Water Vapour in Venus' Middle Atmosphere; Pioneer Venus Revisited

M E Koukouli[1] and P G J Irwin
Atmospheric, Oceanic and Planetary Physics, Oxford University,
Clarendon Laboratory, Parks Road,
Oxford, OX1 3PU, U.K.

Abstract

We have used *Pioneer Venus Orbiter Infrared Radiometer* observations of thermal emission from Venus' middle atmosphere between 10°S and 90°N to determine temperature, cloud optical depth and water vapour mixing ratio profiles as a function of altitude. The spectral regions observed include the 45 μm rotational water band and the strong 15 μm carbon dioxide band. New correlated-k radiative transfer and retrieval models have been developed based on k-tables calculated from new line data. The H_2SO_4 cloud opacity and scattering properties have been recalculated from new refractive index data using Mie theory. It is found that the inclusion of scattering does not lead to significantly different radiances than those calculated from more simple thermal emission models. Previous studies (Schofield et al., 1983) have reported a remarkably high abundance of water vapour in the early afternoon, almost a hundred times the planet-wide average, in a localised region above the cloud-tops at equatorial latitudes. We discuss our newly retrieved profiles in the context of this "wet spot" and in conjunction with the findings from the *Fourier Spectrometer* on board the *Venera 15* spacecraft. The *Venera 15* data will eventually be used to constrain our own retrievals and the combined analysis will lead to much more robust water vapour abundance global maps since we intend to combine the information from the high spectral resolution *Venera 15* data with the lower spectral resolution, but better spatially sampled, *Pioneer Venus* data. Brief mention will also be given to other water vapour observations placing our work in a more comprehensive context.

1 The Planet Venus and Water Vapour

Venus, the second planet from the Sun in our Solar System and the Earth's close companion, has captured people's imagination for many thousands of years. Seen both as a "morning" and "evening star" depending on the relative orbits of the two planets, Venus is completely shrouded in bright, reflecting clouds that keep the surface hidden, its atmosphere is almost entirely composed of carbon dioxide and the surface temperature and pressure of ~735K and 92 bar respectively preclude any form of life. And coming from a planet overabundant in water, the question of why Venus is so underabundant in this important chemical element is an interesting and important one.

Figure 1 summarises most of the studies of water vapour in Venus' lower and middle atmosphere. Earth-based, satellite and *in situ* studies have been performed in order to measure the abundance of this minor constituent. An upper abundance limit of 3000 *ppm* (below the cloud levels) has been deduced from the absence of microwave features in the absorption spectrum (Janssen and Klein, 1981), but the lower limit and the actual altitude variation are still open to debate. The highest disagreement between observations can be seen between 40 and 70 km altitude, the region of the thick H_2SO_4 clouds where up to four orders of magnitude difference can be noted on the logarithmic scale for water vapour abundance. In order to

[1] Please direct all correspondence to: mek@atm.ox.ac.uk

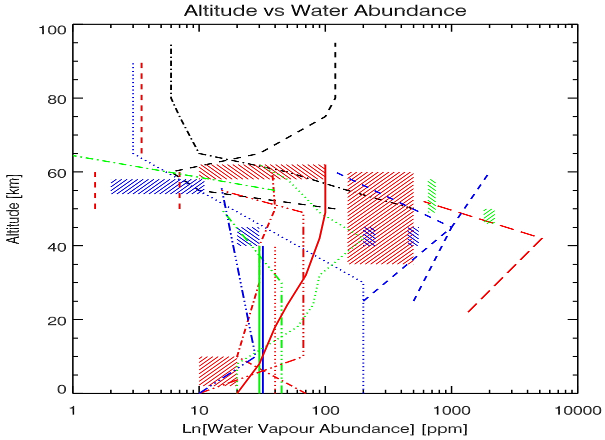

Figure 1: Water vapour abundance in Venus' atmosphere from *in situ* , satellite and Earth-based observations. Red-filled squares left-slanted: Moroz et al. (1990), red-filled squares right-slanted: Moroz et al. (1982), red long-dashes line: Oyama et al. (1980), red-dashed lines: Encrenaz et al. (1995), Encrenaz et al. (1991), red-dotted line: Crisp et al. (1991), red dash-triple dotted line: Donahue and Hodges (1992), red solid line: Moroz et al. (1979), red dash-dotted line: Ignatiev et al. (1997), blue-filled square right-slanted: Ignatiev et al. (1999), blue-dotted line: Bell III et al. (1991), blue dash-triple dotted line: Donahue and Hodges (1993), blue solid line: Pollack et al. (1993), blue dashed lines: Surkov et al. (1982), blue-filled squares left-slanted: Revercomb et al. (1985), green-filled squares right-slanted: Surkov et al. (1982), green-filled squares left-slanted: Mukhin et al. (1982), green dash-dotted line Bezard et al. (1990), green dash-triple dotted line: Meadows and Crisp (1996), green solid line: de Bergh et al. (1995), green dotted line: Young et al. (1984), black dashed line: Schofield et al. (1983)[night-side], black dash-dotted line: Schofield et al. (1983)[day-side].

attempt and reconcile this disagreement, we have decided to study the Pioneer Venus Orbiter Infrared Radiometer, *PV OIR* , data in parallel with the Venera 15 Interferometer data, that have also studied the same region of the atmosphere looking at water vapour abundance. In Figure 1, the black lines depict the first analysis of the *PV OIR* data by Schofield et al. (1983); the black dashed line is the night-side abundance retrieved and the black dash-dotted line is the day-side. The *Venera 15* data is shown as a blue-filled right-slanted square (Ignatiev et al., 1999).

2 Temperature, Cloud and Water Vapour Retrievals

To be able to analyse remote sensing data one must follow two steps; first, to construct a *forward model*. This model predicts the radiance that a specific satellite or telescope would have observed given the atmospheric state, absorber species characteristics and cloud profile. Secondly, to solve the inverse problem using a *retrieval model* which, given real radiance measurements, will infer the atmospheric conditions under which they were taken, using the results of the forward models and *a priori* constraints. Hence knowledge of the temperature structure in the atmosphere, the abundance of its minor constituents and their variation with altitude, latitude and longitude can be obtained. In this study, we are using the non-linear optimal estimation technique of Rodgers (1976) to solve the general *radiative transfer equation* by minimising the difference between the measured and forward-modelled radiance, subject to minimum departure from the *a priori* field.

In the newly created forward and retrieval model, we are using the Rothman and collaborators (1998) molecular spectroscopic database to create correlated-k tables (Lacis and Oinas, 1991) for the absorption properties of the Venus atmosphere which, in our model, contains 98.5% CO_2 , 2.5% N_2 and trace amounts

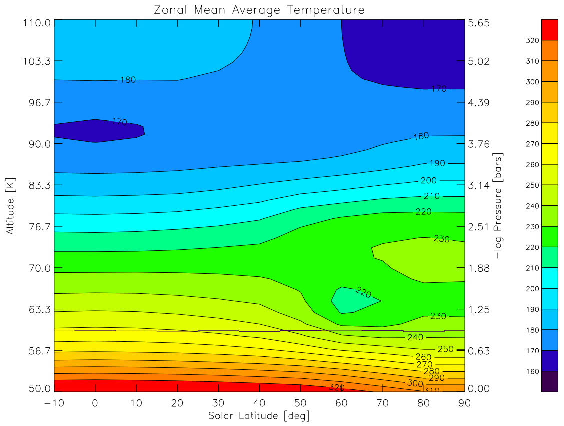

Figure 2: Retrieved zonal mean temperature field [K] as a function of altitude [km] (pressure [-log (bar)]) and latitude [deg]. The black line denotes the unit optical depth for the cloud as retrieved from the 11.5 μm measurements.

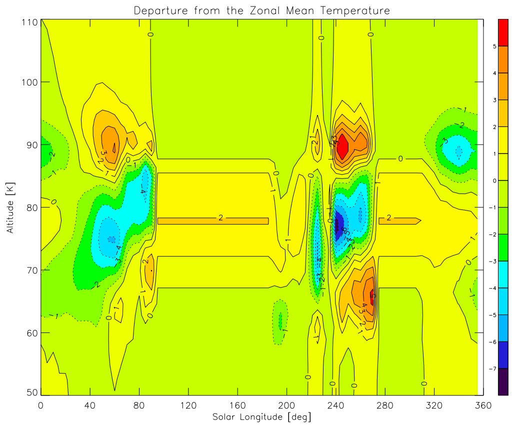

Figure 3: Deviation of the meridional field from 0-30°N from the zonal mean temperature [K] as a function of altitude [km] and longitude [deg].

of SO_2 and H_2O . The optical properties of the H_2SO_4 clouds, that greatly contribute to the radiances observed, have been calculated using Mie theory with experimental data from Jones (1976) and Biermann et al. (2000). Test runs showed that, for the *PV OIR* spectral range $\sim$ 10 to 200 μm to include scattering in the solution of the radiative transfer equation does not contribute significantly to the predicted radiances of the forward model. We thence continued with performing calculations on a thermally emitting atmosphere only.

From the ten *PV OIR* sounding channels, we are focusing on four fixed grating spectrometer channels; three from within the 15 μm CO_2 band and one in the atmospheric "microwindow" near 11.5 μm to sound the clouds. These are used to obtain temperature and cloud structure information at various levels in the atmosphere starting at $\sim$50 km altitude. We are also using a reflecting filter, centred at 45 μm, for the H_2O measurements, using information from five spectral channels in total. The instrument took measurements for 72 orbits covering most of the North hemisphere and down to 10° of the South hemisphere, with an unfortunate gap between 120 and 150°W. In this work, we have binned this data, within each orbit, into 5° in latitude and 5° in longitude bins, without performing any averaging. We then retrieved temperature, cloud-top pressure and water vapour abundance simultaneously within each bin.

Figure 2 shows that at equatorial latitudes, temperatures fall monotonically to a min below 170K at 95km and rise to more than 180K above 100km. At 105km, the pole is 15-20K cooler than the equator but between 70 and 95km the pole is warmer by 25K. The polar collar region is evident from 60-80° N where the temperatures are up to 30K less than those at equatorial latitudes. In Figure 3 we can note the presence of a gradual eastward upwind tilt of solar-fixed wavenumber-2 structure with increasing altitude. The apparent zero deviation seen between 120 and 150°W is due to lack of data for the latitude range in question, and not a retrieved feature. These results agree well with the findings shown in Schofield and Taylor (1982). Due to the preliminary nature of this work, we cannot yet formally present a comprehensive water vapour abundance map but investigations show strong day-to-night variations, an interesting feature to be discussed in later work.

3 Conclusions

In this paper, we have presented the first results from the new retrievals of the *Pioneer Venus Orbiter Infrared Radiometer* and shown that the new radiative transfer and retrieval algorithm validates results presented in the past by Schofield and Taylor (1982) and Schofield et al. (1983). The next step in our study will be to use this retrieval algorithm to analyse and examine the *Venera 15* spectra. The overlapping spectra range and planetary coverage will allow us to use common assumptions and *a priori* information in a new comprehensive analysis that will greatly reduce discrepancies between the two instruments' results presented in previous studies. A major source of uncertainty in our retrievals has always been the poor understanding of the optical properties of the H_2SO_4 cloud and its precise contribution to the thermal atmospheric emission. To overcome this problem, Ignatiev et al. (1999) have used a small correction factor in their absorption coefficients that we intend to adopt in our retrievals and for the first time combine to different data sets in this manner to create robust water vapour abundance global maps.

Acknowledgements

The authors would like to thank the Bodossaki Foundation, Athens, St Peter's College, Oxford and the Local Organising Committee, Heraclion, for generously facilitating the presence of *M E Koukouli* in the 5th Hellenic Astronomical Society meeting.

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