

The transit of Venus in June 2012 provided a unique chance to view a well studied planetary atmosphere as we might see that of a transiting exoplanet, through scattered and refracted illumination of its parent star. This is the second time that Venus's IR atmospheric transmission has been measured during a transit; previous observations were made with the Tenerife Infrared Polarimeter during the 2004 transit by Hedelt et al. (2011), who confirmed well established isotopic abundances and atmospheric scale height. We performed spectroscopy and polarimetry during the transit of Venus focusing on extracting signatures of  $CO_2$  absorption. Observations were taken during the first half of the transit using the Facility InfraRed Spectropolarimeter on the Dunn Solar Telescope. The transit also gave us an opportunity to investigate instrumental effects using the very dark background provided by the planet. In this poster we discuss the status of the data reduction and compare of Venusian transmission models with the observed spectra.

The Facility InfraRed Spectropolarimeter (FIRS) is a high-cadence imaging-spectrograph for the study of solar magnetic phenomena of the photosphere and chromosphere. The typical operating modes of FIRS allow simultaneous observation of 630.2 nm in the visible and 1565 or 1083 nm in the infrared, using multiple slits coupled with narrow-band filters to achieve higher cadence than a typical long-slit spectrograph, see Jaeggli et al. (2010) for more details.

Although the predicted CO<sub>2</sub> transmission spectrum of Venus is not particularly strong at 1565 nm, this region of the H-band often used in magnetic-field studies of the Sun's photosphere provides a particularly flat solar continuum with few atmospheric and molecular lines, against which the CO<sub>2</sub> lines can be detected. A 40  $\mu$ m (0.3" wide, 75" tall) single slit was used and the narrowband filter was removed to expand the spectral coverage, but the broad-band filter was retained to attenuate neighboring orders of the spectrograph. Removing the narrow-band filter also required the addition of a field stop near a pupil plane to avoid saturating the detector at the minimum exposure length and adjustment of the focus of the final lens before the detector.

First contact of the transit began at a local time of 16:09:38 on June 5, 2012, during which Venus had an apparent size of 57.8". Local conditions were clear, although there was a high level of low-lying haze along the western horizon due to wildfires. Seeing conditions were typical for late afternoon, with intermittent periods of good seeing gradually deteriorating toward sunset. The High-Order Adaptive Optics system was used to track and stabilize the image after about half of Venus was visible on the disk.

Observations with FIRS started slightly before first contact. The FIRS slit was aligned perpendicular to the transit path and was scanned in the direction of the planet's path across the Sun. Only intensity was measured during the first part of the transit so that rasters could be performed rapidly as Venus was crossing the solar limb, but polarimetry was used as Venus approached greatest transit. A summary of the observation parameters and timeline is given below.

Intensity Rasters: 4.5 minute scans, 125 msec single exposure, 250 step scans

Full-Stokes Rasters: 20 minute scans, 125 msec exposure with 2 coadds at 4 polarization states, 250 step scans



3. Data Reduction and Analysis

All images were dark subtracted and then corrected for the significant detector non-linearity. Flat field images were constructed from observations of Sun center taken before and during the transit. A solution to the spectral geometry and wavelength was determined based on line fitting in spectra taken with a calibration grid. The spectra were then interpolated to make the spectral and spatial coordinates rectilinear. The average quiet-Sun profile determined from the geometrically transformed images was used to produce a master flat with the spectral lines removed. The flat field was divided from the data and the resulting spectra were stacked into cubes for each scan.



Sarah A. Jaeggli Post-Doctoral Researcher

email: jaeggli@solar.physics.montana.edu address: Montana State University, Physics Dept. Bozeman, MT 59715 **phone:** 406.994.6072

# 1565 NM OBSERVATIONS OF THE TRANSIT OF VENUS PROXY FOR A TRANSITING EXOPLANET

Sarah A. Jaeggli<sup>1</sup>, Kevin P. Reardon<sup>2</sup>, Jay M. Pasachoff<sup>3</sup>, Glenn Schneider<sup>4</sup>, Thomas Widemann<sup>5</sup>, & Paolo Tanga<sup>6</sup> <sup>1</sup>Montana State University, <sup>2</sup>NSO/Sacramento Peak, <sup>3</sup>Williams College, <sup>4</sup>Steward Observatory, <sup>5</sup>Paris Obs./LESIA, <sup>6</sup>Obs. de la Côte d'Azur

# Abstract

### . Instrument

# 2. Observations

Contact



Figure 1: A scan map of Venus crossing the solar limb showing how the spectral cubes were restructured for analysis.

#### Fringes

The FIRS infrared data is contaminated by fringes which are often difficult to remove  $\overline{T}_{\sigma}$  0.4 even with frequent flat fields. These fringes seem to be from two different sources. High-frequency fringes have been found to be well-aligned with the detector and are likely features of the readout electronics. Low frequency fringes are aligned with the spectra and due to optical interference in the instrument. The image power spectrum in Figure 2 from a single raw image of the



Figure 2: Power spectrum of a raw flat field image.

disk-center quiet-Sun clearly shows power at two spatial frequencies, vertical fringes with a 5 pixel period, and diagonal fringes with periods of 3 and 20 pixels in the x and y directions. These peaks in the power spectrum appear at a consistent frequencies in all images. Casini et al. (2012) have successfully removed fringes in portions of the fully reduced FIRS 1083 nm data using a PCA method. This technique works well for the He I lines, but not for lines which are still present in the quiet Sun. Successful removal of the fringes will be critical for accurate fitting of the narrow  $CO_2$  lines in individual spectra.

The scan starting at 16:19 MDT taken while Venus was crossing onto the solar limb had the brightest arc from which the spectrum could be extracted. The spectra in Figure 3 were produced by averaging over the arc positions in the limb-justified data cube (top panel), the average offlimb stray light spectrum was subtracted and the residual solar spectrum was divided (middle panel), and a line spectrum was made by averaging over the spatial extent of the arc (bottom panel). A synthetic spectrum given to us by Pascal Hedelt (Hedelt et al., 2011) of the Venus model atmosphere was resampled and convolved with the FIRS spectrograph profile determined from laser measurements (Jaeggli, 2011) to produce the model spectrum shown in violet.



Figure 3: The mean spectrum in the arc of Venus during the scan starting at 16:19 MDT.

# (3. cont.)

The limb of Venus was fit in each of the data cubes. For on-disk positions, the derivative was taken in the dimension along the slit and the position of the peak was determined at the upper and lower edge. For off-limb positions the aureole arc was fit directly from the image. These limb positions were then used to re-map the data cubes such that the edge of Venus is at the same vertical position for all scan steps as shown in Figure 1.

# 4. Aureole Spectrum

To extract the transmission spectrum from the scans on the solar disk, the series of 10 limb-justified data cubes starting at 16:32 MDT were averaged together. Spatial averages were taken separately in the north, south, east, and west quadrants. Figure 4 shows the spectrum from one quadrant (top panel), each spatial position was normalized to the mean continuum intensity (second panel), and the mean solar spectrum was divided (third panel). The final plot shows the averaged spectra from the east and west limbs of Venus alongside the model spectrum.



Figure 4: The mean spectrum of Venus over the 10 on-disk scans starting 16:33 MDT. The top panels show the progression from the original data. The bottom plots show the average spectra over East and West limbs.

The comparison between the aureole spectrum and the transmission model is highly encouraging for a more detailed analysis that will be carried out in the future. However, in the on-disk spectra it is difficult to distinguish all but the strongest Venusian lines from the solar spectrum due to instrumental effects. The priorities for future work are:

- channel of the FIRS instrument.
- is to produce a spatial and spectral stray light profile for the instrument.

This work was performed in collaboration with the Williams College Venus transit expedition, which was sponsored by Natl. Geog./Comm for Research and Exploration. All observations were taken at the National Solar Observatory, operated by the Association of Universities for Research in Astronomy, Inc. (AURA), under cooperative agreement with the National Science Foundation.

#### References

Casini, R., Judge, P. G., & Schad, T. A. 2012, ApJ, 756, 194

- Schreier, F., & Titz, R. 2011, A & A, 533, 136
- Jaeggli, S. A. 2011, PhD thesis, University of Hawai'i
- Insights, 763



# 5. On-Disk Spectrum

# 6. Conclusions

• Fringe Removal – A technique for accurate removal of the electronic and optical fringe patterns would improve future analysis of this data and benefit all other observations taken with the IR

• Stray Light Modeling – The unique nature of the Venus transit makes it possible to distinguish the various components of the stray light from the instrument and telescope. The ultimate goal

• Atmospheric Modeling – After successful fringe removal, atmospheric modeling of the Venus spectrum can yield information on the heights and compositions sampled during the transit.

Hedelt, P., Alonso, R., Brown, T., Collados Vera, M., Rauer, H., Schleicher, H., Schmidt, W.,

Jaeggli, S. A., Lin, H., Mickey, D. L., Kuhn, J. R., Hegwer, S. L., Rimmele, T. R., & Penn, M. J. 2010, in MmSAI, Vol. 81, Chromospheric Structure and Dynamics: From Old Wisdom to New