Exoplanet Transit and Eclipse spectra with JWST:

potentials and limitations

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Exoplanet Spectroscopy Status

Figure courtesy of M. Swain

Swain et al. 2008
HD 189733b
Transmission

HD 189733b
Emission
Grillmair et al. 2008

Swain et al. 2008
HD 189733b
Emission

Grillmair et al. 2008
Some Outstanding Issues

- What spectral features are really present?
- Are observed strengths of spectral features due to intrinsic abundances or temperature profiles?
  - Distinguish temperatures, T profiles, compositions
  - Are ice giants overabundant in carbon / metals like Neptune?
- How is energy absorbed and transported in highly irradiated planets?
  - Measure & determine causes of temperature inversions
  - Study transport via day / night side differences
  - Is there non-equilibrium chemistry?
    - Hydrocarbons like C$_2$H$_2$ (acetylene), C$_2$H$_6$ (ethane) indicate photo-chemical production
- What is the composition of mini-Neptune atmospheres?
- Can Kepler Earth candidates (1 Me, 1AU) be confirmed?
- Can we detect any features in Super/Earth atmospheres?
How Can JWST Help?

• JWST has 6.5 m aperture vs. 2.4 m for HST and 0.85 m for Spitzer
  - Photon noise-limited SNR goes as aperture size, so JWST should be capable of SNR ~ 3 – 8 times present values

• JWST has great spectroscopic capabilities, particularly:
  - $\lambda = 0.7 – 5 \mu m$, $R \sim 100$ mode with NIRSpec prism
  - $\lambda = 0.7 – 2.5 \mu m$, $R \sim 700$ mode with NIRISS grism+prism (slitless)
  - $\lambda = 2.5 – 5 \mu m$, $R \sim 1700$ mode with NIRCam grisms (slitless)
  - $\lambda = 5 – 12+ \mu m$, $R \sim 70$ mode with MIRI LRS prisms (slitless)

• JWST is being designed and will be operated to maximize exoplanet spectroscopy SNR
  - Wide NIRSpec slit (1400 mas) and slitless mid-IR spectroscopy
  - Testing spectrophotometric precision and simulating operations
  - Systematic noise due to pixel size and observatory parameters are being modeled (P. Deroo PASP submitted), mitigation possible
What are the optimum JWST targets?

• Ideally we need planets transiting / eclipsing IR bright nearby but small stars
  – SNR \sim \sqrt{\text{star signal}}, \text{ planet emitting / absorbing area, } & R_*^{-2}
  – M stars are ideal if stable
  – Kepler planets are too faint / distant for spectroscopy

• Large planet atmospheric scale heights \( H = \frac{kT}{\mu g} \) will have relatively high SNR transit spectra: \( A_{\text{atm}} \sim 2\pi R_{pl}^5 H \)
  – Gas giants, ice giants, mini-Neptunes will be good

• Do harder (smaller / cooler) planets with JWST

• Impossible to characterize true Earth / Sun analog via transit spectroscopy
JWST Simulations

- Transmission and emission models from J. Fortney group
- Semi-realistic model of telescope and instrument wavelength-dependent resolution and throughput
  - Includes reflections, grating functions, filters
  - Use actual instrument models or guesstimates
- Photon noise and systematic noise added
- Systematic noise is difficult to predict but starting to model it
  - Different for each instrument and mode
  - May have large wavelength dependencies (Deroo sub. PASP)
- Compare simulations of model variants to determine what science issues can be addressed with JWST data
JWST Systematic Noise Estimates

• Variable PSF and image jitter will induce spectrophotometric errors due to non-uniform intra-pixel detector response and residual flat field errors

• These effects were noted in the Spitzer IRAC InSb detectors and calibrated out to about 1E-4 precision

• Use of slitless spectrographs and JWST NIRSpec wide slit (1600 mas) will eliminate any systematic noise due to jitter-induced slit losses

Deming et al. 2009 PASP

Fig. 8.—Intrapixel sensitivity variation for a representative NIRSpec detector pixel, from engineering measurements of the flight detector. The upper traces show the average variation in the dispersion direction (solid line), and the spatial direction (dashed line). The lower traces divide the pixel into 10 strips parallel to the spectral dispersion, and they show the difference from a parabolic fit of response vs. distance from pixel center. The differences have been amplified by a factor of 4, and offset by 0.3, for clarity of presentation.
Systematic Noise Estimate Models

- Focus and pointing drifts are likely the biggest impact for JWST NIRSpec due to its undersampled PSF. Most critical below 2.5 or 3 microns.

- NIRISS GR700XD, NIRCam grism, and MIRI LWS all minimal impact

P. Deroo 2011 submitted
HD 189733b Gas Giant

- Only 1 transit (top) or eclipse (bottom) plus time on star for each (1 NIRSpec + 1 MIRI)
- Multiple features of several molecules separate compositions, temperature, and distributions (J. Fortney group models + JWST simulation code)
GJ 436b (warm Neptune) transmission spectra simulations

- Simulated single transit model absorption spectra distinguish between equilibrium 30X solar (black), reduced CH4 & H2O (blue, red) or non-equilibrium chemistries where H2O and CH4 are absent in favor of higher order hydrocarbons HCN, C2H2, and other molecules (purple, cyan and green curves). 1 transit each: 30 min star + 30 min in-transit integration time. Noise has been added (Shabram et al. 2011).
2 Earth super Earth, a smaller GJ 1214b analog

See radiation from star transmitted through the planet's atmosphere

Single transit NIRSpec + MIRI

4 MIRI eclipses summed

Secondary Eclipse
See thermal radiation and reflected light from planet disappear and reappear

Orbital Phase Variations
See cyclical variations in brightness of planet

GJ 1214b-like planet R = 2Re, 4 eclipses

Transmission

RED = metal-enhanced solar spectrum
BLUE = H2O dominated (small H)
Next Steps: Better noise models & retrieval

• Will update systematic noise estimates with info from instrument tests

• Need to assess what information can be extracted from simulated spectra:
  – What features are present at what strengths and significance?
  – What is uncertainty in derived atmospheric parameters?

• I'll probably start with simple $\chi^2$ retrieval methods

• I welcome your comments / advice / participation
Are Earth transmission spectra possible?

Transit of Venus visible photo
5.6.2012 (H. Chapman)
Earth transit facts of life

- Earth disk area is $\sim 1E^{-4}$ of a G2V star or $1E^{-3}$ of M3V (GJ 581)

- Absorbing area of Earth atmosphere is $A \sim 2\pi R_e^5 H$, $H = k T_e / \mu g \sim 8$ km, so $A \propto T_e / \mu \rho$ and $A/A_e \sim 0.01$

- Therefore a completely absorbing spectral line would have a signal (Area) of $\sim 1E^{-5}$ relative to M3V star

- Detecting this signal at SNR=3 requires precision of $3E^{-6}$ (3 ppm)

- Would require co-addition of $\sim 100$ transits to get $1E^{11}$ photons per spectral element, but systematic noise must be $> 20x$ lower than HST

- Super-Earths? Remember $A \propto T_e / \mu \rho$

  Area is independent of radius $R$
How to progress beyond individual planets?

- Need a dedicated, smaller mission to conduct a statistical survey to advance exoplanet atmosphere science:
  - How are exoplanet atmosphere compositions related to host stars, and what does this tell us about their formation?
  - What equilibrium and non-equilibrium chemistry is present, and what internal / external processes drive this?
  - How is stellar energy absorbed and transported in planets; what causes inflated radii?
    - Measure & determine causes of temperature inversions
    - Study transport via day / night side differences
  - How does the solar system and its formation compare with nearby planetary systems?

- Transit spectroscopy performance is not a strong function of aperture (SNR goes as D, not D^2) and is improved by simultaneous wavelength coverage and low systematic noise
Some Conclusions

• Expect exquisite JWST spectra of gas and ice giants
  – Determine abundances, temperature profiles, and energy transport in hot Jupiters with little degeneracy using transit & eclipse spectra over 0.7 – 10+ microns.

• Easily constrain compositions of mini-Neptunes like GJ 1214b (down to 2 $R_E$ and smaller)

• Possibly detect CO$_2$ absorption in Super-Earths, but Earth-like planets are difficult otherwise

• There is plenty of exoplanet spectroscopy to do:
  – Cool, dense planets with JWST
  – Statistical survey of giant planet atmospheres with FINESSE or EChO
  – Stability and low systematics are as important as aperture