Report written by Peizhi Liu (peizhiliu2023@u.northwestern.edu) with some help for Jason Wang (jwang4@caltech.edu), Cobi Rabinowitz (JacobRabinowitz2021@u.northwestern.edu) and Mel Ulmer (m-ulmer2@northwestern.edu) July 2, 2020

Results of applying pyKlip to CHARIS observations of κ And b and HD 1160 b in comparison to the literature.

Abstract/Summary: The κ And b went well in that compared to the literature, our results were in general agreement across all choices of movements and KL vectors. However, to achieve the best agreement with the literature, especially at higher wavelengths, for the HD 1160 b, we needed to choose a high "movement" and a low number of KL basis vectors (less than 10). We are currently working to process more κ And b and HD 1160 b spectra on different observational dates to determine how well we can set limits to "true variability" in the spectra derived from CHARIS data.

1. κ And b

We have produced results that are very similar to what is published when we assumed that the formula given in Currie *et al.* , 2018 (PASP 130:044405), page 7, 8; $\mathrm{atten}_{\lambda} = \mathrm{atten}(1.5\ \mu\mathrm{m}) \times (\lambda/1.55\ \mu\mathrm{m})^{-2}$, where $\mathrm{atten}(1.55\ \mu\mathrm{m}) = 2.72 \times 10^{-3}$ in linear units.

We first obtained the 42 raw CHARIS images taken on September 8, 2017, used by Currie *et al.* from SMOKA. These 42 broadband images all have a 20.7 second exposure time and range from a parallactic angle of approximately 168.09˚ to 178.68˚. While the SMOKA database contains over 300 similar images with the same exposure time, object, and date, it is highly probable that these are the images Currie *et al.* used given these are the only 42 image sequence with a continuous parallactic angle. We further hypothesize, however, that the unused images were of lower quality, and that the image header might be missing some data quality flag, as suggested by the SMOKA website, which indicates that "current FITS headers may have missing information on the observation and data reduction," and/or a discontinuity in parallactic angle means there was a gap caused by bad weather or a data taking of processing glitch such as it was safest to ignore these data.

The 42 raw images that we suspect were used were then extracted into data cubes via the CHARIS Data Reduction Pipeline (CHARISDRP), a pipeline developed by the CHARIS team to generate CHARIS IFS calibration files and reduce raw images into data cubes, by first creating a wavelength calibration (lowres) of the images at 2.346μm. Then using the wavelength calibration, the raw images were converted into data cubes with the least-square extraction method, as noted in Currie *et al*.

Table 1: Parameters used in FM class and processing.

Parameter	Value
Separation of planet (pixels)	56.790
Parallactic angle of planet relative to North (˚)	49.102
Number of KL basis vectors (KL)	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 12, 14, 16, 18, 20
Stamp size (pixels)	10
Movement (pixels)	3, 5, 7
Half-width size of PSF (pixels)	10
High pass	True
Inversion method	Least-squares
Factor to scale spectra	None

Following the initial data cube extraction from CHARISDRP, we used pyKLIP's implementation of Karhunen–Loève Image Processing Forward Modeling (KLIP-FM) (Pueyo 2016) to extract κ And b's spectra from the 42 data cubes. First, the 42 data cubes were then passed into pyKLIP's CHARIS module. A point spread function at each wavelength was generated with a half-width size of 10 pixels in preparation for the forward modeling of the spectrum. Then using the parameters shown in Table 1, a forward modeling class was set up in pyKLIP followed by the actual PSF subtraction via the KLIP algorithm. Finally, the spectrum of κ And b, which are in units relative to the PSF, what we assumed to be satellite spots, as indicated by pyKLIP's documentation, can be recovered by reversing the forward model without scaling (scaling = None). In total, there are as many spectra for each movement value as there are choices for the number of basis vectors (KL) used specified in the parameters.

While some of the forward modeling and klipping parameters were chosen with good reason, others were chosen based purely on trial and error. For example, we did not run a forward model of the κ And b's astrometry to determine its precise location. Rather, to get the planet parallactic angle and separation, we simply "eyeballed" the PSF subtraction result such that the planet looked relatively centered in the frame for each wavelength slice. On the other hand, the KL value used for the KL-transform was intentionally kept low since κ And b is relatively bright. As Jason noted, since the forward modeling assumes a linear perturbation of the planet on the KL modes, this assumption will break down when using lower movements or a greater KL value to extract the spectrum of a bright object. As for the width of the region surrounding the planet (stamp size), we found that a greater stamp size of 10 pixels, compared to lower values like 5 pixels, reduced background noise in the final klipped image, leading us to use a larger stamp size. Finally, the azimuthal as well as the radial movements of the planet amongst different images and slices can be accounted for via the "movement" parameter. While we know that the selection of the movement parameter should be high for the same reason KL should be low, we tested various values to experiment with this parameter. There will be more discussion on this later.

To determine the uncertainty of the extracted spectrum, we injected a total of 11 fake signals at even spacing around the same annulus (separation) in which the real planet (κ And b) occupies. The injected PSFs of the planets were determined by scaling the PSF at each wavelength by the spectrum of the real planet. The dataset with the fake planets injected was then forward modeled and processed to extract the spectrum of each fake planet at various KL. The approximate $1\boldsymbol{\sigma}$ of the spectrum at each wavelength and KL was determined to be the interquartile range of the 11 planet's spectrum value. This was used rather than the standard deviation since the data variance rarely resembled a Gaussian distribution.

As we have done above, the first step to produce a spectrum of the planet was to derive a spectrum relative to the brightness of the satellite spots via KLIP-FM. However, before converting the relative spectra into absolute spectra, a further calibration step, as suggested by Jason, is necessary, which is to take the spectra of the fake injected planets used to calculate the error bars, and use the average of the spectra to derive a bias factor used to correct for the algorithmic bias in pyKLIP. The reason this recalibration is needed with κ And b is that, once again, the planet is relatively bright, invalidating the assumption in the forward modeling that the planet causes a linear perturbation on the KL modes. Appendix A shows the extracted spectra for κ And b without the aforementioned correction factor, and Appendix B shows the same spectra with the correction factor.

After applying the correction factor to the spectra, to convert the relative values of the spectra into absolute values, we first converted the planet spectra to a magnitude relative to the magnitude of the star and then converted the magnitude of the planet spectra into the actual value of flux. In other words,

$$(planet\ mag) = -2.5\log_{10}\big((relative\ planet\ spectrum) * (spot\ to\ star\ ratio)\big) + (star\ mag)$$

$$(absolute\ planet\ flux) = 10^{\frac{(star\ mag)-(planet\ mag)}{2.5}} * (star\ spectrum)$$

Simplifying these expressions, we get

$$(absolute\ planet\ flux) = (relative\ planet\ spectrum) * (spot\ to\ star\ ratio) * (star\ spectrum)$$

Given we have extracted the planet spectrum, we only need two other quantities, the satellite spot to star ratio and the star spectrum to determine the absolute flux of the planet. As mentioned before, the satellite spot to star ratio was assumed, given by Currie *et al.*, to be

$$atten_{\lambda} = atten(1.55\ \mu m) \times (\frac{\lambda}{1.55}\ \mu m)^{-2}$$

where $atten(1.55\ \mu m) = 2.72 \times 10^{-3}$. For the star spectrum, since κ And is a type B9IV/B9V star, we used the same standard stellar atmospheric model (Castelli and Kurucz 2004) that Currie *et al.* used. Necessary parameters for the star include effective temperature (T_{eff}), metallicity ([M/H]), and surface gravity ($\log g$). These values for κ And are shown in Table 2.

Table 2: Used parameters for κ Andromedae.

Parameter	**Value**	**Source**
$T_{eff}\ (K)$	11327	Currie *et al.*, 2018
[M/H]	-0.36	Hinkley *et al.*, 2013
$\log g\ \ (cm\ s^{-2})$	4.174	Currie *et al.*, 2018
Distance from Earth (pc)	50.0 ± 0.1	Currie *et al.*, 2018
Radius ($R_{\odot}$)	2.29 ± 0.06	Hinkley *et al.*, 2013

The resulting star spectrum is shown in Figure 1 after multiplying the relative spectra from the model by a factor of $\left(\frac{Radius\ of\ \kappa\ Andromedae}{Distance\ to\ \kappa\ Andromedae}\right)^2$ to get the flux density values as seen from Earth.

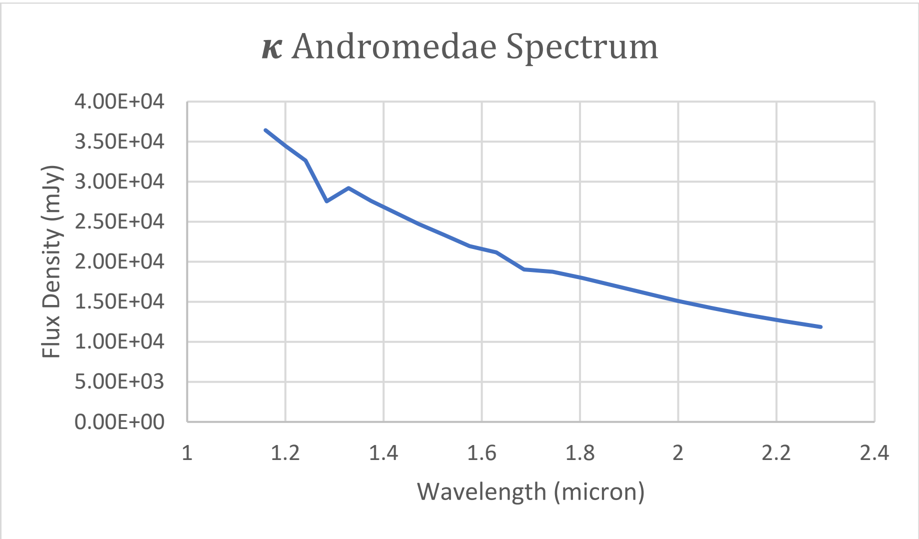


Figure 1: κ Andromedae spectrum.

With the satellite spot to star ratio as well as the star spectrum known, the spectrum of κ And b in absolute units can be found. Figures B1, B2, and B3 in Appendix B show the extracted spectrum at different KL values at movement combinations of 3, 5, and 7 respectively. The aforementioned figures in Appendix B also depict the spectrum mentioned in Currie *et al.* for comparison.

Aside from comparing the spectrum in terms of absolute flux density values, we also compared our derived ΔJ, ΔH, and ΔK band magnitudes for κ And b with Currie's values (Figure 2) using a similar expression used to calibrate the flux of the planet,

$$\Delta J = (kappa\ And\ b\ mag\ at\ J\ band) - (kappa\ And\ mag\ at\ J\ band)$$
$$\Delta J = -2.5 * \log_{10}((relative\ planet\ spectrum\ at\ J\ band) * (spot\ to\ star\ ratio\ at\ J\ band))$$

where J can denote any band.

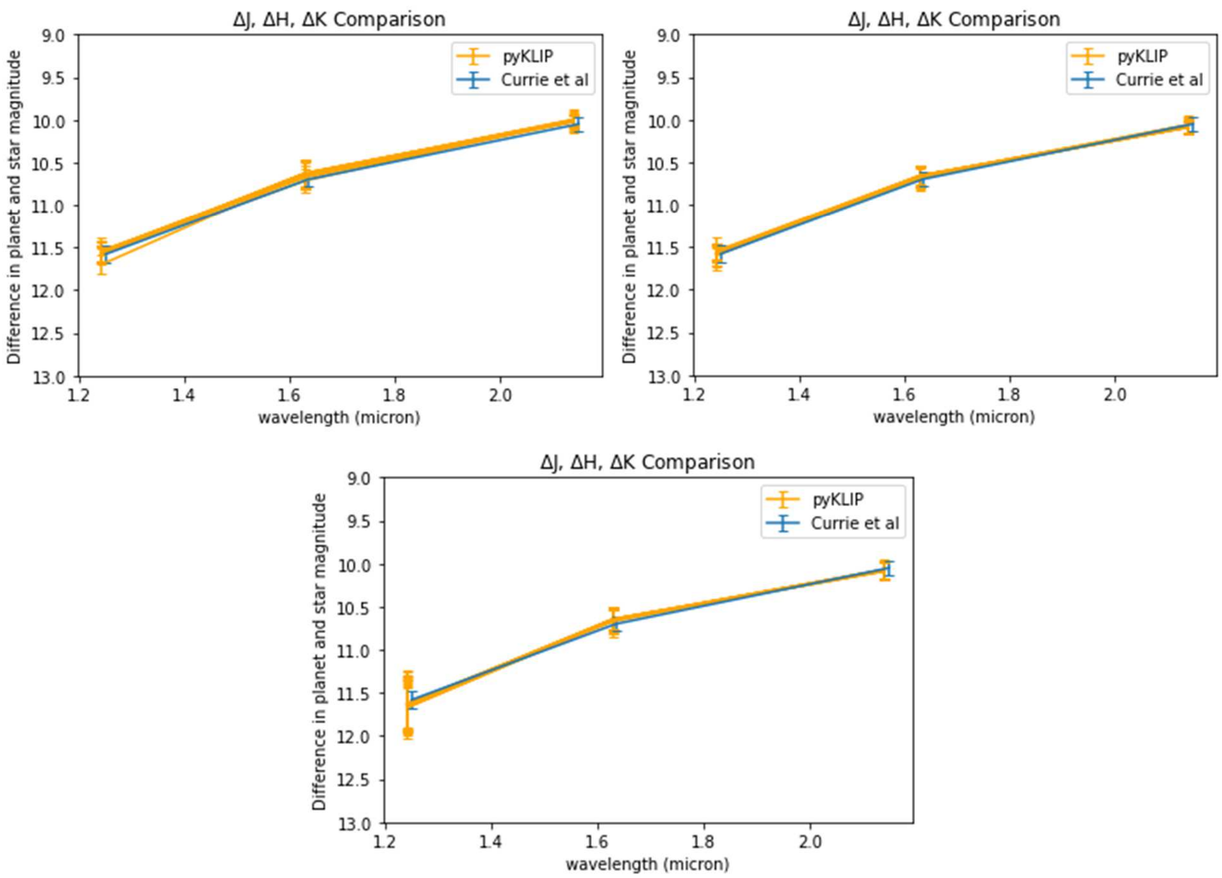


Figure 2: A comparison between the difference in planet and star magnitude in the J, H, and K bands for movements of 3 (top left), 5 (top right), 7 (bottom), and in each plot, KL vectors ranging from 1-20 were used. The variation in KL vectors gives the orange some small but discernable width. While all three movements all closely match the reference, a movement of 5 looks to give the best results as the uncertainty in the J band is low and the spectra across all KL vectors stay relatively consistent.

When comparing our results with Currie's in terms of the difference in planet and star magnitude as shown in Figure 2, there does not seem to be any discrepancies and all three movements closely match the reference. Further inspecting the three movements, however, we note that a movement of 5 appears to give the best results as uncertainty in the J band is low and the spectra across all KL stay consistent. However, comparing the spectrum in physical units at different movements, movements of 5 and 7 are noted to perform very similarly, each with its compromises. While movement=7 produces spectra that are more consistent across the KL values, movement=5 has noticeably lower uncertainty values. Furthermore, while movement=5 performs better (closer to reference) at lower wavelengths (less than 1.3 μm), movement=7 performs better at mid and higher wavelengths (greater than 1.7 μm).

As for the optimal number for KL, the number for KL does not appear to matter once the "correct" movement is chosen since the variation in the spectra across different KL values decrease, although we do hypothesize that this would only hold up to a certain KL; after which, increasing the number of KL vectors will only produce worse results. This is because increasing KL also increases the "aggressiveness" of the KLIP algorithm, which is not optimal for processing fairly bright objects like κ And b. Overall, it might be safe to assume that the correct movement parameter can be chosen by examining the variances among spectra found using different KL values.

2. HD 1160 b

We have also produced spectra for HD 1160 b that is fairly consistent with Garcia *et al* (2016). We discovered that low movement values will result in more variance in the spectra across KL values at greater wavelengths. Furthermore, greater KL also resulted in greater uncertainty of the spectra at greater wavelengths. These two observations are concurrent with the fact that HD 1160 b is very bright.

Similar to the κ And system, 10 CHARIS raw images of HD 1160 taken on August 31, 2017, were used to analyze HD 1160 b's spectrum. Each of these broadband images had an exposure time of 60.5 seconds and a parallactic angle ranging from 32.88˚ to 38.56˚. While these images are not the exact images used by Garcia, whose images are from October 31, 2015, via the SCExAO and NIR HiCIAO camera, they were chosen due to their availability of post-CHARISDRP pipeline data and alsofor comparison as we had a "manual'' spectral extraction that was done by grad student Cobi Rabinowitz on the same dataset.

Table 3: Parameters used in FM class and processing.

Parameter	Value
Separation of planet (pixels)	48.5123
Parallactic angle of planet relative to North (˚)	243.20
Number of KL basis vectors (KL)	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 12, 14, 16, 18, 20
Stamp size (pixels)	10
Movement (pixels)	3, 5, 7, 9
High pass	True
Inversion method	Least-squares
Factor to scale spectra	None

We then extracted HD 1160 b's spectrum using the same methodology as the κ And system. However, we varied our parameters (Table 3) as some appear to give better results than others. Error bars were also calculated in the same manner as the κ And system, via injecting 11 fake planets into the dataset at the same separation as the real planet and finding the interquartile ranges of the fake signals. Additionally, a further calibration step against algorithmic bias, similar to κ And b, was applied given HD 1160 b is even brighter. Similar to κ And b, Appendix C shows the extracted spectra for HD 1160 b without the aforementioned correction factor, and Appendix D shows the same spectra with the correction factor.

Table 4: HD 1160 absolute magnitude.

Band	Magnitude	Source
M_J	1.91 ± 0.10	Garcia *et al.*, 2017
M_H	1.94 ± 0.10	Garcia *et al.*, 2017
M_{Ks}	1.97 ± 0.10	Garcia *et al.*, 2017

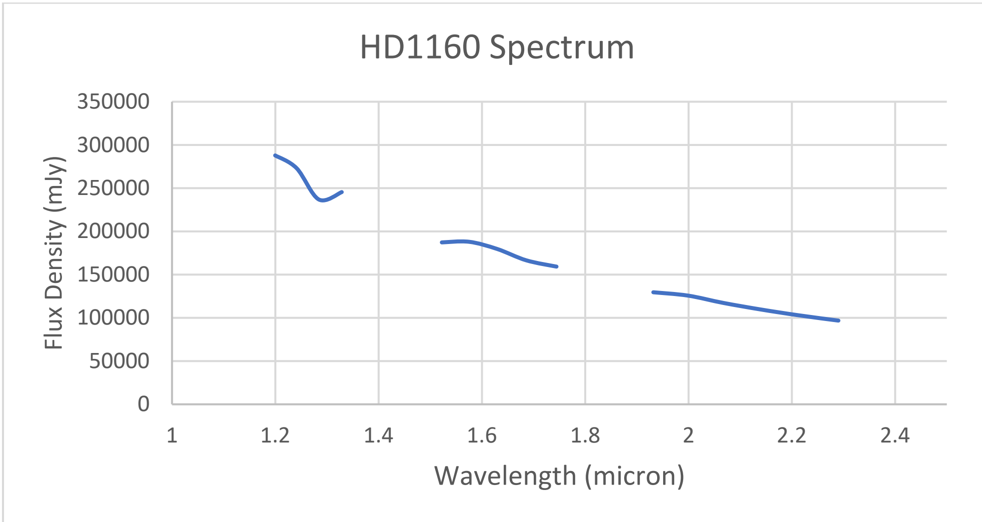


Figure 3: Calibrated HD 1160 Spectrum in the J, H, and K bands.

For absolute calibration of the planet flux, we used the same derived expression as above.

$$(absolute\ planet\ flux) = (relative\ planet\ spectrum) * (spot\ to\ star\ ratio) * (star\ spectrum)$$

However, for HD 1160, we used the Pickle's spectral library this time to represent HD 1160's spectrum as an A0V type star. Since the Pickles spectral library gives flux units relative to Vega, the absolute flux of HD 1160 was found by calibrating Vega's spectrum with the absolute magnitude of HD 1160 given in Table 4. The calibrated spectrum for HD 1160 is shown in Figure 3.

$$HD\ 1160\ flux = (Vega\ spectrum) * 10^{\left(\frac{HD\ 1160\ apparent\ magnitude}{-2.5}\right)}$$

Figures D1, D2, D3, and D4 in Appendix D give the extracted spectra in contrast units relative to the satellite spots with Cobi's results as a reference. While the shape of the spectra seem to be in good agreement with the spectrum Cobi derived at larger movement values or lower KL, the KLIP results appear to be consistently higher than Cobi's result. Examining the spectra across the different movement values, the shape of the spectra becomes more consistent across the number of KL basis vectors as movement increases. This suggests, once again, that greater movement values are best suited for HD 1160 b similar to κ And b.

Figures D1, D2, D3, and D4 in Appendix D also give the extracted spectra in absolute units. Comparing these results with that of Garcia *et al.*'s (reference), the values of the flux density of our method appear to be fairly consistent with the reference, given KL is low and movement is high. Furthermore, the *shapes* of both spectra at higher movements also agree as both spectra show a peak at around 1.4, 1.7, and 2.2 microns. While the peaks we produced were not as pronounced as the reference, the order in which their heights are ranked is mostly consistent with the reference in higher movements.

Aside from comparing the spectrum in terms of absolute flux density values, we also compared our derived ΔJ, ΔH, and ΔK band magnitudes for HD 1160 b with Garcia et al. (Figure 4) using the same expression as before with κ And b.

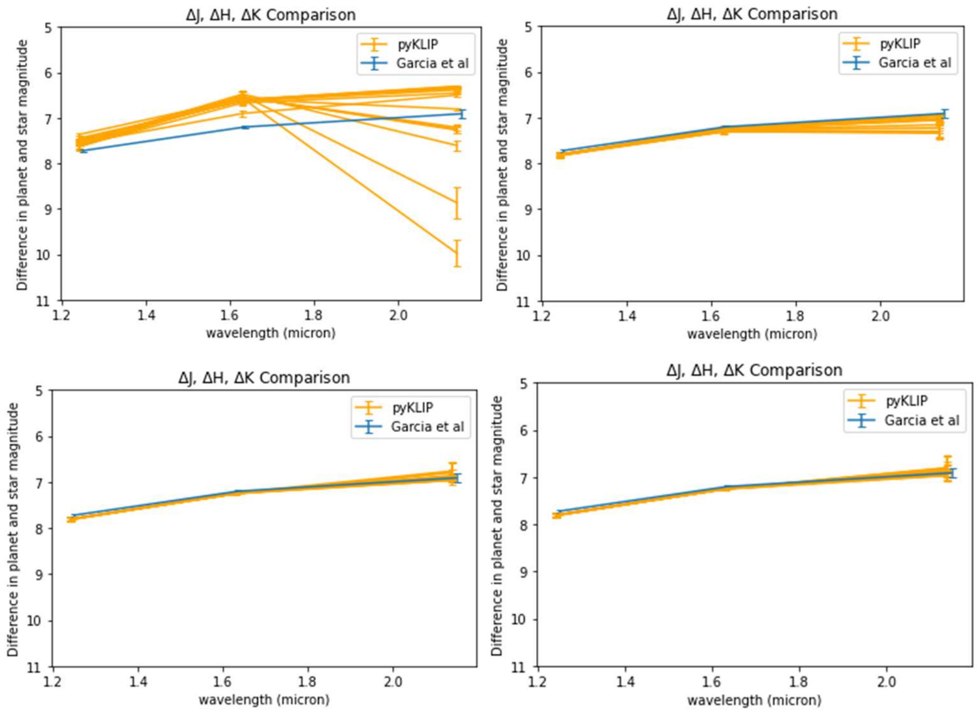


Figure 4: A comparison between the difference in planet and star magnitude in the J, H, and K bands for movements of 3 (top-left), 5 (top-right), 7 (bottom-left), and 9 (bottom-right). Movements of 7 and 9 as at lower KL values seem to produce to best results. Note: Higher Δmagnitudes correspond to fainter objects and vice versa.

From the ΔJ, ΔH, and ΔK comparison with the reference, movements of 7 and 9 at lower KL values appears to produce the most consistent and least variable result. Looking at Figure 4, there seems to be an interesting pattern where variance in the spectra across the number of KL basis increases as wavelength increases across all 4 movements. We hypothesize that this may be due to a lower SNR of HD 1160 b as wavelength increases.

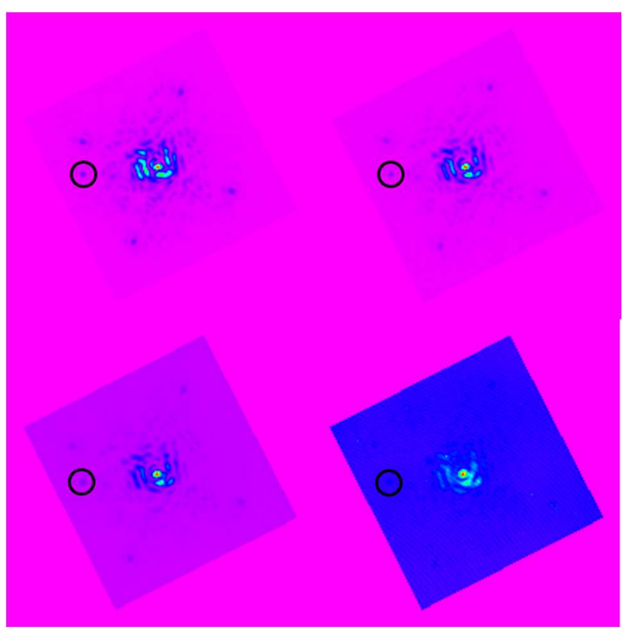


Figure 5: Slice 16 (1.93 µm) at the top left, slice 18 (2.07 µm) at top right, slice 20 (2.21 µm) at the bottom left, and slice 22 (2.37 µm) at the bottom right. As wavelength and slices increases, there is less contrast between HD 1160 b (circled in black) and its background.

As shown in Figure 5, the contrast between HD 1160 b and the background decreases substantially in the last few slices, leading to greater uncertainty in the K band differences as seen in Figure 4. The reason for this drop in contrast is still uncertain.

3. HD 1160 Variability

Aside from applying a secondary calibration step to the HD 1160 b spectra, we also examined the exoplanet's spectra at 4 different observational dates. As before, all these images of HD 1160 b were taken via CHARIS and obtained from the SMOKA database. They were all run through the CHARISDRP for reduction using a wavelength calibration of 2.346μm. Figure E1 in Appendix E below shows spectra compare to the reference at a movement of 7.

Examining the figure, the resulting spectra from July 16, 2017, is consistently lower across all number of KL basis vectors compared to the spectra from other dates as well as the reference. Upon examining the summit log, it was indicated that the sky was cloudy on July 16, 2017. Furthermore, when examining the summit log of the other 3 dates, the log indicated for all that the sky was clear. Therefore, it is likely that the lower spectra values from July 16, 2017, was a result of the attenuation of clouds.

4. Progress Update

We are currently working to process and extract more κ And b and HD 1160 b spectra on different observational dates. By using multiple spectra of the same objects but from different dates, we can statistically compare one spectrum with the others and determine how well we can detect the "true variability" of CHARIS or perhaps, though unlikely, of exoplanets. That said and given the anomaly of HD 1160 b data on July 16, 2017, we are currently trying to use the Kolmogorov–Smirnov test to verify that there indeed is a difference in the extracted spectrum that day due to cloud cover compared to the other spectra, and to also verify that the other spectra, which are not anomalies, are from the same distribution.

Appendix A: κ And b Without Algorithm Correction Factor

Referring to the figures below, a movement of 3 and a higher KL results in the result that best resembles the reference for this dataset. In addition, increasing the movement decreases the overall value or height of the spectrum. Thus, a movement of 5 and 7 for this dataset produces results that are consistently lower than the reference.

An interesting note is that as the movement increases, the variance in the spectra among the number of KL basis vectors used seems to decrease. However, the error bars of the spectra using a movement of 7 in the omitted dataset are also greater, perhaps compensating for the lower variance in the plot between the number of KL basis. Furthermore, it can be seen in both datasets that as KL increases, the values of the spectra also increases relative to the reference. Therefore, the values of the spectra appear to be affected by the parameters used during extraction, being negatively correlated with movement and positively correlated with KL. However, it is also important to reiterate that once the "correct" value for movement is chosen, the variation in the spectra extracted using different numbers of KL basis vectors used seems to decrease. Therefore, it is assumed that the correct movement parameter can be chosen by examining the variances among spectra found using different KL values.

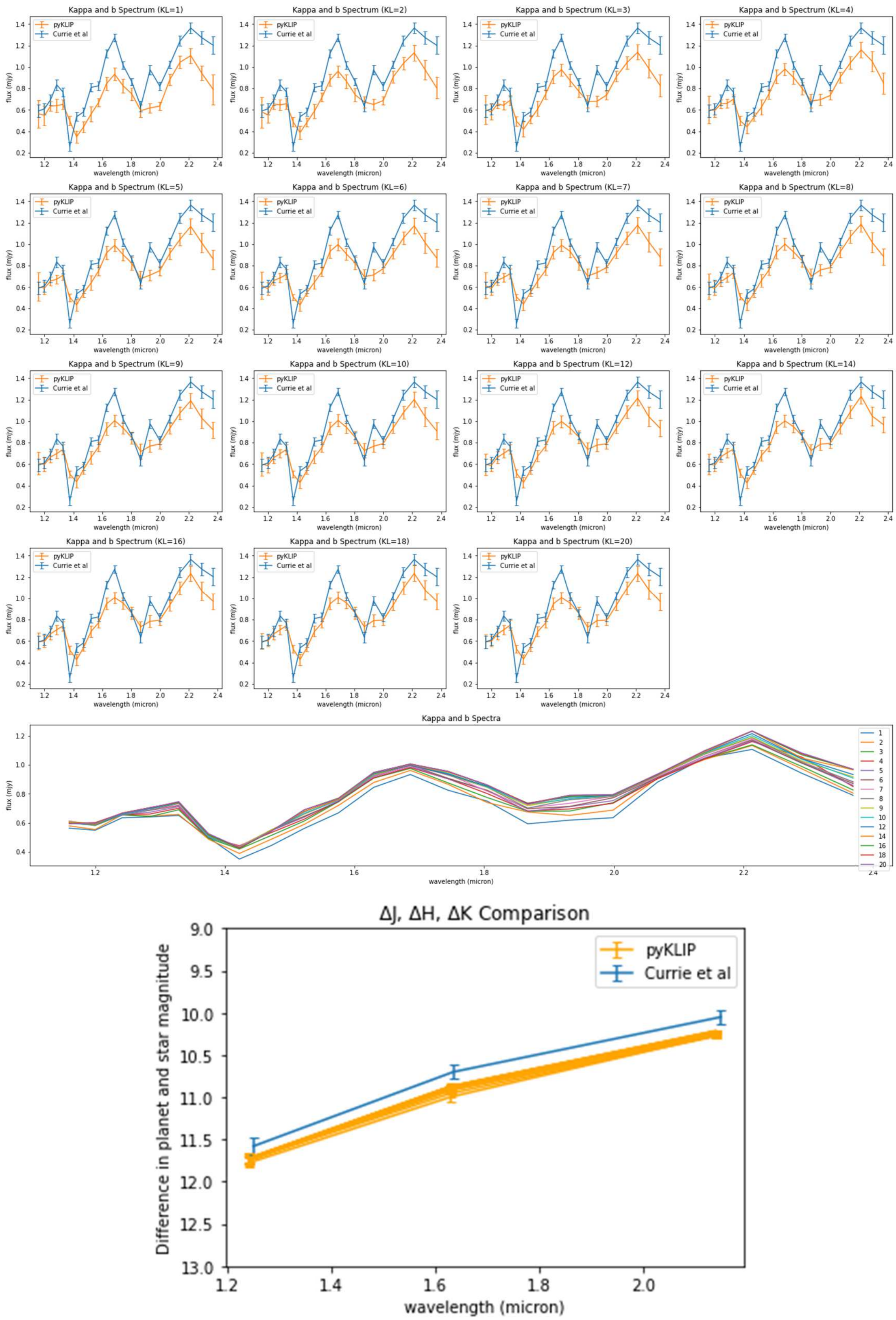


Figure A1: Top: Extracted spectra (movement = 3) at each KL value compared with spectrum produced by Currie et al. Middle: Extracted κ And b spectra at all KL numbers. Bottom: A comparison in the difference in magnitude between κ And b and κ And with the reference.

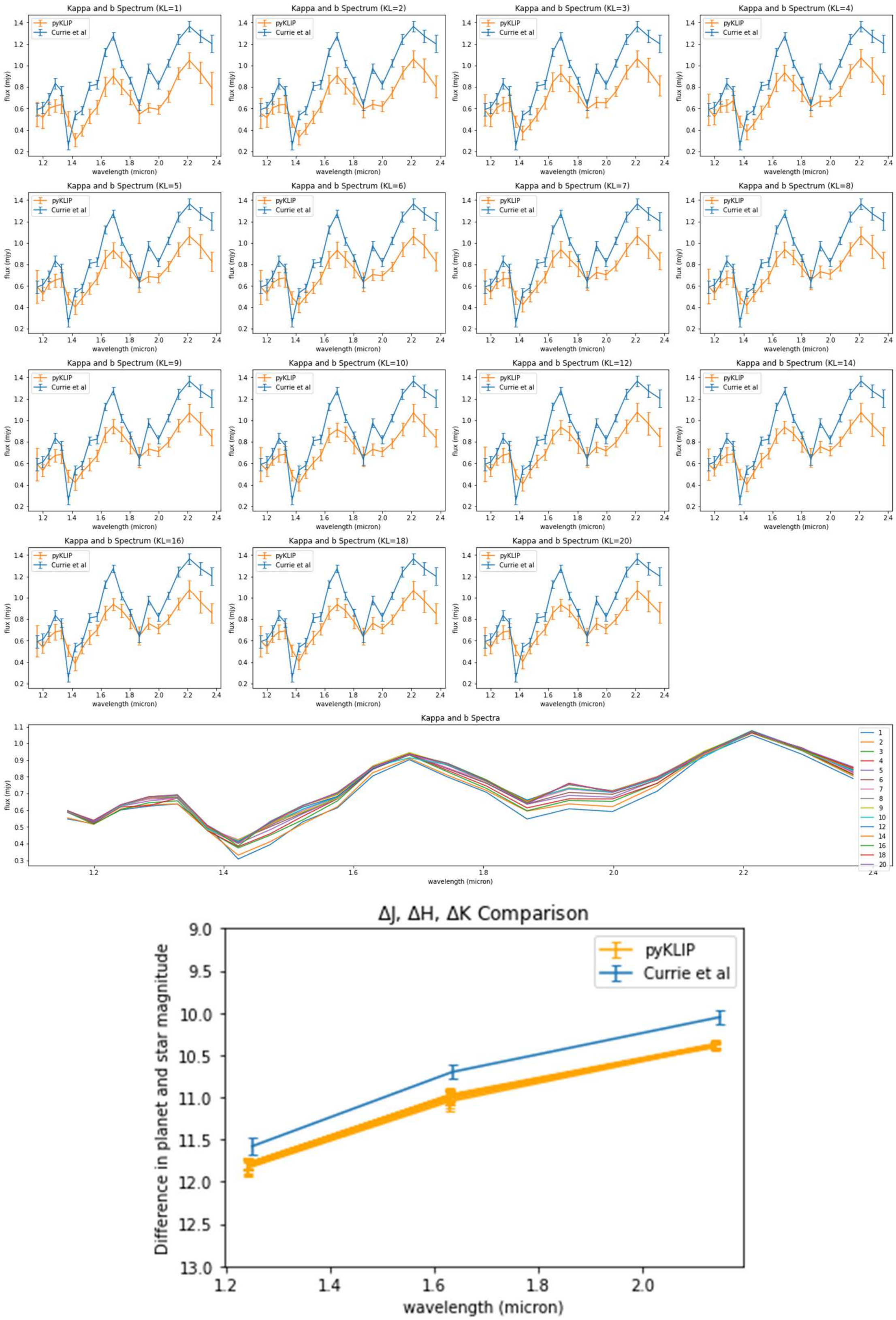


Figure A2: (movement = 5)

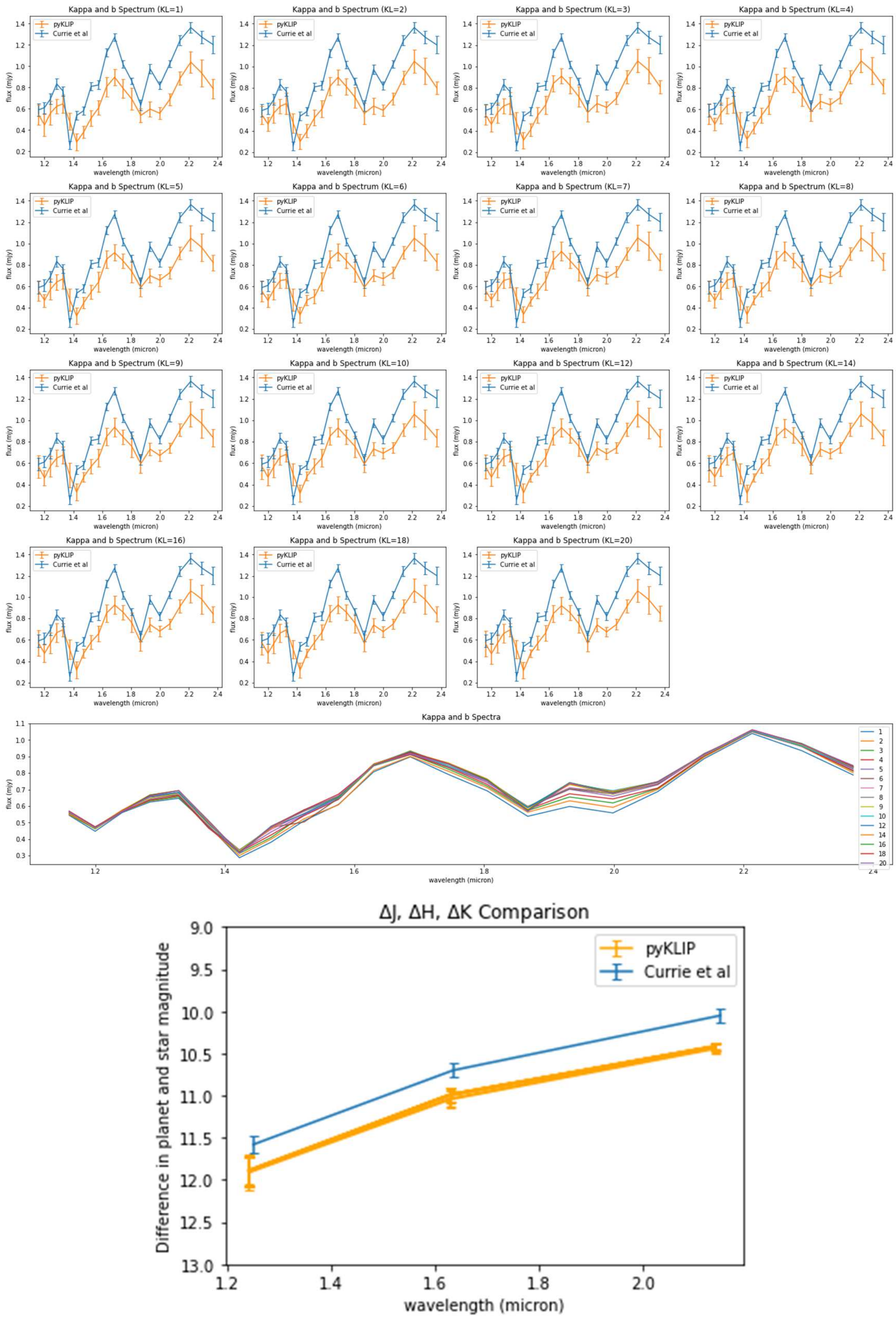


Figure A3: (movement = 7)

Appendix B: κ And b With Algorithm Correction Factor

After sending the initial report to Jason Wang, Jason suggested us to take the spectra of the fake injected planets used to calculate the error bars, and use the average of the spectra to derive a bias factor used to correct for the algorithmic bias in pyKLIP. After deriving a bias factor by taking the mean of the spectra at each wavelength at a specific KL value, we obtained much more reasonable spectra and magnitude.

The reason this recalibration is needed is that κ And b is relatively bright. As Jason noted, since the forward modeling assumes a linear perturbation of the planet on the KL modes, this assumption will break down when using lower movements or a greater number of KL basis vectors to extract the spectrum of a bright object.

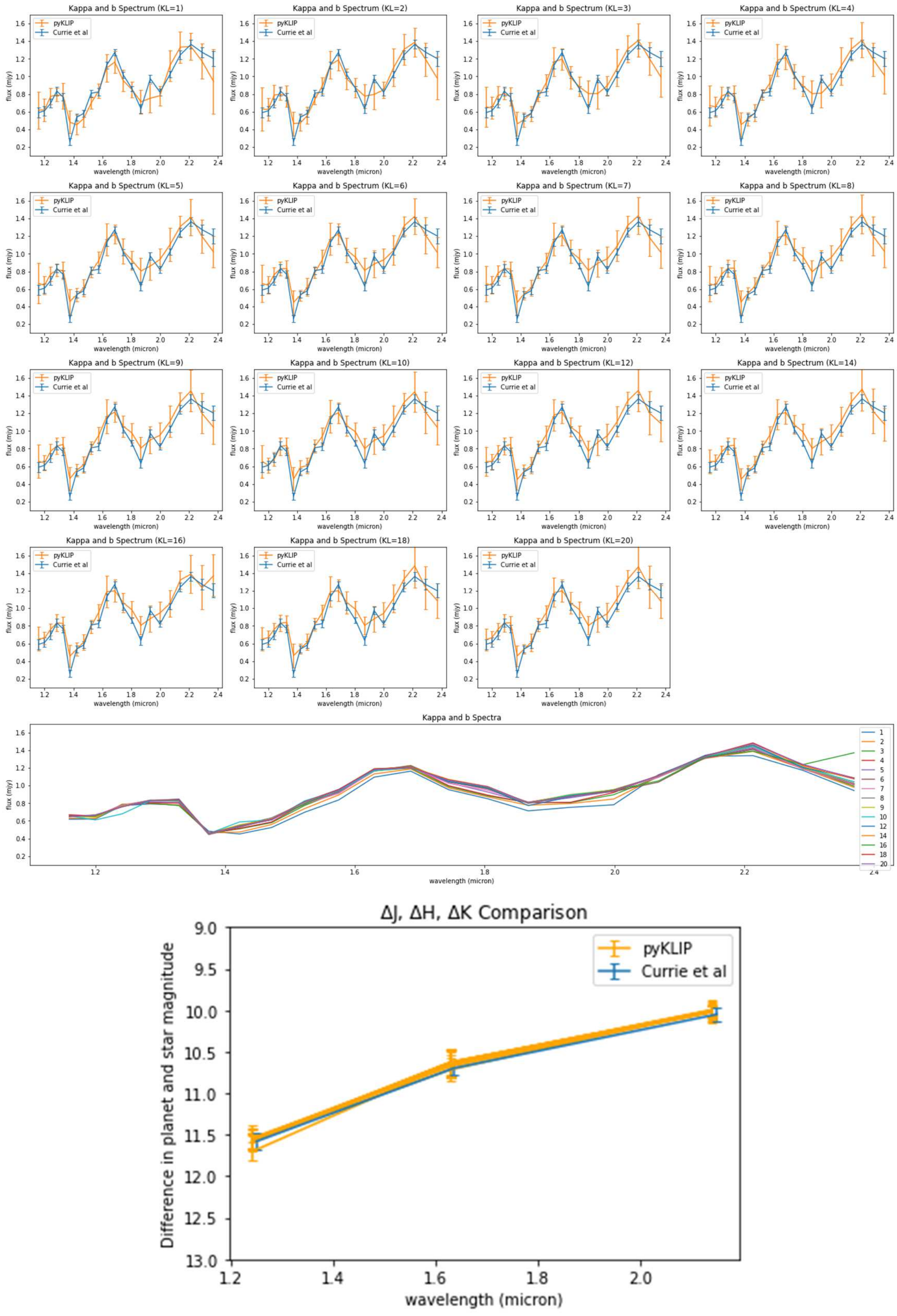


Figure B1: (movement = 3) Top: Extracted spectra at each KL value compared with spectrum produced by Currie et al. Middle: Extracted κ And b spectra at all KL numbers. Bottom: A comparison in the difference in magnitude between κ And b and κ And with the reference.

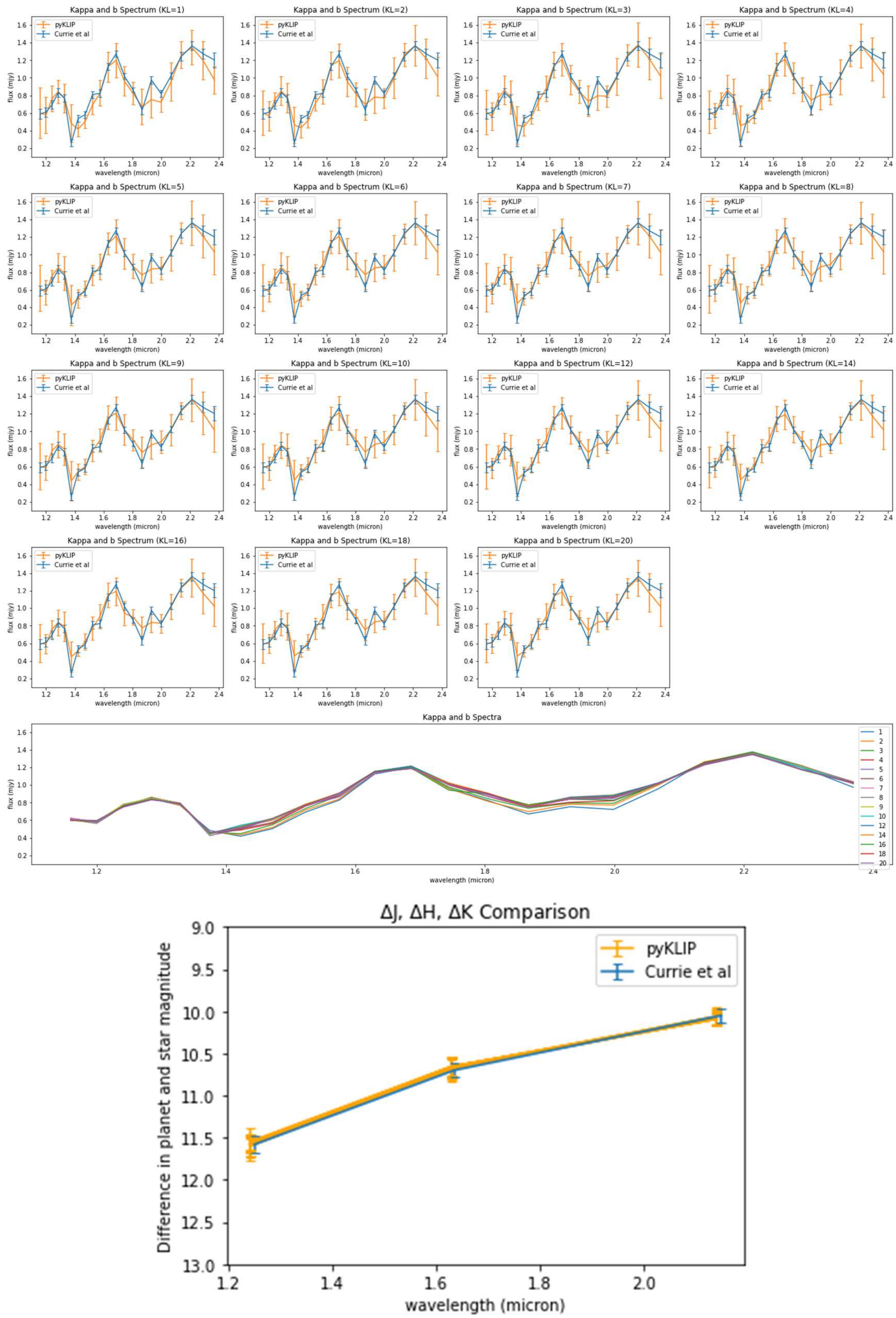


Figure B2: (movement = 5)

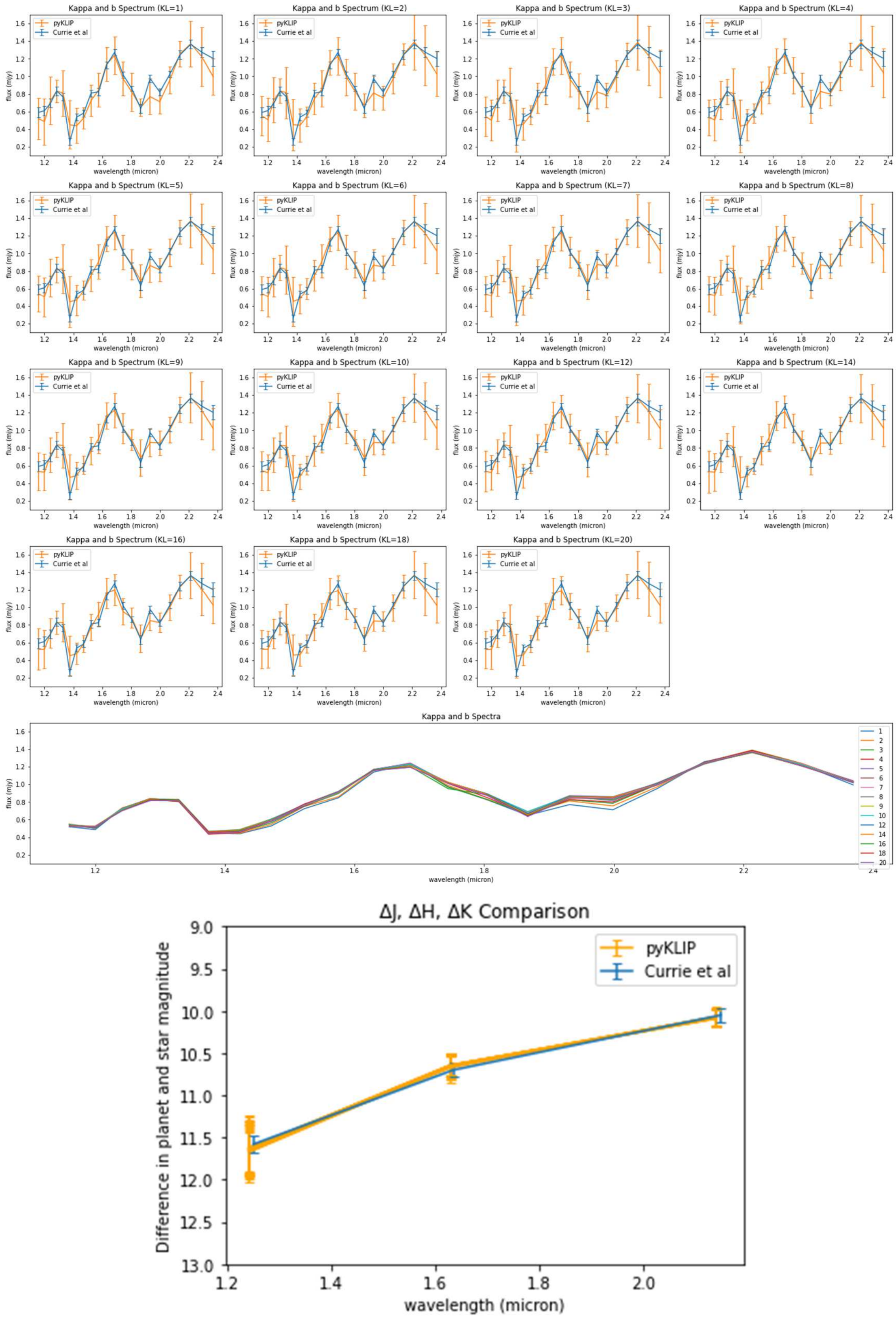


Figure B3: (movement = 7)

Appendix C: HD 1160 b Without Algorithm Correction Factor

The figures below give the extracted spectra in contrast units relative to the satellite spots with Cobi's results as a reference (top left). These results seem to be in good agreement with the spectrum Cobi derived at larger movement values or lower KL values. Examining the spectra across the different movement values, the shape of the spectra becomes more consistent across the number of KL basis vectors as movement increases. This suggests that perhaps greater movement values are best suited for HD 1160 b compared to κ And b.

The figures also give the extracted spectra in absolute units (top right). Comparing these results with that of Garcia *et al.*'s (reference), the values of the flux density of our method are consistently lower than the reference; however, spectra with lower movement appears to be closer to reference than spectra extracted using higher movement values. The shapes of both spectra at higher movements, however, agree as both spectra show a peak at around 1.4, 1.7, and 2.2 microns. While the peaks we produced were not as apparent as the reference, the order in which their heights are ranked is mostly consistent with the reference in higher movements.

Aside from comparing the spectrum in terms of absolute flux density values, we also compared our derived ΔJ, ΔH, and ΔK band magnitudes for HD 1160 b with Garcia et al. (bottom). From the ΔJ, ΔH, and ΔK comparison with the reference, it is clear that the actual values of the spectra are different at higher movements, while the consistency in the shape of the spectra degenerates at lower movements. In other words, there is a contradiction in the evidence for which movement is best. If we simply were to look at values, then a movement of 3 with a lower number of KL basis vectors is better than the others. Contrarily, if we were to only look at the shape, then a movement of 7 or 9 produces the most consistent results across all different numbers of KL vectors.

Overall, a movement of 3, and 5 to 8 KL basis vectors seem to give the most comparable result to the reference, although we are uncertain whether this happened strictly by chance. Similar to what was seen before with the κ And b spectra, greater movements result in an overall lower spectrum, but also one that has less variance across the number of KL basis vectors. In the case of increasing KL values, however, there does not appear to be any evidence to suggest a positive correlation between the KL and the values of the spectrum.

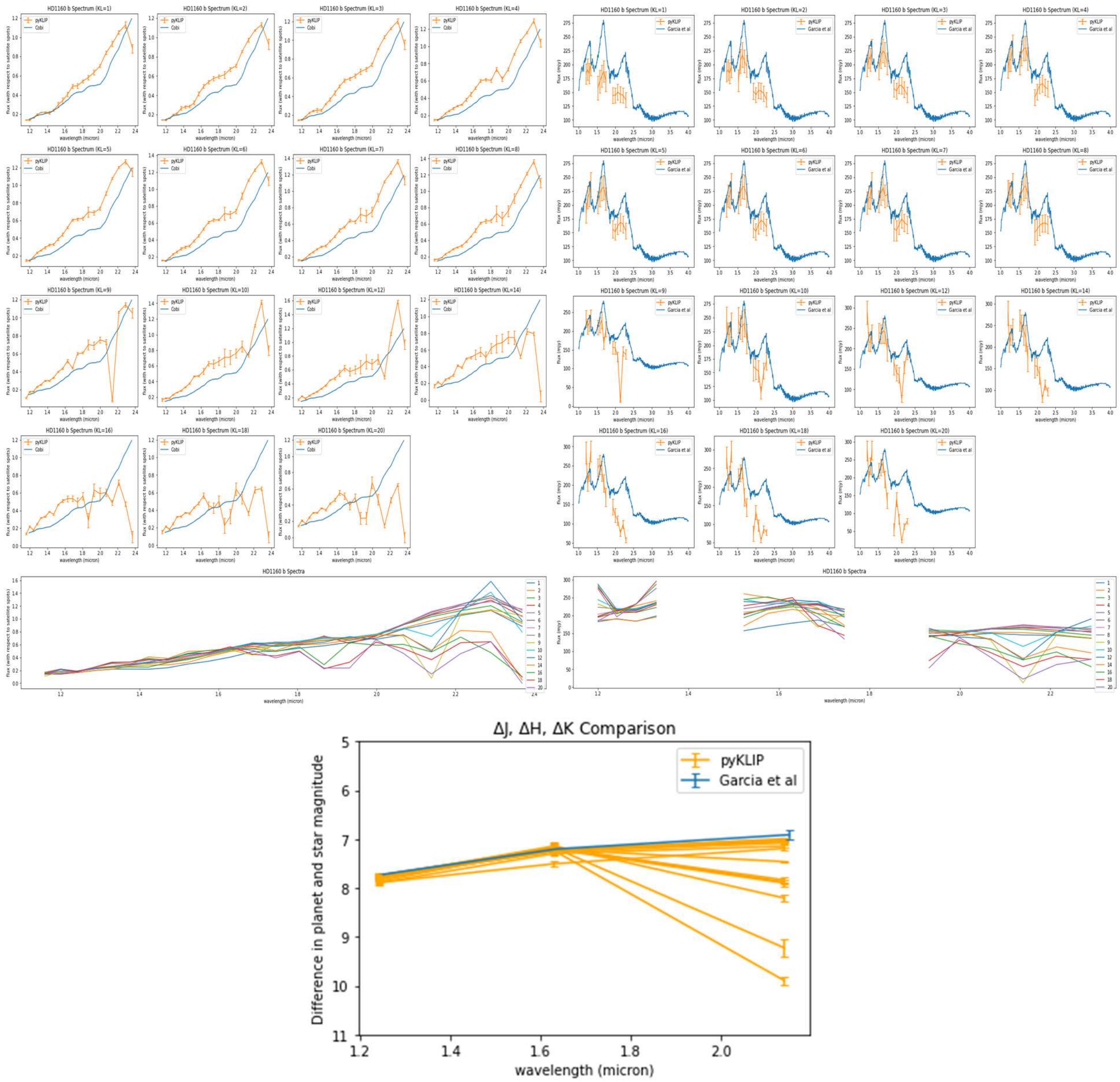
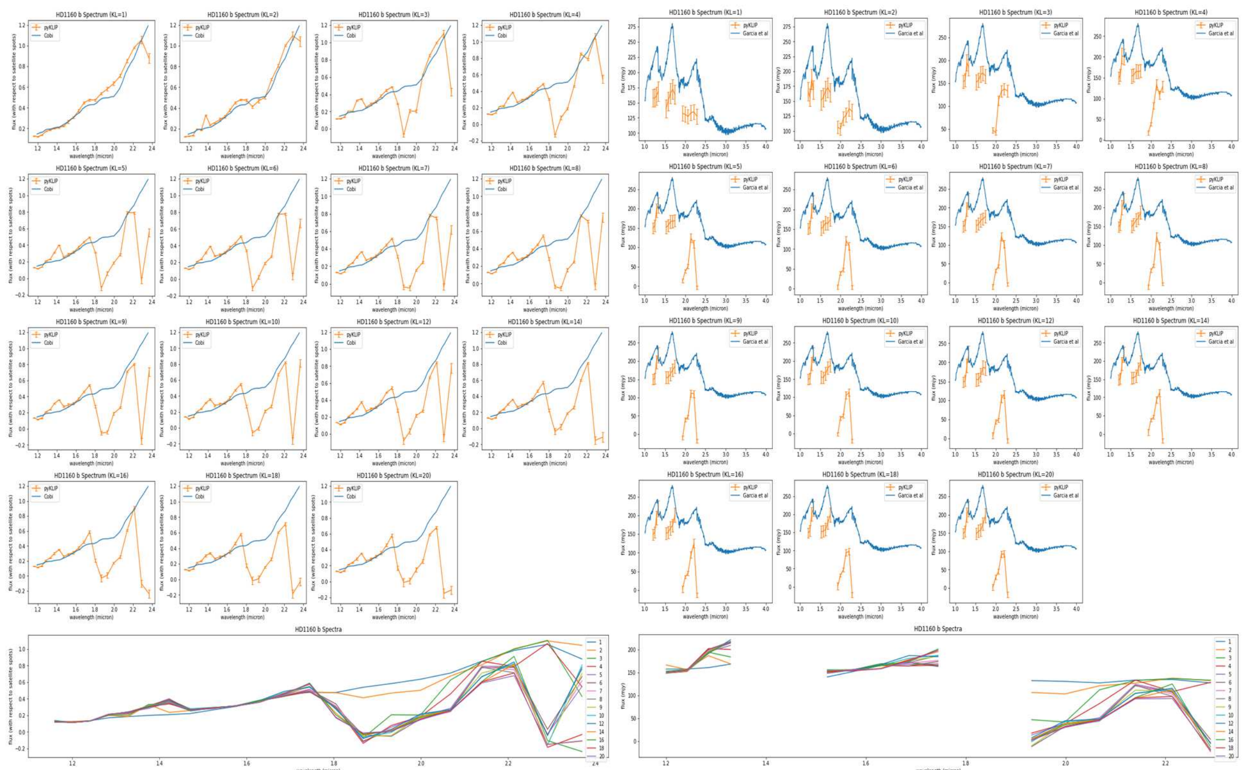


Figure C1: (movement = 3) Top Left: extracted spectra in contrast units relative to the satellite spots with Cobi's results as a reference. Top Right: Extracted spectra in absolute physical units. Bottom: ΔJ, ΔH, and ΔK band magnitudes comparison for HD 1160 b with Garcia et al.



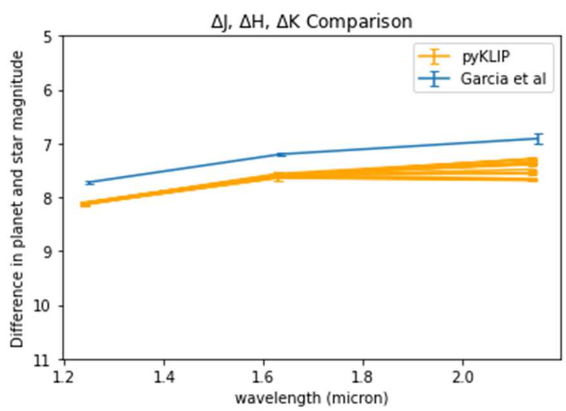


Figure C2: (movement = 5)

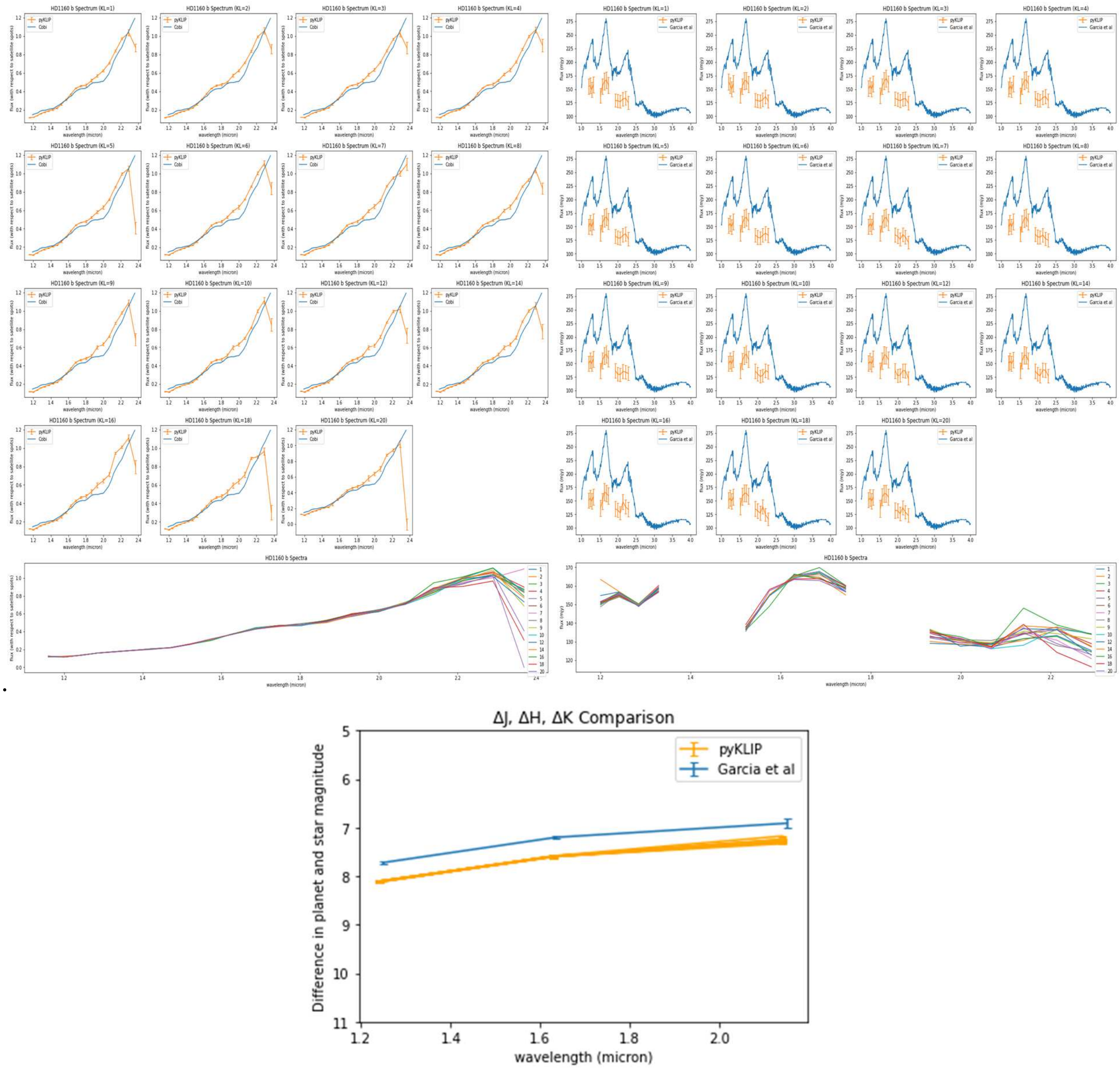


Figure C3: (movement = 7)

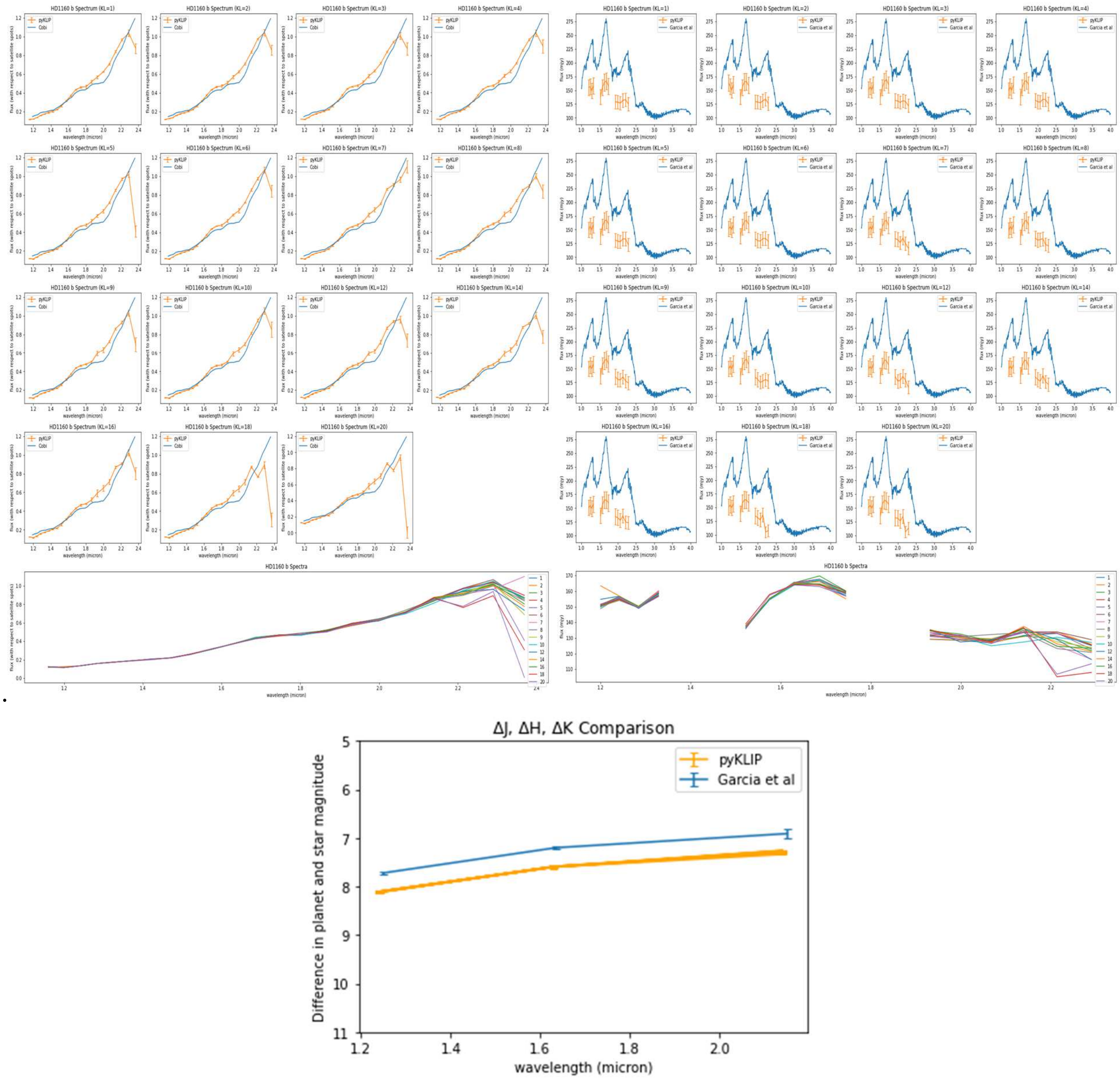


Figure C4: (movement = 9)

Appendix D: HD 1160 b Without Algorithm Correction Factor

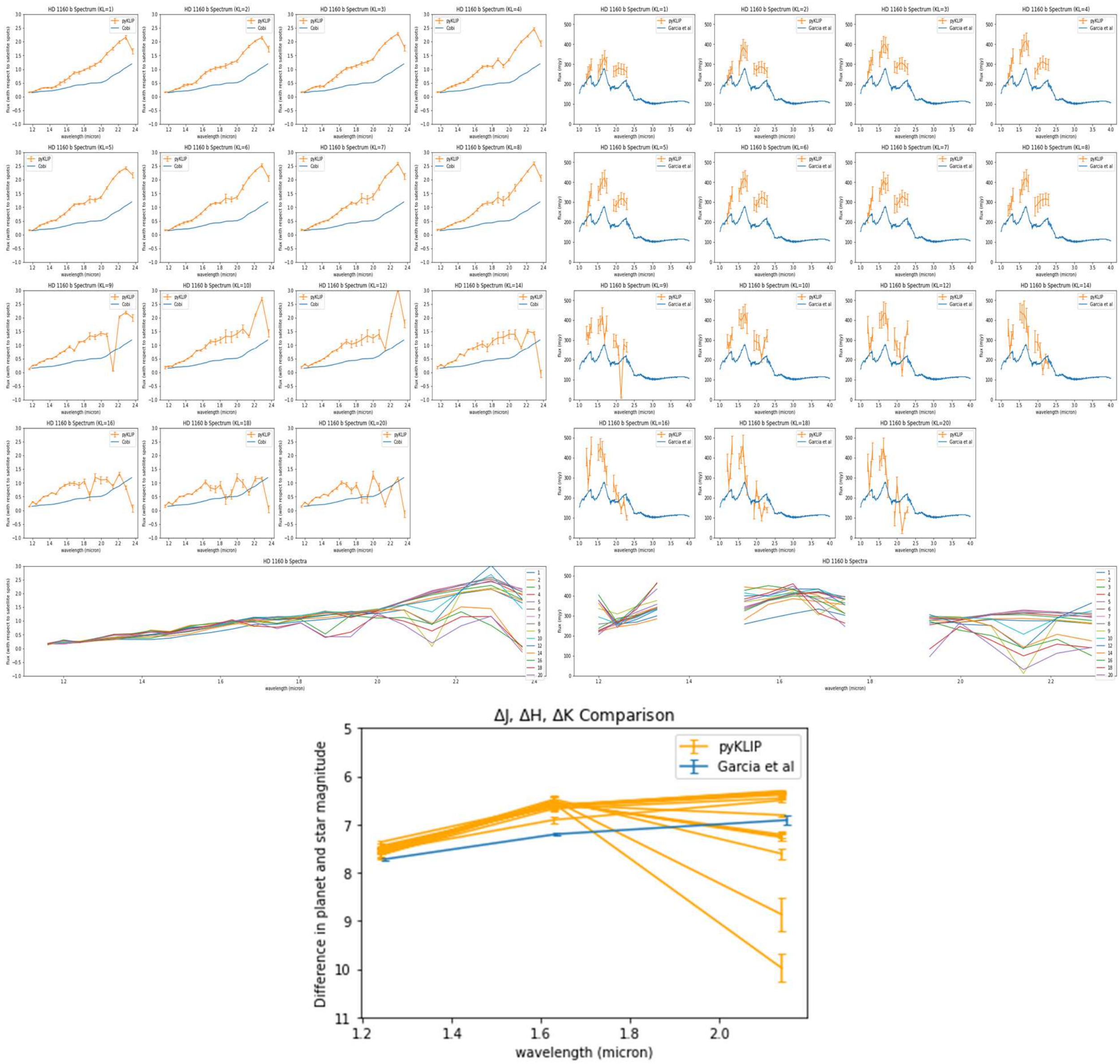


Figure D1: (movement = 3) Top Left: extracted spectra in contrast units relative to the satellite spots with Cobi's results as a reference. Top Right: Extracted spectra in absolute physical units. Bottom: ΔJ, ΔH, and ΔK band magnitudes comparison for HD 1160 b with Garcia et al.

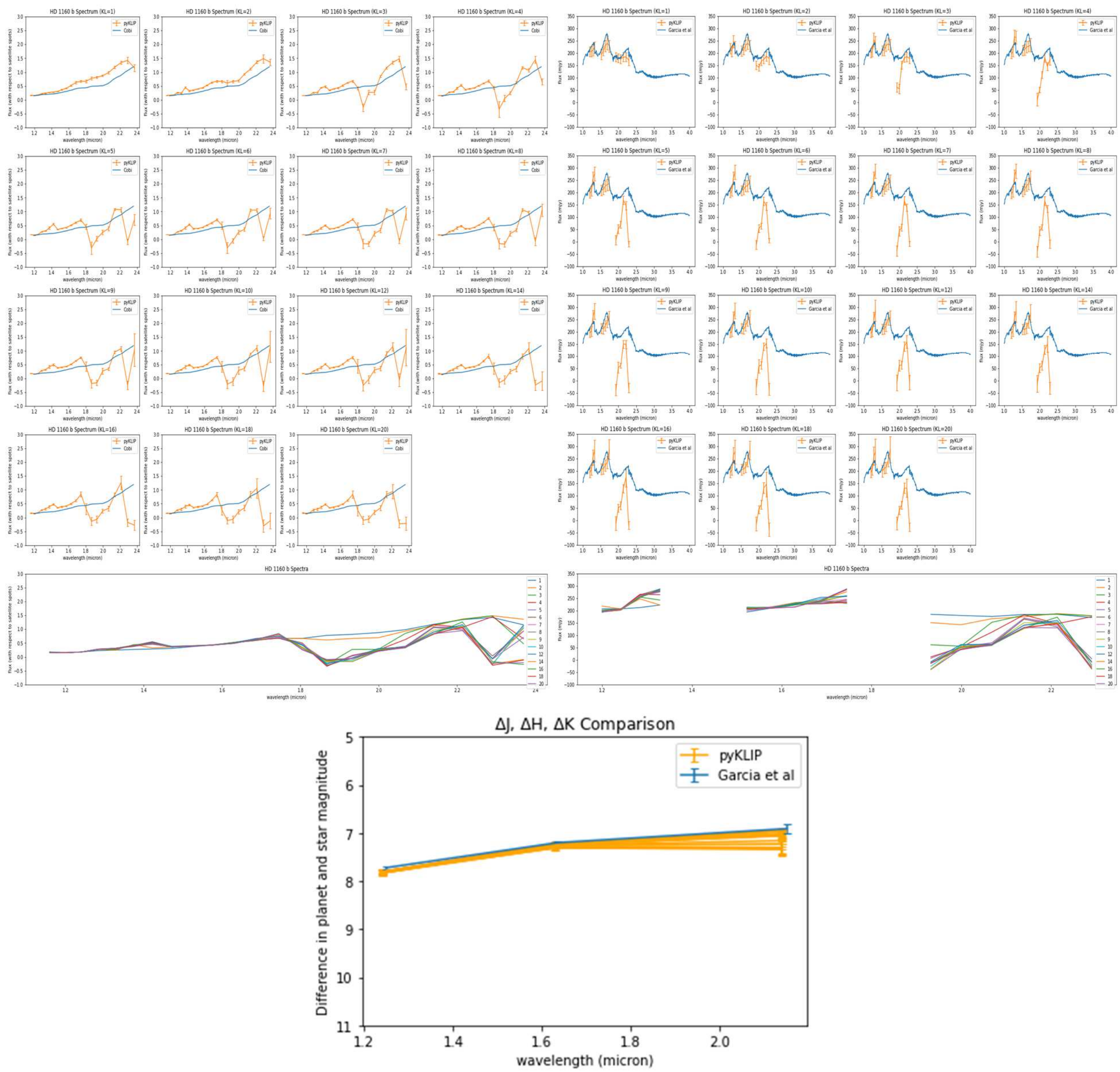


Figure D2: (movement = 5)

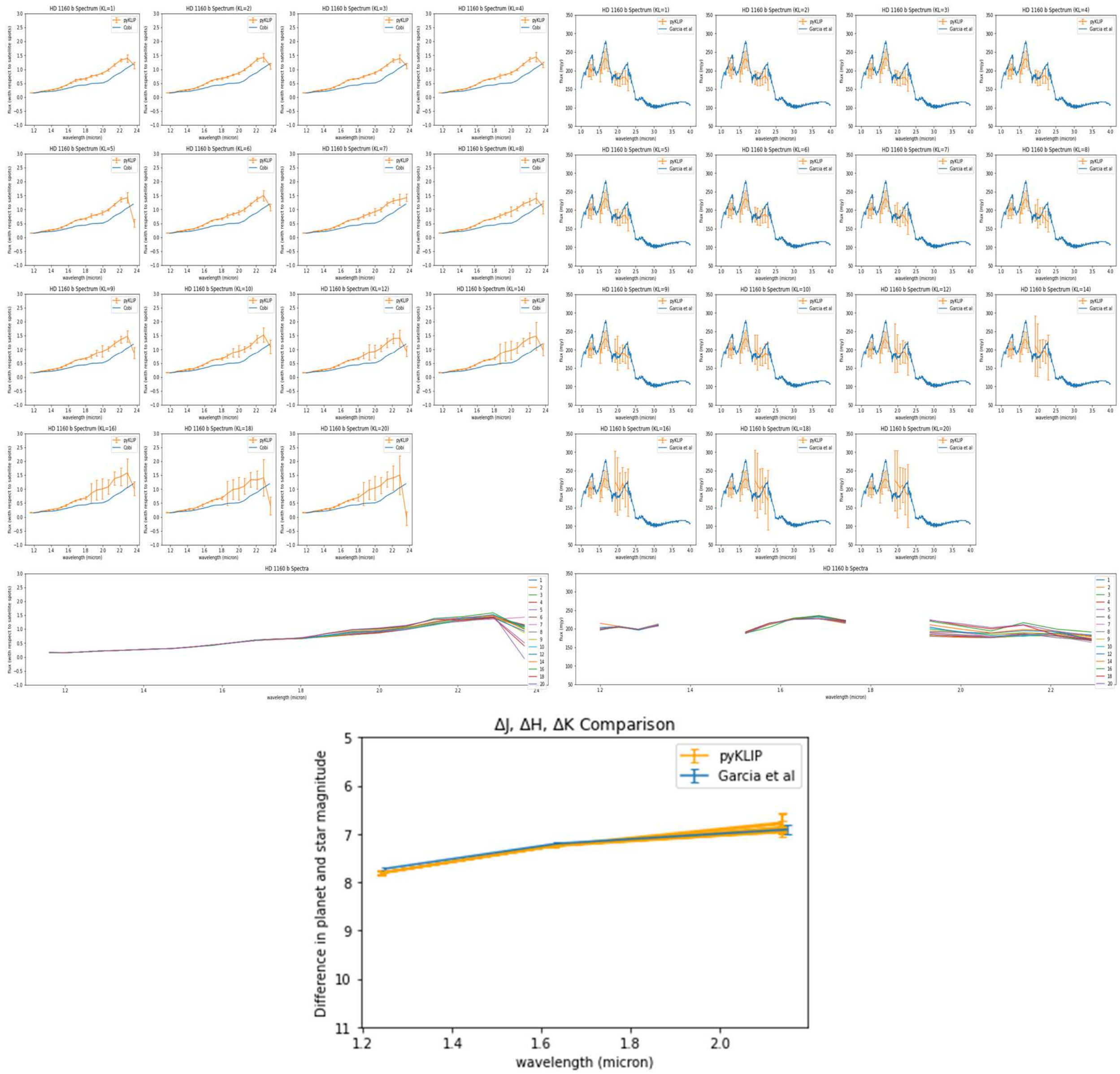


Figure D3: (movement = 7)

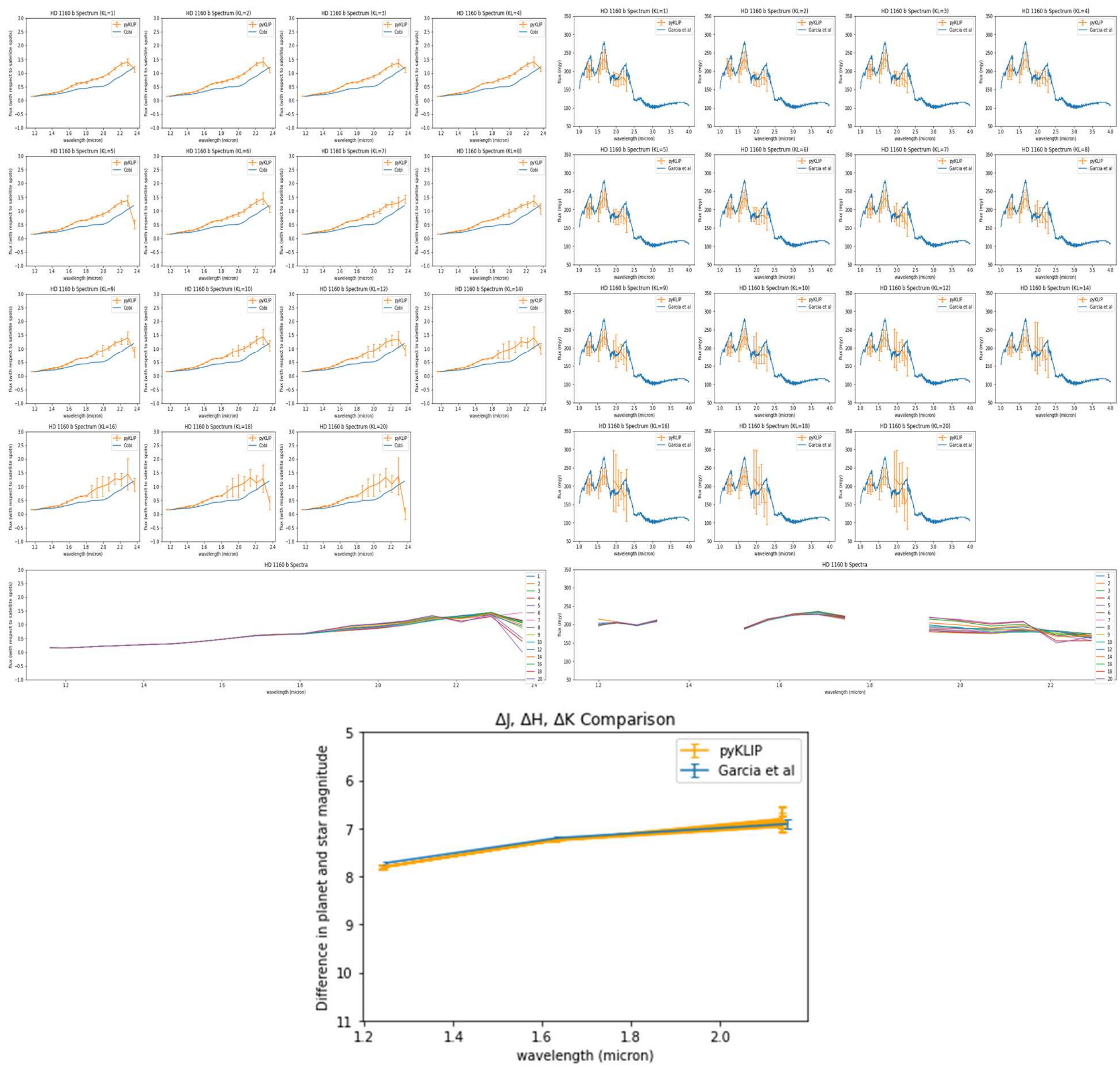


Figure D4: (movement = 9)

Appendix E: Comparison of HD 1160 b spectra at different observation dates.

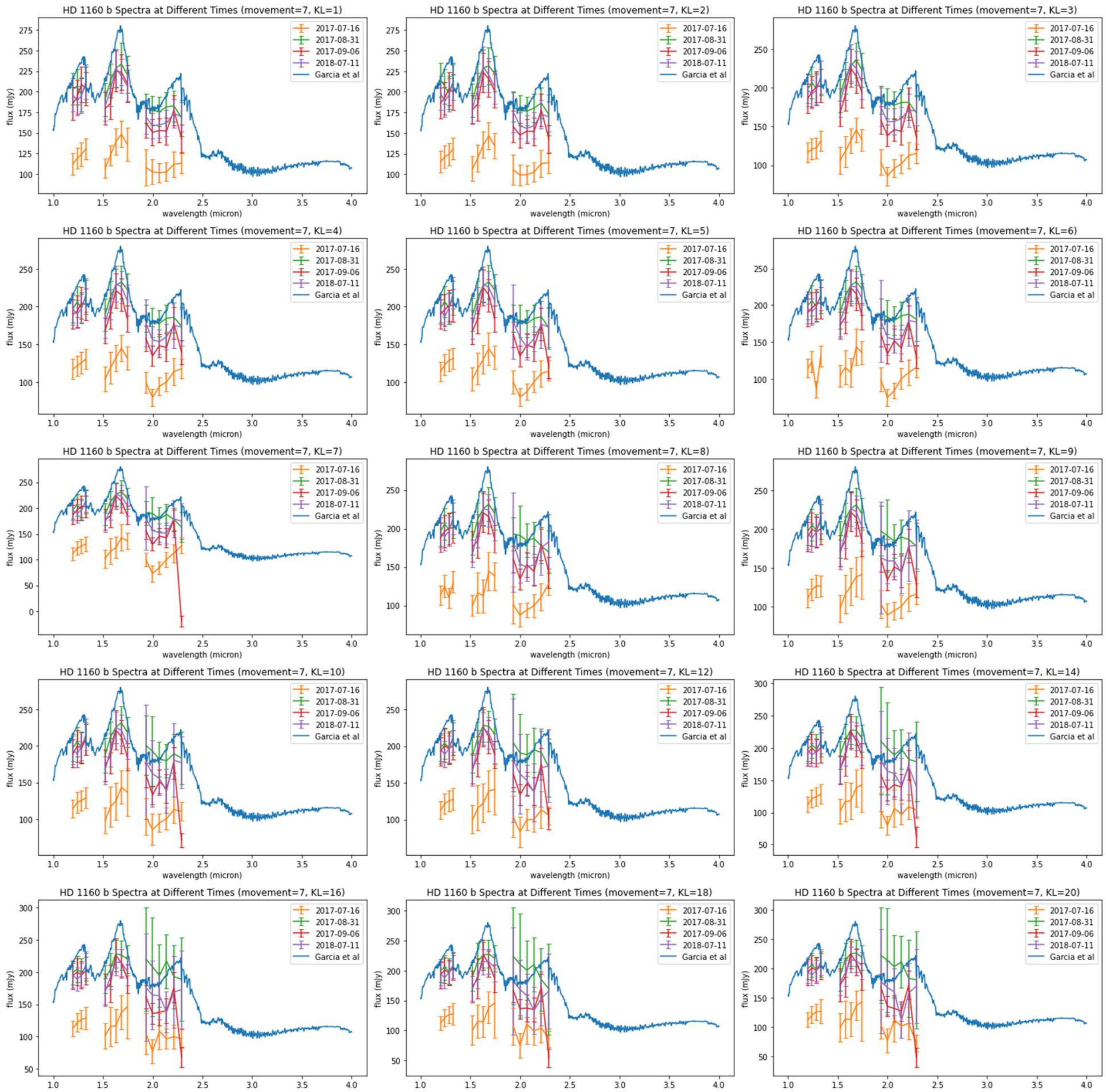


Figure E1: Comparison of HD 1160 b spectra on different observation dates at different KL basis vectors.

References

https://iopscience.iop.org/article/10.3847/1538-3881/aae9ea

https://iopscience.iop.org/article/10.3847/1538-4357/834/2/162

https://iopscience.iop.org/article/10.1088/0004-637X/779/2/153/meta

https://arxiv.org/pdf/1604.06097.pdf

https://smoka.nao.ac.jp/

http://princetonuniversity.github.io/charis-dep/index.html

https://pyklip.readthedocs.io/en/latest/

https://pysynphot.readthedocs.io/en/latest/index.html

Code and Results: https://github.com/peizhiliu168/Spectrum-Extraction-using-pyKLIP.git