Airborne observations of Venus: Past, Present and Future
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Summary
The role of airborne observatories and their study of the most basic parameters concerning Solar System bodies usually reside as footnotes in the annals of planetary science exploration. This is due in part to the high profile and obvious advantages of spacecraft observations over terrestrial platforms. However, airborne observations of the planets have a long and vibrant history. In this paper, we review the past airborne observations of Venus starting in the mid 1960’s, what was achieved and its context within the planetary missions of its time. We will then discuss the current regeneration and investment by NASA for airborne observations and its potential to provide concurrent, cheap and effective science.

Introduction
With the current and next generation of spacecraft orbiters, equipped with advanced remote sensing instruments, and increasingly powerful ground-based telescopes, it may be thought that airborne observations of Venus could be redundant. Spatial resolutions provided by spacecraft are unrivaled whilst ground-based telescopes provide complementary observations in wavelength and temporal coverage. However, investment in planetary exploration missions is expensive and time consuming, with stiff competition for prospective targets, whilst astrophysics and cosmology have the lions share of ground-based telescopes usage. Airborne observations of the planets provide a cost effective way of conducting excellent science. High in the atmosphere, good seeing, especially for a large extended source like Venus, with a small airborne telescope can compete with much larger ground-based telescopes, at a fraction of the cost.

With the plethora of new data of the Venus atmosphere and surface from the recent Venus Express mission, as well as the upcoming Akatsuki orbiter, it has become apparent that we need to observe Venus for long periods with a dedicated system. Phenomena such as long period waves in the lower atmosphere and short temporal and highly random events such as polar haze brightening events, means understanding these important atmospheric mechanisms is difficult to do from the current standard telescope facilities.

These issues were to some degree understood during the mid-1960’s, when Venus became the target for planetary exploration during the start of the space race. Airborne observations can be broken down to three forms, all of which aim to penetrate most of the Earths atmosphere; i) balloon-borne, ii) sounding rockets, iii) aircraft. By far the most used to date are observations by aircraft.

Past Balloon and Rocket Observations
Initial airborne observations of Venus were with balloons, first in 1959 and then in 1964, detecting and confirming water on Venus for the first time (Bottema et al. 1965). Flying at ~80,000 ft, the 1.19 μm reflectance spectra showed Venus was as dry as the Earths stratosphere. The concept of balloon-borne Venus observations was again resurrected in 1983 when 200-320 nm reflectance spectra were measured and the SO₂ abundance above the cloud-tops were determined (Parisot et al. 1986). They found the abundance of 0.07 ppmv to be consistent with previous measurements.

Sounding rockets have occasionally viewed Venus, primarily in the UV region. Jenkins et al. (1969) were the first, measuring the 2100 and 3070 Å range, and with gyro-stabilization, the spectral resolution was ~1 Å. Upper limits were placed on the species of O₃, NH₃, SO₂ (6x10⁻² cm⁻²), NO, NO₂, and OCS. This was followed more recently by the studies of Na et al. (1994) and McClintock et al. (1994), where two rocket launches were made in 1988 and 1991. Viewing between 190-230 nm, Venus SO₂ and SO were measured. They found the SO₂ abundance was 80 ± 40 ppb for 1988 and 120 ± 60 ppb for 1991 for the same altitude region, in good agreement with Pioneer Venus Orbiter (PVO) measurements.

Past Aircraft Observations
The concept of observing Venus from an aircraft was pioneered when Gerard Kuiper in 1967 used a NASA Ames Convair CV-990 converted civilian airliner to observe the Venus cloud-tops. The 1 – 2.5 μm (R=20 cm⁻¹) spectra, taken with a
12" telescope at 37,000 ft, confirmed Venus was extremely dry, and additionally, the clouds were devoid of water ice crystals (Kuiper et al. 1967). The ratio of Lunar to Venus spectra gave a value of only a few µ of water as measured at 1.4 and 1.9 µm. This low level of water vapor also preclude what was then the real possibility of water ice in the clouds on Venus. This was later challenged by Plummer (1970) who showed the data could still be fitted with water ice particles.

Further progress was made in the mid-1970s with observations of the Venus clouds using a NASA Ames Learjet (Pollack et al. 1974, 1975). A f/5.5 30 cm (11") Cassegrain telescope was placed in the executive jet, viewing through a window aperture, which was gyro-stabilized to ± 2 arcminutes. Flying at 13 km (~42,000 ft) for periods up to 2.5 hr. A circular variable filter covered wavelengths from 1.2 to 4.1 µm. Reflectivity measurements as a function of phase angle of the sunlit Venus cloud-tops were measured with great success. It provided a large body of data, which finally resolved the issue of the nature of the Venus clouds to be of sulfuric acid in composition. By fitting theoretical reflectivity curves (created by a Mie multiple-scattering doubling radiative transfer model) to the data, the authors were able to not only come to the conclusion of sulfuric acid clouds, but also to determine its mean acidity to be 85% H₂SO₄. They also showed the cloud must also extend to many tens of optical depths, and derived a theoretical limit for the cloud base altitude of 45 km. The cloud makeup was further validated with 17 – 38 µm infrared spectra from the Learjet using a cooled grating spectrometer (Reed et al. 1978). These observations were concurrent with NASA’s PVO program.

At the same time, with the same aircraft, Gull et al. 1974 used an echelle grating spectrometer to measure the 0.82 µm H₂O band
and derived a disc-integrated cloud-top value of 3 ± 20 µ. This was in-line with an earlier study of Fink et al. 1972 using the near-infrared on the CV-990, who measured a model dependent value between 0.6 and 1.0 ppmv.

The development of the Kuiper Airborne Observatory (KAO) was completed at the same time in 1974. This converted C-141 Starlifter military transport, operated again by NASA Ames, held a 91 cm (36") telescope, which operated from 1 – 500 µm range, including Michelson interferometer FTS systems (Larson et al. 1978), and could operate up to 41,000 ft. By the end of its 21 year lifetime in 2005, it made important discoveries such as the first observation of the rings of Uranus and the discovery of the thin Pluto atmosphere.

Observing Venus, KAO was used to measure the cloud structure. Aumann et al. (1979) observed using a Michelson interferometer between 500 and 800 cm⁻¹ (12 to 20 µm). They found the disc-integrated spectrum was fitted with mode 0 haze particles at the cloud tops, whilst still requiring some additional larger (R>1 µm) particles to fit the spectra. They also retrieved temperature profiles down to 1.6 mbar, the temperature of which were between those obtained by Mariner 5 and Mariner 10. This was validated by further measurements in the 110 cm⁻¹ (91 µm) to 270 cm⁻¹ (39 µm) far-infrared region (Aumann et al. 1982), again on KAO. The later study was conducted 3 months after PVO was inserted into Venus orbit.

The most recent airborne observation of Venus was made by Bjoraker et al. (1992) using KAO in the 2.59 – 2.64 µm range (R=0.029 cm⁻¹) to measure H₂O, HDO, HF, D/H and ¹⁸O/¹⁶O species at the cloud tops (72 km).

Current and Future Aircraft Observations

The current NASA airborne observatory is SOFIA, the Stratospheric Observatory for Infrared Astronomy. This Boeing-747SP houses a 2.5 m telescope in its rear port side, and will be capable of accommodating numerous infrared instruments, from near-infrared spectrometers to mid-infrared imagers. First light occurred in May 2010 with the FORECAST imaging of Jupiter and its moons at 5.4, 24, and 37 µm. At an operational altitude of 45,000 ft, SOFIA will be start science operations in late-2011.

Already, Venus science is expected to benefit from this new observatory. Current theoretical studies with the EXES spectrometer (Echelon-crossed Echelle Spectrograph) by Encrenaz et al. 2010 will observe Venus between 5 and 25 µm, at spectral resolutions up to R~100,000. Measurements of SO₂, H₂SO₄, H₂O, HDO and temperature, all at the cloud-top level, are expected to provided details into the chemistry and dynamics of the atmosphere which was lost with the failure of PFS (Planetary Fourier Spectrometer) on Venus Express. This spectral range has not been studied since Venera 15 in the mid-1980s. The EXES spectrometer is due for first light in 2011 on the Infrared Telescope Facility on Mauna Kea, with its first flight on SOFIA expected in 2014.

A second, less well-known platform that is currently being modified to observe Venus is the WB-57F Canberra. Onboard is the WAVE imaging system, originally designed to observe the Space Shuttle in its ascent into orbit, as part of the Return-To-Flight program after the Columbia Accident in 2003. The WAVE system comprises a Schmidt-Cassegrain 11” mirror on a stabilized gimbal to reduce jitter, with a dichroic beam splitter. Attached is a HD camera and an infrared camera, capable of broad-band imaging between 0.8 to 1.7 µm. Flying at an altitude of ~65,000 ft, the 2010 Venus inferior conjunction will provide the first test of this instrument for astronomy purposes (Tsang et al. 2010). Narrow-band filters (FWHM=0.01 µm) at wavelengths of 0.85, 0.90, 0.95, 0.97, 1.01 and 1.05 µm is currently being setup in a filter wheel for spectral imaging, to observe the Venus surface at these rarely used wavelengths. This will help form part of the validation for the NIR1 camera onboard the Japanese Akatsuki mission, due to arrive at Venus in December 2010. These measurements will help elucidate on the surface emissivities and the atmospheric water vapor abundance in contact with the surface. It is hoped these measurements will pave the way for future observations of faint transiting objects, such as Pluto, at locations where telescopes are almost impossible to observe from.

Future Observations

An inherent drawback to aircraft observatories is the limitation of fuel, which restricts the total contiguous observing time possible. An exciting new possibility is to observe Venus from a balloon platform, one which circumnavigates the globe, has no reliance on fuel and can continually observe Venus for weeks on end. Current studies by Young et al. (2008) show a 1 m telescope can achieve diffraction limited seeing of 0.3" at 1.74 µm, at near space altitudes of 35 km. The synoptic picture of the Venus cloud structure and atmosphere seen by such a platform would be.
unrivalled, even from the equatorial Akatsuki orbiter. The cost of such a mission would also be relatively inexpensive for the science return. It also provides the quickest way of continued observations by NASA, which currently has no concrete plans for a mission to return to Venus.

References

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