Wavelength-Diversity Derived Low Resolution Spectra of HR 8799b

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Abstract

We present low resolution spectra for HR 8799b from data from the OSIRIS integral field spectrograph (IFS) at Keck observatory. These are derived via an advanced method of PSF subtraction that leverages the spectral diversity available in IFS data to generate an optimally compacted decomposition of imaging data [Marois et al., 2010a, Soummer et al., 2012]. This method allows for the quantification of overall signal throughput and residual noise variance and enables forward modeling of astrophysical sources. We compare the derived spectra to previously published results, and present a discussion of the algorithm and validation of its performance via recovery of simulated spectra injected into the original data set.

HR 8799

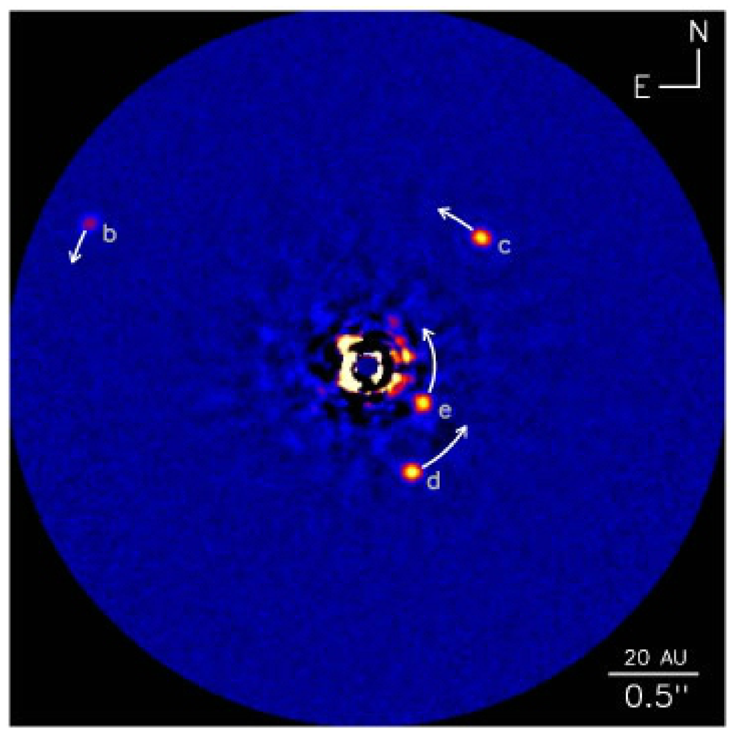

Figure : Keck image of the HR 8799 system [Marois et al., 2010b].

HR 8799 is the first directly imaged exosystem, with four known planets [Marois et al., 2008].

	Semi-major Axis (AU)	Period (years)	Mass (M_J)	Radius (R_J)	Temperature (K)
b	68	450	5	1.2	870
c	38	200	7	1.2	1090
d	24	100	7	1.2	1090
e	15	50	7	?	?

The system is approximately 30^{+20}_{-10} Myr old, and has been imaged with multiple instruments at multiple observatories including Keck and Gemini.

OSIRIS Spectroscopy

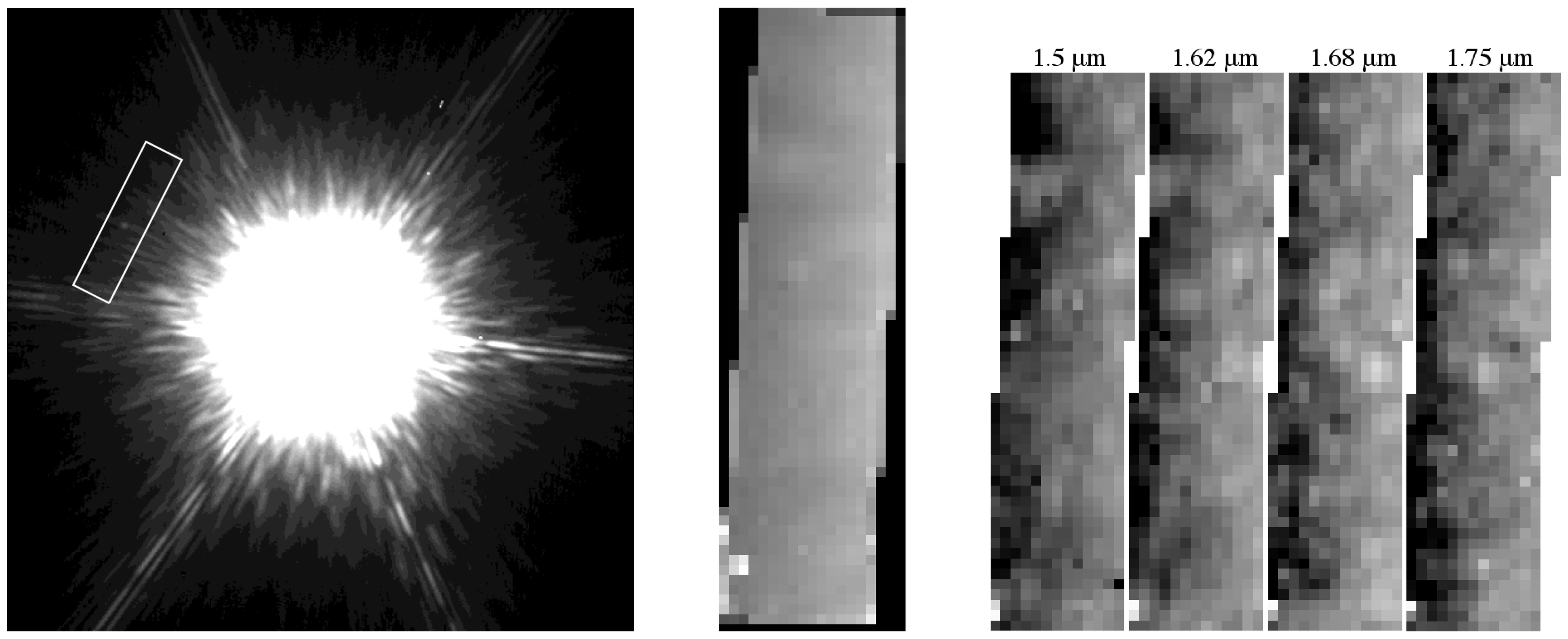

Figure : *Left*: NIRC2 image of HR 8799 with the OSIRIS field of view marked by the white rectangle [Barman et al., 2011]. *Center*: OSIRIS cube summed across all wavelengths. *Right*: Four slices of an OSIRIS cube with floating average over 100 neighboring wavelength channels applied. You can see speckles moving from right to left as the wavelength increases.

OSIRIS is a cryogenic lenslet-based integral field spectrograph (IFS) designed to work with the Keck adaptive optics system. It operates between 1 and 2.4 μm and has an average spectral resolution of 3800, with 16 x 64 spatial pixels covering 20 mas each.

Integral Field Spectrographs like OSIRIS can produce detailed spectra of exoplanets, but signal to noise is low in individual spectral slices and speckle noise makes planets difficult to detect even in summed images.

Goal:
Use IFS cubes to construct optimal reference PSFs and extract planet spectra.

Method

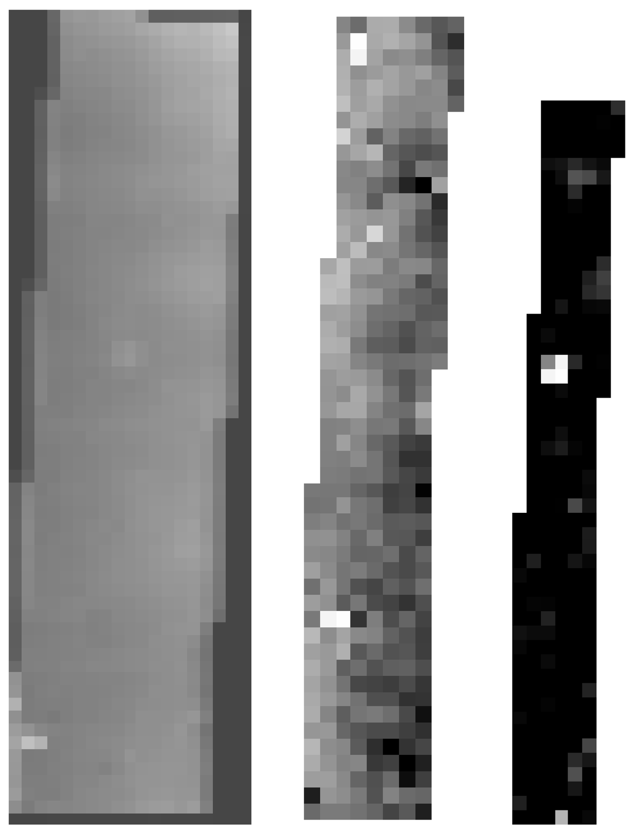

Figure : *Left*: Summed cube. *Center*: One KL basis slice. *Right*: Summed post-processed cube with planet visible.

- Scale cube slices so that speckles are spatially aligned
- Package the K slices (of N pixels each) where planet is spatially offset into reference matrix $R \in \Re^{K \times N}$
- Construct Karhunen-Loève basis from references via SVD or eigendecomposition of covariance of R [Soummer et al., 2012, Marois et al., 2010a]:

$$S = \frac{1}{N-1} R R^T \qquad S\Phi = \Phi\Lambda \qquad Z = \Phi^T R$$

- Reference PSF is the projection of the target slice $\mathbf{t}$ onto the M-element subset of the normalization of Z that captures most of the noise information, but little of the planet signal:

$$Z_M = \left[I_{M \times M} \; \mathbf{0}_{M \times (K-M)} \right] \frac{\sqrt{\Lambda^{-1}}}{\sqrt{N-1}} Z \qquad \hat{\mathbf{t}} = Z_M^T Z_M \mathbf{t}$$

- Choose M such that you capture mostly noise information and little of the planet signal by setting a threshold on the sum of Λ.
- Subtract estimate from target slice and repeat for all wavelengths:

$$\hat{\mathbf{s}} = \mathbf{t} - \hat{\mathbf{t}}$$

Error Estimation and Validation

- The KL transform (and any subset of Z) completely decorrelates and optimally compacts the signal: the covariance of Z is equal to the eigenvalue matrix Λ.
- If the noise is orthogonal to the signal (i.e, extended speckle vs. point sources), the first few rows of Z will contain none of the planet signal, so signal throughput is high.
- The estimate variance can also be derived from the same decomposition:

$$\sigma^2 = E\left[(\hat{\mathbf{s}} - \mu(\hat{\mathbf{s}}))^T (\hat{\mathbf{s}} - \mu(\hat{\mathbf{s}})) \right] = \left(I - Z_M^T Z_M \right) \mathbf{t}\mathbf{t}^T \left(I - Z_M^T Z_M \right)^T$$

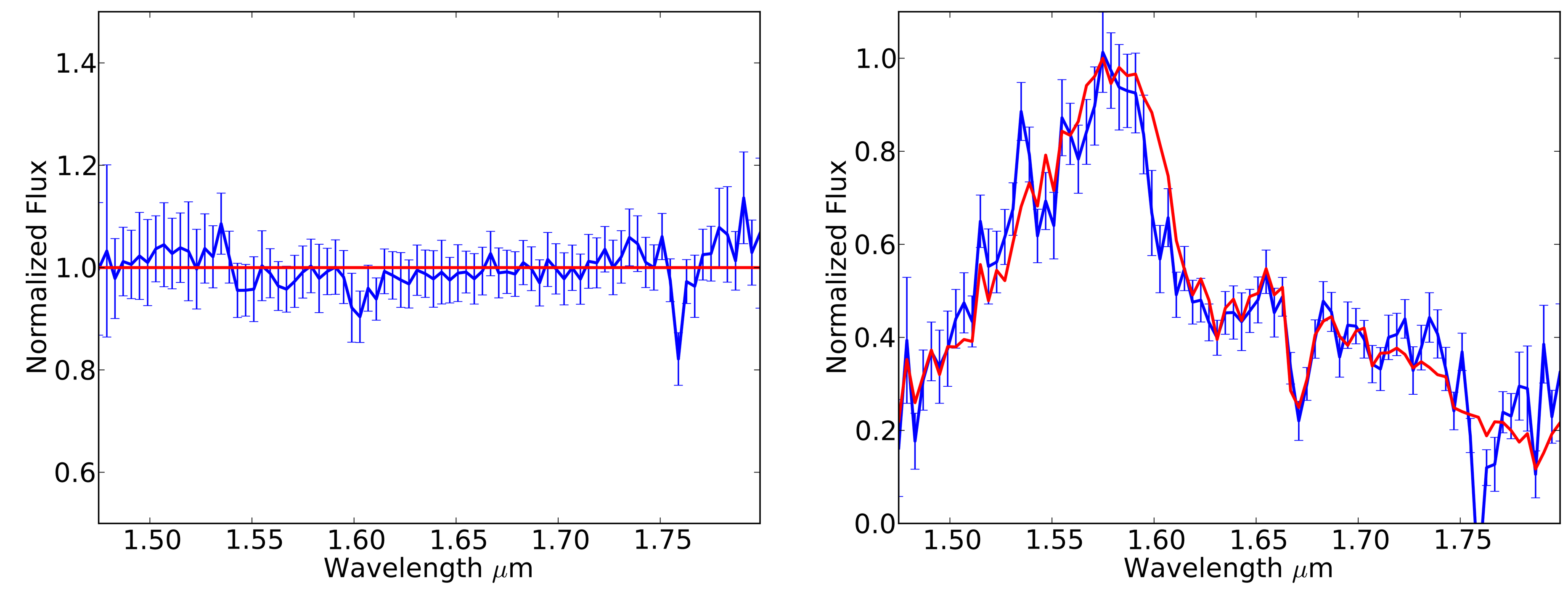

Figure : Injected (red) and recovered (blue) spectra with a flat spectrum (*left*) and a T4 spectrum (*right*). Both spectra correspond to a contrast of 10^{-5}. HR 8799b is detected at a contrast of approximately 1.15×10^{-5}.

Results

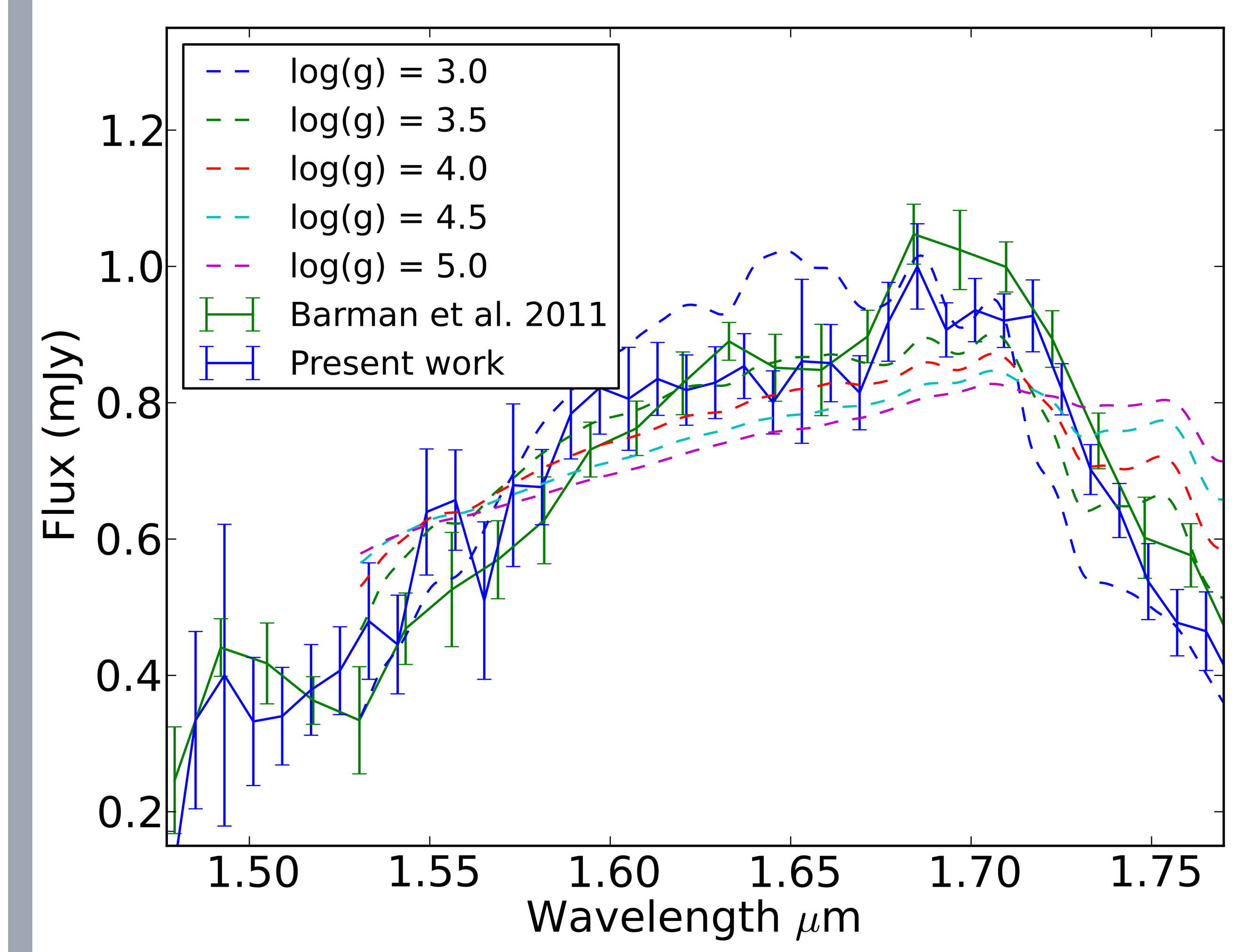

Figure : HR 8799b H-band spectrum from Barman et al. [2011] (green) and present work (blue). The data set consists of 21, 900 second OSIRIS observations taken in July 2009 and July 2010. Dashed lines are model spectra at different gravities. See Barman et al. [2011] for details.

Table : Correlation coefficients between model and extracted spectra.

$\log(g)$	Barman et al. 2011	Present Work
3.0	0.86	0.91
3.5	0.93	0.95
4.0	0.94	0.94
4.5	0.92	0.80
5.0	0.77	0.56

Conclusions and Future Work

- The KL processing appears to have fewer systematic biases than wavelength subtraction or classical LOCI processing.
- This procedure also allows for the quantitative evaluation of error bars
- Better image processing will result in higher final SNR, allowing detection of planets at shorter wavelengths
- The new HR 8799b spectrum is somewhat more consistent with theoretical models, yielding a correlation coefficient with the $\log(g) = 3.5$ spectrum of 0.95, versus a value of 0.93 for the Barman et al. [2011] spectrum.
- The H-band spectrum is consistent with $\log(g)$ values between 3.5 and 4, equivalent to 1.8 to 5.8 M_J assuming 1.2 R_J, confirming that this object is a planet rather than a brown dwarf.

References

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