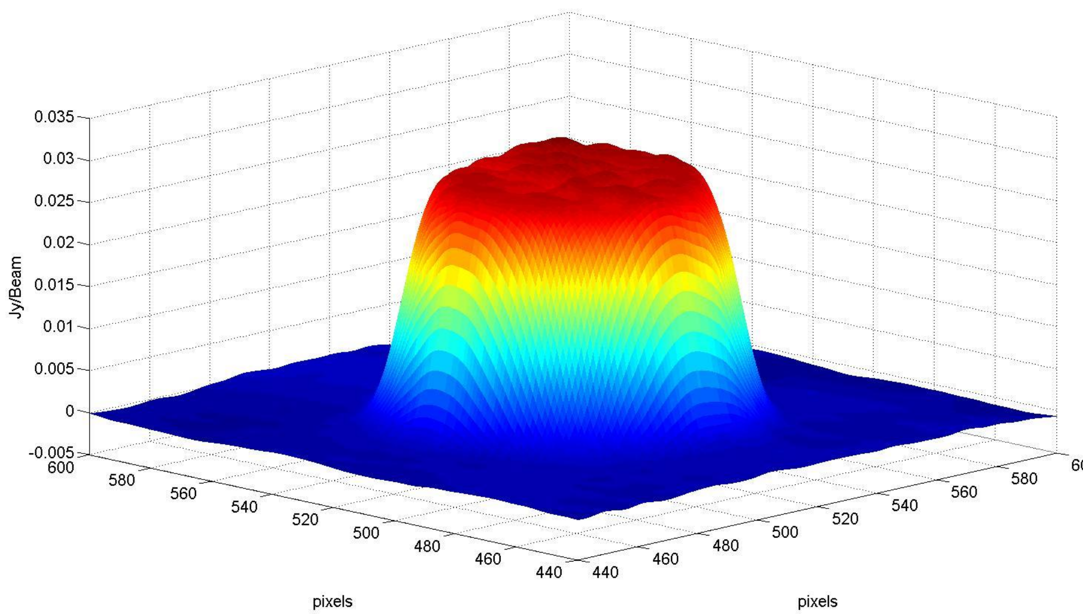

Figure 5: 3D surface plot of Venus image

Our final noise was greater than our estimated noise by a factor of about 18. This is due to extra sources of noise in our observations. One obvious source of noise was the fact that Venus was relatively close to the Sun at the time of the observations. The separation between the two was only about 39.3 degrees. Another source of noise that the sensitivity calculator does not account for was that Venus was moving with respect to the background. Therefore, we had different background objects for each observation, all of which were smeared out by the dishes tracking on Venus. Another obvious source of extra noise is radio frequency interference (RFI).

Model Fitting

We attempted fitting several models. First, we (unsuccessfully) tried using the task UVFIT. Next, using JMFIT we tried to apply a Gaussian model. The estimated integral flux density was 1.3653 Jy, with a chi-squared of 0.295. The model calculated a size of 31 arcsec, about 9 arcsec smaller than the actual size. A Gaussian is not the best model for a planet. Finally, we fit a flat disk using the MODELFIT (component type 2) routine in Difmap (Shepherd, Pearson, & Talyor, 1994), with a resulting chi-squared of approximately 4.

After fitting a disk to the surface, we subtracted the model from the data. The result was a bright ring that the model had not included and some features on the surface (see Figure 6). Some of these features are likely deconvolution errors. However, some of the larger ones may be real. The dark blue patches are areas with about 5% less flux than expected from the model. These could be high-level clouds or convective regions where the temperatures would be significantly lower than surrounding areas. The red and yellow regions have higher flux than expected, and may be areas with less cloud cover where we can see deeper in the atmosphere and nearer to the surface than surrounding regions.

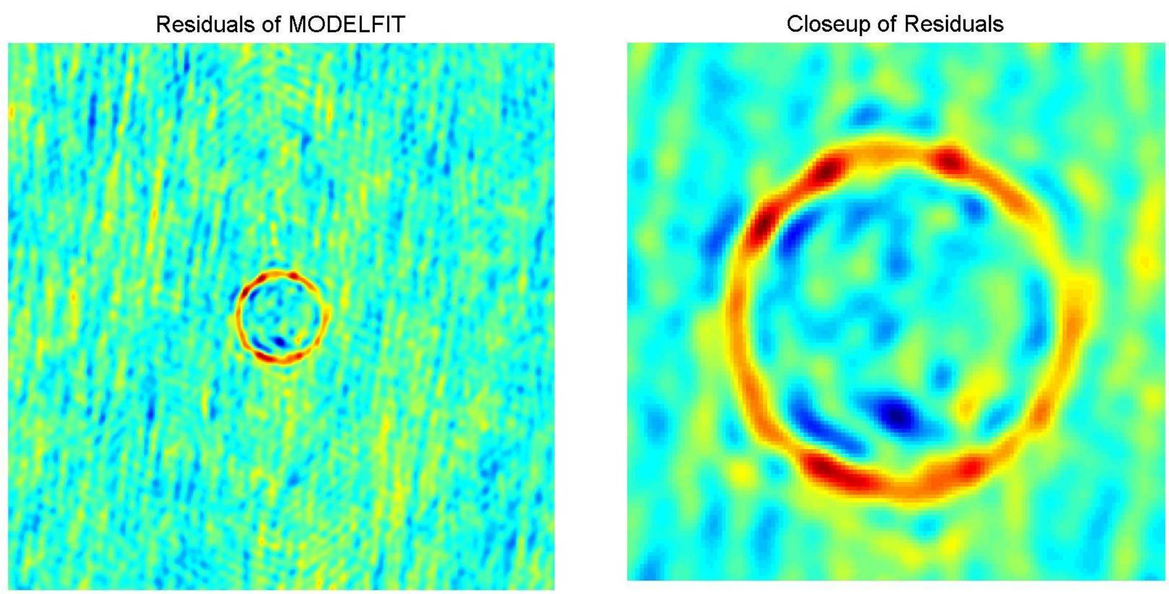

Figure 6: Venus image with model of uniform disk subtracted

Far-Field?

We suspected that Venus may have been too close to use the far-field approximation for our observations. An object is considered to be in the far-field when

$$R \gg \frac{D^2}{\lambda}.$$

Here, R is the distance to the source, D is the diameter of the receiver (or the maximum baseline in our case), and λ is the wavelength at which the observations are made. From JPL's HORIZONS ephemeris generating program, we know that Venus was 0.413 AU, or 6.18×10^7 km from Earth at the time of the observations. The maximum baseline of the VLA in B configuration is 11.4 km and the observations were made at ν=1.4 GHz, or λ=21cm.

$$R = 6.18 \times 10^{12}\ cm, \qquad \frac{D^2}{\lambda} = 6.19 \times 10^{10}\ cm$$

So, Venus was still within the far-field limit, but not by much.

Diameter Estimate

Given the distance to the planet, we can use our measurement of its angular size to estimate its diameter. Because the distance to Venus is much larger than its radius, we can use the small-angle approximation.

$$\theta = \frac{d}{D}\ or\ d = \theta D$$

Here, θ is the angular size in radians, d is the diameter of the planet, and D is the distance to the planet. To find our angular size, we took a slice of the disk at the widest point. Then, we found the size at ½ maximum, where more than 99% of the flux is included (see Figure 7). We found this size to be about 78 ± 1 pixels. When we made the image, we used a pixel scale of 0.5 arcsec. Therefore, our angular size is 39.55 arcsec. According to JPL's HORIZONS program, Venus was 0.413 AU from Earth at the time of the observations. This leads to a diameter of 11879 km. Following Fomalant's treatment of image analysis from chapter 14 of *Synthesis Imaging in Radio Astronomy II*, we estimate the uncertainty in our width measurement to be

$$\Delta Width = \frac{rms\ noise\ (off\ source)}{Peak\ Flux\ Density} \times Width(measured)$$

This gives us an uncertainty of 160 km. Our calculated diameter is 1.9% smaller than the known diameter of 12103.6 km, again from HORIZONS.

As mentioned above in the Model Fitting section, we also found the diameter by using the MODELFIT routine in Difmap to model the planet as a uniform disk. This gave us an angular size of 39.478 arcsec, leading to a diameter of 11857 ± 160 km. Therefore, both methods of estimating the diameter give us very nearly the same result.

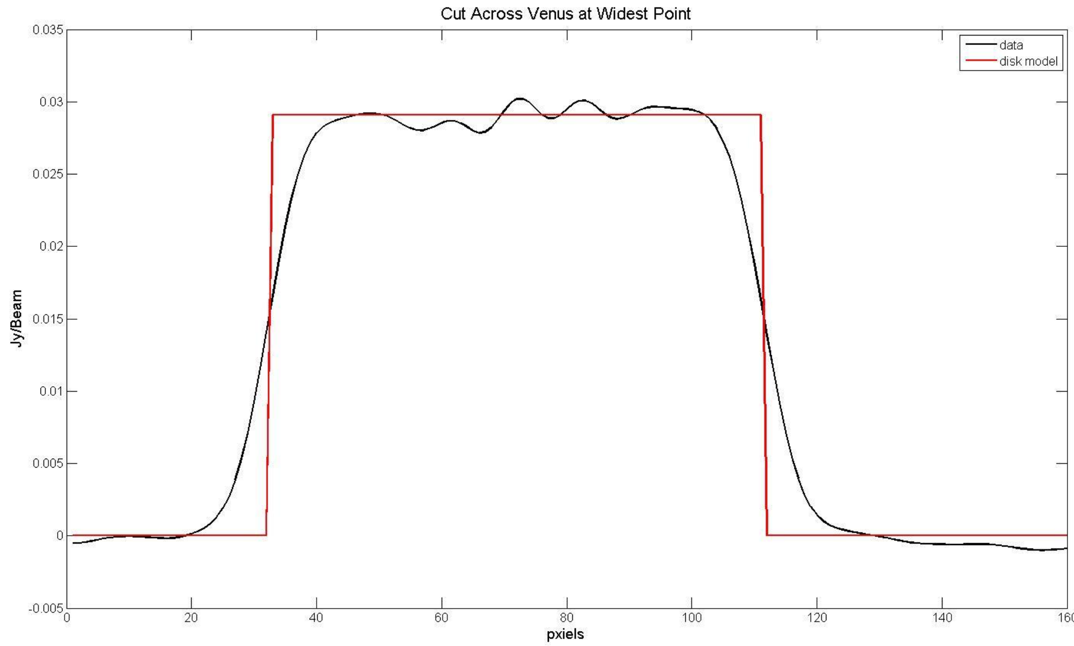

Figure 7: Cross-section of Venus (black line) at widest point and model of a uniform disk at 1/2 maximum (red line)

Brightness Temperature

Given a total flux from an object, we can calculate the object's brightness temperature. That is, the temperature that explains thermal emission at the appropriate wavelength. However, calculating the brightness temperature for a planet is slightly different than a smaller point-like source. We will follow the procedure described by Bulter, *et al.*, in their 2001 *Icarus* paper.

The flux density of an object radiating only via blackbody emission is given by

$$S_\nu = \iint B_\nu\,(\theta, \psi) d\Omega$$

Where S_ν is the flux density, θ and ψ are the angular sky coordinates, $d\Omega$ is the element of solid angle, and B_ν is the blackbody emission as given by the Planck Function.

$$B_\nu = \frac{2h\nu^3}{c^2}\frac{1}{e^{h\nu/kT} - 1}$$

For our observations, we can safely assume that we are in the Rayleigh-Jeans limit ($h\nu << kT$). This leads to

$$B_\nu \approx \frac{2k\nu^2 T}{c^2}$$

For an object at a distance D, the element of solid angle becomes

$$d\Omega = \frac{r dr d\psi}{D^2}$$

Using this and our Rayleigh-Jeans emissivity in our expression for the flux density equation, we get

$$S_\nu = \frac{2k\nu^2}{c^2}\frac{1}{D^2}\int_0^{2\pi}\int_0^R T_b\,(r,\psi) r dr d\psi$$

However, we are not actually getting the true brightness temperature. What we really observe is the effective brightness temperature across the disk of the planet.

$$\overline{T_b} = \frac{\int_0^{2\pi}\int_0^R T_b(r,\psi) r dr d\psi}{\pi R^2}$$

Substituting this into our equation for flux density gives

$$S_\nu = \frac{2k\nu^2}{c^2}\frac{\pi R^2}{D^2}\overline{T_b}$$

Solving for the brightness temperature, we get

$$\overline{T_b} = S_\nu \frac{c^2 D^2}{2k\pi R^2 \nu^2}$$

Because Venus is a large solid object, we must account for the fact that it is blocking the cosmic microwave background radiation. Therefore, our effective brightness is

$$\overline{T_b} = S_\nu \frac{c^2 D^2}{2k\pi R^2 \nu^2} + T_{CMB}$$

The temperature of the cosmic microwave background is well-known to be 2.7K. For the radius of Venus, we have to account for the fact that we are still seeing some of the atmosphere. The thick cloud layers can reach altitudes of 70 km above the surface (Elkins-Tanton, p.136). We will use the value given by Muhleman *et al.* (1979) of R = 6120 km. We used JPL's HORIZONS ephemeris program to give us the distances to Venus at the times of our observations. The average distance was 0.413 AU, or 6.18×10^7 km. Therefore, with our measurement of the flux density of 1.122 Jy from above, we get an effective brightness temperature of 607 K. We note that the uncertainty in our flux is about 2%, and the uncertainty in the distance is about 0.05% due to the planet's movement during our observations. This leads to an uncertainty of ±12.75 K in our temperature estimate.

Previous calculations of Venus' brightness temperature at 1.4 GHz have given results similar to ours. See TABLE II below for a comparison:

TABLE II

Reference	Frequency (GHz)	T_b (K)
This Project	1.385	607 ± 12.75
Butler *et al.* (2001)	1.385	612.8 ± 12.3
Muhleman *et al.* (1979)	1.421	620 ± 30
Lilley (1961)	1.428	~600

The brightness temperature measured at 1.4 GHz is somewhat lower than expected by models, and much lower than the surface temperature measured by landers like Venera 9 and 10. It also does not compare well with the brightness temperature measured at 4.86 GHz of about 680 K (Butler *et al*, 2001). This problem has been known for some time but no reasonable explanation has yet been found (Muhleman *et al*, 1979, and Butler *et al*, 2001). Muhleman and his colleagues theorized that the lower temperature at frequencies lower than 4 GHz might be due to scattering effects caused by large rocks in the subsurface of the planet (Muhleman *et al*, 1979). However, no radiative transfer models have been able to demonstrate this.

Curiously, using a flux density of 1.3653 Jy that we estimated, poorly, with JMFIT, one calculates an effective brightness temperature of 738 K. Although it is in clear disagreement with other calculations, it is comparable to the actual surface temperature, as measured by the landers. It is, however, almost certainly a coincidence.

The major source of uncertainty in our calculations for the brightness temperature is the absolute flux calibration.

Summary

Venus is a very interesting object to observe at any wavelength. Radio observations give us the opportunity to probe deeper into its thick atmosphere. Our observations at a frequency of 1.4

GHz resulted in a measured diameter of 11879 km, which is somewhat smaller than the known diameter. We fit a uniform disk model to the data with a chi-squared of approximately 4. The diameter estimated by the model was in good agreement with our measurements. We also measured a brightness temperature of 607 K, which agrees well with previous observations but is cooler than predicted by models. There is still no explanation for the cooler temperatures seen at frequencies lower than 4 GHz.

Given the opportunity, we would like to make more observations of Venus with the VLA. It would be very helpful to have more time on the source, and more observations of the primary flux calibrator to prevent some of the problems we had this time. Observations at other frequencies, especially 4.86 GHz, would also be helpful in getting better estimates of the brightness temperature.

Acknowledgements

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