Differential NICMOS Spectrophotometry at High Signal-to-Noise

A Search for Water vapor in the atmosphere of HD 209458b

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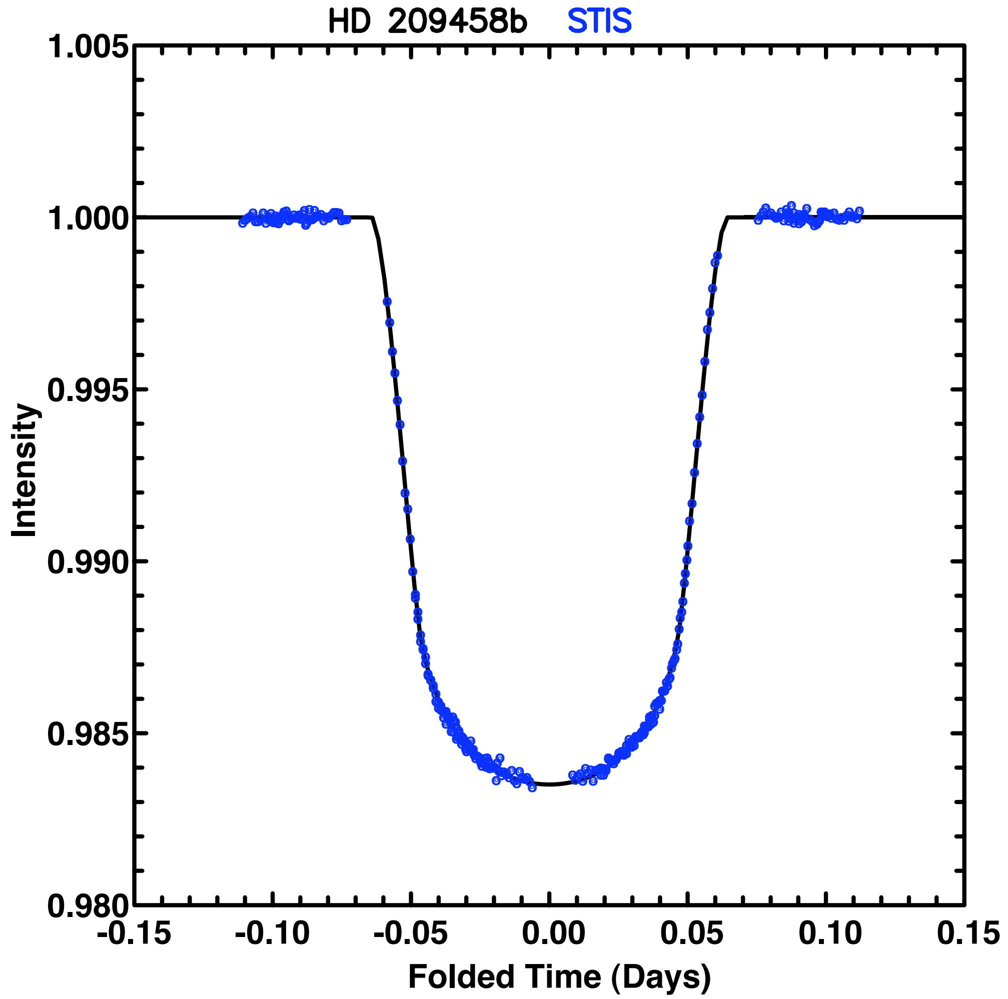
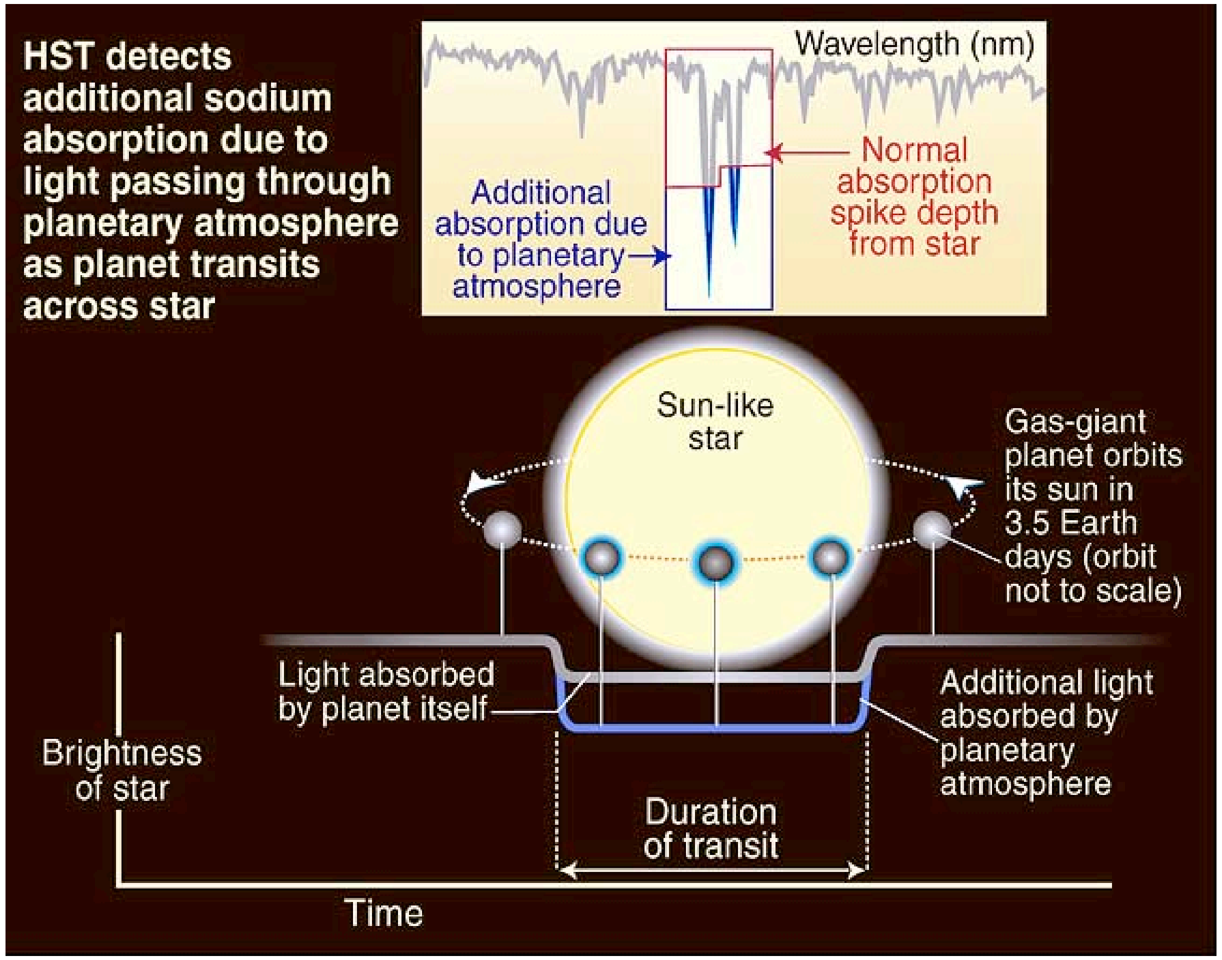
Thanks to Tim Brown (PI GO-9832), Eddie Bergeron, and Santiago Arribas.

Still a work in progress -- comments/advice welcome.

Science Motivation -- STIS results on HD 209458b in 2000



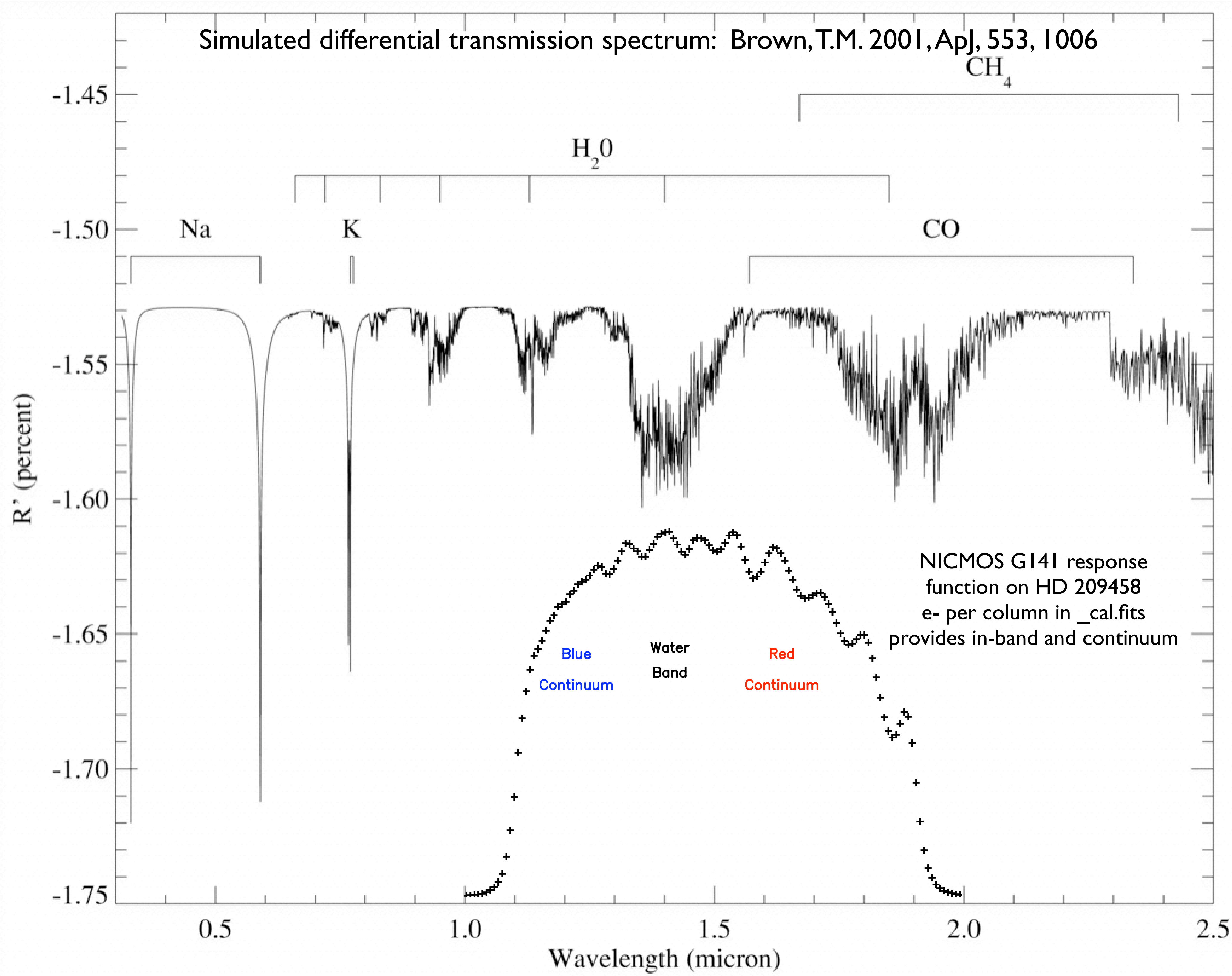


Series of 60s spectra on V = 7.54 star with G750M centered at 600 nm.

Summed over wavelength and cross-dispersion each time point contains 1.55 x 10^8 e-,
and a realized time-series rms of 1.1 x 10^-4 (30% above Poisson limit).
Brown, T.M. et al., 2001, ApJ, 552, 699

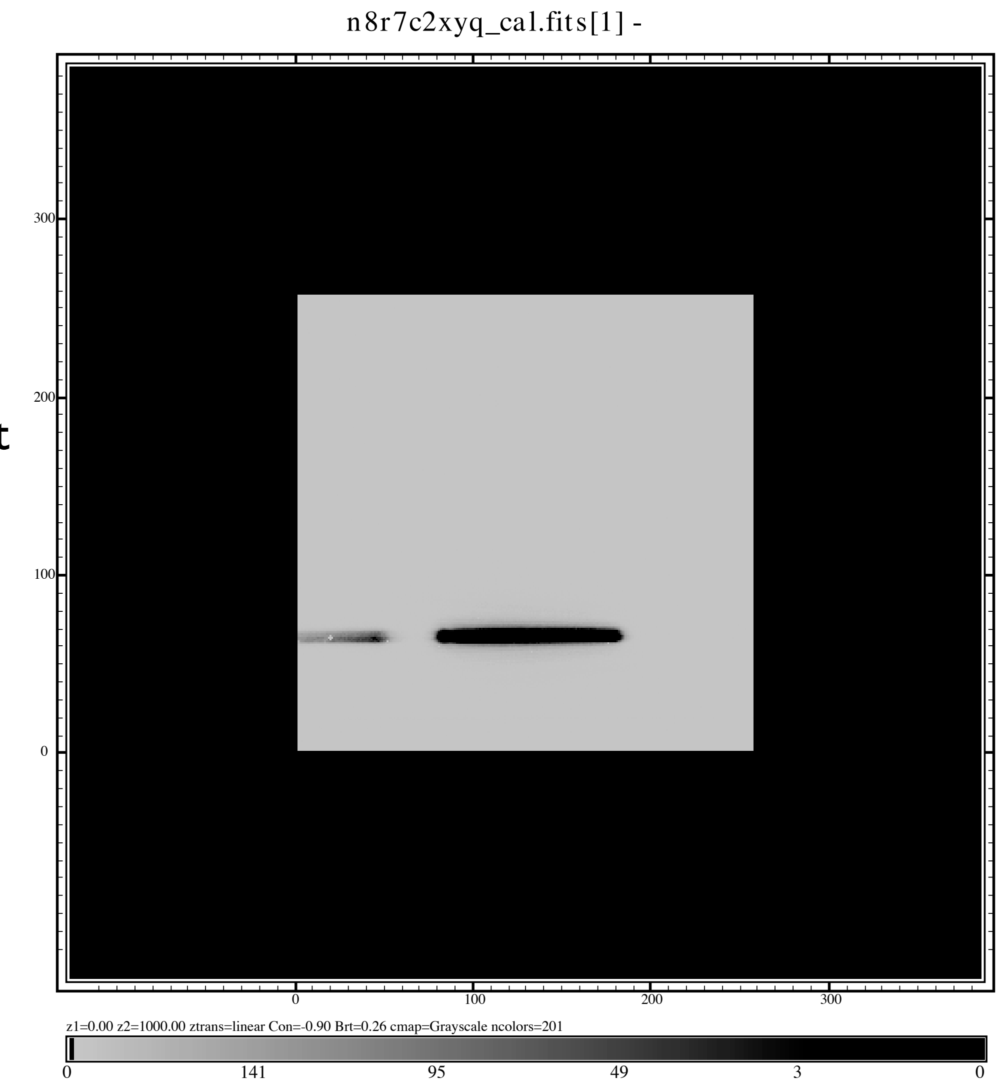
A 1.2 nm bandpass centered on the sodium resonance doublet at 589.3 nm was deeper by 2.32 +/- 0.57 x 10^-4
relative to nearby continuum during transit signifying extra absorption in this line from rays passing through the atmosphere.
Charbonneau, D. 2002, ApJ, 568, 377

Search for Water Vapor in Atmosphere of HD 209458b -- NICMOS



The NICMOS Observations

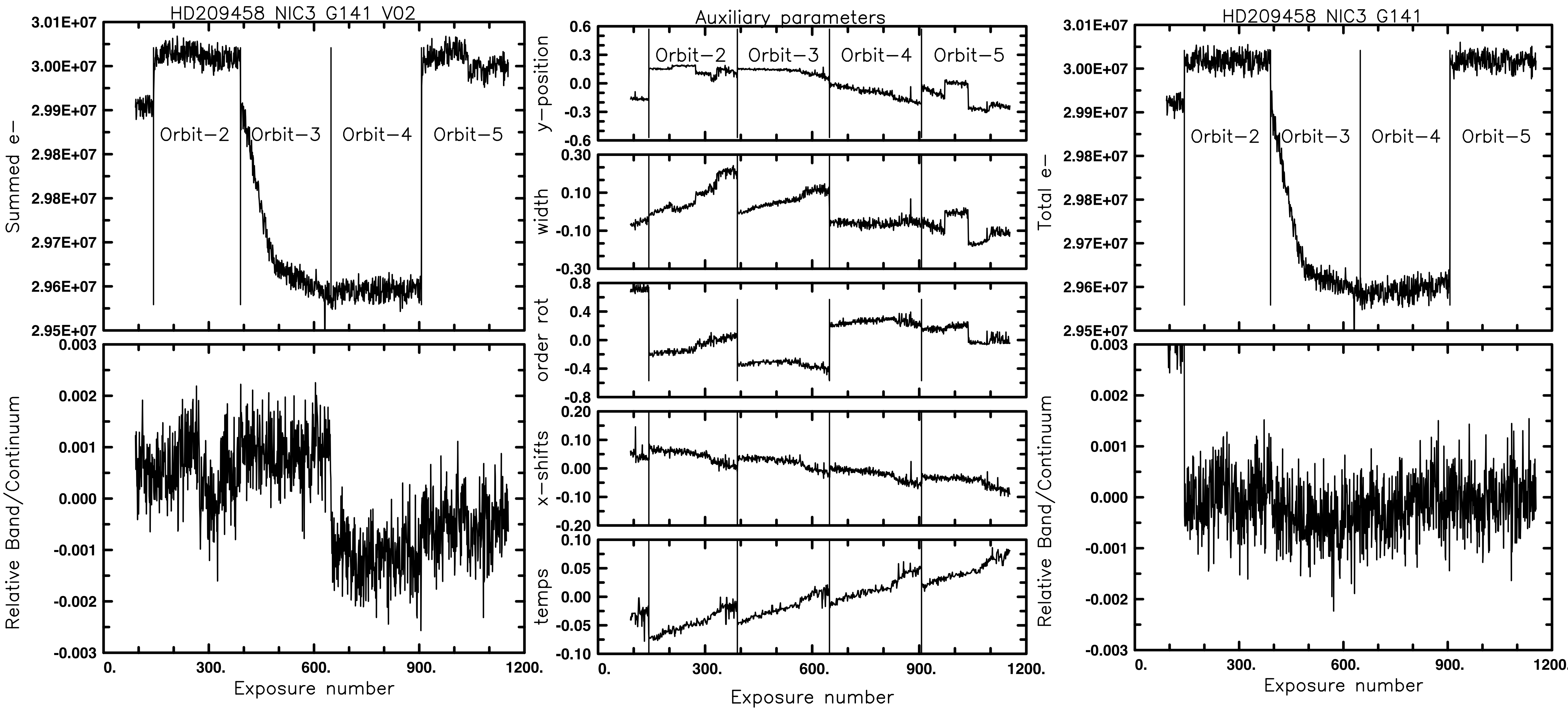
- G141 spectroscopy to provide H2O-band to continuum index during, versus out-of-transit
- H = 6.13 for HD 209458 would imply detector saturation in < 1 second.
- PAM defocus to -0.5 mm was used such that spectrum width is ~ 5-6 pixels FWHM, which leads to less noise from the undersampled PSF interacting with jitter and intra-pixel quantum efficiency variations on NIC3. But this comes at the acceptable cost of degrading spectral resolution by a factor of a few.
- Used STEP1 Multiaccums with NSAMP = 4 (texp = 1.99 seconds) yielding spectra with peak count levels of about 70,000 e- per pixel, or about 400,000 e- after summing over cross dispersion. (Duty cycle is 18%.)
- Data from GO-9832 consists of 3 visits (observed in 2003, 2004, 2005), each of 5 orbits roughly centered on the 3-hour planetary transit. We obtain ~250 exposures per HST orbit.
- During out-of-transit orbits small dithers in y of +/- 0.05 pixels were applied.



One randomly selected image (from 3,142 used). The G141 spectrum is placed on a relatively clean (in terms of pixel quality) portion of NIC3.

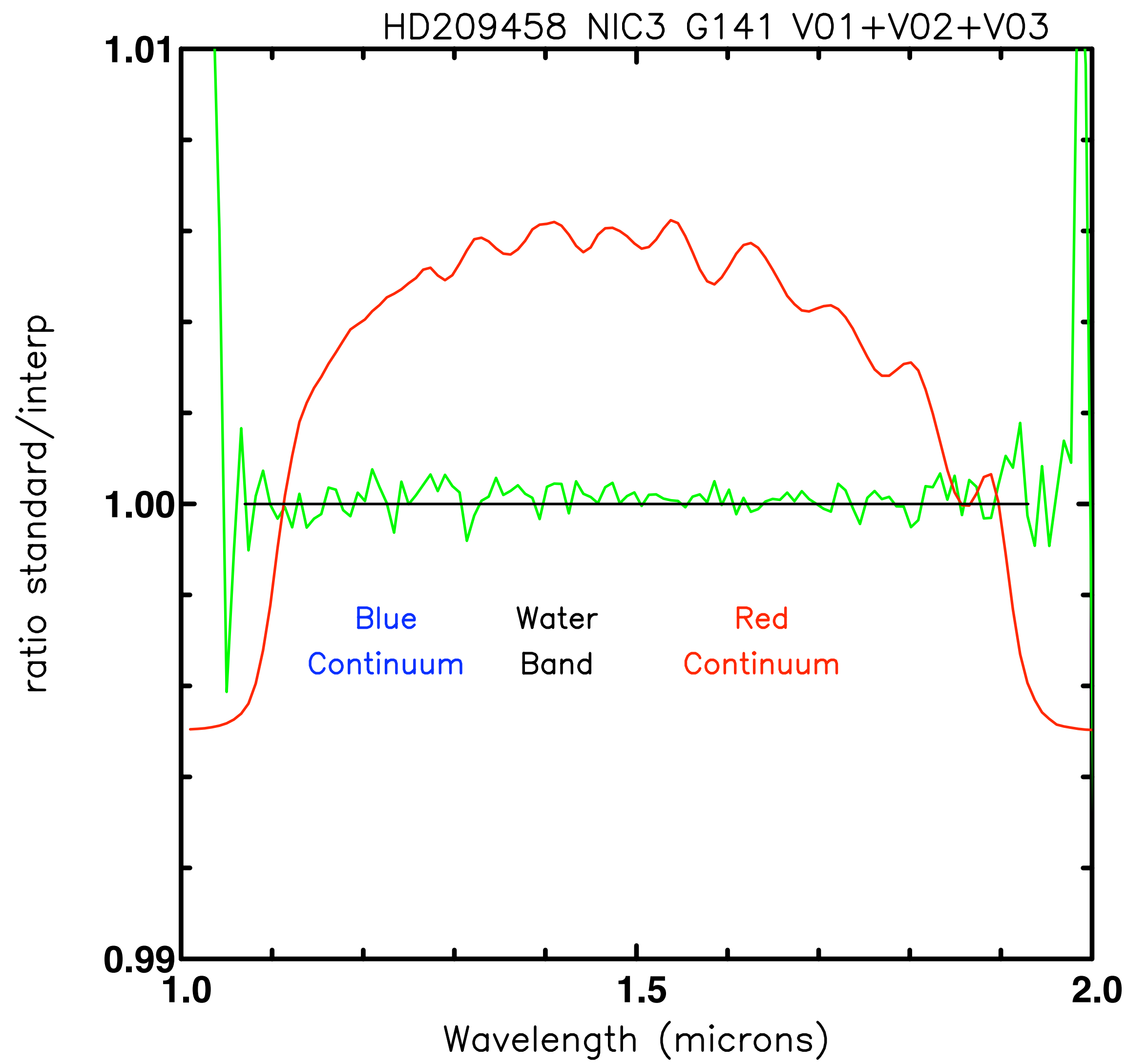
Data Reductions

- Start with pipeline **_cal.fits** products.
- Apply a wavelength dependent flat-field based on quadratic fit to flats for F108N, F113N, F164N, F166N, F187N, F190N, and F196N.
- Evaluate and subtract a mean, per-frame background.
- Evaluate proxies for detector temperature changes based on shading variations.
- Identify pixels within spectral region that are either dead or noisy and interpolate over these.
- Compute for each frame a measure of spectrum position (x, y offsets and a rotation parameter), cross-dispersion width, and the temperature proxies.
- Decorrelate time series variations of intensity with changes in x, y position etc.



Nonlinearity Test

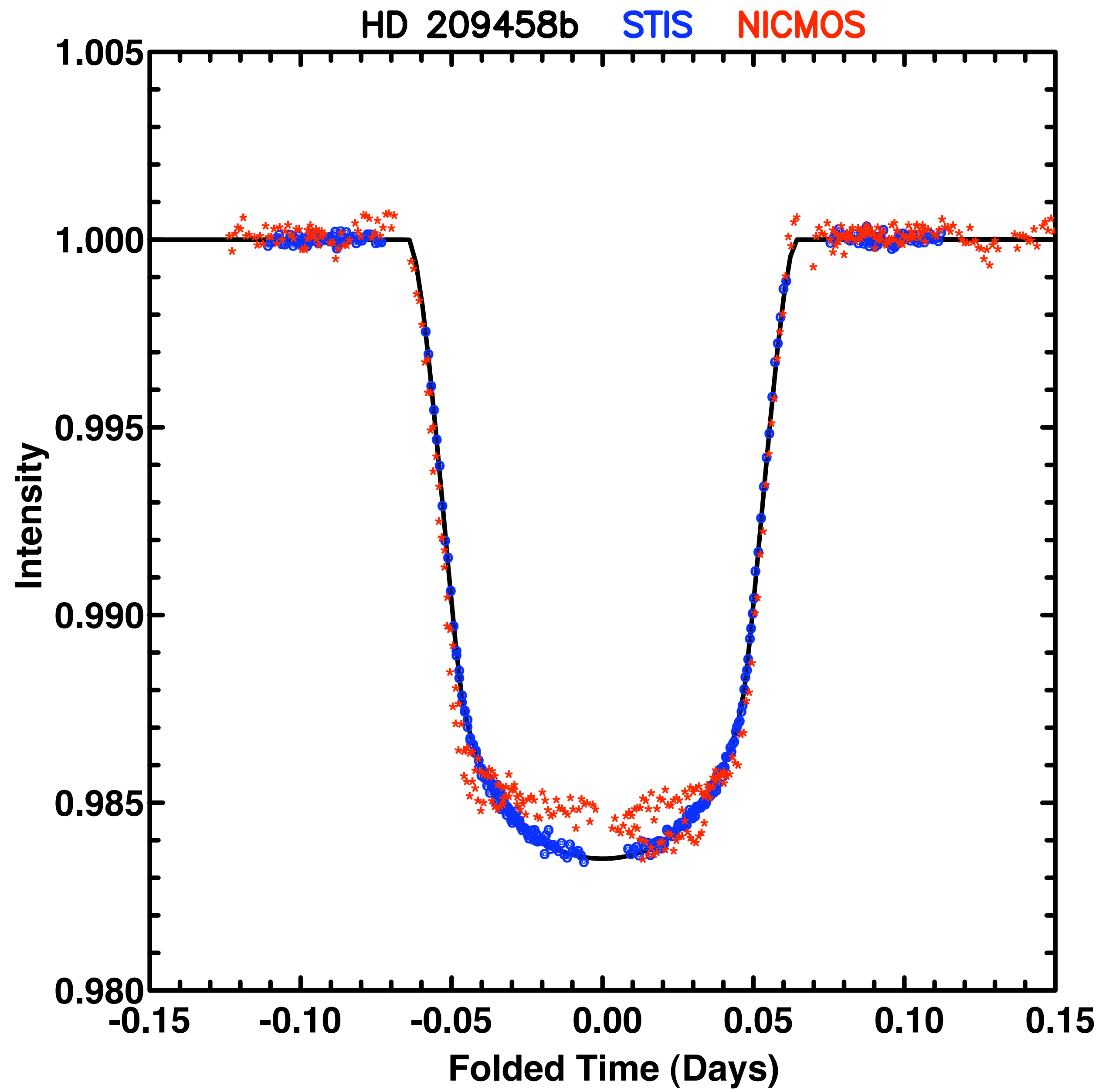
- During first orbit only we obtained series of 10 exposures with MCAMRR, STEP = 6 and 7 respectively, yielding exposure times of 1.82 and 2.11 seconds interleaved with the primary 1.99 second case used for science.
- This is used to test whether the Water-band normalized to continuum regions shows any response to count level per exposure, thus deriving a correction, or establishing an upper limit.
- Taking into account that the ratio of 7/6 is a larger change than the 1.5% deep transits induce, the constraint available is close to the overall Poisson limit of the science data. There are of order 10^10 photons detected in the Water-band and continuum bands when summed over all three visits, therefore we hope to work near the level of 10^-5!
- The constraint obtained with preliminary analysis is a change of relative Water-band to continuum ratio as a result of count-level nonlinearity at 1.5 x 10^-5 +/- 1.5 x 10^-5, consistent with zero and near the limiting precision available from the science data.



Mean of spectra ratios (multiplied by inverse ratio of exposure times) at t_exp = 1.82 to 1.99s, and 1.99 to 2.11 s plotted as the green curve. There seems to be little if any residual nonlinearity over the spectral domain of interest.
The red curve illustrates the relative intensity of G141 spectra.

Time Series Photometry -- Comparison with STIS

- STIS spectra were 60s + 20s overhead, total counts of 1.55 x 10^8 e- per exposure.
  - STIS provided rms of 1.1 x 10^-4, about 30% above Poisson noise limit.
- NICMOS spectra rebinned to 80 seconds have total counts of 2.16 x 10^8 e- per exposure.
  - NICMOS provides rms of 1.8 x 10^-4, about x2.4 the Poisson noise limit.
  - The noise level on the purely differential index tracking water to continuum bands is closer to being Poisson limited.



Shallower transit bottom from IR observations is expected due to smaller stellar limb darkening.

NICMOS results are still in a preliminary stage, all time-series results to date follow from simple sums over a rectangle enclosing the spectrum. Application of a Difference Image Analysis procedure may provide better results allowing closer to Poisson limit.

Summary

- NICMOS provides the best current spectroscopic capability on HST for probing extrasolar planet atmospheres given the presence of broader absorption features expected in the near IR.
- Current reductions have not yet reached limits provided by fundamental error sources, improvements may still follow, but already constraints are at an interesting level.
- Time series signal-to-noise precisions of 5,500 per 80 second sum (< 0.2 mmag) have been demonstrated for direct photometry.
- Nonlinearity does not seem likely to be a limiting factor in searching for minor changes of in-band relative to out-of-band changes indicative of water vapor in the planetary atmosphere.