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(NASA-CR-169874) ABSORPTION OF SUNLIGHT IN  
THE ATMOSPHERE OF VENUS Final Report, 1  
Jan. 1980 -30 Apr. 1982 (Arizona Univ.,  
Tucson.) 16 p HC A02/MF AC1 CSCL 03B

N83-18630

Unclas  
G3/91 08600

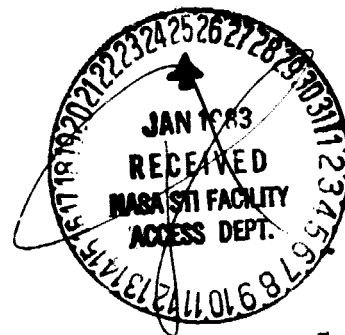
# FINAL REPORT

For NASA Grant NAGW-55

Absorption of Sunlight in the  
Atmosphere of Venus

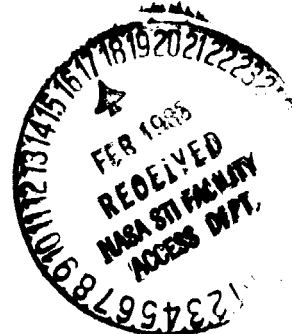
by

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For the period: January 1, 1980 - April 30, 1982

M. G. Tomasko, Principal Investigator  
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December 20, 1982

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## I. INTRODUCTION

M. G. Tomasko and L. R. Dose served as the scientific investigators for the Solar Flux Radiometer (LSFR) experiment on the large Pioneer Venus probe that entered the Venus atmosphere on December 9, 1978. This experiment successfully measured the profiles of upward, downward and net solar flux on Venus at altitudes from about 62 km to the surface in three spectral bands at a vertical resolution of a few hundred meters. These data measured the penetration and absorption of solar energy in Venus' lower atmosphere - quantities that are essential in evaluating the role of the greenhouse mechanism in supporting Venus' remarkably high surface temperature. In addition, the data constrained the vertical structure and optical properties of the Venus clouds - a part of the Venus atmosphere of considerable interest and importance in its own right.

For the period up to one year following the Venus encounter (during calendar year 1979) support was received from the Pioneer Project Office at Ames Research Center for the reduction and preliminary analyses of these data. As might be anticipated following such an unique experimental program, the analysis and interpretation of these new data were hardly complete at the end of one year. Support was obtained from a grant through NASA Headquarters (NAGW-55) for the further analysis and publication of the results of this experiment for a period of two additional years (January 1, 1980 - March 30, 1982). This final report summarizes briefly the work accomplished with the support of grant NAGW-55. More complete discussion of the results of the LSFR experiment and their implications for the cloud structure and thermal balance of Venus can be found in the scientific publications describing this work (see list on pages 15 and 16 below and the attached reprints and preprints).

## II. WORK ACCOMPLISHED

During the first of these two years, we proposed to work in four main areas:

1. to build a model for the clouds of Venus consistent with the LSFR and other available data;
2. to use the cloud model to evaluate the globally averaged solar net flux profile and to compare it to the best measurements and calculations of the thermal net flux profile to study the thermal balance of Venus' lower atmosphere;
3. to use the LSFR data containing azimuthal structure to estimate the optical depth of the clouds above the large probe at the beginning of data collection;
4. to compute the spectrum of the downward solar radiation at the Venera 11/12 entry sites for the PV cloud model and to consider the revisions in the model necessary to reproduce the Soviet results.

During the second year, we proposed to continue work on the third and fourth tasks above, and in addition to work in two other areas:

5. to prepare a review chapter on the thermal balance of the lower atmosphere of Venus for the book VENUS being prepared by Hunten, Colin, Donahue, and Moroz; and
6. to consider further the problem of reconciling the visible and thermal opacity of the clouds at pressure levels of  $\leq 100$  mb which became apparent during the first year.

Our progress in each of these areas is outlined briefly.

### A. Cloud Models

A main goal of this work was to build a cloud model which would closely reproduce the LSFR broadband solar flux profiles at the Pioneer Venus Sounder entry site. This goal was accomplished during the first year. The model incorporates particle size distribution data from the Cloud Particle Size Spectrometer (LCPS) experiment and is consistent with flux measurements at the ground made at the Venera 8 through 12 entry sites. The results indicate that about 2.5% of the sunlight incident on Venus is absorbed at the ground. Detailed results appear in a series of articles in the special Pioneer Venus issue of J.G.R. (December 1980 - see bibliography below).

Recently we have become aware of labeling error in the description of our best fitting cloud model (model F) in our article "Measurements of the Flux of Sunlight in the Atmosphere of Venus", JGR 85 8167, 1980 (called paper I below). The smallest cloud particles (termed size mode 1) were described as having a refractive index of 1.44 in this model when in fact the model was computed using a refractive-index of 1.93 for the mode 1 particles, as would be appropriate if these small particles had a large sulfur component. With other support, we are preparing a note for publication pointing out the labeling error in the index of refraction of the mode 1 particles in the published model, indicating the change in fluxes (~15%) which results when an index of 1.44 is actually used in the model F structure, and pointing out the changes in the optical thicknesses of the mode 1 component necessary to bring the model solar fluxes again into agreement with the measured values for an index of 1.44 for mode 1. It is interesting to note that amorphous sulfur recently has been suggested as the ultraviolet absorber by Toon et al. (Icarus in press 1982), so model F using an index of 1.93 for mode 1 may in fact remain as one of the best attempts to fit the optical scattering properties of the Venus clouds.

B. Globally Averaged Solar and Thermal Radiative  
Fluxes and the Thermal Balance

Despite the incorrect label for the refractive index of the mode 1 particles, model F of our paper I describes the measured solar fluxes at the PV large probe entry site quite well. Assuming the cloud structure is similar at other sites, (and the Venera data suggest that it is) we have computed the globally averaged solar flux profile. This profile is compared with the thermal flux profiles originally measured by the Net Flux Radiometer (SNFR) experiment on the small PV probes in the article "The Thermal Balance of Venus in Light of the Pioneer Venus Mission", by Tomasko et al., JGR 85, 8187, 1980 (paper II below). The thermal flux measurements were greater than the global net solar flux profile estimated from the LSFR experiment. This implied either a large error in at least some of the measurements or the existence of significant "windows" in the thermal opacity of the gases in the Venus atmosphere at high temperature and pressure. Recently, Revercomb et al. (Icarus in press, 1982) have identified an effect which could have systematically increased the thermal flux measurements. Revising these measurements to correct for this effect results in thermal fluxes in approximate agreement with the measured solar fluxes, and indicates that the greenhouse mechanism is indeed primarily responsible for the high surface temperature of Venus. More details are given in the attached preprint "The Thermal Balance of the Lower Atmosphere of Venus" by M. Tomasko (paper III below) which will appear in the book VENUS currently in press.

C. Visible Optical Depth Above Probe at Beginning  
of Data Collection

The azimuthal structure of the solar radiation field was measured at three altitudes during the early part of the descent. During the third of these three sets of measurements, the probe was falling nearly vertically and the location of the data samples was that planned for the experiment. This third data set was analyzed during the first year of this work and published in paper I. The results (Fig. 5 of of paper I) indicate a visible cloud optical depth between about 3.5 and 4 above the  $\sim 100$  mb level.

The first and second data sets were obtained just after deployment of the main parachute on the large probe while the probe was turning from its relatively flat entry trajectory to falling vertically on the parachute. The exact location of the data samples relative to the sun depend critically on the angle of attack of the spacecraft when the data were taken - values which are not well known. Thus, the data from the first two data sets have not been able to improve materially the optical depth estimate obtained and published for the third measurement set. Nevertheless, the optical depth estimate from the third measurement set has proven to be quite useful in constraining cloud properties below the level probed well by orbiter measurements and above the region sampled directly by instruments such as the particle size spectrometer and the nephelometers on the probes.



D. Model for Comparison with the Venera 11/12 Spectra  
of the Downward Intensity Below the Clouds

The broad-band LSFR measurements give directly a good measure of the solar flux in the spectral bands from 0.4 - 1.0  $\mu\text{m}$ , from 0.4 - 1.8  $\mu\text{m}$  and in a narrower band from 0.59 - 0.67  $\mu\text{m}$  at the large probe entry site where the solar zenith angle was 65.7°. In order to scale these measurements to other solar zenith angles and to globally averaged conditions, model calculations are necessary. The models must be computed on a frequency grid which is sufficiently fine to include, in some manner, the molecular absorptions in the spectral interval where solar radiation is found. Many strong  $\text{CO}_2$  bands are found in the region from 1 - 4  $\mu\text{m}$ , such that little solar radiation in these wavelengths penetrates to the ground. Also, adequate laboratory measurements exist for the strengths of the strong bands found in this region. On the other hand, in the region shortward of 1  $\mu\text{m}$ , the  $\text{CO}_2$  bands are weaker, more difficult to measure in the laboratory, and in a spectral region where significant sunlight can penetrate to the ground. While some formulation of weak  $\text{CO}_2$  and  $\text{H}_2\text{O}$  absorptions was used in our earliest LSFR broad-band models, we were eager to compute spectra using the models for comparison with the spectra of the downward intensity field measured at various altitudes on Venus by Venera 11 and 12.

This comparison has been done at various levels of approximation. In the first step, our modeling program was used with no modifications to evaluate spectra at the Venera 11 and 12 sites (see Fig. 15 in paper I). At this level of comparison, several similarities were found as well as some significant differences with the Venera spectra. First, the major absorptions in the region between 0.4 and 1.0  $\mu\text{m}$  occurred in both spectra at about the same locations. However, the shape of the absorption at the blue end of the

spectrum, the "continuum" level between the bands, and the shapes of the bands obviously were not in detailed agreement.

As a second level of approximation, we modified our program to include the continuum opacity in the visible due to the far wings of strong CO<sub>2</sub> bands beyond 1.0  $\mu$ m using an algorithm employed by the Soviets; the variation of ground reflectivity with wavelength measured by Venera 9 and 10; a better description of the blue absorber reported by the Soviets in their analyses of Venera 11 and 12; and an improved water vapor abundance profile. The agreement of our computed spectrum with the Venera 11/12 spectra were not significantly affected by these changes.

In our third round of models, we included the Elsasser band treatment of the visible CO<sub>2</sub> and H<sub>2</sub>O absorptions used by Moroz et al. (1979, Cosmic Res., 17, 727). Two main conclusions came from this effort. First, these models produce broadband fluxes in good agreement with LSFR measurements despite the changes in the details of the treatment of the visible absorption bands. Second, models computed with this approach yield high resolution spectra which cannot be compared directly with the Venera spectra before smearing with the Venera spectral resolution function which is not well known (at least to us). When Gaussian smearing functions are convolved with the model profiles, the wavelengths of the absorptions are not in agreement with the locations of the observed absorptions. Apparently, either the spectral response function is very asymmetrical, or significant errors are present in either the absorption strengths given in Moroz et al. (1979) or in the wavelength calibration of the published Venera spectra.

Finally, in an attempt to better reproduce the wavelengths of some features in the Venera spectra, we computed some models using a combination of absorption strengths for the H<sub>2</sub>O bands shortward of 0.8  $\mu$ m taken from McClatchey et al. (AFCL Environmental Research Papers, No. 411, 1972) with

the other  $H_2O$  bands and the  $CO_2$  bands following the Soviet Elsasser treatment. In this case, the results show a discrepancy between the relative strengths of the  $H_2O$  and  $CO_2$  bands - the  $CO_2$  band strengths in Moroz et al. (1979) are too strong to match the observed spectra. The  $H_2O$  bands are in rather good agreement with the Venera spectra, although the comparison again depends somewhat on the instrumental profile. Further laboratory data on the weak  $CO_2$  bands at  $0.76 \mu m$  and  $0.85 \mu m$  are necessary to make a meaningful detailed comparison, but these weak bands are difficult to measure in the laboratory. Indeed, the best approach for the present may be to use the Venera spectra to determine the absorption coefficient of these bands. In any case, we have now checked the treatment of these bands in several of our Venus models and have confirmed that they are in reasonable agreement with the Venera spectra, and so can be used with confidence in the extension of our broad-band PV models to other solar zenith angles.

#### E. Review Paper on Thermal Balance

Part of this grant was used to support the preparation of a review chapter on the thermal balance of Venus' lower atmosphere (paper III) in the book VENUS being edited by Hunten, Colin, Donahue and Moroz which is currently in press. A preprint of this paper is attached.

#### F. Mode 0 Opacity

Schofield and Taylor (Icarus 1982, in press) have reported that the thermal opacity (at  $\sim 11 \mu m$ ) due to clouds must reach unity near the 100 mb level over most of the planet to account for the thermal emission observed by the Infrared Radiometer (OIR) experiment on the PV orbiter. The azimuthal

structure observed by the LSFR experiment at  $0.63\text{ }\mu\text{m}$  at about the 100 mb pressure level indicates a visible optical depth of  $\sim 4$  for clouds above this level at the large probe entry site. Assuming that the cloud particles are composed of sulfuric acid and extrapolating the particle size distribution measured by the LCPS instrument at slightly deeper levels to greater altitudes, it seemed that the infrared and visible cloud opacities were not compatible. Of course, the structure near the cloud top could have been somewhat different from average conditions, but early estimates of the  $11\text{ }\mu\text{m}$  optical depths required by the OIR and computed from the visible cloud opacity differed by a fairly large factor of about 2, and no hot spots were reported in thermal maps at the relevant latitudes.

Suomi et al. (1980, JGR 85, 8200) proposed the existence of an additional distinct mode (termed mode 0) of very tiny aerosol particles which might not be detected by the LCPS or the LSFR experiments because of the small size of the particles, but which could have sufficient aerosol mass per unit area of the atmosphere to contribute significantly to the  $11\text{ }\mu\text{m}$  opacity. While the suggestion of these tiny aerosols suffered from the need for a very high production rate for replenishment in the face of rapid coagulation, the need for additional thermal opacity was clear, and we proposed to examine the problem briefly in our second year.

During this year, several developments occurred which reduce the apparent conflict between visible and infrared cloud opacity in this part of the atmosphere. First, we became aware of the sensitivity of the thermal to infrared opacity ratio to the assumed partition of mode 1 and mode 2 particles (with effective radii of  $\sim 0.5$  and  $1.1\text{ }\mu\text{m}$ , respectively) into the region above that measured by the LCPS. Extrapolating upward from the highest altitude LCPS data, we assumed roughly equal visible optical depths of mode 1 and mode 2 in the calculation of model F and obtained an  $11\text{ }\mu\text{m}$  opacity of  $\sim 0.6$  rather than

1 at 100 mb. However, at a pressure level of  $\sim 40$  mb, the Cloud Photopolarimeter (OCPP) experiment finds that mode 1 contributes  $\leq 15\%$  to the visible optical depth. If nearly all of the visible opacity above 100 mb is due to mode 2 particles, the corresponding  $11\ \mu\text{m}$  opacity would be  $\sim 0.8$ , almost 1 as required.

Second, Toon and Blamont (1982, Icarus, in press) have recently suggested that the still larger mode 3 particles measured in the middle and lower cloud layers occur as a natural large particle tail of the mode 2 particle population. This would imply that some of these larger particles might also exist in the less dense upper cloud region as well, where poor sampling statistics may have prevented their measurement by the LCPS. The large particles in mode 3 have a much larger infrared to visible opacity ratio than the particles in modes 1 or 2, and so even a relatively small visible optical depth of these particles could perhaps make up the last 0.1 or 0.2 of the  $11\ \mu\text{m}$  opacity required above the 100 mb level.

Finally, the labeling error in the refractive index of mode 1 in our model F calculations means that these particles were more effective visible scatterers than we realized when papers I and II were published. If only half of the mode 1 particles (instead of all of them) in model F were converted to mode 2 above 100 mb, the  $11\ \mu\text{m}$  opacity would be nearly the required value.

Thus, while detailed thermal flux calculations near  $11\ \mu\text{m}$  still remain to be done for comparison with the OIR data, we feel we have identified several effects which substantially reduce the need for a new mode of previously unseen particles with their attendant physical problems. A somewhat more detailed discussion of these effects is given in paper III.

In summary, we believe we have extracted a great deal of information from

these data during the past two years and basically have accomplished the tasks proposed under this grant. Highlights of the results of our analysis include the following:

1. The measurement of the upward, downward, and net profiles of solar flux from  $0.4 - 1.8 \mu\text{m}$  at the large probe PV entry site from  $\sim 62 \text{ km}$  to the surface with a vertical resolution of a few hundred meters. These data have been placed in the PV UADS system and transmitted to the National Space Science Data Center.
2. Fitting this profile with a cloud model, and evaluating the solar net flux profile for globally averaged conditions. This profile showed that  $\sim 2.5\%$  of the sunlight incident on Venus is absorbed at the ground - an amount sufficient to produce a very strong greenhouse effect which dominates the thermal balance of Venus' lower atmosphere.
3. Determining several details of the cloud structure on Venus including
  - a. a visible optical depth of  $\sim 4$  above 100 mb;
  - b. the existence of three distinct cloud layers with boundaries at 57, 50 and 48 km, as well as the optical thickness of each and;
  - c. the confinement of the absorption of significant solar energy by cloud particles essentially to only the upper cloud.
4. Exerting significant impact on the interpretation of data from other experiments including
  - a. the indication that the mode 3 particles may not be spherical or that the calibration of the large particle size range of the LCPS should be readjusted based on the relatively small flux change observed in the middle and lower clouds, and;
  - b. the need for re-examination of the thermal net flux measurements in light of their large values compared with the solar fluxes.

We do plan to continue to incorporate the LSFR data in other studies of Venus' atmosphere including a model of the radiative heating rate profile in the clouds and above, a study of the penetration of short wavelength solar radiation into Venus' atmosphere, and continued comparisons between the broadband LSFR data and the Soviet visible spectra obtained beneath the clouds.

We are very grateful to have had the opportunity to participate in the Pioneer Venus program, and are very appreciative of the support we have received through grant NAGW-55 for the extended analysis of these unique measurements.

### III. PUBLICATIONS

Papers published during the period from 1980 - 1982 covered by grant NAGW-55 are listed below.

Pioneer Venus Sounder Probe Solar Flux Radiometer, M.G. Tomasko, L.R. Doose, J.M. Palmer, A. Holmes, W.L. Wolfe, A.G. deBell, L.R. Brod, and R.R. Sholes, I.E.E.E. Trans. Geosci. Rem. Sensing GE-18, 93, 1980.

Broadband Radiometry with Spectrally Selective Detectors, J.M. Palmer and M.G. Tomasko, Optics Letters 5, 208, 1980.

Narrow-field Radiometry in a Quasi-isotropic Atmosphere, A. Holmes, J.M. Palmer, and M.G. Tomasko, S.P.I.E. Proc. 196, 27, 1980.

Measurements of the Flux of Sunlight in the Atmosphere of Venus, M.G. Tomasko, L.R. Doose, P.H. Smith, and A.P. Odell, JGR 85, 8167, 1980.

The Thermal Balance of Venus in Light of the Pioneer Venus Mission, M.G. Tomasko, P.H. Smith, V.E. Suomi, L.A. Sromovsky, H.E. Revercomb, F.W. Taylor, J.V. Martonchik, A. Seiff, R. Boese, J.B. Pollack, A.P. Ingersoll, G. Schubert, and C.C. Covey, JGR 85, 8187, 1980.

The Clouds of Venus: A Synthesis Report, R. Knollenberg, L. Travis, M.G. Tomasko, P.H. Smith, B. Ragert, D. McCleese, J.V. Martonchik, and R. Beer, JGR 85, 8059, 1980.

Distribution and Source of the UV Absorption in Venus' Atmosphere, J.B. Pollack, R. Boese, B. Ragert, M.G. Tomasko, L. Esposito, L. Travis, and D. Wiedman, JGR 85, 8141, 1980.

Cloud Structure and the Flux of Sunlight in the Atmosphere of Venus, L.R. Doose, M.G. Tomasko, P.H. Smith, N.D. Castillo, and A.P. Odell, Bull. Amer. Astron. Soc. 12, 717, 1980.



The Thermal Balance of the Lower Atmosphere of Venus, M.G. Tomasko. In Venus, D. Hunten, L. Colin, T. Donahue, and V. Moroz eds. (Tucson: Univ. of Arizona Press). In press.

The Thermal Balance of the Atmosphere of Venus. Given in Planetary Upper Atmospheres and Ionosphere session of COSPAR, Budapest, Hungary, June 1980.

The Thermal Balance of Venus in Light of the Pioneer Venus Mission. In Proc. of the Workshop on Vibrational-Rotational Spectroscopy for Planetary Atmospheres, Annapolis, MD, March 1980.

The Thermal Balance of the Lower Atmosphere of Venus, M. G. Tomakso. In Proc. of the International conference on the Environment of Venus, Palo Alto, CA; November 1981.