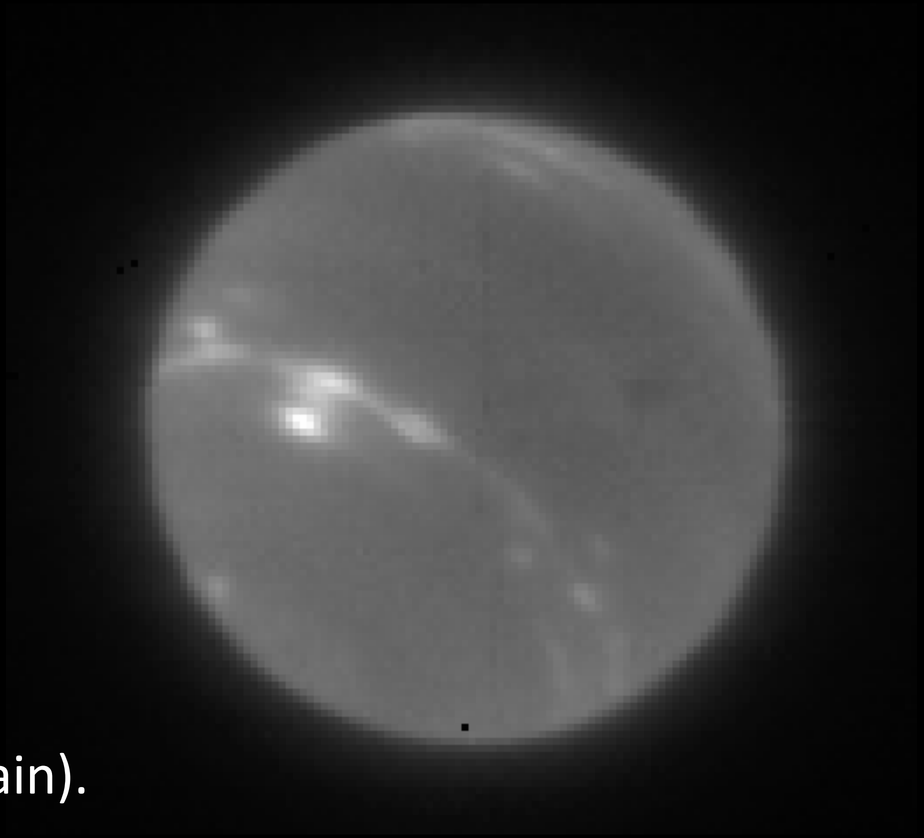
Limb-darkening reanalysis of latitudinal variation of cloud-top methane abundance in Neptune's atmosphere from VLT/MUSE-NFM



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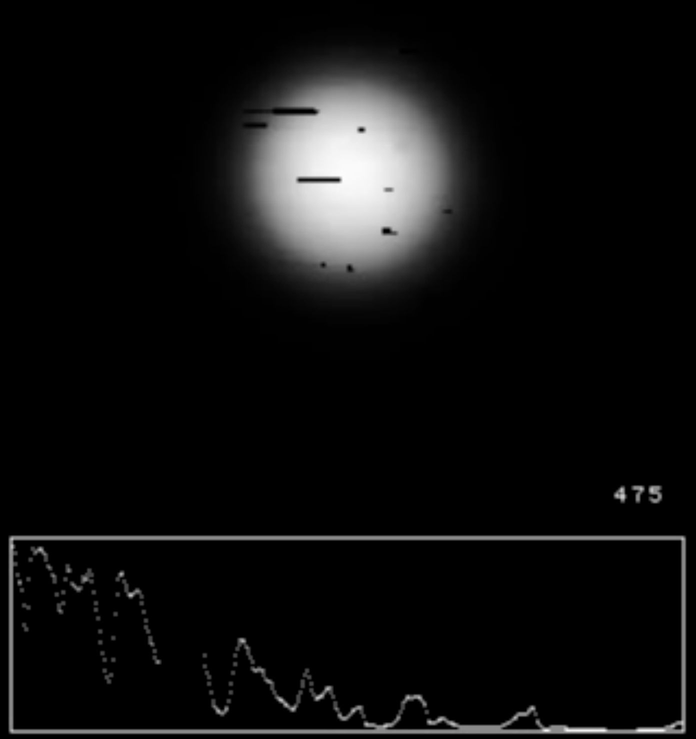
Neptune Observations



- June 19th 2018. VLT/MUSE in NFM-AO mode.
- 475 – 930 nm.
- Methane opacity variation allows probing to different altitudes so that cloud structure can be ‘retrieved’.
- But methane abundance also changes with latitude.
- Fortunately 800 – 900 nm region includes collision-induced absorption bands of H_2-H_2 and H_2-He, which allows methane abundance variations to be discriminated from cloud variations.
- Previous analysis of these data (Irwin et al., 2019) concentrated on central meridian pixels and found methane abundance reducing towards south pole, consistent with earlier HST determinations (Karkoschka and Tomasko 2011).
- New approach to Jupiter observations (Perez-Hoyos et al. 2020) applied to these data to greatly improve retrieval accuracy.

Minnaert Limb-darkening

- The dependence of the observed reflectivity on the incidence and emission angles can be well approximated using an empirical law first introduced by Minnaert (1941):

$$\frac{I}{F} = \left(\frac{I}{F}\right)_0 \mu_0^k \mu^{k-1}$$

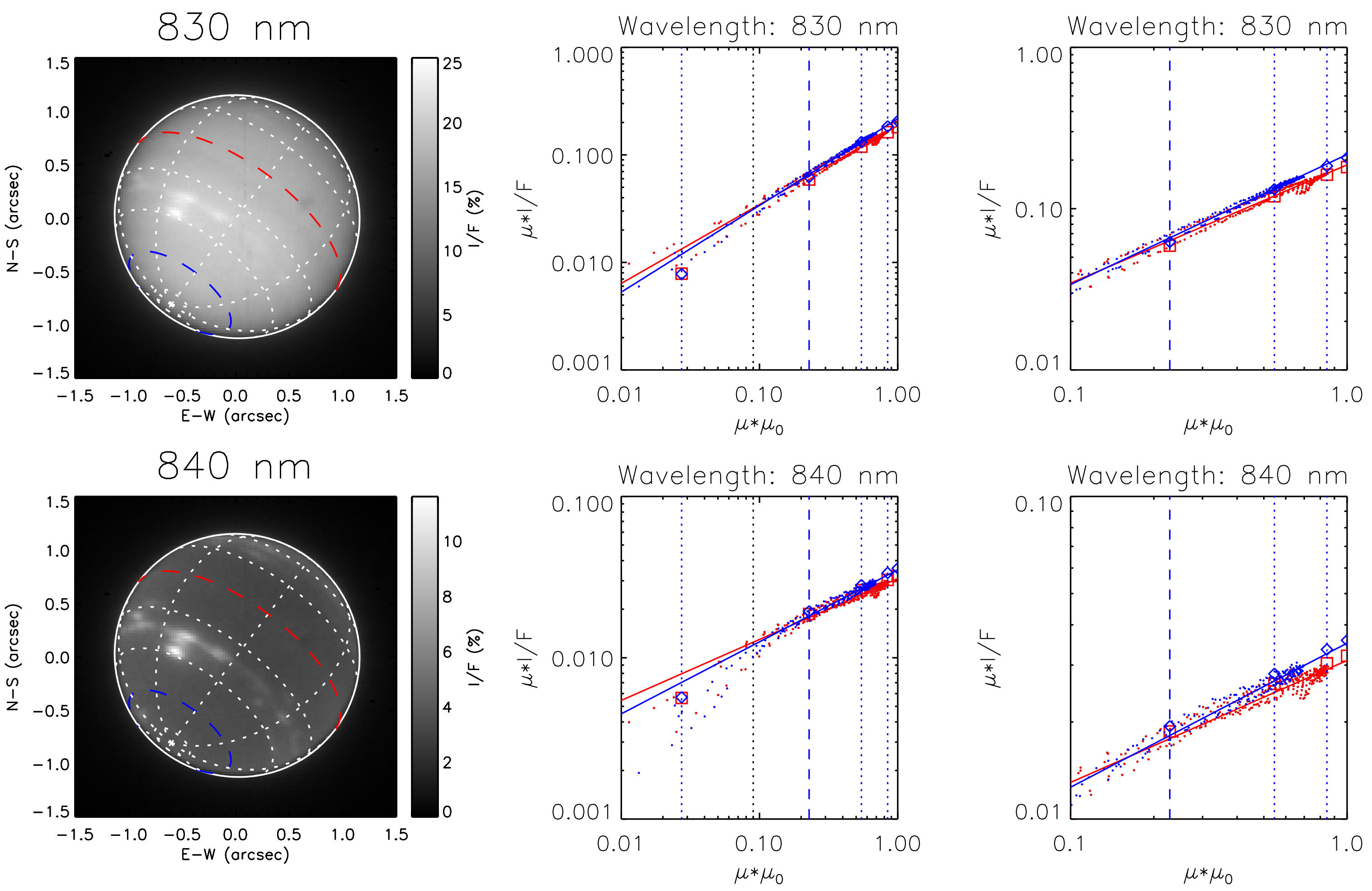
$(I/F)_0$ is the nadir-viewing reflectivity
k is the limb-darkening parameter
μ and μ_0 are the cosines of the emission and solar incidence angles respectively

- Taking logs:

$$\ln\left(\mu\frac{I}{F}\right) = \ln\left(\frac{I}{F}\right)_0 + k\ln(\mu\mu_0)$$

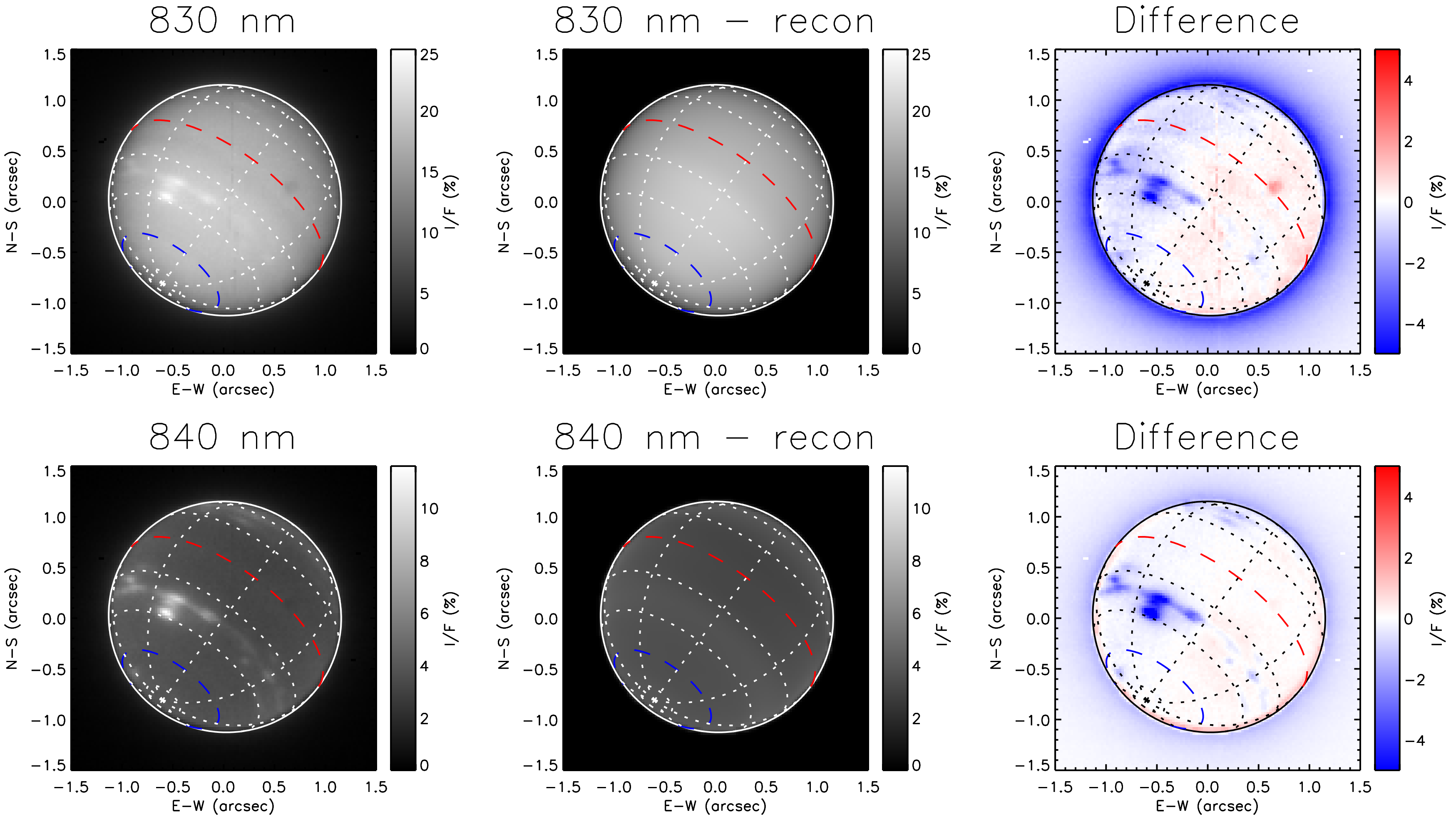
- Plotting ln ($\mu I/F$) against ln($\mu\mu_0$) should give straight line with gradient k and intercept $(I/F)_0$

Minnaert fit to observed data.

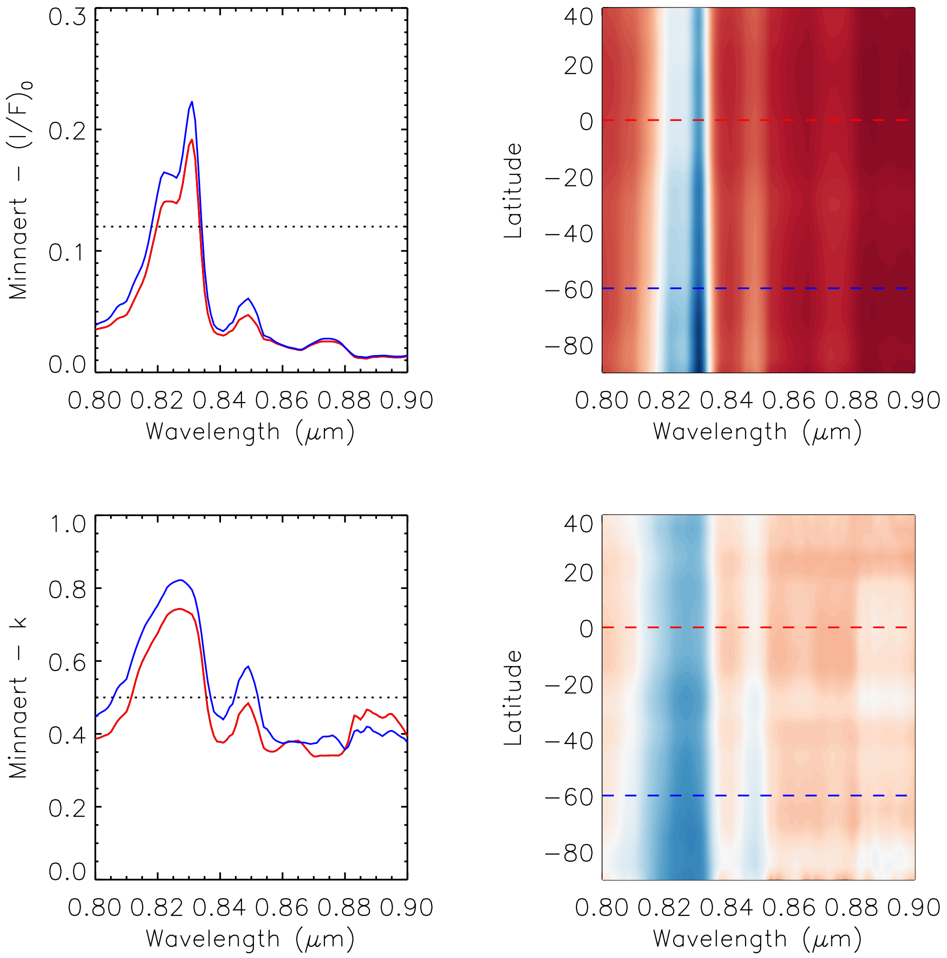


- Analysed latitude bands of width 10^{o}, stepped every 5^{o} to achieve Nyquist sampling.
- Two examples shown here at equator and 60^{o}S.

Minnaert reconstruction of observed data.



Minnaert fit to all wavelengths



N.B. Clear difference in both $(I/F)_0$ and k southwards of 40°S.

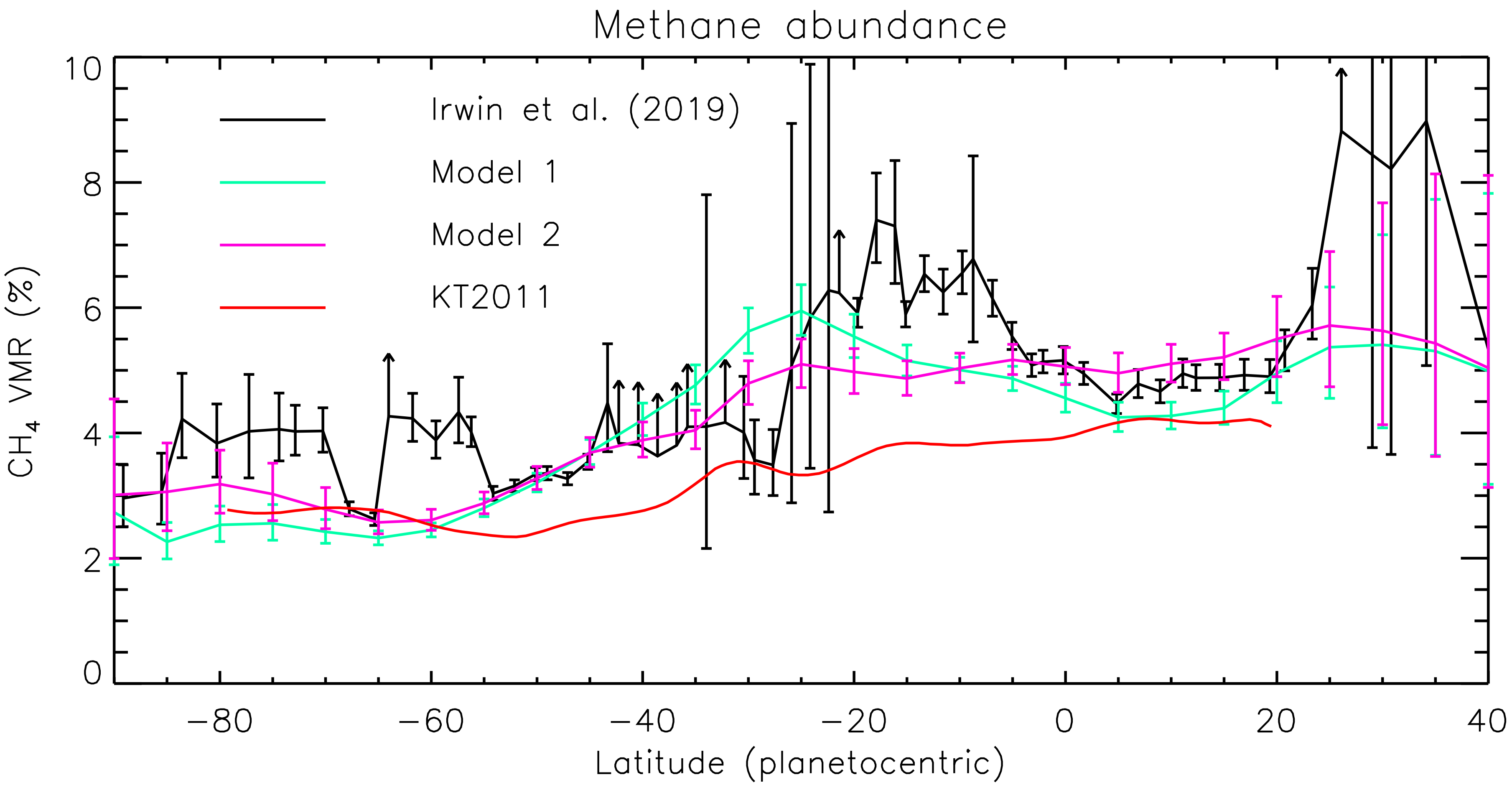
- Once we have $(I/F)_0$ and k at all latitudes we can reconstruct synthetic observations under any conditions we like.
- NEMESIS uses plane-parallel matrix operator multiple scattering code.
- Choose to analyse the spectra at 0° and 61.45°, which are two of the zenith angles in our 5-angle zenith quadrature scheme – wide enough apart to probe limb-darkening/limb-brightening, but not too near the limb to run into ‘mixing’ errors or need excessive numbers of azimuth components. Hence, sufficiently accurate and numerically efficient.
- Random error of Minnaert-synthetic spectra is very low. Need to inject additional forward-modelling noise.

NEMESIS fits

- **N**on-linear Optimal **E**stimator for **M**ultivariat**E** Spectral Analy**SIS**
- Originally developed for solar system studies, but extended for exoplanets/brown dwarfs.
- Core retrieval code based on **Optimal Estimation**, but also extended for Bayesian **Nested-Sampling** retrievals.
- Correlated-k used for gaseous absorption.

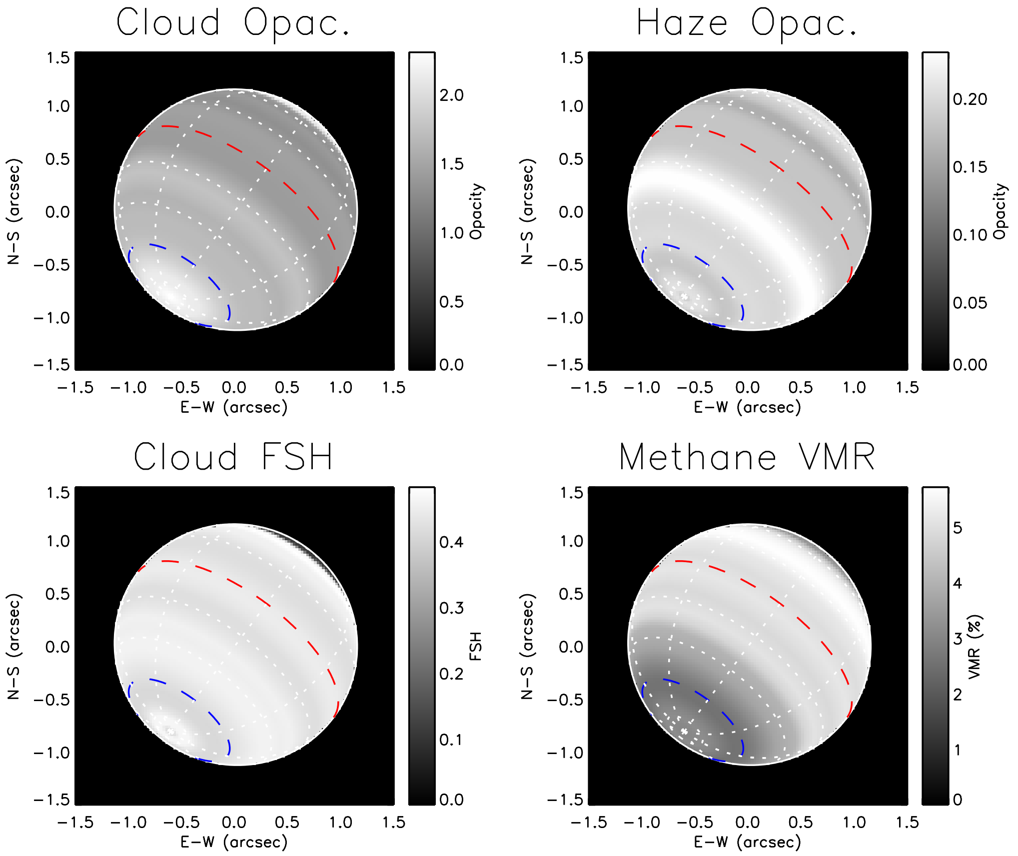
- Fit data with two-cloud model. Wide range of parameters tested, but found following setup led to the closest fits:
    - Cloud based at 4.6 bar with variable opacity and fractional scale height. Particle size ~0.1 μm, n = 1.4 + 0.001i
    - ‘Haze’ based at 0.03 bar, fractional scale height of 0.1 and variable opacity. Particle size ~0.1 μm, n = 1.4 + 0.1i
    - Variable deep methane abundance, limited to 100% VMR above condensation level and further limited to not exceed $1.5*10^{-3}$ in stratosphere.

Fitted methane



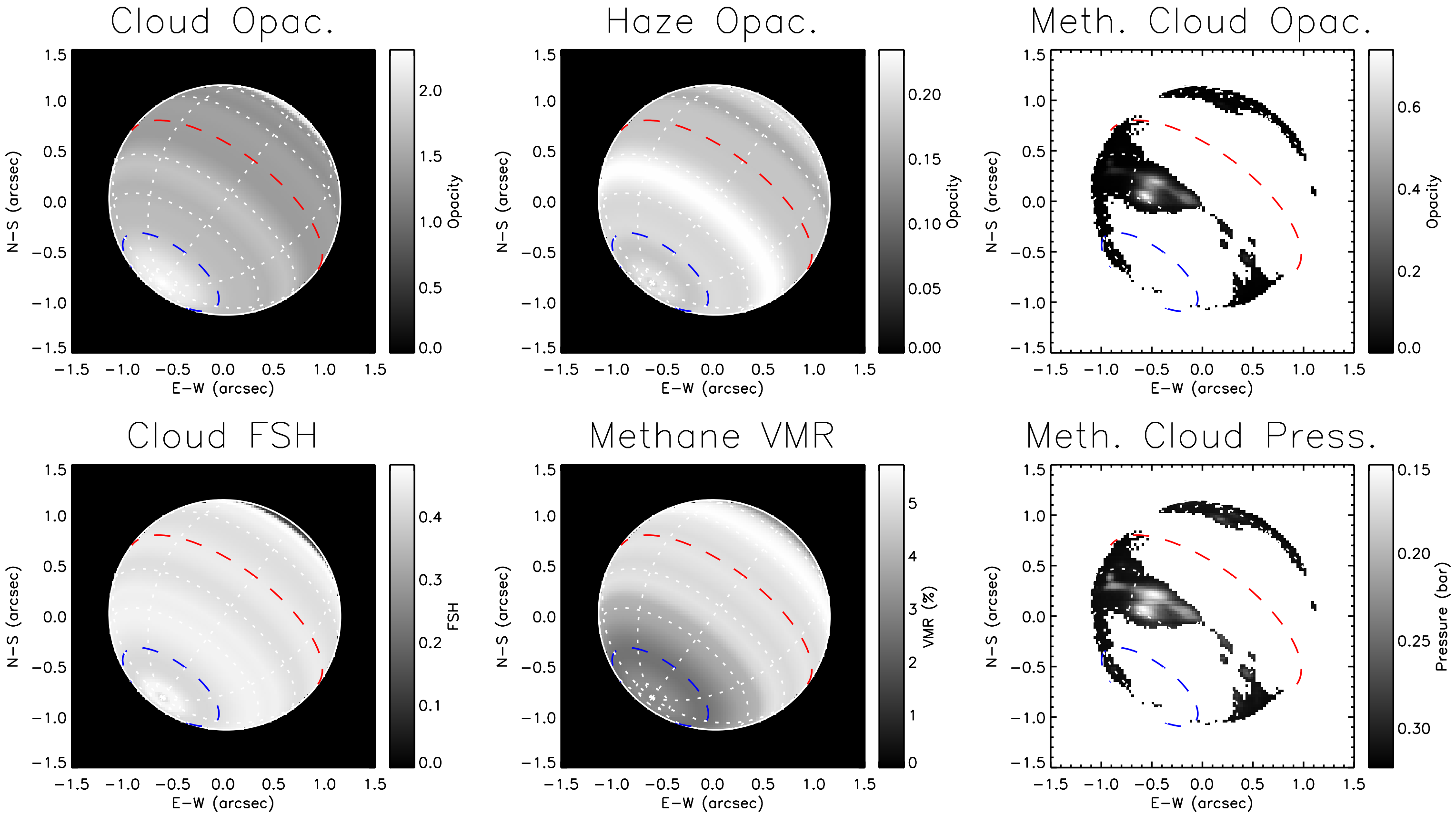
- Model 1 – fixed n_i
- Model 2 – variable n_i
- CH_4 clearly reduces towards pole
- Possible minimum at 60°S but could also be relaxing back to *a priori* of 4%

Fitted methane and cloud/haze



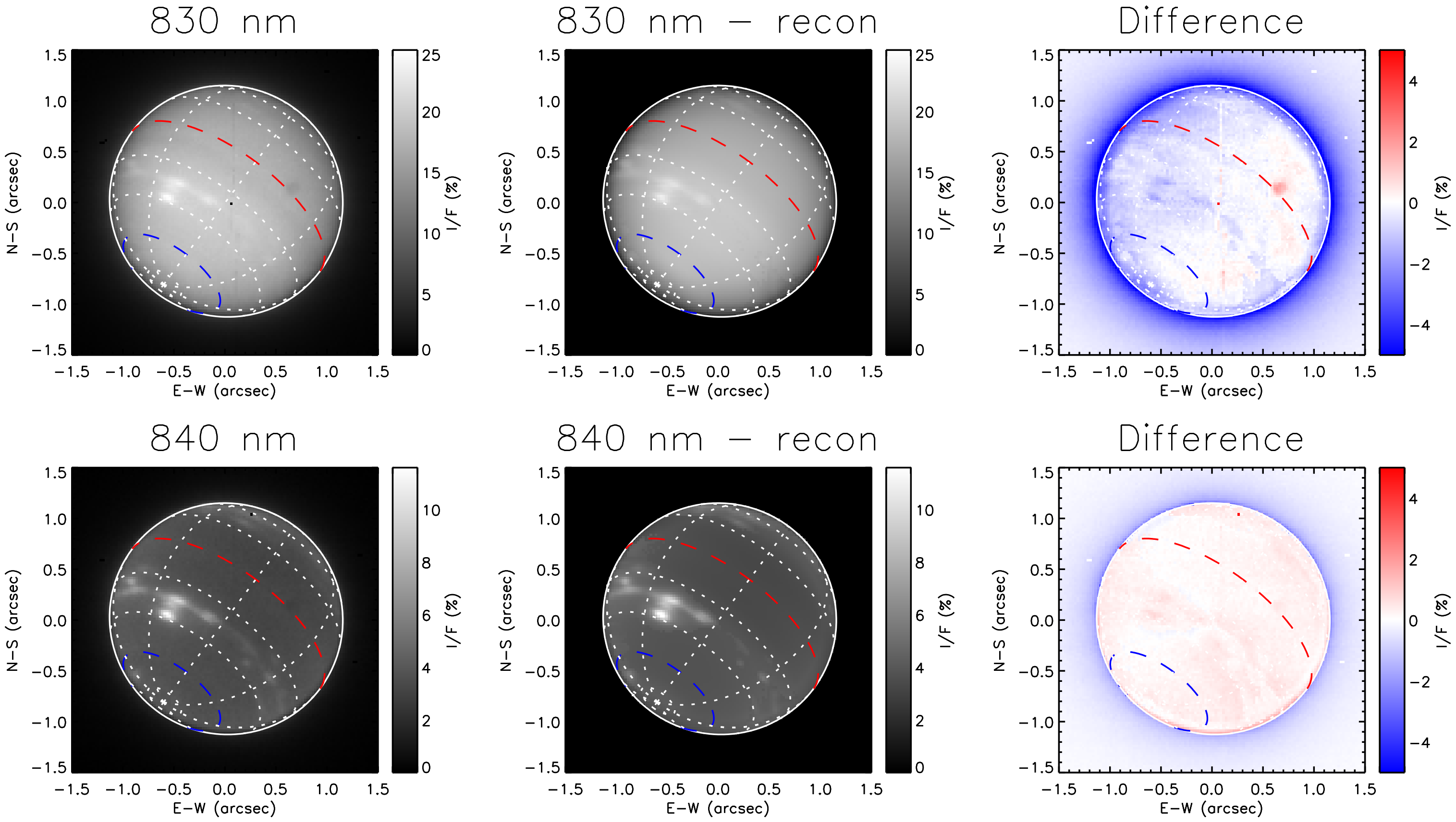
- Reduction of methane polewards of 40^{o}S is very clear.
- Baseline model cannot account for discrete cloud features.

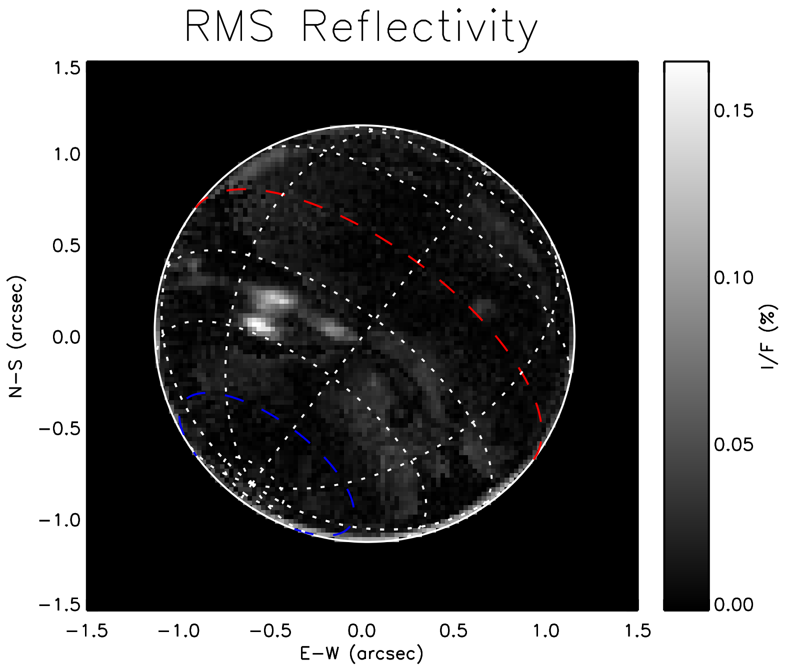
Fitted methane, cloud and additional cloud



- Reduction of methane polewards of 40°S is very clear.
- Baseline model cannot account for discrete cloud features.
- Add additional cloud of methane ice with particles of radius ~0.1 μm and variable opacity.
- Peak pressure variations seen, but not statistically significant. All we can say is $p < 0.4$ bar. However, opacity variations are significant and greatly improve fit to observations at these locations

Fit to observed data





Good agreement not just at 830 and 840 nm, but in fact at all wavelengths.

Summary

- Can fit background Neptune spectrum (800 – 900 nm) with a simple two-cloud zonally symmetric model: 1) deep cloud based at 4.6 bar, with variable fractional scale height; and 2) layer of stratospheric haze based near 0.03 bar.
- Deep abundance of methane (i.e., at the top of the H_2S cloud, based at 4.6 bar) found to decrease by a factor of 1.9 ± 0.2 from equator to pole, from 5% at the equator to 2.5% at the south pole.
- However, absolute abundances at different latitudes depends on the precise choice of cloud and methane profile parameterisation and vary by ± ~1%.
- Adding methane clouds to our zonal model allows us to additionally retrieve the properties of the discrete cloud locations; we find these clouds to lie at pressure levels less than 0.4 bar and to have opacities of up to 0.75 (@800 nm).
- Paper currently under review with Icarus.