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FINAL TECHNICAL REPORT

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National Aeronautics and Space Administration

- Goddard Space Flight Center -

RADIO OCCULTATION STUDIES OF VENUS' ATMOSPHERE WITH MAGELLAN

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Principal Investigator

INTRODUCTION

We have been conducting a systematic study of the middle and lower atmosphere of Venus through analysis of 20 radio occultation experiments conducted with the Magellan spacecraft between October, 1991, and August, 1994. These studies have revealed a rich but sparsely sampled trove of information regarding the structure, composition and dynamics of the Venus atmosphere. The five sets of experiments sampled a variety of latitudes (see Table I). Basic results include vertical profiles of: (i) electron density in the ionosphere, (ii) pressure, temperature, density, and static stability in the neutral atmosphere (from 33 km to 98 km), and (iii) sulfuric acid vapor (H_2SO_4) abundance below the main cloud deck (Jenkins et al., *Icarus* **110**, 79-94, 1994). Further analysis of the temperature profiles led to the discovery of small vertical-scale gravity waves in the neutral atmosphere (Hinson and Jenkins, *Icarus* **114,** 310-327, 1995). The retrieved profiles show intriguing zonal variations that might be due to planetary-scale waves. During the performance period of this grant, we have concentrated on reanalyzing the 15 experiments conducted in 1994 using improved trajectory files for Magellan provided by JPL, obtaining more reliable results, and on conducting an error analysis of the derived profiles. In addition, we have begun an analysis of microwave emission maps of Venus obtained at the Very Large Array (VLA) in April, 1996. These maps were obtained by Dr. Paul G. Steffes (Georgia Tech) under a separate Planetary Atmospheres grant. Dr. Jenkins' contribution to the VLA work has been to assist in the application of the Magellan results to the interpretation of the maps.

This report is organized as follows: A summary of results is presented, giving representative examples of the various physical profiles retrieved from all the Magellan radio occultation studies, emphasizing latitudinal variations evident in the data. Next, a preliminary analysis of the VLA maps is given. A summary of activities follows the scientific results, detailing papers published and presented at various conferences. This report concludes with a "Conclusions and Suggestions for Future Work" section.

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SUMMARY OF RESULTS

Occultation Geometries

The latitudes, longitudes and solar zenith angles of the region of the atmosphere probed during an occultation experiment at Venus depend on the relative positions of the Earth, Venus and Sun at the time of occultation, and the trajectory of the spacecraft. Table I summarizes the geometries encountered for each of the sets of occultations conducted with the Magellan Spacecraft. Naturally, these quantities vary during the experiment as the geometry changes. The values listed in Table I are appropriate "averages" for the neutral atmosphere.

Table I. Radio Occultation Experiments Conducted with the Magellan Spacecraft

Date	Number of Experiments	Latitude*	Longitude* (E)	Solar Zenith Angle*
5-6 Oct. '91	3	66°N	129°	110°
7 Dec. '92	2	88°S	67°	92°
24 June '94	2	82°N/88°S	262°/48°	85°/90°
16 July '94	3	76°N	191°	75°
9 Aug. '94	10	45°N/60°S	254°/250°	45°/61°

*approximate

A total of 20 experiments were successfully planned and executed on five separate dates, with data collected on as many as five successive orbits. The orbital period of Magellan was 3.26 hr for the first two sets of experiments. The 1994 studies were carried out after circularization by pioneering aerobraking maneuvers that reduced the orbital period to 1.55 hr. The experiments were conducted in two-way mode with the DSN uplinking a stable reference carrier to Magellan, which downlinked a carrier locked to the reference signal. Measurements were made at the two telecom frequencies utilized by Magellan: 2.3 GHz (13 cm) and 8.4 GHz (3.6 cm).

Figure 1 illustrates the geometry for each set of occultations as viewed from Earth. The unlighted Venus hemisphere is colored blue. Latitude and longitude lines are spaced every 15°, and the north pole of Venus is "up" in each cartoon. The portion of the spacecraft's orbit is denoted by the red curve which is dotted when the spacecraft was behind the planet, and solid otherwise. In all but the December 1992 geometry, the spacecraft traveled behind Venus from North to South.

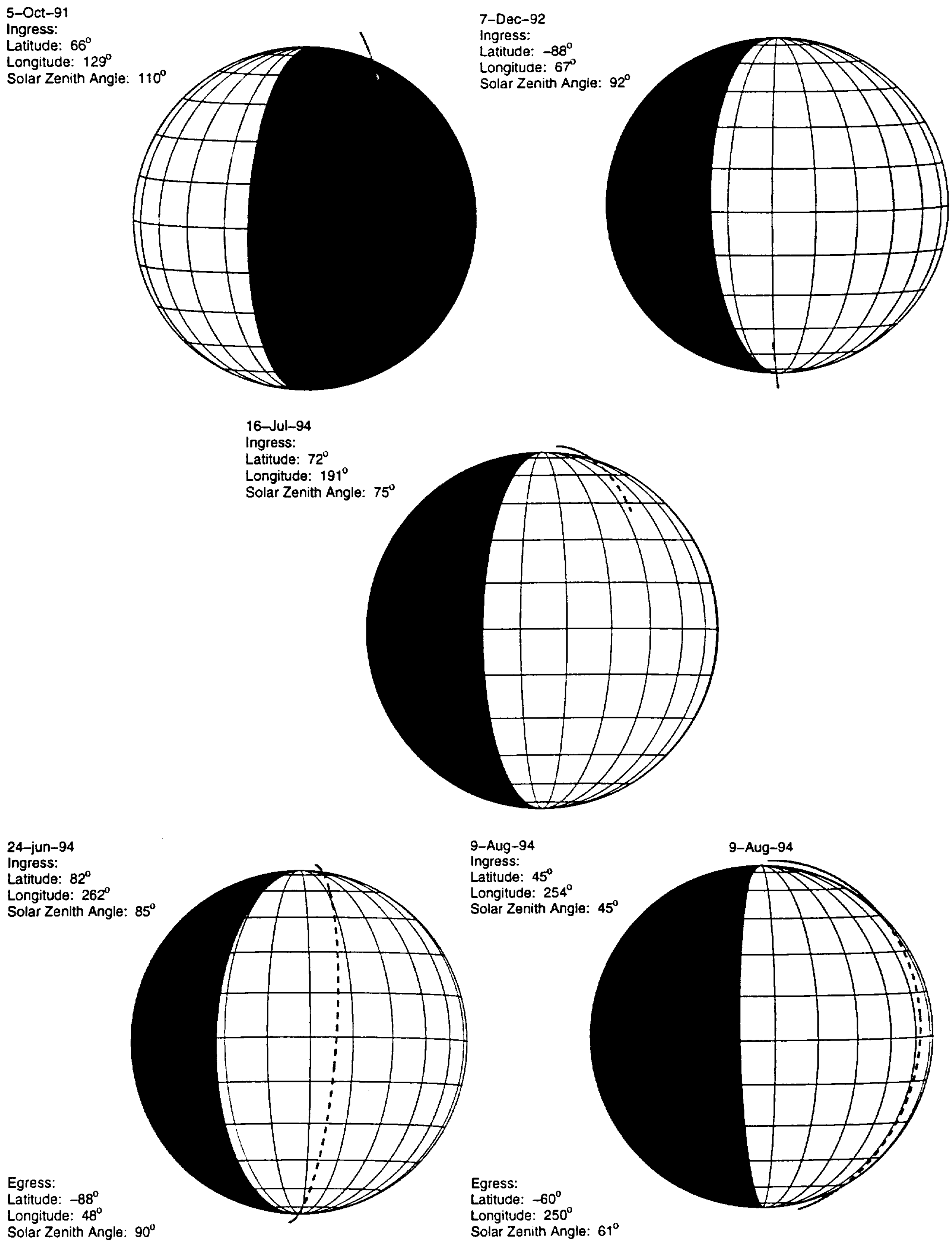

Figure 1. Magellan occultation geometry for each set of experiments

Retrieved Thermal Profiles

We retrieved temperature/pressure profiles at both 13-cm and 3.6-cm using standard techniques combined with a new method for reducing data from two-way radio occultations (Jenkins et al. 1994). These profiles extend from ~95 km to as low as 33.6 km, depending on experiment geometry and Earth-Venus distance, which determined the noise level of each data set. (Throughout this paper we adopt a mean radius of 6052 km for Venus.)

Figure 2 shows temperature profiles retrieved from each of the seven different occultation geometries (ingress and egress occultations on the same orbit are considered separately). These profiles generally agree with previous Pioneer Venus (PV) radio occultation measurements (Kliore and Patel 1982). The meridional variations are also qualitatively consistent with current models of the zonal circulation on Venus (Schubert 1983). However, there is a strong latitudinal relationship evident in this figure, with the more poleward profiles exhibiting warmer temperatures above ~57 km, and cooler temperatures below this level. Also, the level of the tropopause varies significantly with latitude and with time, as evidenced by the two profiles obtained at 88°S in Dec. '92 and Jun. '94. There is variability with respect to the depth of the temperature minimum at the tropopause, which may be related to change in the location or strength of the midlatitude jet. Zonal variations in the temperature profiles retrieved from adjacent orbits are significant, but well below the meridional variations shown here.

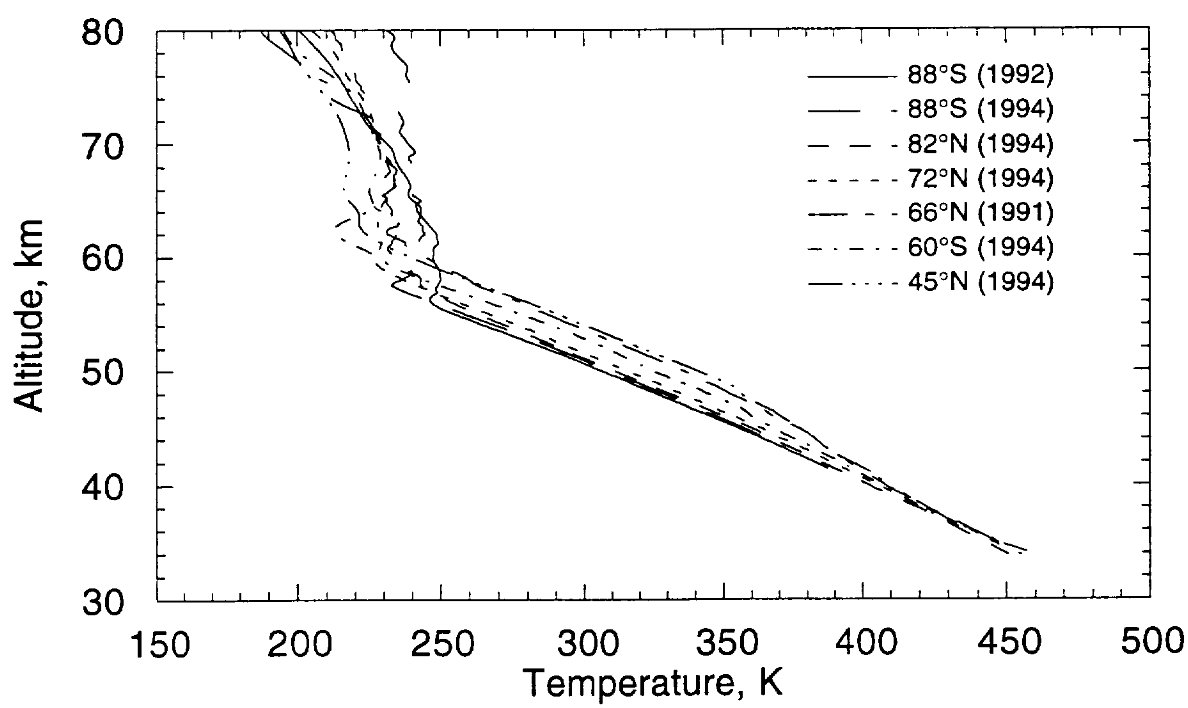

Figure 2. Retrieved temperature profiles from Magellan Radio Occultation Studies

Static Stability

We computed the static stability, S=dT/dz-Γ, from the retrieved temperature profiles, where z is altitude, T is temperature. and Γ is the adiabatic temperature gradient, calculated as per Seiff et al. 1980. Results from seven representative occultations are shown below. All profiles are stable above 60 km, with S≈10 K/km. The stability decreases abruptly somewhere between 55 and 60 km to near 0 K/km. For profiles above 70° latitude, S rises only to about 1 K/km at 35 km, while the three profiles below 70° latitude reach stabilities as high as 4 K/km near 42 km. This phenomenon has important consequences for the dynamics of the Venus atmosphere. The reduced stability in the near polar latitudes enhances transport of trace constituents from lower levels, dampens vertical wind shear at these levels, and affects propagation of gravity (buoyancy) waves in the Venus atmosphere. In particular, the greater opportunities for mixing afforded by the weaker stability in the polar regions might explain in part the strong latitudinal variation in cloud particle size observed by the NIMS instrument on Galileo on its Venus flyby (Carlson et al. 1993), especially in the high northern latitudes and southern polar regions, where the particles were 10 times larger than those at mid-Southern latitudes. We have reanalyzed previous PV radio occultation measurements from the polar region and find that the peculiar polar stability has persisted for at least 6 years and is present in both hemispheres. This aspect of Venus' atmospheric structure has not been documented previously.

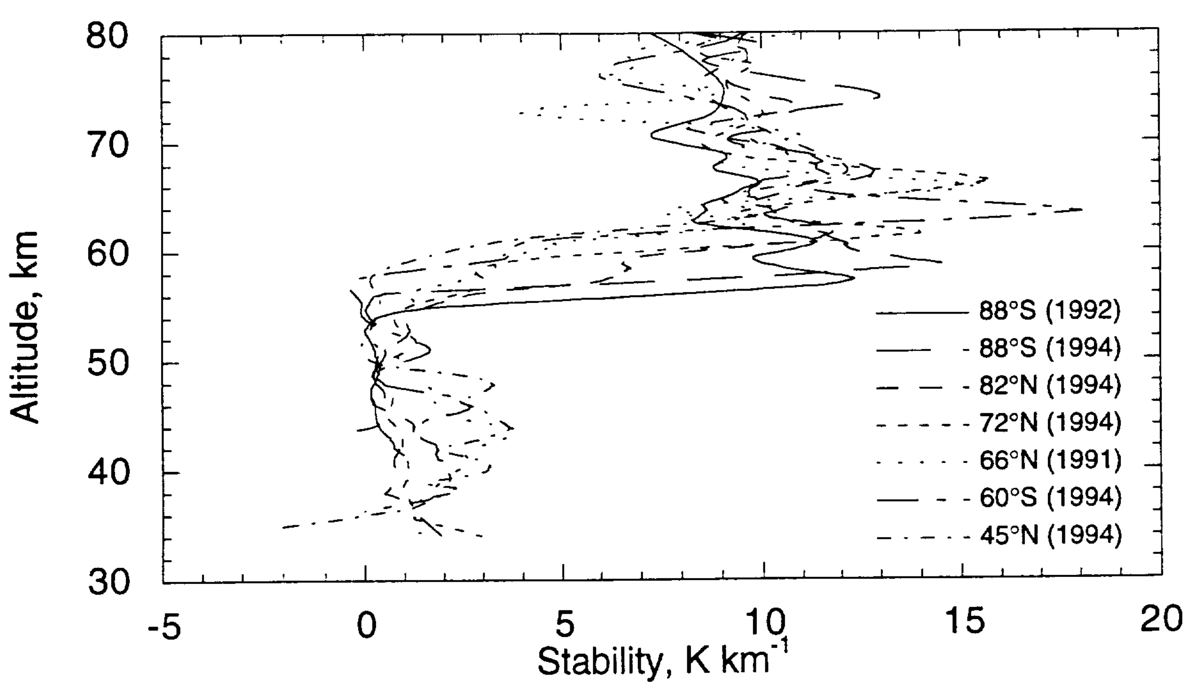

Figure 3. Static Stability profiles at seven different locations/times retrieved by Magellan

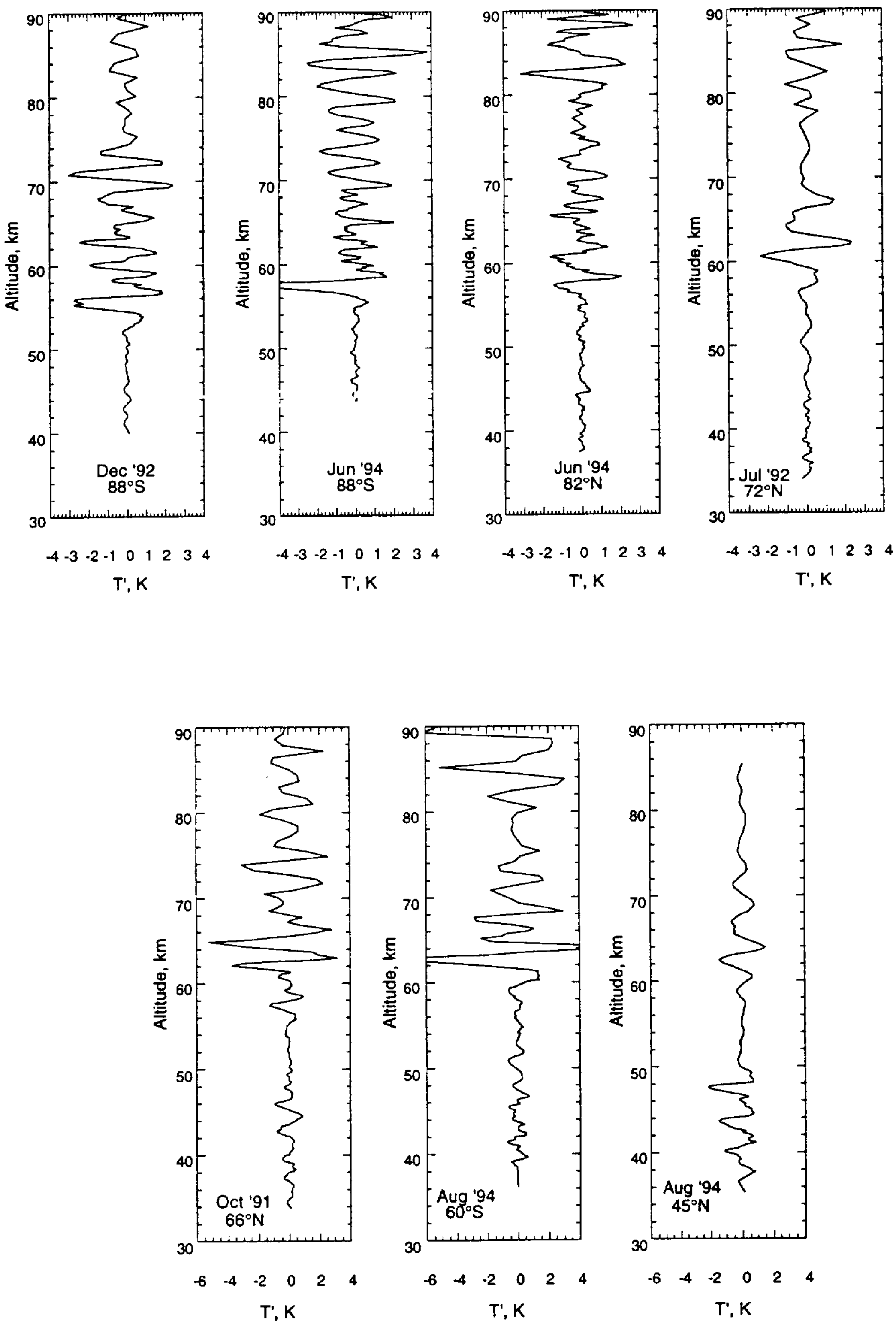

Figure 4. Small-scale temperature oscillations in the Venus atmosphere sorted by latitude

Wave-Like Temperature Oscillations

Figure 4 shows the results of applying a high-pass spatial filter to the Magellan profiles to isolate structure with vertical wavelengths of 5 km or less. All profiles exhibit intriguing wavelike temperature oscillations above 55-60 km on a variety of vertical scales. The profiles poleward of 70° display few or no oscillations below this level, consistent with the stability profiles discussed earlier, which would prevent or retard the vertical propagation of gravity waves in regions of low stability. The highly regular oscillations above 70 km retrieved at 88°S in '94 are rather striking. The three profiles equatorward of 70° do, however, display significant oscillations below 50 km. Hinson and Jenkins (1995) argued that the temperature oscillations observed at 66°N in Oct. '91 are caused by freely propagating internal gravity waves.

Meridional Winds

New information about atmospheric winds on Venus can be extracted from these measurements. We estimated the cyclostrophic component of the meridional winds by first comparing profiles of pressure vs altitude from consecutive orbits of Magellan and then interpreting the pressure gradients in terms of cyclostrophic balance. Figure 5 shows preliminary results at two locations. At 67°N (Oct. '91), meridional wind speeds are small, less than about 2 m/sec, consistent with results deduced at latitudes up to 60°N from interferometric tracking of the Pioneer Venus probes (Schubert 1983). At 76°N, where meridional winds had not been measured previously, wind speeds are much larger, up to 15 m/sec, and they are directed poleward at altitudes below 54 km and equatorward at higher altitudes. This is the latitude at which the "polar dipole" was previously observed by the PVO Infrared Radiometer (Taylor et al. 1980, Apt and Leung 1982).

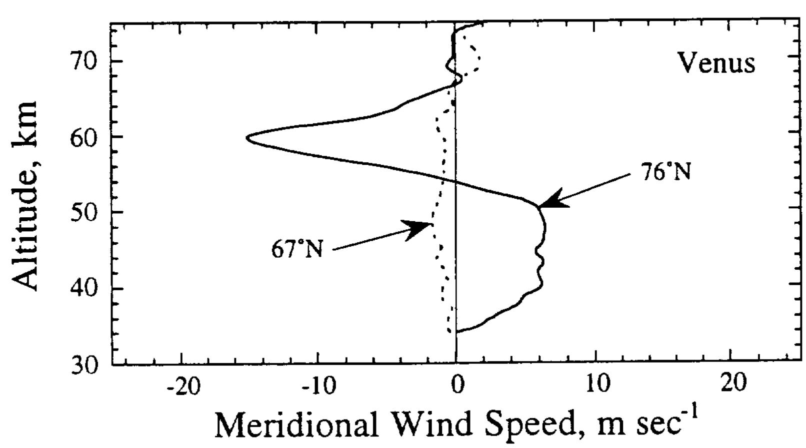

Figure 5. Meridional winds retrieved at two latitudes from Magellan radio science data

Electron Density Profiles

Electron density profiles were retrieved from dual frequency radio occultations with Magellan for 6 of the 7 different geometries (figure below). For these profiles, solar zenith angle (SZA) is the dominant parameter. In addition to the strong SZA dependence of the peak electron density, there are smaller-scale features evident in some of the profiles – hints of dynamic processes taking place in the Venus ionosphere. These results are consistent with earlier PV Orbiter Radio Occultation studies conducted in the early 1980s (Brace et al. 1983). There are notable orbit-to-orbit variations which are not displayed in this figure, but which are discussed in Jenkins et al. (1994).

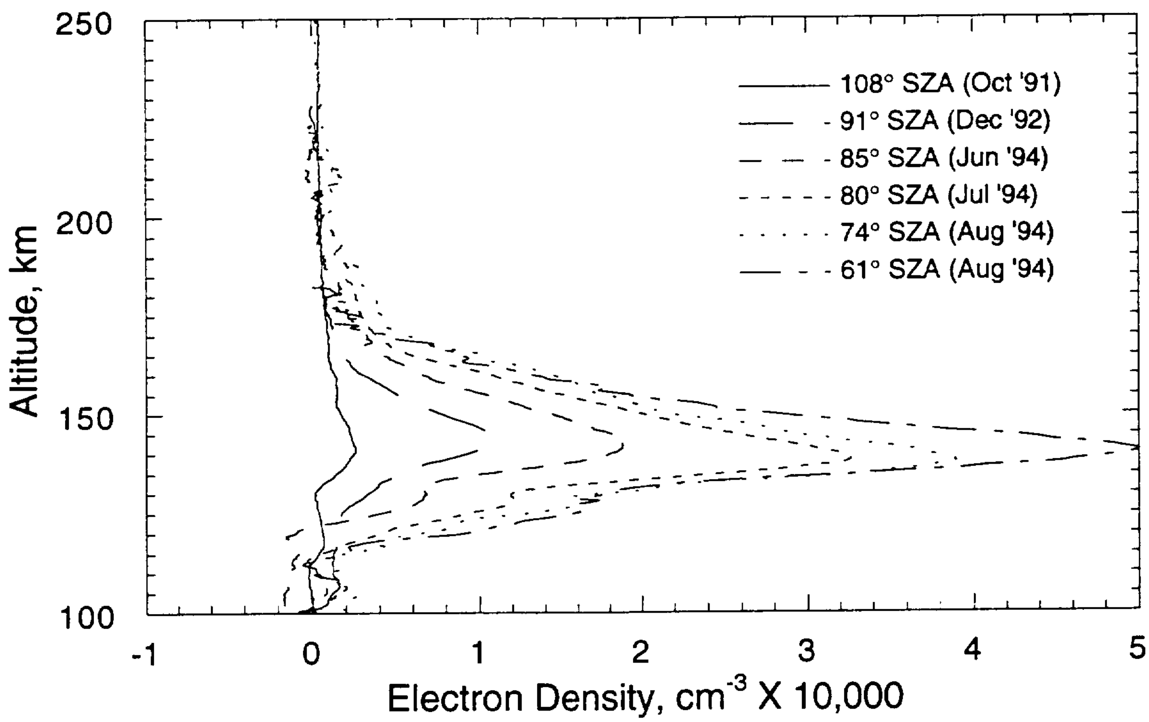

Figure 6. Average electron density profiles obtained by Magellan, illustrating dependence on solar zenith angle.

Sulfuric Acid Vapor Profiles

Vertical profiles of sulfuric acid vapor (H_2SO_4) abundance were retrieved from the Magellan data set. The quality of the profiles is highly dependent on the viewing geometry and Earth-Venus distance, resulting in high-quality profiles for Oct. '91, Jun. '94 and July '94. Data from August '94 is less accurate due to a grazing geometry, while the profiles from December '92 were compromised by a large Earth-Venus separation. Figure 6 shows representative H_2SO_4(g) abundance profiles for each of the data sets, along with the saturation vapor abundance (dashed curves). The difference in the altitude at which significant H_2SO_4(g) appears is due to the colder temperatures in the polar regions. All the profiles look rather similar in the peak abundance reached, and the extent of the profiles.

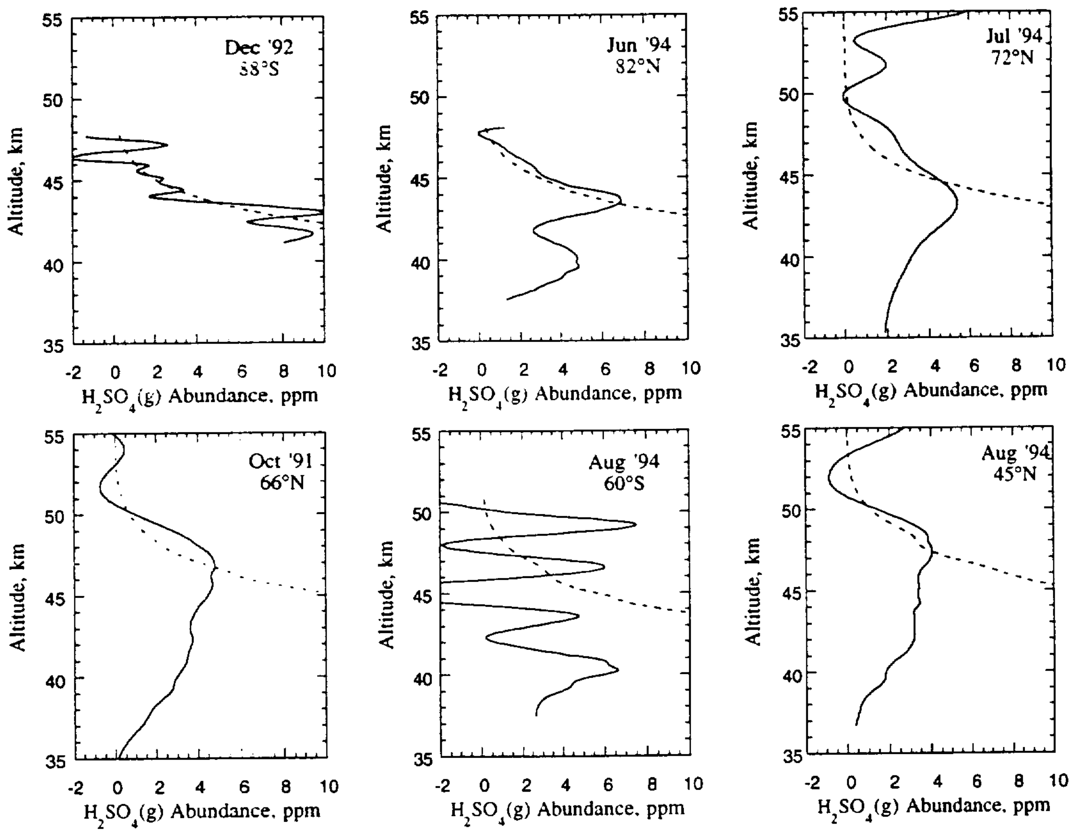

Figure 7. Representative sulfuric acid vapor abundance profiles retrieved by Magellan radio occultation studies.

GROUND-BASED MICROWAVE OBSERVATIONS

A preliminary analysis of one dual-frequency observation of Venus at the VLA in April, 1996, has been completed by Dr. Marc Kolodner (Georgia Tech) and Dr. Bryan Butler (NRAO). Funding for this analysis was provided by a Planetary Atmospheres grant under the direction of Dr. Paul G. Steffes (Georgia Tech). These observations are described and discussed in Kolodner et al. (1997), Kolodner (1997), Butler et al. (1997) and Suleiman (1997). The principal features of the two maps retrieved to date are a significant amount of limb darkening in the low to mid-latitudes beyond that due to the pressure-broadened CO_2 absorption, and even greater darkening in the polar regions. The excess equatorial limb darkening is well explained by an H_2SO_4(g) profile similar to that retrieved by the results from the Mariner 10 radio occultation of Venus near the equator (Howard et al. 1974), along with 75 ppm of SO_2 below the main cloud. The dark polar caps are matched by an $H_2SO_4(g)$ profile following that derived from the Oct. '91 Magellan experiment at 67°N (Jenkins et al. 1994), along with an additional 75 ppm of SO_2 (for a total of 150 ppm SO_2). This model does not explain all the significant features apparent in the maps, especially the smaller-scale features whose explanation requires more sophisticated modeling efforts. Dr. Jenkins' role in this work was to assist with the application of the Magellan results to the interpretation, and a verification of the radiative transfer model by comparison with results from software developed to support radio occultation studies. The weighting functions in Figure 8 illustrate that the source of microwave emission from Venus' atmosphere is a bimodal function except near the limb of the planet. One peak occurs in the layer of $H_2SO_4(g)$ below the lowest cloud deck. The second one occurs in the deep atmosphere below this layer. Figure 9 shows the result of removing a mean limb-darkening function from the 15 GHz map, illustrating the significant polar darkening relative to the equatorial and midlatitude limbs. Intriguing features include warm bands in the midlatitudes enclosing a cooler equatorial region.

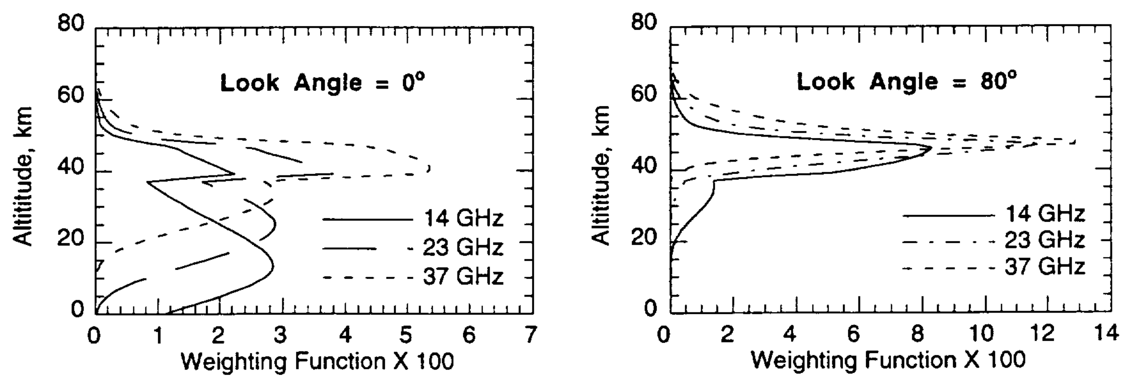

Figure 8. Weighting Functions for Venus at look angles 0°(nadir) and 80° (near the limb).

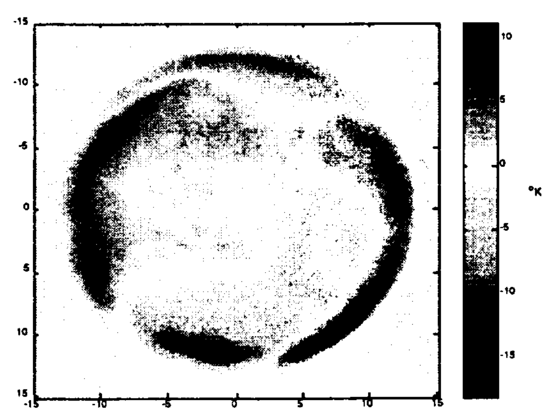

Figure 9. Residual 15 GHz Brightness Temperature Map obtained at the VLA in 1996.

SUMMARY OF ACTIVITIES

In addition to conducting the investigation summarized above, Dr. Jenkins attended the 29th Annual Meeting of the Division for Planetary Sciences of the American Astronomical Society, held in Cambridge, Massachusetts, July 28-August 1, 1997, at which he presented a paper titled "Magellan Radio Occultation Studies of Venus' Atmosphere (1991-1994)". Dr. Jenkins traveled to the VLA to observe Venus at 15 GHz and 22 GHz on December 20, 1997 .

CONCLUSIONS AND FUTURE WORK

The basic analysis of the Magellan radio occultation data set has been completed. Dr. Jenkins has been invited to coauthor a chapter for VIRA II (Venus International Reference Atmosphere) titled "Structure of the Venus Atmosphere from 0 to 100 km" with Dr. Ludmilla Zasova. This is an excellent opportunity to showcase the results of all the Magellan radio occultation studies. Dr. Jenkins is also preparing a paper detailing atmospheric dynamics revealed by this investigation with Dr. David P. Hinson (Stanford), a Co-I under a parallel Planetary Atmospheres grant. Dr. Jenkins will extend the work presented here under a new Planetary Atmospheres Program grant by applying the Magellan results to the interpretation of VLA maps of Venus. This work will incorporate the effects of Venus' varying surface topography and surface dielectric "constant" in the radiative transfer model (RTM) used to interpret the maps, as well as to explicitly account for the curvature of the atmosphere. This step, together with the inclusion of the known spatial variability in the TP field and sulfuric acid vapor abundance should allow us to differentiate topographically- and thermally-forced brightness temperature variations from spatial variations in the distribution of sulfur-bearing gases in the Venus atmosphere. Such variations may be indicative of various dynamical processes occurring in the Venus atmosphere, or of active volcanism, if such variations are correlated with specific surface features but not with solar angle. Analyzing sequences of images generated from subsets of the data will determine if the spatial variations are tied to topography or solar angle, or whether they rotate with the atmosphere. The enhanced RTM will be applied to additional VLA observations of Venus, planned for 2000, and will provide an opportunity to compare the spatial variability and global abundances of these two important sulfur compounds at three discrete times over a 5-year interval.

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Magellan Radio Occultation Studies of Venus' Atmosphere (1991-1994)

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We have been conducting a systematic study of the middle and lower atmosphere of Venus through analysis of 20 radio occultation experiments conducted with the Magellan spacecraft between October, 1991, and August, 1994. These studies have revealed a rich but sparsely sampled trove of information regarding the structure, composition and dynamics of the Venus atmosphere. The five sets of experiments sampled a variety of latitudes (see Table I). Basic results include vertical profiles of: (i) electron density in the ionosphere, (ii) pressure, temperature, density, and static stability in the neutral atmosphere (from 33 km to 98 km), and (iii) sulfuric acid vapor (H_2SO_4) abundance below the main cloud deck (Jenkins et al., Icarus **110**, 79-94, 1994). Further analysis of the temperature profiles led to the discovery of small vertical-scale gravity waves in the neutral atmosphere (Hinson and Jenkins, Icarus **114**, 310-327, 1995). The retrieved profiles show intriguing zonal variations that might be due to planetary-scale waves. New results obtained in the past year include profiles of meridional wind speed at several latitudes. This paper will focus on presenting results from the 1994 occultations, and on comparing the results from all experiments to study latitudinal and meridional variations.

Table I. Radio Occultation Experiments Conducted with the Magellan Spacecraft

Date	Number of Experiments	Latitude (approximate)
5-6 October, 1991	3	67°N
7 December, 1992	2	88°S
24 June, 1994	2	82°N/87°S
16 July, 1994	3	76°N
9 August, 1994	10	49°N/62°S

This work was supported under NASA Planetary Atmospheres Program Grants NAGW-4346, NAGW-4341, and NAG5-4321.