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The *JWST* Early Release Science Program for Direct Observations of Exoplanetary Systems I: High Contrast Imaging of the Exoplanet HIP 65426 b from 2–16 μm

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ABSTRACT

We present *JWST* Early Release Science (ERS) coronagraphic observations of the super-Jupiter exoplanet, HIP 65426 b, with the Near-Infrared Camera (NIRCam) from 2–5 μm , and with the Mid-Infrared Instrument (MIRI) from 11–16 μm . At a separation of $\sim 0.82''$ (87_{-31}^{+108} au), HIP 65426 b is clearly detected in all seven of our observational filters, representing the first images of an exoplanet to be obtained by *JWST*, and the first ever direct detection of an exoplanet beyond 5 μm . These observations demonstrate that *JWST* is exceeding its nominal predicted performance by up to a factor of 10, with measured 5σ contrast limits of $\sim 4 \times 10^{-6}$ ($\sim 2.4 \mu\text{Jy}$) and $\sim 2 \times 10^{-4}$ ($\sim 10 \mu\text{Jy}$) at $1''$ for NIRCam at 3.6 μm and MIRI at 11.3 μm , respectively. These contrast limits provide sensitivity to sub-Jupiter companions with masses as low as $0.3 M_{\text{Jup}}$ beyond separations of ~ 100 au. Together with existing ground-based near-infrared data, the *JWST* photometry are well fit by a BT-SETTL atmospheric model from 1–16 μm , and span $\sim 97\%$ of HIP 65426 b’s luminous range. Independent of the choice of forward model atmosphere we measure an empirical bolometric luminosity that is tightly constrained between $\log(L_{\text{bol}}/L_{\odot}) = -4.35$ to -4.21 , which in turn provides a robust mass constraint of $7.1 \pm 1.1 M_{\text{Jup}}$. In totality, these observations confirm that *JWST* presents a powerful and exciting opportunity to characterise the population of exoplanets amenable to direct imaging in greater detail.

1. INTRODUCTION

Across the last twenty-five years a variety of observational techniques have been employed to uncover and characterise the current population of over 5000 confirmed exoplanets (NASA Exoplanet Science Institute 2020). Of these techniques, the direct detection of photons from an exoplanetary atmosphere – direct imaging – remains one of the most challenging due to the substantial contrast in flux between host stars and their exoplanetary companions. The emitted flux of an exoplanet can be many magnitudes fainter than the stellar diffraction halo at its angular separation, and bespoke instrumentation (e.g., Macintosh et al. 2014; Beuzit et al. 2019) and/or image post-processing (e.g., Chauvin et al. 2004; Marois et al. 2008) is needed to isolate the exoplanet emission. Nevertheless, these “high contrast” observations offer considerable advantages to other techniques. At present, direct imaging is the most viable technique for characterising the population of exoplanets at orbital separations greater than ~ 10 au. Furthermore, beyond the large population of irradiated, close-in planets with atmospheric measurements obtained via exoplanet transit observations, high contrast observations of exoplanet emission remain the most readily accessible path towards the characterisation of exoplanet atmospheres. Constraints on atmospheric composition may improve our understanding of exoplanet formation and evolution (e.g., Öberg et al. 2011; Morley et al.

2019; Zhang et al. 2021; Mollière et al. 2022), although these determinations can be highly dependent on the post-formation accretion of solid material. Compared to close-in transiting exoplanets, directly imaged planets present a distinct advantage in this regard, as they are easier to detect at younger ages where they are less likely to have experienced significant migration and/or accretion. Additionally, at young ages bulk properties such as temperature, radius, and bolometric luminosity provide independent constraints on formation conditions (Marley et al. 2007; Marleau & Cumming 2014) that can be contrasted to atmosphere-driven conclusions on formation. Finally, the study of exoplanet atmospheres continues to advance towards smaller, and more Earth-like exoplanets, and could ultimately lead to the discovery of life outside our Solar System (Schwieterman et al. 2018).

At present ~ 20 planetary mass companions (PMCs) have been detected and characterised through high contrast observations (Currie et al. 2022), and all exoplanets directly imaged to date have estimated or dynamically-measured masses $\gtrsim 2 M_{\text{Jup}}$. Despite the small sample size, this subset of objects has driven significant developments in our overall understanding of exoplanet atmospheres and architectures. For example, the formation of exoplanets through gravitational instability is rare (Vigan et al. 2017; Nielsen et al. 2019; Vigan et al. 2021); brown dwarfs and exoplanets may exhibit different eccentricity distributions (Bowler et al. 2020); clouds and disequilibrium chemistry influence measured spectra (e.g., Skemer et al. 2012; Apai et al. 2013; Morley et al. 2014); similar to brown dwarfs, exoplanets can be variable (Zhou et al. 2019, 2020; Vos et al. 2022); wide

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separation exoplanets may be more prevalent within systems that also host a circumstellar disk (Meshkat et al. 2017); and transits of exomoons may be observable around isolated planetary mass objects (Limbach et al. 2021). Nevertheless, upgraded or new observatories and instruments (e.g., Gardner et al. 2006; Males et al. 2018; Chilcote et al. 2020) will be necessary to directly image and characterise a wider diversity of closer separation and/or lower mass exoplanets at a higher precision and across a broader wavelength range.

1.1. High Contrast Observations with JWST

Launched on December 25th, 2021, *JWST* (Gardner et al. 2006) is an international collaboration between NASA, ESA, and the CSA, and the first large strategic mission of the NASA Astrophysics Division to launch since the 1990’s (National Academies of Sciences & Medicine 2017). With a primary mirror diameter of 6.5 m, an operational wavelength range from 0.6–28.1 μm , and a diverse range of instrumental modes, *JWST* presents a revolutionary opportunity for scientific exploration and discovery across all branches of astronomy and astrophysics. Within this remit, high contrast observations of exoplanets and exoplanetary systems are no exception.

JWST is located at the second Sun–Earth Lagrange point, far from the thermal background, telluric contamination, and wavefront aberrations generated by Earth’s atmosphere. The combination of excellent optical performance (~ 75 – 130 nm RMS wavefront error, depending on the instrument), highly stable wavefront (< 2 nm drift over a few hours), and large telescope aperture, enables *JWST* to reach better photometric and spectroscopic limiting sensitivities than both past or current ground- (i.e., 8–10 m class telescopes) and space-based (e.g., *Hubble*, *Spitzer*) observatories (Rigby et al. 2022). It is not only this increased sensitivity that improves our ability to detect and characterise faint objects such as exoplanets, but its combination with *JWST*’s access to the near- and mid-infrared. At these wavelengths, the flux emitted from a hotter host star steadily decreases as a function of increasing wavelength, whereas the flux emitted from cooler exoplanetary companions reaches a peak. Hence, the natural star-planet contrast is diminished. To realise these advantages, *JWST* offers a selection of instrumental modes designed for, or that can be applied to, high contrast observations. Specifically, both NIRCcam (Rieke et al. 2005) and MIRI (Rieke et al. 2015) are equipped with coronagraphic masks (Krist et al. 2009; Boccaletti et al. 2015), NIRISS (Doyon et al. 2012) is equipped with a non-redundant mask which enables aperture masking interferometry (AMI; Sivaramakrish-

nan et al. 2012), and although lacking any hardware for starlight suppression, both NIRSpec (Bagnasco et al. 2007) and MIRI are equipped with integral field units (IFUs; Wells et al. 2015; Böker et al. 2022).

In anticipation of the range of capabilities that *JWST* would provide, a similar range of predictions and simulations were constructed in an effort to forecast its potential for exoplanet imaging science. Brande et al. (2020) predict that Saturn and Jupiter mass planets should be detectable with MIRI coronagraphy at 1–5 au separations across a sample of nearby ($\lesssim 10$ pc) M-dwarfs. Similarly, Carter et al. (2021a) demonstrate that both NIRCcam and MIRI coronagraphy may be sensitive to sub-Jupiter mass planets for the majority of stars within the β Pictoris moving group (β PMG) and TW Hydrae Association (TWA), albeit at separations > 20 – 50 au. Ray et al. (submitted) further expands on the work of Carter et al. (2021a), and shows that sub-Jupiter mass planets could be detectable from 1–20 au for several stars within β PMG, TWA, and the Taurus Auriga Association with NIRISS AMI. At even closer separations, Beichman et al. (2020) predict that MIRI coronagraphy of α Centauri A may be sensitive to $\sim 5 R_{\oplus}$ companions from 0.5–2.5 au. Danielski et al. (2018) demonstrate that already discovered companions (e.g., HR 8799 b/c/d Marois et al. 2008, 2010), β Pictoris b (Lagrange et al. 2010)) should also be detectable with MIRI coronagraphy, and NH_3 absorption could be identified for a subset of targets. Finally, Patapis et al. (2022) show that molecular mapping is possible with the MIRI IFU and may result in the detection of atmospheric species such as H_2O , CO , CO_2 , CH_4 , NH_3 , and PH_3 .

These predictions are based on ground-based testing and observatory simulations, however, the true capabilities of *JWST* hinge on its on-sky performance. Preliminarily, the performance of both the NIRCcam and MIRI coronagraphic modes exceeded expectations during observatory commissioning (Girard et al. 2022; Kammerer et al. 2022; Boccaletti et al. 2022), but the first scientific demonstrations of *JWST*’s capabilities are being conducted as part of the Director’s Discretionary Early Release Science (ERS) Programs¹. Our ERS program “*High Contrast Imaging of Exoplanets and Exoplanetary Systems with JWST*” (ERS-01386, Hinkley et al. 2022a) is the only ERS program that has tested the high contrast exoplanet imaging modes of *JWST* and includes: coronagraphic imaging from 2–16 μm of the known ex-

¹ <https://www.stsci.edu/jwst/science-execution/approved-ers-programs>

oplanet HIP 65426 b (Chauvin et al. 2017, this work) and circumstellar disk HD 141569 A (Weinberger et al. 1999, Millar-Blanchaer et al. in preparation, Choquet et al. in preparation), spectroscopy from 1–28 μm of the PMC VHS J125601.92-125723.9 AB b (VHS 1256 b, Gauza et al. 2015, Miles et al. submitted), and AMI observations of HIP 65426 at 3.8 μm (Ray et al. in preparation). This program is rapidly disseminating these crucial initial data, and demonstrating the true capabilities of *JWST* for high contrast imaging and spectroscopy for the first time. Furthermore, we will provide a range of science enabling products (e.g., data analysis pipelines, recommendations for best observing practices) to the community to support their own proposals and investigations in Cycle 2 and beyond (Hinkley et al. 2022a).

In this work we focus exclusively on the coronagraphic imaging observations of the HIP 65426 system within this ERS program, and their context within a broader understanding of *JWST* as a tool for high contrast imaging.

1.2. HIP 65426 b

Discovered by Chauvin et al. (2017), HIP 65426 b is a super-Jupiter mass exoplanet at a wide physical separation of 110_{-30}^{+90} au (Cheetham et al. 2019) to the star HIP 65426 (A2V, 2MASS $J=6.826$, $\Delta J-K=0.055$, $M_{\odot}=1.96\pm 0.04$). HIP 65426 is located at a distance of 107.49 ± 0.40 pc (Gaia Collaboration 2020), has no signs of binarity from radial velocity and sparse aperture masking observations (Chauvin et al. 2017; Cheetham et al. 2019), and is a fast rotator ($v\sin(i)=299\pm 9$ km s^{-1} , Chauvin et al. 2017). Furthermore, HIP 65426 is a likely member of the Lower Centaurus-Crux association as derived from its proper motion and radial velocity measurements (89% probability, Gagné et al. 2018), constraining its age to 14 ± 4 Myr. This association has grown in interest over time with the increasing number of directly imaged exoplanet discoveries within it (e.g., HD 95086 b Rameau et al. 2013, PDS 70 b/c Keppler et al. 2018, and TYC 8998 b/c Bohn et al. 2020).

Although HIP 65426 b was initially observed with a combination of low resolution spectroscopy and photometry from $\sim 1-2$ μm (Chauvin et al. 2017), follow up observations expanded this coverage to $\sim 1-5$ μm (Cheetham et al. 2019; Stolker et al. 2020b), including a medium-resolution spectrum from $\sim 2-2.5$ μm ($R\approx 5500$, Petrus et al. 2021). Photometric analysis has demonstrated that HIP 65426 b is similarly located to mid-to-late L-dwarfs in colour-magnitude diagrams (Figure 1), and lies between already discovered early L-dwarf exoplanet companions (e.g., β Pic b, HD 106906 b) and those at the L/T transition (e.g.,

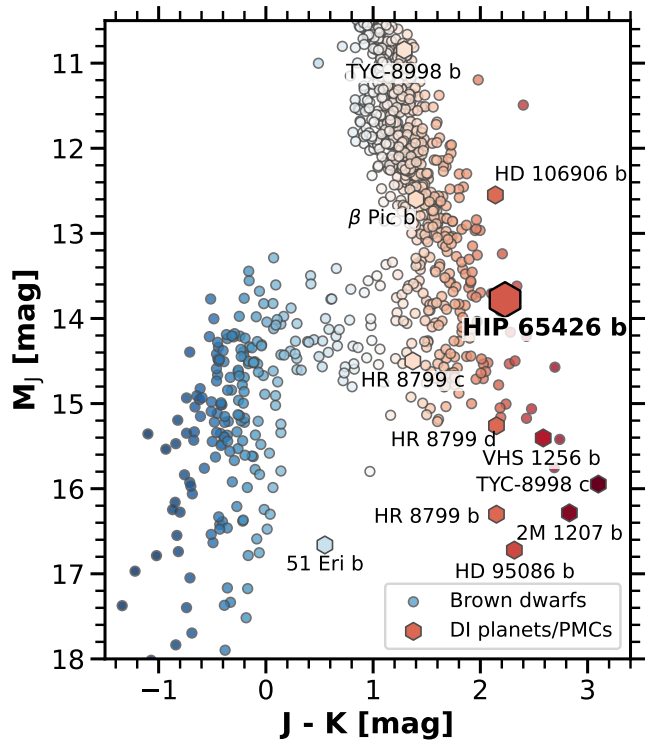


Figure 1. Colour-magnitude diagram showing the position of HIP 65426 b (Chauvin et al. 2017) relative to both the population of brown dwarf objects (circles) and a selection of directly imaged planetary mass companions (PMCs, hexagons), as obtained from Best et al. (2020).

HR 8799 c/d/e). Using combined photometric and spectroscopic observations, Petrus et al. (2021) performed an atmospheric forward model analysis of HIP 65426 b, indicating that it has $T_{\text{eff}}=1560\pm 100$ K, $\log(g)\leq 4.40$ dex, $[M/H]=0.05_{-0.22}^{+0.24}$ dex, and the atmospheric carbon-to-oxygen ratio has an upper limit of $C/O\leq 0.55$. Furthermore, Petrus et al. (2021) also detect the presence of H_2O and CO in the atmosphere of HIP 65426 b using cross-correlation molecular mapping, in addition to non-detections of CH_4 and NH_3 . Finally, from evolutionary model analyses to the data reported in Chauvin et al. (2017), Marleau et al. (2019) estimate the mass of HIP 65426 b to be $9.9_{-1.8}^{+1.1} M_{\text{Jup}}$ or $10.9_{-2.0}^{+1.4} M_{\text{Jup}}$ for hot- or cold-start initial entropy conditions, respectively (see e.g., Marley et al. 2007; Spiegel & Burrows 2012).

In Section 2 we describe our *JWST* observations of HIP 65426 b and all necessary data reduction. In Section 3 we describe the analysis steps taken to produce residual starlight subtracted images and measurements of contrast performance. We present a discussion of these observations in the context of both the overall performance of *JWST* and our individual understanding of

HIP 65426 b in Section 4. Finally, we summarise our conclusions in Section 5.

2. OBSERVATIONS & DATA REDUCTION

The NIRCcam and MIRI coronagraphic imaging observations of HIP 65426 b presented here were taken as part of program ERS-01386 (Hinkley et al. 2022a) and exist as a subset of a broad range of observations to assess the performance of *JWST*’s high contrast imaging and spectroscopic modes with respect to the study of exoplanetary systems (Hinkley et al. 2022a).

2.1. Observational Structure

The observational strategies used for this program were adopted following the recommended best practices as known prior to launch and described in the *JWST* user documentation^{2,3}. All observations of HIP 65426 b are repeated at two independent roll angles separated by $\sim 10^\circ$ to enable subtraction of the residual stellar point spread function (PSF) through angular differential imaging (ADI, Müller & Weigelt 1985; Liu 2004; Marois et al. 2006). Although a large number of rolls across a larger angular range would be desirable for an optimal subtraction using this technique, the combination of lengthy exposure times, increased overheads, and spacecraft orientation constraints prohibit an observing strategy more complex than described. Given the maximum possible roll offset for *JWST* at any given epoch is 14° , a larger roll offset than we have adopted would also require multi-epoch observations.

We also perform similar observations of a bright reference star, HIP 68245 (B2IV, 2MASS $J=4.628$, $\Delta J-K=0.137$), to additionally enable subtraction through reference differential imaging (RDI). This star was selected as it is: a) bright, therefore reducing the exposure time required to attain a similar signal-to-noise as the science target, b) a similar spectral type to the science target, therefore reducing the impact of spectral type mismatch, c) is relatively close ($\sim 10^\circ$) to the science target, therefore reducing slew overheads and minimising position dependent wavefront drift between science and reference observations, and d) has no evidence of binarity as determined by *VLT*/SPHERE AMI observations (Proposal ID: 108.22CD). For information on selecting a suitable reference star, see the *JWST* User

Documentation⁴. All exposure settings for the science and reference observations are shown in Table 1.

An RDI based subtraction is likely to reach superior contrast limits to ADI from pre-launch predictions (Lajoie et al. 2016; Perrin et al. 2018; Carter et al. 2021b), and is therefore also more representative of the optimal performance of *JWST* coronagraphy (also see Section 4.1). The exposure settings for these reference observations were chosen to reach an approximately equivalent fraction of full well saturation per integration as the corresponding target observations. Additionally, each reference observation was repeated at nine separate dither positions following small-grid dither patterns 9-POINT-CIRCLE and 9-POINT-SMALL-GRID for the NIRCcam and MIRI observations, respectively (Soummer et al. 2014; Lajoie et al. 2016). The goal of this strategy is to produce a small library of reference PSFs for each science exposure which captures different misalignments between the star and the center of the coronagraphic mask, and can in turn facilitate more advanced PSF subtraction techniques (e.g., KLIP, Soummer et al. 2012). Further discussion on the relative benefits between ADI and RDI subtraction strategies, or a combination of the two, with respect to these *JWST* observations can be found in Section 4.1.

For MIRI, we also add background observations to both our science and reference observations in both filters of a nearby “empty” region of sky (as identified in WISE images, Wright et al. 2010) separated $\sim 1.5'$ away the target star to measure the stray light “glow stick” that is inherent to MIRI coronagraphic observations (Boccaletti et al. 2022). Specifically, this position corresponds to a right ascension and declination of $\alpha = 13^\circ 24' 44.2915''$, $\delta = -51^\circ 29' 31.54''$, respectively. To best match the science and reference observations, the exposure parameters for each background observation exactly match the parameters for a single roll/dither of the associated science or reference target. These observations were intended to be performed at two separate dither positions to identify astrophysical sources that might impact the background subtraction, however, due to a previously unresolved issue they were instead repeated at an identical pointing (Dean Hines, private communication).

The NIRCcam and MIRI observations were executed as two separate non-interruptible sequences, ensuring that observations between rolls, and also between science, reference, and background targets, are minimally

² <https://jwst-docs.stsci.edu/jwst-near-infrared-camera/nircam-observing-strategies/nircam-coronagraphic-imaging-recommended-strategies>

³ <https://jwst-docs.stsci.edu/jwst-mid-infrared-instrument/miri-observing-strategies/miri-coronagraphic-recommended-strategies>

⁴ <https://jwst-docs.stsci.edu/methods-and-roadmaps/jwst-high-contrast-imaging/jwst-high-contrast-imaging-proposal-planning/hci-psf-reference-stars>

Filter	λ_{mean} (μm)	W_{eff} (μm)	Mask	Readout	N_{groups}	N_{ints}	t_{exp} (s)	N_{dithers}	N_{rolls}	t_{total} (s)
HIP 65426										
F250M	2.523	0.179	MASK335R	DEEP8	15	4	1235.892	1	2	2471.784
F300M	3.067	0.325	MASK335R	DEEP8	15	4	1235.892	1	2	2471.784
F356W	3.580	0.769	MASK335R	DEEP8	15	2	617.946	1	2	1235.892
F410M	4.084	0.436	MASK335R	DEEP8	15	2	617.946	1	2	1235.892
F444W	4.397	0.979	MASK335R	DEEP8	15	2	617.946	1	2	1235.892
F1140C	11.307	0.608	FQPM1140	FASTR1	101	41	1002.102	1	2	2004.204
F1550C	15.514	0.703	FQPM1550	FASTR1	250	60	3609.341	1	2	7218.682
HIP 68245										
F250M	2.523	0.179	MASK335R	MEDIUM8	4	4	166.852	9	1	1501.669
F300M	3.067	0.325	MASK335R	MEDIUM8	4	4	166.852	9	1	1501.669
F356W	3.580	0.769	MASK335R	MEDIUM8	4	2	83.426	9	1	750.835
F410M	4.084	0.436	MASK335R	MEDIUM8	4	2	166.852	9	1	750.835
F444W	4.397	0.979	MASK335R	MEDIUM8	4	2	83.426	9	1	750.835
F1140C	11.307	0.608	FQPM1140	FASTR1	52	10	126.791	9	1	1141.116
F1550C	15.514	0.703	FQPM1550	FASTR1	100	19	459.706	9	1	4137.356

Table 1. Target and reference exposure settings. Background observations were also performed for the MIRI F1140C and F1550C filters with parameters identical to two exposures of a single roll or dither of the target and reference observations, respectively (see Section 2.1). Filter mean wavelengths (λ_{mean}) and bandwidths (W_{eff}) are taken from `spaceKLIP` (see Section 2.2). See <https://jwst-docs.stsci.edu/understanding-exposure-times> for further detail on *JWST* exposure settings.

separated in time. This reduces the extent to which the wavefront can vary across observations, due to variations in the telescope mirror alignment, the thermal evolution of the telescope, or both (Perrin et al. 2018; Carter et al. 2021b). Changes in the wavefront will lead to variations in the residual PSF between exposures, hinder our ability to perform an optimal subtraction of these residual PSFs, and suppress the overall achievable contrast.

2.2. *spaceKLIP*

For all observations we perform data reduction using the newly developed and publicly available `python` package, `spaceKLIP`⁵ (Kammerer et al. 2022). Briefly, `spaceKLIP` takes a collection of data products from the `jwst` pipeline^{6,7} (Bushouse et al. 2022) as inputs, and generates PSF subtracted images, contrast curves, and measurements of companion photometry and astrometry. The majority of this functionality is provided by the underlying `pyKLIP` (Wang et al. 2015) package, with `spaceKLIP` providing a user friendly interface, streamlined code execution, custom *JWST* data reduction routines, and built-in plotting procedures.

⁵ <https://github.com/kammerje/spaceKLIP>

⁶ <https://jwst-pipeline.readthedocs.io>

⁷ All data were processed using pipeline version, `CAL_VAR=1.6.2`, and calibration reference data, `CRDS_CTX=jwst_0942.pmap`

2.3. *NIRCam* Coronagraphy

The *NIRCam* observational sequence was executed from 23:00 July 29th to 05:16 July 30th 2022 UTC, with exposures taken for HIP 65426 b using the MASK335R round coronagraphic mask (Krist et al. 2010) in the F250M, F300M, F410M, F356W, and F444W filters at one roll angle, then once again at a second roll angle, and then finally for the reference star. This sequence structure significantly reduces overheads, as once the target acquisition has been performed it is not necessary to reacquire the target to switch the observational filter.

We begin data reduction using the Stage 0 (`*uncal.fits`) files as generated by the `jwst` pipeline. These products are then processed to Stage 1 (`*rateints.fits`) files using `spaceKLIP`, which follows a slightly modified version of the `jwst` pipeline. Where possible the *JWST* detectors have reference pixels that can be used to track pixel drifts due to readout electronics. In the absence of such a reference, these variations may be misinterpreted as “jumps” in the up-the-ramp (MULTIACCUM) detector readout. The *NIRCam* coronagraphic subarrays do not have any embedded reference pixels and default pipeline processing leads to multiple erroneous jump detections and greatly increased noise in processed images. Therefore, we manually define all pixels within a four pixel border of each image as reference pixels within the pipeline to mitigate these effects. Additionally, we identify a significant improvement in image quality by skip-

ping the dark current subtraction step that is turned on as a default in the `jwst` pipeline. This improvement is primarily driven by the poor quality of the dark current reference file, which exhibits a large number of hot pixels, persistence, and cosmic rays. Once this reference file is improved through further calibration observations, we do not anticipate a need to skip this step for NIRCcam coronagraphic data.

During the jump detection step, the `jwst` pipeline will make use of a detection threshold value based on the estimated signal and noise to assess whether a deviation between groups is significant enough to be considered a jump (see ⁶ for further detail). The default value for this threshold is 4, but we repeat an early version of our F444W analysis across thresholds of 4 to 16 to search for potential improvements. We find that the contrast is slightly improved from a threshold of 4 to 5 by $\sim 5 \times 10^{-8}$ at $1''$, but at larger thresholds it does not vary (deviations $< 1 \times 10^{-8}$ at $1''$). Hence, we adopt a detection threshold of 5 for all of our NIRCcam analyses.

The Stage 1 products are processed further to Stage 2 (`*calints.fits`) files using `spaceKLIP`, with some additional pixel cleaning procedures as follows. Firstly, every pixel with a data quality flag (e.g., indicating hot or warm pixels, unreliable data processing) is replaced by the median of its orthogonal and diagonal neighbours, with the notable exclusion of pixels with a jump flag which are typically grouped in clusters. We also inspect each pixel for temporal flux variations and identify situations where: a) the pixel is bright ($\text{MJy/sr} > 1$) for at least one integration, and b) the pixel is relatively faint (a $> 80\%$ decrease in flux compared to the brightest integration) for at least one integration. The pixel values for the integrations that are not marked as faint are then replaced by the median value of the integrations that are marked as faint. We note here that an outlier identification process based on variations from the standard deviation of each pixel in time may be preferable, but is difficult to incorporate given the small number of integrations in these exposures (see Table 1). Despite the above corrections, ~ 25 static hot pixels remain across all images. Although these pixels do not impact our ability to recover HIP 65426 b, they introduce residuals in the PSF subtraction process (see Section 2.6) that bias our measurements of the contrast performance. Therefore, we provide the locations of these pixels to `spaceKLIP` manually and correct them in an identical manner as the pixels marked with data quality flags.

As the NIRCcam PSF in the F250M filter is undersampled, ringing artifacts are generated by the interpolation methods in `pyKLIP` used for image registration and spatial shifting of input PSFs. These artifacts bias

the image registration process, and limit our ability to accurately inject synthetic PSFs for contrast curve calibration and companion astrometry and photometry. To overcome this issue, we smooth all of the F250M images by a Gaussian filter, as implemented by `scipy`, with $\sigma = 1.3$ pixels. This value of σ was chosen as it was the minimum possible value that removed the observed artifacts across a test of ten equally spaced values from $\sigma = 1$ to $\sigma = 2$. We note that this factor of 1.3 is consistent with the ratio of the detector pixel scale and the theoretical Nyquist sampling at $2.5 \mu\text{m}$ (assuming a reduced primary mirror diameter of 5.2 m due to the NIRCcam Lyot stop). Smoothing these images may lead to reduced precision in our astrometric analysis, however, it should not influence the accuracy of our retrieved photometry.

2.4. MIRI Coronagraphy

The MIRI observational sequence was executed from 21:05 July 17th 2022 to 05:19 July 18th 2022 UTC. Exposures were taken for HIP 65426 b in the F1140C filter at one roll angle, then once again at a second roll angle, and then for the reference star. This sequence was then repeated in reverse for the F1550C filter. This structure is slightly different to that of the NIRCcam observations as each filter is tied to a specific four-quadrant phase mask coronagraph (FQPM, Boccaletti et al. 2015), and target acquisition must be repeated when switching between them. Inserting the reference observations between the observations of HIP 65426 b minimises the time separation between science and reference exposures for each filter, and therefore the extent of the wavefront evolution between them. After all science and reference observations are complete, we perform the dedicated background observations that are used to subtract the dominant “glow stick” stray light feature (Boccaletti et al. 2022) as described in Section 2.1.

We begin data reduction using the Stage 0 (`*uncal.fits`) files as generated by the `jwst` pipeline. These products are then processed to Stage 1 (`*rateints.fits`) files using `spaceKLIP`. Similarly to NIRCcam (see Section 2.3) we explore the impact of the jump detection threshold on our analysis. For these data in particular, we found that the default jump detection threshold value of 4 is too low and leads to a number of pixels being erroneously flagged as containing a jump. Flagged pixels are interpreted differently to unflagged pixels in the ramp fitting procedure and the resulting Stage 1 files contain a large number of pixels with unrealistic (negative) flux values as a result. After repeating an early version of our F1140C analysis across thresholds of 4 to 16, we observe an improvement in contrast between a threshold value of 4 and 5 of $\sim 2 \times 10^{-5}$ at $1''$, and $\sim 1 \times 10^{-5}$ at $2''$.

Beyond this value there is only slight improvement, and the obtained contrast varies within $\sim 5 \times 10^{-6}$ at $1''$. For our final analyses we select a threshold value of 8, as it has the best contrast at $2''$ and fewer pixels with unrealistic flux values than lower thresholds (as determined from visual inspection).

Following ramp fitting we found that the first integration of each exposure contained a significantly increased level of noise indicative of a detector reset anomaly. The current available calibration dark exposures that are used to correct for this anomaly were usually acquired in quick succession, and do not have a similar amount of dead time (e.g., due to telescope slews/dithers) as our science exposures. As a result, during our observations the detector electronics were given a much longer time to settle, and our integrations exhibit an entirely different reset anomaly. This effect is most dominant for the first integration of each exposure, but appears to persist throughout the entire exposure as well. In the future better calibration darks will be provided that may resolve this issue, but for the purpose of this study we simply exclude the first integration of each exposure from all further analysis.

The Stage 1 products are processed further to Stage 2 (*calints.fits) files using `spaceKLIP`, with some additional pixel cleaning procedures as follows. First, every pixel with a data quality flag (e.g., indicating hot or warm pixels, unreliable data processing) is replaced by the median of its orthogonal and diagonal neighbours, with the notable exclusion of pixels with a jump flag which are typically grouped in clusters. Following this correction, ~ 30 static hot pixels remain in our images and are corrected following an identical procedure by manually providing the pixel locations to `spaceKLIP`. Similarly to NIRCcam, these final pixels primarily impact the measured contrast performance, and not our ability to recover HIP 65426 b.

As shown in Boccaletti et al. (2022), the MIRI coronagraphic fields of view are subjected to a stray light “glow stick” feature along the horizontal edges of the FQPMs that dwarfs the residual stellar flux (see Figure 2). We subtract this feature from our processed Stage 2 products for each filter using a median background image of every 4–5 integrations from the dedicated background observations to the corresponding 4–5 science or reference integrations. The value of 4–5 was selected as it provided a slightly improved contrast at $1''$ compared to other tested numbers of integrations per median, ranging from 1 ($\sim 1 \times 10^{-4}$ improvement) to all available integrations ($\sim 1 \times 10^{-5}$ improvement). Grouping the median subtraction in this manner better captures the diffuse reset anomaly noise between integrations mentioned

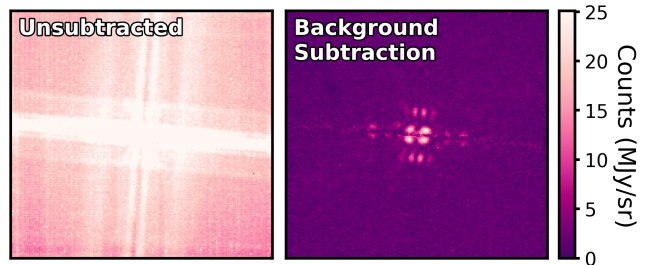


Figure 2. *Left:* A single integration in the Stage 2 (*calints.fits) file for MIRI coronagraphy of HIP 68245 in the F1550C filter. *Right:* As on the left, except following subtraction of a median background frame of an “empty” region of the sky. Both images are identically scaled. Before subtraction the residual stellar flux is completely obscured by the stray light “glow stick” (Boccaletti et al. 2022), but can be easily recovered.

above. Additionally, it may help capture variations in the stray light feature, which varies with a standard deviation of $\sim 0.5\%$ (as identified by variations in the median pixel flux for pixels above 50% of the peak pixel flux across integrations).

Following the median background subtraction we find that the residual stellar flux is easily recovered (see Figure 2). We also attempted to model the stray light glow stick as a principal component within both KLIP (Soummer et al. 2014) and LOCI (Lafrenière et al. 2007) based subtractions, but found that they were susceptible to oversubtraction of the residual stellar flux and/or could not additionally account for background variations between integrations. We anticipate that with careful masking and optimisation of these algorithms it may be possible to overcome these issues, however, the median frame background subtraction is already highly effective and improvements to the achieved contrast are likely to be minimal.

2.5. Image Alignment

The NIRCcam and MIRI coronagraphic modes adopt independent target acquisition procedures to correctly center a star behind each focal plane mask. The in-flight positions of the NIRCcam mask centers are known to better than ~ 10 mas but the distortion model is still being refined. At present the target acquisition error for the MASK335R is as large as ~ 12 – 30 mas, or 0.2 – 0.5 pixels (Girard et al. 2022). This error is dominated by the precision of the centering algorithm, which is not well adapted to the PSF shape with coronagraphic optics (wider in x -axis), and not by the small angle maneuver (SAM) that places a target at its desired position behind the mask (which for NIRCcam is repeatable to ~ 6 mas). For MIRI the mask center positions have been

measured to $\sim 5\text{--}10$ mas, or ~ 0.1 pixels (Boccaletti et al. 2022). However, the SAM has a typical uncertainty of $\sim 10\text{--}20$ mas, leading to positional offsets between different rolls or targets. Finally, between integrations the pointing stability of *JWST* (~ 1 mas) and the accuracy of the small-grid dither maneuvers ($\sim 2\text{--}4$ mas) will lead to further positional shifts for both the NIRCcam and MIRI coronagraphs.

For NIRCcam the absolute star position is only explicitly measured for the first science image in each filter. This position is measured using a cross correlation of a model coronagraphic PSF as obtained from `webbpsf_ext` to the science PSF using the `scikit-image` package (van der Walt et al. 2014). To best match the science PSF, the model PSF is generated using the telescope optical path difference (OPD) map as obtained on July 29th. To identify the accuracy of this process we repeat the procedure, except comparing the model PSF to itself, and to a second model PSF that was generated using a pre-launch measurement of the telescope OPD (which exhibits comparable differences to the model PSF as our data). In each case, we manually shift the comparison PSFs across a range of 0.01 to 0.5 pixels and attempt to recover these offsets using the cross correlation process. For the self comparison, we recover the injected shift to at least ~ 0.03 pixels, or 1.9 mas, whereas for the second model PSF comparison, we recover the injected shift to ~ 0.1 pixels, or 6.3 mas. Given the comparable difference between the model PSF for both the second model PSF and our data, we adopt the latter uncertainty as a systematic uncertainty in our astrometric measurements (see 4.3). The shifts of the other science and reference images are obtained relative to the first science image through a similar cross correlation procedure. However, we instead use a box of 11×11 pixels around the coronagraph center position, where the flux is dominated by the central core of the coronagraphic PSF. All measured relative shifts match expectations for the *JWST* pointing precision of ~ 1 mas (1σ , radial) (Rigby et al. 2022).

To estimate the absolute star position for MIRI, we use the current measurements for the centers of the coronagraphic masks and assume the the star is perfectly centered behind the coronagraphic mask. In zero-indexed subarray x - y coordinates these values are (119.749, 112.236) and (119.746, 113.289) for the FQPM1140 and FQPM1550, respectively (Jonathan Aguilar, private communication). As a result, the stellar position is not known better than a minimum of ~ 10 mas (Boccaletti et al. 2022). Similarly, the relative alignment between images may be discrepant by $\sim 1\text{--}4$ mas (Rigby et al. 2022), or <0.05 pixels. At-

tempts to estimate the absolute star position in a similar manner to the NIRCcam data were unsuccessful, and this process led to significantly larger estimated shifts than the known pointing stability of *JWST* (~ 50 mas, vs ~ 1 mas). This is most likely due to the variable spatial structure of the residual PSF, which significantly changes with small pointing shifts. An effort was also made to fit each MIRI image with model PSFs across all feasible pointings using `webbpsf_ext`⁸ within an `emcee` (Foreman-Mackey et al. 2013) Markov chain Monte Carlo (MCMC) framework. However, these fits were unable to converge and upon visual inspection the spatial structure of the empirical and model PSFs were different, despite modelling the PSFs based on measurements of the telescope OPD within ~ 1 day of our observations. We do not believe that using the coronagraphic mask centers as a proxy for the absolute star position has significantly affected our results, but it is certainly an area of improvement for future studies using MIRI coronagraphy.

For NIRCcam all images are aligned to a common center based on the measured shifts, however, for MIRI we opt to not perform any realignment. This decision is made under the assumption that because a pointing shift does not primarily cause a translation of the residual PSF in the MIRI images (in contrast to NIRCcam), the unshifted reference images are more descriptive of variations in the science images. When comparing a RDI subtraction using unshifted reference images, and a separate RDI subtraction with a realignment based on the ideal small-grid dither positions, the measured contrasts are in agreement and this choice does not significantly impact our results.

2.6. PSF Subtraction

We perform a subtraction of the residual stellar PSF in each filter following three different principal component analysis (PCA) based methods as implemented in `spaceKLIP`. First, we take the two independent rolls of HIP 65426 b and perform an ADI subtraction. Second, we perform an RDI subtraction by using the corresponding observations of the reference star, HIP 68245, as a PSF library. Finally, we perform an ADI+RDI subtraction, which is identical to the RDI subtraction except that images at the opposite roll angle are also included in the PSF library. In each case the subtraction is performed on each integration from both science rolls individually, before being rotated to a common orientation as marked in Figure 3 and summed together. Although

⁸ https://github.com/JarronL/webbpsf_ext

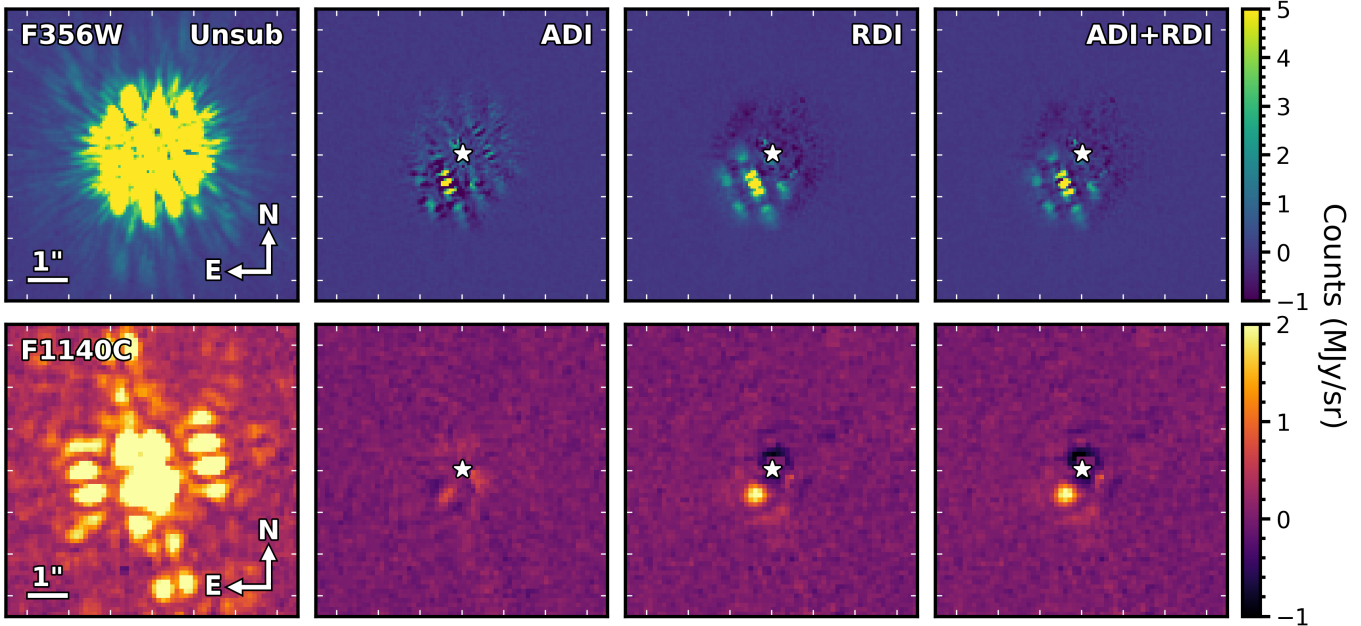


Figure 3. Unsubtracted and KLIP subtracted image stamps for the NIRCcam F356W (top row) and MIRI F1140C (bottom row) filters. The leftmost column displays the median unsubtracted image for a single science roll, and all other columns display the KLIP subtracted images for ADI, RDI, and ADI+RDI subtraction methods using the maximum number of KLIP PCA modes. All images are oriented as shown by the directional arrow in unsubtracted image column, the position of the star (white star) is also marked. Additionally, the intensity of all images for a given filter are identically scaled. The exoplanet, HIP 65426 b, can be easily identified at a position angle of $\sim 150^\circ$ in the subtracted images. We note that the distinct “hamburger” shaped central core and six-lobed structure of the companion PSF in the NIRCcam images is an expected feature that is related to the Lyot stop design, and not indicative of discrete astrophysical sources.

the number of annuli and subsections the PSF subtraction is performed across can be adjusted, we find that this does not improve the observed contrast. Hence, we perform all subtractions using a single annulus and a single subsection (i.e., the entire image). The number of KLIP PCA modes can also be adjusted to tune the aggressiveness of the PSF subtraction. Hence, we perform the PSF subtraction across the full range of possible PCA modes to investigate the impact on our measured contrast and companion fitting. The maximum number of PCA modes is dependent on the exposure settings for each filter and corresponds to: the number of integrations in a single roll for ADI, the total number of integrations across all 9 dithers for RDI, and the sum of the two for ADI+RDI (see Table 1 for precise values).

Pre- and post-subtraction images for the NIRCcam F356W and MIRI F1140C filters are shown in Figure 3, and images for all filters are shown in Appendix A. We note that the distinct “hamburger” shaped central core and six-lobed structure of the companion PSF in the NIRCcam images is an expected feature that is related to the Lyot stop design, and not indicative of discrete astrophysical sources.

3. ANALYSIS

3.1. Contrast Calibration

All proceeding contrast measurements are determined relative to a synthetic spectrum of HIP 65426 in each of the *JWST* filters, as estimated from fitting stellar and disk models to existing photometry following Yelverton et al. (2019), see Figure 4. We use data of HIP 65426 from *Hipparcos/Tycho-2* (Høg et al. 2000), *Gaia* DR2 (Gaia Collaboration 2018), 2MASS (Cutri et al. 2003), ALLWISE (Wright et al. 2010), *AKARI* IRC (Ishihara et al. 2010), and *Spitzer* MIPS (Chen et al. 2012). The fitting procedure compares synthetic photometry of models to the data to compute a χ^2 value, and posterior distributions are found using MultiNest (Feroz et al. 2009; Buchner et al. 2014). We derive our own zero points using the CALSPEC Vega spectrum (Bohlin et al. 2014). We use PHOENIX models (Allard et al. 2012) for the stellar photosphere, and a Planck function for the disk model. There is a small excess at $24 \mu\text{m}$ that was previously reported at 3.5σ by Chen et al. (2012), though not considered significant in that paper. The best fit model has an effective temperature of 8600 ± 200 K and luminosity $16 \pm 1 L_\odot$. The dust temperature and luminosity are very poorly constrained

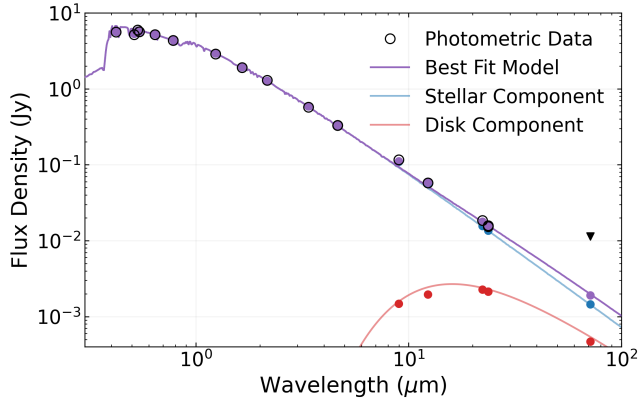


Figure 4. The best fit stellar model (purple) to existing: *Hipparcos/Tycho-2*, *Gaia* DR2, 2MASS, ALLWISE, *AKARI* IRC, and *Spitzer* MIPS data for HIP 65426 (black circles). The stellar (blue) and disk (red) components of the model are also shown, along with the equivalent model fluxes in each photometric band (solid circles). Error bars are smaller than the circle diameter, except for the 70 μm MIPS point, which is instead marked as an upper limit (black triangle).

($T_{\text{dust}} = 300_{-100}^{+200}$ K, and $L_{\text{dust}}/L_{\star} \sim 2 \times 10^{-5}$), though this uncertainty does not significantly impact the flux estimation in *JWST* bandpasses because the excess is small. The flux excess at 24 μm is not high, but if real the dust would reside relatively close to the star, probably less than 1 au (hence we use the total model flux to compute the contrast, as any dust component that contributes IR flux would remain unresolved). We use the posterior distribution of model parameters and synthetic photometry to generate a distribution of fluxes in the *JWST* bands, and adopt the maximum likelihood solution for the stellar flux in each bandpass.

3.2. Contrast Curves

Following PSF subtraction, we obtain metrics of the sensitivity as a function of angular separation (i.e., contrast curves) for all observational filters using *spaceKLIP*. To avoid biasing the contrast measurement we mask regions of the subtracted images near HIP 65426 b, background sources, and the FQPM edges. These “5 σ ” contrast curves report the flux level corresponding to a 5 σ -equivalent false alarm probability of 2.9×10^{-7} after correcting for small sample statistics at small separations (Mawet et al. 2014). We call them 5 σ contrast curves for brevity.

To obtain a more accurate measurement of the contrast performance, the throughput of the coronagraph and the intrinsic throughput of the KLIP subtraction must be accounted for by injecting and then recovering the flux of artificial sources (Adams & Wang 2020). All

artificial sources are generated using *webbpsf*⁹ (Perrin et al. 2012, 2014) at an initial intensity equivalent to a signal-to-noise ratio of 25. Immediately prior to injection and based on a desired injection location, each source is modulated by the coronagraphic throughput using a synthetic throughput map.

Synthetic coronagraphic throughput maps are provided in the calibration reference files¹⁰, however, both the provided NIRCcam and MIRI FQPM maps are inaccurate. For the NIRCcam MASK335R, the position of the occulting masks within the throughput map does not correspond with its actual location. Therefore, we modify the throughput map by extracting the pixels impacted by the occulting mask and repositioning them at the true mask center location of (149.9, 174.4) in zero-indexed subarray x - y coordinates (Jarron Leisenring, private communication). In the case of MIRI, all of the FQPM maps are rudimentary and do not accurately capture the spatial throughput variations. Therefore, we instead use custom simulated maps of the FQPM throughput produced using *webbpsf_ext*. In brief, *webbpsf_ext* generates position-dependent PSFs based upon interpolation over a densely-sampled grid of individual PSFs along the FQPM axes. A uniform (flat) illumination of 10^{-7} Jy was convolved with the position-dependent PSFs to produce an illumination pattern that was then normalised and scaled to the subarray dimensions for each MIRI FQPM.

Once scaled by the coronagraphic throughput, PSFs are injected into multiple copies of the unsubtracted science images across a range of separations extending to 4”, and for a range of position angles from 0 to 360°. Sources are not injected within $2\lambda/D$ of each other or a masked region. These images then undergo KLIP subtraction in an identical manner to the science images, and the relative flux of an initial source PSF and the KLIP processed PSF as estimated within *pyKLIP* describes the overall coronagraphic mask plus KLIP throughput at each location. Finally, the basic 5 σ contrast is divided by an interpolation of the median throughput across all position angles to obtain the calibrated contrast.

For the ADI subtraction, the measured contrast does not vary significantly when using more than 1 PCA mode for the NIRCcam filters and more than 2 PCA modes for the MIRI filters. For RDI, the measured contrast does not vary beyond ~ 6 modes for both NIRCcam and MIRI. Finally, for ADI+RDI we find that there is a

⁹ <https://webbpsf.readthedocs.io/en/latest/>

¹⁰ <https://jwst-crds.stsci.edu>

transition to improved contrast at $P_{\max} - P_{\text{ADI}}$ modes, where P_{\max} is the maximum possible number of PCA modes possible, and P_{ADI} is the maximum number of modes for the ADI subtraction. This is likely a result of the much larger number of reference images weighting the calculation of the PCA modes to be mostly RDI-like, until a sufficient limit is reached where the influence of the opposing roll images appears in the principal components. Beyond this transition value, the measured contrast does not vary significantly.

Example calibrated contrast curves for the NIRCам F356W and MIRI F1140C filters using the maximum number of PCA modes are shown in Figure 5, and contrast curves for all filters are shown in Appendix B.

3.3. HIP 65426 b PSF Fitting

To analyse the properties of HIP 65426 b in greater detail, we make use of the forward model PSF fitting routine provided by `pyKLIP` and implemented in `spaceKLIP`. Briefly, this routine takes a model of the companion PSF and uses a forward model of the KLIP subtraction to apply PSF distortions that arise naturally from the KLIP process. This resultant PSF can then be scaled/shifted to best match the observed companion PSF and obtain a measurement of its location and intensity (Pueyo 2016; Wang et al. 2016).

For our analysis we adopt an independent model PSF for each filter using `webbpsf_ext` functionality as implemented in `spaceKLIP`. Specifically, we use `webbpsf_ext` to generate an offset PSF at the predicted location of HIP 65426 b as adopted from `whereistheplanet` (Wang et al. 2021) and at the appropriate position for each science roll image. Each NIRCам and MIRI PSF is generated using a measured OPD map as determined from wavefront sensing and control observations on July 29th 2022 and July 17th 2022, respectively. Particularly for MIRI, the PSF of an off-axis source is sensitive to its location relative to the FQPM edges, and explicitly generating a model PSF close to this location is important for obtaining a close match to the true companion PSF. As the spatial intensity of the model PSF depends on an assumed spectral energy distribution (SED), we use an existing best fit BT-SETTL model for HIP 65426 b from Cheetham et al. (2019). We note that as our initial model PSF is normalised to unit intensity, the primary purpose of selecting a model SED is to capture the relative variation in flux as a function of wavelength across each bandpass, and is not meant to accurately predict the absolute flux of HIP 65426 b in each bandpass.

The input model PSF is converted to physical units by scaling it to the flux of HIP 65426 as estimated by the stellar model described in Section 3.1. Therefore, all

derived photometry is anchored relative to our assumption of the stellar flux. Furthermore, any comparisons between the intensity of this PSF and the observed PSF is subject to an implicit assumption that the absolute flux calibration of *JWST* is perfect. In reality, the absolute flux calibration accuracy requirement for NIRCам and MIRI coronagraphy is 5% and 15%, respectively¹¹. Both these fundamental uncertainties on the absolute flux calibration and the uncertainty on the stellar model flux as derived from the distributions described in Section 3.1 are propagated as an increased uncertainty on all of our flux measurements.

For each filter we fit the location and intensity of the model PSF to the true PSF of HIP 65426 b from the ADI+RDI subtraction using 6 PCA modes. The fitting procedure is executed in an MCMC framework as implemented by `emcee` (Foreman-Mackey et al. 2013), with 50 walkers for 300 steps, of which the first 100 steps are discarded as burn-in. `spaceKLIP` allows for the spatial scale of noise in an image to be fit with a variety of different kernels as implemented in a Gaussian process framework. For NIRCам the noise in our images appears to be correlated at the separation of HIP 65426 b, so, following Wang et al. (2016), we initially adopt a Matérn 3/2 kernel to better capture this spatially correlated noise structure. However, the generated model PSF is slightly mismatched to the observed data and a positive flux residual was present at the PSF core. Future improvements to model PSF generation may alleviate this issue, but in this work we instead assume uncorrelated noise (using the “diagonal kernel” option), which is able to better capture the flux of the companion at the expense of underestimating the obtained error bars. Therefore, more realistic error bars for the NIRCам photometric measurements are determined through a process of companion injection and recovery. For each filter, the best fit model PSF is used to subtract away the companion flux, and is then injected at 20 different position angles spanning 0–105° and 195–360° across an equivalent number of duplicate science images. The HIP 65426 b PSF fitting procedure is then repeated on these synthetic PSFs and the standard deviation in the measured flux across all 20 position angles is adopted as the estimated error. In the case of MIRI the observed noise is visually consistent with uncorrelated noise, so we adopt a diagonal kernel here as well.

Results from the PSF fitting procedure are discussed further in Section 4, and images of the data, model, and residuals to each PSF fit are displayed in Appendix C.

¹¹ <https://jwst-docs.stsci.edu/jwst-data-calibration-considerations>

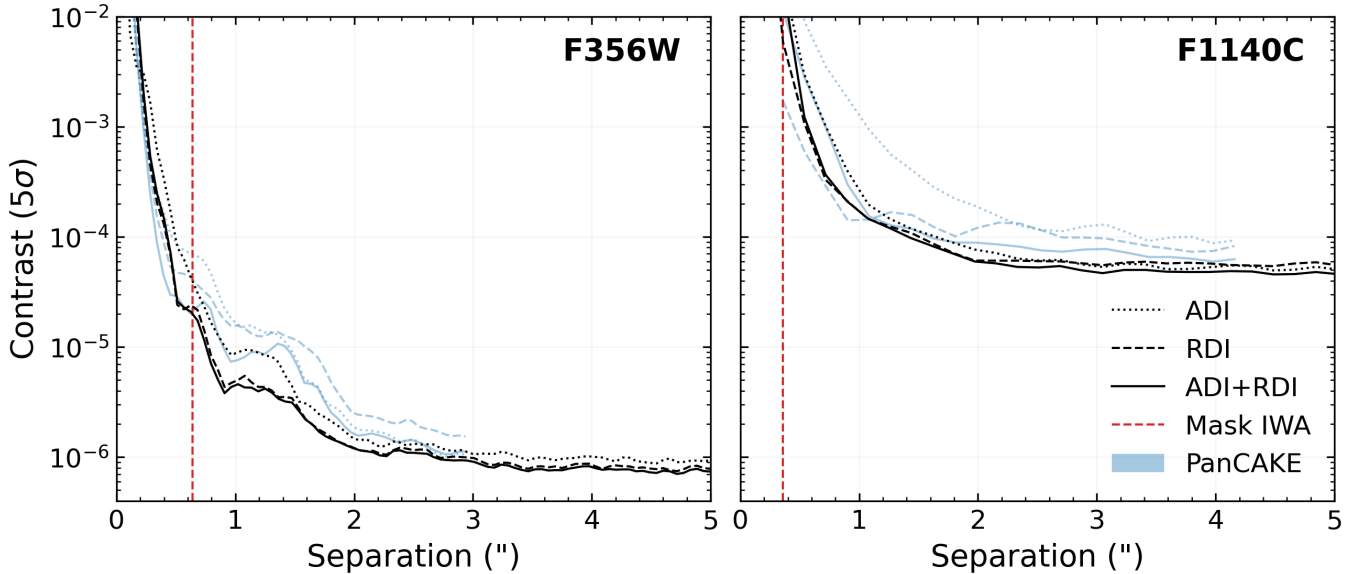


Figure 5. Contrast curves for observations in the F356W and F1140C filters using both an ADI (dotted lines), RDI (dashed lines) and ADI+RDI (solid lines) subtraction with the maximum possible number of PCA modes. Both the measured contrast of the true on-sky observations (black lines) and predicted contrasts as generated from PanCAKE (Carter et al. 2021b) (light blue lines) are displayed. The effective inner working angles (IWA), corresponding to the separation at 50% transmission, are also marked (red dashed lines). Contrast curves for all other filters are displayed in Figure 14.

4. DISCUSSION

The known companion HIP 65426 b is clearly detected in all seven of the observational filters using RDI, and all filters except the MIRI F1550C using ADI. These observations represent the first images of an exoplanet to be obtained with *JWST*, and the first ever direct detection of an exoplanet beyond $5 \mu\text{m}$. Furthermore, these observations provide a first look at the achieved contrast for *JWST*'s high contrast imaging modes following the completion of observatory commissioning.

4.1. Achieved Contrast

These observations demonstrate that, in addition to the existing work of Girard et al. (2022), Kammerer et al. (2022), and Boccaletti et al. (2022), both NIRCcam and MIRI coronagraphic imaging are exceeding their predicted contrast performance. Examples of this improvement in comparison to pre-launch contrast estimates as obtained by PanCAKE (Carter et al. 2021b) are demonstrated in Figure 5, and contrast curves for all seven filters are displayed in Appendix B.

At the MASK335R nominal IWA of $0.64''$, the F356W data achieve a contrast of $\sim 2 \times 10^{-5}$, sloping down to $\sim 4 \times 10^{-6}$ at $1''$ and then $\sim 9 \times 10^{-7}$ beyond $3''$. In comparison, at the FQPM1140C nominal IWA of $0.36''$, the MIRI F1140C data achieve a contrast $\sim 1 \times 10^{-2}$, sloping down to $\sim 2 \times 10^{-4}$ at $1''$ and then $\sim 5 \times 10^{-5}$ beyond $3''$. For brevity we do not describe the achieved con-

trast in the other filters, and instead refer the reader to Appendix B.

In the background limited regime beyond $\sim 2''$ our measured contrast approximately matches the predicted sensitivity for NIRCcam ADI and ADI+RDI subtractions, and is ~ 2 times more sensitive than the prediction for the RDI subtraction. For MIRI in this regime, all three subtraction methods outperform their predicted sensitivity by a factor of $1.5 - 2$. In the contrast limited regime below $\sim 2''$ we observe similar improvements upon the predicted contrast, with the ADI and RDI subtractions demonstrating a factor of up to 10 times deeper contrast, and the ADI+RDI subtraction improving by a factor of ~ 2 . In some instances at the shortest separations below $\sim 0.4''$ the contrast does underperform by up to a factor of ~ 2 compared to predictions for RDI subtractions. The primary driver for these improvements is likely the improvement in the overall optical and stability performance of *JWST* compared to expectations. The total throughput is $\sim 10 - 20\%$ larger than predictions, driving analogous improvements in signal-to-noise; the overall telescope wavefront error is $\sim 50\%$ smaller than requirements ($75/110 \text{ nm}$ vs $150/200 \text{ nm}$ for NIRCcam/MIRI), improving the raw contrast; and the pointing stability of 1 mas is $\sim 6 - 7$ times smaller than predictions, meaning smaller drifts in alignment behind the coronagraphic mask throughout an observation (Rigby et al. 2022).

The different contrasts as achieved by the ADI, RDI, and ADI+RDI subtractions allow for more concrete recommendations in observing structure for future programs. Most significantly, the improvement between RDI and ADI+RDI subtractions is negligible. Future observers will may be able to achieve their science goals with less telescope time by focusing on purely ADI or RDI subtraction strategies, however, a broader range of observations will be required to rule out ADI+RDI strategies entirely. Within $1-2''$ the ADI subtraction for MIRI F1550C, and to some extent F1140C, struggles to fully subtract the residual stellar PSF and an RDI based subtraction strategy should be preferred. Although ADI subtractions provide demonstrably worse contrast across all filters, they require a significantly smaller amount of observing time due to the cost-intensive nature of dithered reference observations. However, similar contrasts to ADI can be achieved with an undithered reference observation as well (Girard et al. 2022). To reduce the overall telescope time required for high contrast imaging programs, future observers should carefully consider the contrast performance necessary to meet their science goals, and adjust their PSF subtraction strategy accordingly.

Beyond this work, there is significant potential for the contrast performance for both NIRCcam and MIRI to improve. Kammerer et al. (2022) have already demonstrated that the NIRCcam bar masks can provide deeper contrasts at shorter separations, if a full 360° field-of-view is not required. Similarly, in later cycles it may be possible to position a star at the “NARROW” bar mask position in an attempt to reduce the effective inner working angle (IWA) even further. The efficacy of RDI subtractions may improve with the use of a larger PSF library populated by on-sky observations across multiple programs. It may also be possible to perform an effective PSF subtraction using a much larger PSF library composed either entirely or partially of model PSFs. A particular opportunity for improvement will also come from JWST program GO-02627 (Ygouf et al. 2021), which aims to estimate the on-sky instrumental aberrations that drive variations in the observed PSF structure with a model based phase retrieval algorithm.

4.2. Mass Sensitivity

Using the obtained contrast curves we also determine the detectable mass limits for our observations following the approach of Carter et al. (2021a). Briefly, we convert our contrast curves to magnitude sensitivity curves using the stellar magnitudes as described in Section 3.1, and then convert these to a mass sensitivity using an interpolation of the evolutionary models of Linder et al.

(2019) (BEX) and Phillips et al. (2020) (ATMO) assuming an age of 14 ± 4 Myr (Chauvin et al. 2017) and distance of 107.49 ± 0.40 pc (Gaia Collaboration 2020). As in Carter et al. (2021a) we select the chemical equilibrium, non-cloudy models to maintain model consistency across mass ranges. Clouds and disequilibrium chemistry likely play a significant role in sculpting the emission of sub-stellar atmospheres, however, an investigation into these effects is beyond the scope of this work.

Following the calculation of mass sensitivity curves we use the Exoplanet Detection Map Calculator (Exo-DMC, Bonavita et al. 2012, 2013; Bonavita 2020)¹² to estimate detection probability maps. In this case, we produce a population of synthetic companions with masses and semi-major axes from $0.1 M_{\text{Jup}}$ to $100 M_{\text{Jup}}$ and 0.1 au to $10,000$ au respectively. All orbital parameters are uniformly distributed except for the eccentricity, which is generated using a Gaussian distribution with $\mu = 0$ and $\sigma = 0.3$ (excluding negative eccentricities; Hogg et al. 2010). Implicit in this is an assumption that these synthetic companions do not necessarily have a similar inclination to HIP 65426 b. The resulting map takes into account the effects of projection when estimating the detection probability, and the probability for a potential companion to truly lie in the instrumental field of view.

For these particular observations of HIP 65426, we identify the F444W and F1140C filters as the most sensitive to the lowest mass companions for NIRCcam and MIRI, respectively, and display their detection probability maps in Figure 6. Of the two, the F444W filter is the most sensitive, reaching a sub-Jupiter mass sensitivity from $\sim 150-2000$ au at a 50% probability, and a minimum sensitivity of $\sim 0.4 M_{\text{Jup}}$ from $\sim 300-1500$ au at a 50% probability. In contrast, the F1140C is unable to reach sub-Jupiter mass sensitivity, and has a minimum sensitivity of $1-2 M_{\text{Jup}}$ from $\sim 150-2000$ au. As we detect no sources within the observed field-of-view that have colours consistent with a planetary mass companion, we set equivalent limits on the presence of additional companions in the HIP 65426 system.

As discussed in Carter et al. (2021a), at a given distance A stars are generally poor targets for detecting the lowest mass planets in terms of detection sensitivity, whereas M stars are among the best. Given the improved performance of JWST, it is likely that for targets within (or outside of) the M star sample from Carter et al. (2021a) it will be possible to detect Uranus and Neptune mass objects beyond $\sim 100-200$ au, and Sat-

¹² <https://github.com/mbonav/Exo.DMC>

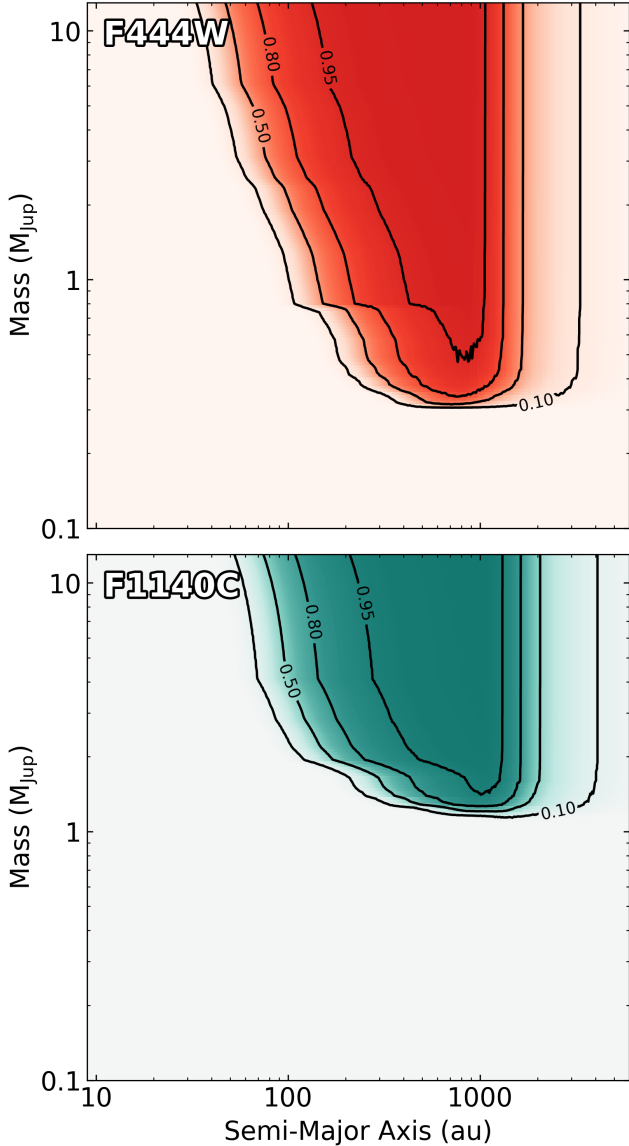


Figure 6. Detection probability maps as generated by Exo-DMC for the most sensitive NIRCam (F444W, top) and MIRI (F1140C, bottom) filters. Solid black contours signify the 10%, 50%, 85%, and 95% detection thresholds.

urn mass objects beyond ~ 10 au. Initial searches across a small sample of stars for sub-Jupiter mass objects will be performed as part of guaranteed time observations (Schlieder et al. 2017). Furthermore, for the nearest targets we may be able to push these limits even further, with planned observations of α Cen A aiming to be sensitive to $5 R_{\oplus}$ companions from 0.5–2.5 au (Beichman et al. 2020, 2021).

4.3. Astrometry

The measured astrometry in each of the observed filters is obtained from the ADI+RDI reduction and shown

in Table 2. Each of the measured uncertainties for the NIRCcam astrometry are propagated with an additional uncertainty of 6.3 mas (0.1 pixels), and the uncertainties of the MIRI astrometry are propagated with an additional uncertainty of 10 mas (0.1 pixels) to account for the assumed precision of the absolute star centering as described in 2.5. All NIRCcam and MIRI astrometry are consistent within 1σ , and in combination the NIRCcam and MIRI astrometry provide a measurement of the separation, $\rho=820\pm 6$ mas, and the position angle, $\theta=149.5\pm 0.4^{\circ}$. To compute these average values, we do not treat the NIRCcam filters as independent and instead average both the quantities and their uncertainties. The absolute position of the star on the detector does not change significantly (<1 pixel) between NIRCcam filters, and it is feasible that the measured position has a similar systematic offset in each filter (see Section 2.5). As the dominant noise source for the NIRCcam alignment is this systematic offset, it is not appropriate to propagate the uncertainties of the NIRCcam astrometry in a typical fashion.

We combine these new measurements with the existing astrometry from Chauvin et al. (2017) and Cheetham et al. (2019) to determine updated orbital parameters using the *orbitize!* package (Blunt et al. 2020). As in Cheetham et al. (2019), we exclude the NaCo epochs due to the inconsistency with the SPHERE epochs. Additionally, we exclude the MIRI epoch as the observations were taken just two weeks after the NIRCcam observations and have larger uncertainties. *orbitize!* is initialised assuming one companion to the primary (HIP 65426 b), a total system mass of $1.97\pm 0.046 M_{\odot}$ (Chauvin et al. 2004), and a parallax of 9.3031 ± 0.0346 mas (Gaia Collaboration 2020). Orbit generation is performed using the Orbits for the Impatient (OFTI) algorithm (Blunt et al. 2020) until 100,000 possible orbits are identified. A random sample of 100 of the possible orbits along with posterior distributions for the entire sample are shown in Figure 7. We are able to constrain the semi-major axis, $a = 87_{-31}^{+108}$ au, and the inclination, $i = 100_{-6}^{+15}$ degrees. Additionally, as the motion of HIP 65426 b is primarily radial, solutions that place the line of nodes close to its position angle are preferred, and the position angle of nodes is also constrained to two possible solutions.

The addition of the NIRCcam astrometry does not significantly improve the orbital constraints for HIP 65426 b, and all retrieved properties are consistent with those from Cheetham et al. (2019) and Bowler et al. (2020). Although our eccentricity distribution more strongly favours higher eccentricities compared to Cheetham et al. (2019), it remains essentially uncon-

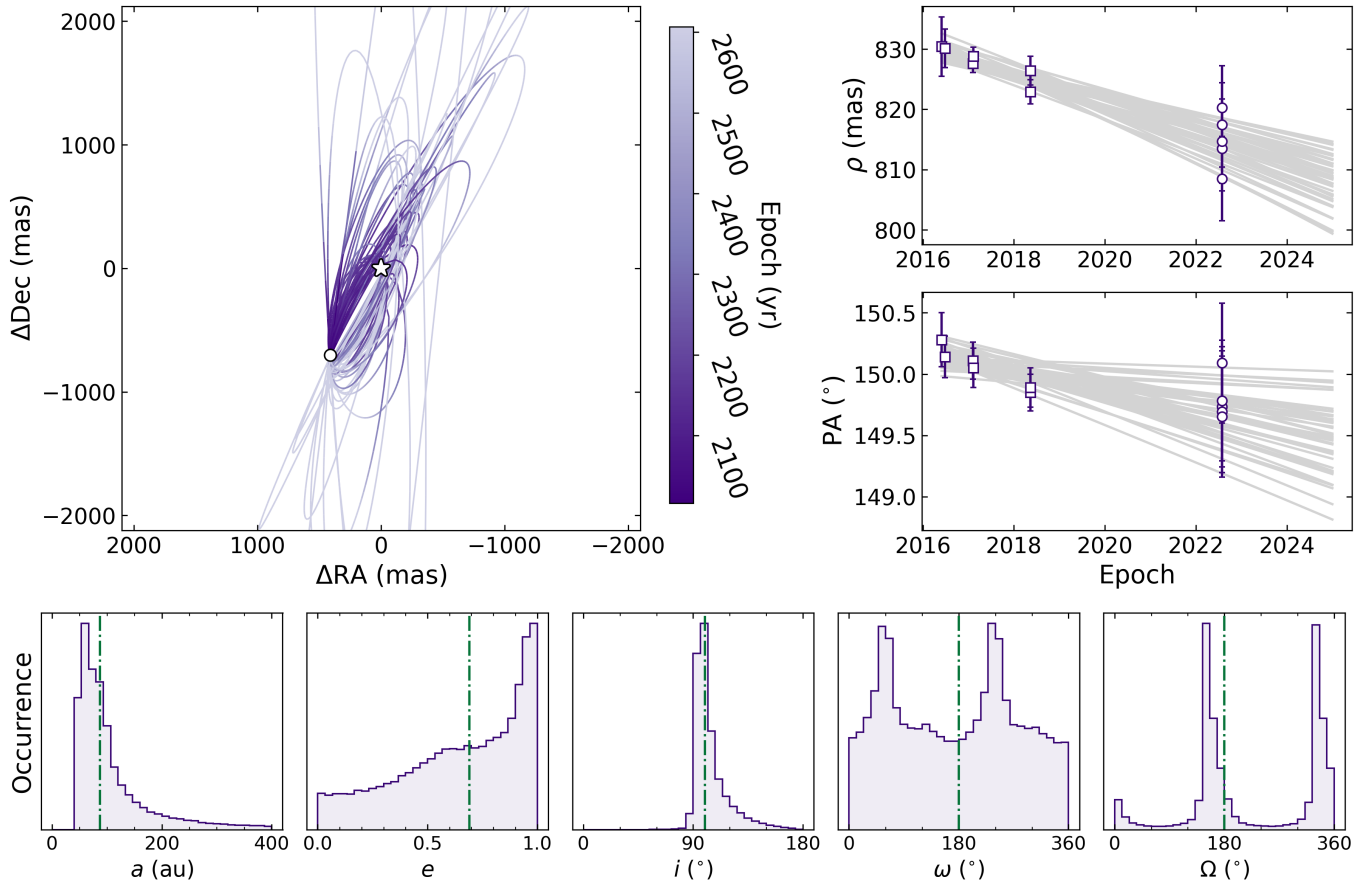


Figure 7. Orbital fitting of both *JWST* NIRCcam (this work) and SPHERE (Chauvin et al. 2017; Cheetham et al. 2019) astrometric measurements of HIP 65426 b using *orbitize!* (Blunt et al. 2017). **Top Left:** A random sample of 100 orbit models from the retrieved posterior (purple curves). The position of the planet (white circle) and the star (white star) are marked, and the epoch at a given position in an orbit is indicated by the colour bar. **Top Right:** Separation and position angle versus epoch for both the SPHERE (squares) and *JWST* NIRCcam astrometry (circles). The same random sample of 100 orbits is also displayed (grey lines). **Bottom:** Posterior distributions for the semi-major axis (a), eccentricity (e), inclination (i), argument of periastron (ω), and position angle of nodes (Ω). The 50% quantile from these distributions (green dot-dashed line) are also indicated. In this particular case, these additional *JWST* observations do not significantly increase the constraints on the measured orbital parameters.

strained and should not be interpreted as evidence for a highly eccentric orbit for HIP 65426 b. However, if this high eccentricity is real, it would give credence to the scenario proposed in Marleau et al. (2019), where HIP 65426 b initially formed through core accretion before being scattered to a wider separation by an additional companion. The ability of *JWST* to provide high precision astrometry may improve with improvements to the measurement of the absolute star position in the NIRCcam images, which in this case is limited by the precision with which we can locate the star center behind the coronagraphic mask (see Section 2.5).

Separate to *JWST*, HIP 65426 b has been observed as part of the ExoGRAVITY program (Lacour et al. 2020, Program ID: 1104.C-0651), which has routinely demonstrated sub-mas astrometric precision (e.g., Gravity

Collaboration et al. 2019; Lacour et al. 2021; Hinkley et al. 2022b) and has an even greater potential to improve upon our reported constraints.

4.4. Photometry

As with the astrometry, the measured photometry in all of the observed filters is obtained from the ADI+RDI reduction and shown in Table 2, the subtracted images of all of these filters is shown in Figure 8, and the photometric data points themselves are shown in Figure 9. The measured contrast of the planet relative to the star ranges from 10.403 mag in the F250M filter to 8.445 mag in the F1550C filter. Images for the ADI and RDI subtractions can be found in Appendix A. Additional literature photometric measurements as shown in Figure 9 are provided in Appendix D.

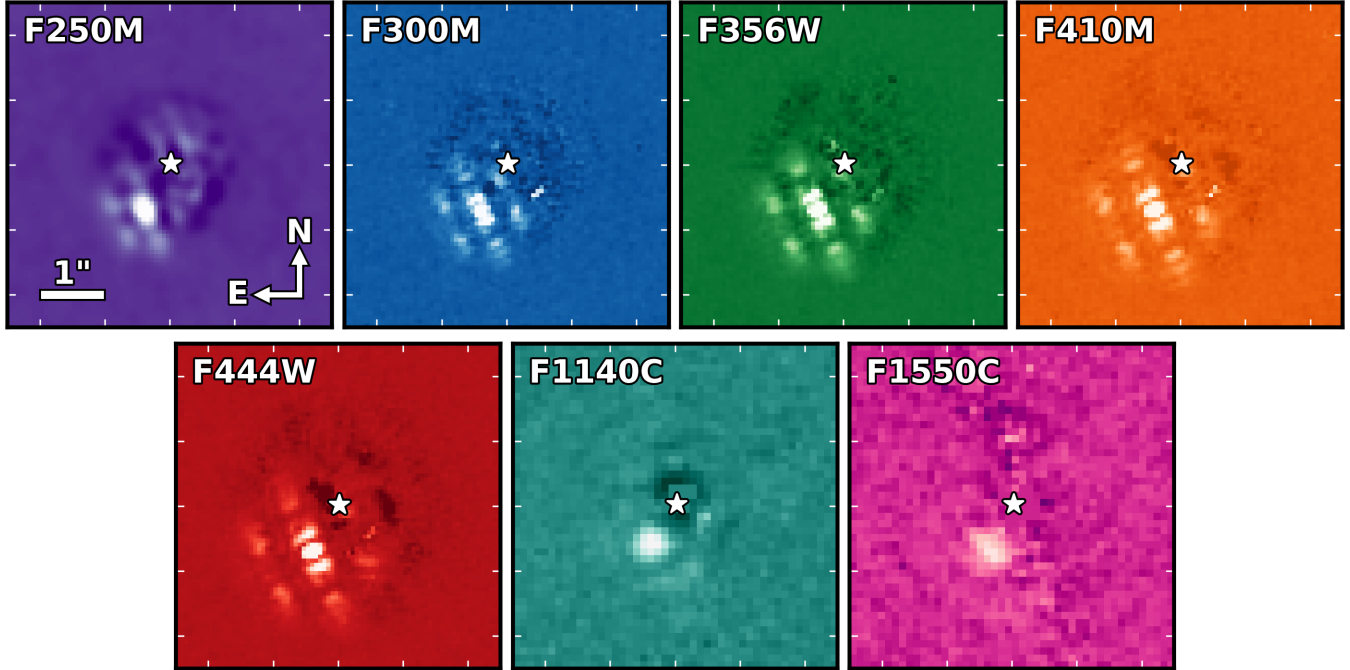


Figure 8. Images of the exoplanetary companion, HIP 65426 b, in all seven NIRCcam and MIRI filters used in our observations. Each image is produced following an ADI+RDI KLIP subtraction of the residual stellar PSF. The measured position of the star is marked (white stars), and the orientation and pixel scales of all images are marked in the top left panel.

Filter	ρ (mas)	θ (deg)	m_* (mag)	Δ (mag)	Δ_{corr} (mag)	m_b (mag)	Flux ($\text{Wm}^{-2}\mu\text{m}^{-1}$)
F250M	820 ± 7	150.1 ± 0.5	6.783 ± 0.054	10.403 ± 0.046	10.403 ± 0.071	17.186 ± 0.088	$(3.35\pm 0.27)\times 10^{-17}$
F300M	817 ± 7	149.7 ± 0.5	6.766 ± 0.046	10.014 ± 0.043	10.014 ± 0.069	16.780 ± 0.083	$(2.44\pm 0.19)\times 10^{-17}$
F356W	808 ± 7	149.7 ± 0.5	6.767 ± 0.048	9.280 ± 0.021	9.280 ± 0.058	16.047 ± 0.076	$(2.55\pm 0.18)\times 10^{-17}$
F410M	813 ± 7	149.7 ± 0.5	6.765 ± 0.051	8.978 ± 0.020	8.978 ± 0.058	15.743 ± 0.077	$(1.99\pm 0.14)\times 10^{-17}$
F444W	815 ± 7	149.8 ± 0.5	6.764 ± 0.054	8.939 ± 0.019	8.939 ± 0.058	15.703 ± 0.078	$(1.59\pm 0.11)\times 10^{-17}$
F1140C	827 ± 11	149 ± 1	6.722 ± 0.038	8.653 ± 0.018	8.653 ± 0.164	15.375 ± 0.168	$(5.17\pm 0.80)\times 10^{-19}$
F1550C	828 ± 15	149 ± 1	6.766 ± 0.072	8.445 ± 0.035	8.445 ± 0.167	15.211 ± 0.182	$(1.72\pm 0.29)\times 10^{-19}$

Table 2. *JWST* astrometry and photometry of HIP 65426 b, m_* corresponds to the stellar magnitude in each filter, and Δ_{corr} corresponds to the relative magnitude following the propagation in uncertainties of a 5% or 15% absolute flux calibration accuracy for NIRCcam and MIRI, respectively. The position angle (θ) is provided from North through East, and all apparent magnitudes are relative to Vega.

A notable tension can be seen between the *JWST* NIRCcam data shown here and the *VLT* NaCo L' , NB4.05, and M' data (Cheetham et al. 2019; Stolker et al. 2020b, Appendix D). The model fit shown in Figure 9 (also see Section 4.7) does not include the NaCo data, and matches the *JWST* NIRCcam data well. The *VLT* NaCo L' and M' photometric points are the average of the values reported in Cheetham et al. 2019 and Stolker et al. 2020b, and are discrepant with the predictions of this model by 2.1σ and 2.7σ , respectively. In light of this, and given the recent advent of high contrast imaging with *JWST*, we explore the potential for either data set to be biased in some way.

In the case of *JWST*, we focus our efforts on investigating the flux calibration of NIRCcam coronagraphy. The required absolute flux prediction accuracy for this mode is 5%¹³, but has yet to be formally verified from calibration observations. First, we perform simple aperture photometry on calibration observations of the star 2MASS J18022716+6043356 (A2V, 2MASS $K_s=11.83$) from CAL-01536 (PI: K. Gordon) with NIRCcam F356W imaging. The retrieved flux is $\sim 7\%$ higher than a synthetic F356W observation of an A2V PHOENIX

¹³ <https://jwst-docs.stsci.edu/jwst-data-calibration-considerations>

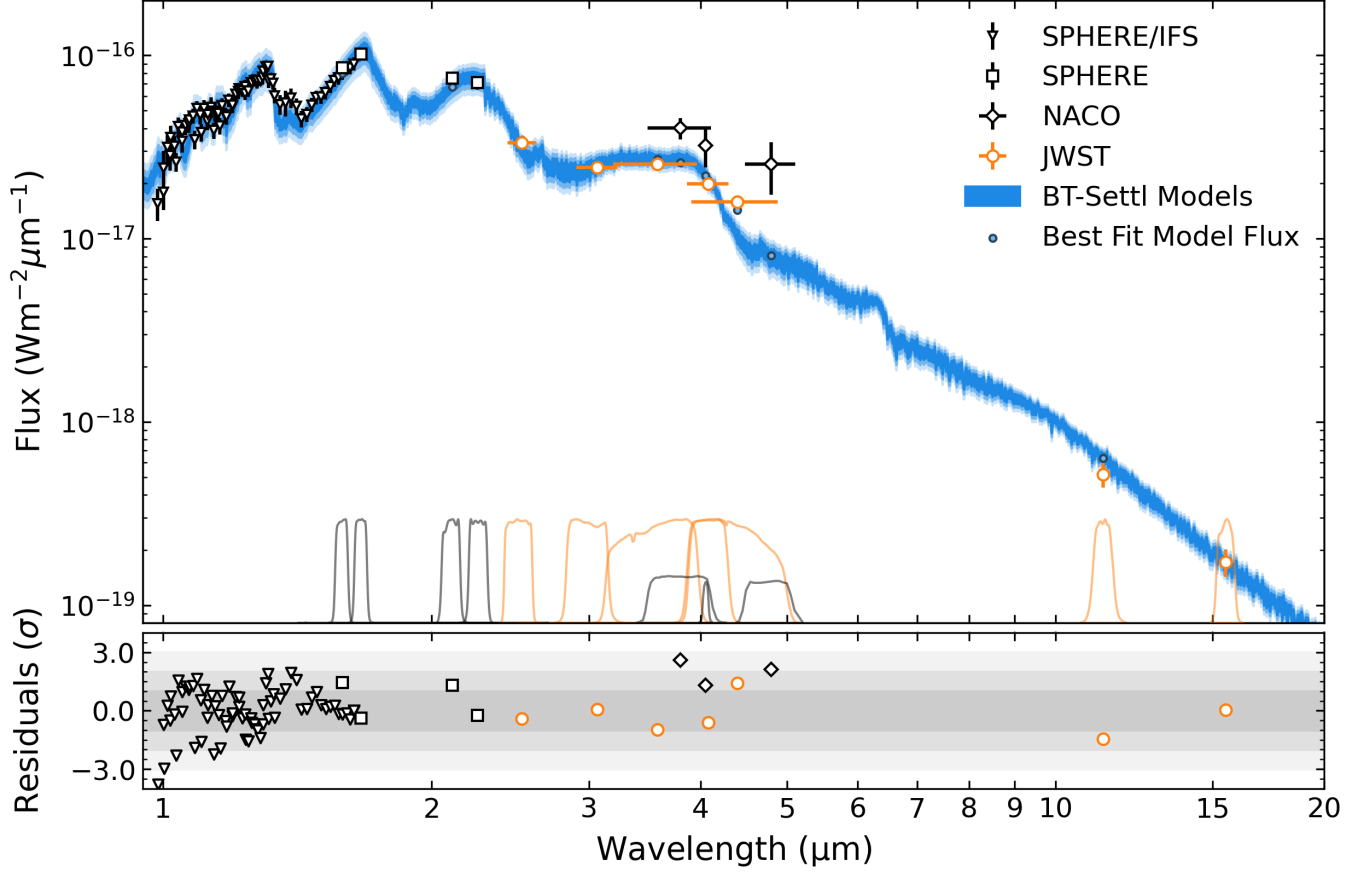


Figure 9. All existing spectroscopic and photometric observations of HIP 65426 b as obtained from SPHERE/IFS (triangles), SPHERE/IRDIS (squares), NaCo (diamonds), and *JWST* (circles). **Top:** Data are plotted alongside the 1, 2, and 3σ confidence intervals obtained from fitting to a collection of BT-SETTL atmospheric forward models (blue shaded regions), and the model values in the photometric bandpasses (small blue circles). At 3σ , the best fit models occupy parameter ranges of $T_{\text{eff}} = 1673_{-25}^{+27}$ K, $\log(g) = 4.10_{-0.17}^{+0.20}$ dex, and $R = 0.90_{-0.04}^{+0.04}$ R_{Jup} . The NaCo data have not been included in the model fitting process. Also plotted are the normalised filter throughput profiles for all photometric observations, with the NaCo throughputs scaled by a factor of 2 to improve clarity. **Bottom:** Residuals of each data point relative to the best fit model in addition to 1, 2, and 3σ regions (grey shading).

model (Husser et al. 2013) which was normalised to the 2MASS K_s magnitude listed above. Secondly, following a similar approach we compare the flux of sources that were observed in both NIRCcam Imaging and NIRCcam Coronagraphy from COM-01070 (PI: J. Girard) in the F335M filter. We selected three sources from the coronagraphic observations that were: underneath the mask substrate, not near an occulting mask, not overlapping with a nearby source, and present in the imaging observation field-of-view. The fluxes as estimated from the coronagraphic observation were 1%, 4%, and 7% higher than those estimated from the imaging observation. Given the simplicity of this analysis, we do not attempt to precisely quantify the accuracy of the current flux calibration, however, these measurements provide strong evidence that it is not driving the ob-

served tension with the NaCo data, which is a factor of ~ 2 larger than the analogous *JWST* data.

With reference to the NaCo data, using independent analyses Cheetham et al. (2019) and Stolker et al. (2020b) extract photometry consistent with each other to 1σ . Both the L' and M' observations were taken in average weather conditions, with light but varying cloud cover¹⁴. The non-contemporaneous nature of flux calibrations for ground-based observations can lead to small biases if the weather conditions change between flux and science frames. Further, the M' observation is subject to a high thermal background, and the residual intensities near the location of the companion appear to be approximately half of the companion peak inten-

¹⁴ <https://www.eso.org/asm/ui/publicLog>

sity (Stolker et al. 2020b), though the impact of the high background is seen in the error bar of the M' photometry. The NB4.05 observation was taken in particularly poor and variable conditions, with a mean seeing of $1.52 \pm 3.01''$ (Stolker et al. 2020b), hence also susceptible to flux variations. While the points raised above suggest it is conceivable for the NaCo photometry to have been overestimated, pinpointing the exact origin of the discrepancy would involve an in-depth re-analysis of the NaCo data, which is left for future work.

The observed tension may also be influenced by genuine variability of HIP 65426 b, its host star, or both. However, we do not investigate this such a scenario in this work.

4.5. Bolometric Luminosity

With the addition of *JWST* NIRC*am* and MIRI photometric observations, the SED of HIP 65426 b is measured over a significant portion of the range from $1 \mu\text{m}$ to $15 \mu\text{m}$. These measurements enable a tight constraint on the bolometric luminosity of the planet.

To calculate the luminosity, a full SED was created by distributing the flux-density from photometric measurements over the effective bandwidth for each filter and using a model atmosphere to extrapolate beyond and interpolate between measured bands. Luminosity is then determined by integrating this semi-empirical SED over wavelength.

Since all of the flux measured in the NIRC*am*/F410M photometry is accounted for in the F444W measurement, we used only the wider band for our analysis. We also added measurements from the literature at shorter wavelengths, including the SPHERE-IFS YH-band spectrum (Cheetham et al. 2019), and SPHERE-IRDIS H3, K1, and K2-band photometry (Chauvin et al. 2017; Cheetham et al. 2019; also see Appendix D).

To explore how the luminosity estimate depends on the choice of model spectrum used, we performed the analysis with a broad range of models spanning T_{eff} from 1200 K to 1900 K and $\log(g)$ spanning 3.5 to 5.5. These models were drawn from three different grids, including two with different cloud implementations – BT-SETTL (Baraffe et al. 2015), and DRIFT-Phoenix (Witte et al. 2009) – and the cloud-free Sonora-bobcat models (Marley et al. 2021). No matter which model we used to fill in the gaps between the measured portions of the SED, $\log(L_{\text{bol}}/L_{\odot})$ is always between -4.21 and -4.35 . Consequently, the luminosity is constrained at the 0.15 dex level and the result is robust across all considered model atmospheres.

4.6. Estimates of Mass and other Companion Properties from Hot-Start Evolutionary Models

The mass of HIP 65426 b is estimated using a method similar to that described in Dupuy & Liu (2017). We first built an interpolated grid of model luminosities as a function of age and mass, with 10,000 equally-spaced age values spanning from 5 to 30 Myr and 10,000 equally-spaced mass values spanning from 0.3 to $21 M_{\text{Jup}}$ using `numpy.griddata` in `python`. We adopted an age for HIP 65426 b of 14 ± 4 Myr based on the Lower Centaurus-Crux age given in Chauvin et al. (2017) and a measured bolometric luminosity uniformly distributed between $\log(L_{\text{bol}}/L_{\odot}) = -4.21$ and -4.35 from the previous section.

We then generated 1×10^6 samples of age and mass from a Gaussian distribution in age around 14 Myr, with $\sigma=4$ Myr, and a uniform distribution in mass from 0.3 to $21 M_{\text{Jup}}$. For each age, mass sample, we then look up the corresponding model luminosity from the interpolated grid of model luminosities. For each age, mass sample, we accept the sample if the corresponding model luminosity is within the measured range of uniformly-distributed bolometric luminosities and reject the sample if it lies outside this range.

We implemented this procedure using the hybrid cloud grid from Saumon & Marley (2008). Given that this is a dusty, young red object, we expect the Saumon & Marley (2008) models, which take clouds into account, to provide the most reliable estimates of the properties of these objects among the model choices available. To sample the corresponding effective temperatures, surface gravities, and radii corresponding to our accepted mass values, we built interpolated grids of model effective temperatures, surface gravities, and radii with the same spacing in age and mass as for the interpolated grid of luminosities, then looked up the corresponding property in the appropriate table for each accepted age, mass sample. Histograms of the final set of accepted masses, effective temperatures, surface gravities, and radii for each model are shown in Fig. 10. The best value of each parameter was taken as the median of the accepted distribution, with error bars given by the 68% confidence interval as calculated from the histogram of each distribution. We find a mass of $7.1 \pm 1.1 M_{\text{Jup}}$, radius of $1.45 \pm 0.03 R_{\text{Jup}}$ (which therefore imply a surface gravity $\log(g) = 3.93_{-0.09}^{+0.07}$), and effective temperature $T_{\text{eff}} = 1282_{-31}^{+26}$ K.

4.7. Atmospheric Forward Model Comparison

To explore the atmospheric properties of HIP 65426 b we performed a forward modelling analysis using the tool ForMoSA (Petruš et al. 2020), which compares spec-

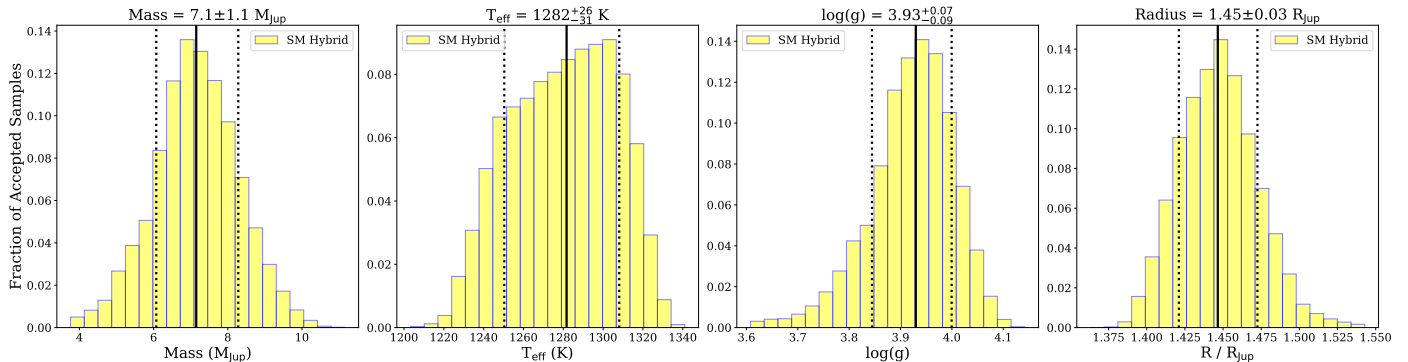


Figure 10. Histograms of the final sets of accepted model properties for the hybrid cloud grid from Saumon & Marley (2008). The median value for each property is shown as a solid black line, with the 68% confidence region falling between the two dotted black lines.

transcopic and/or photometric data with grids of pre-computed synthetic spectra. The code is based on the nested sampling algorithm (Skilling 2004), a Bayesian inversion method, that allows a global exploration of the parameter space provided by the grid. In this work, we limited our analysis to the BT-SETTL grid (CIFIST version, Allard et al. 2012; Baraffe et al. 2015) that accounts for convection using mixing-length theory, and works at hydrostatic, radiative-convective, and chemical equilibrium.

For the fit, we used a data set composed of the low resolution spectra ($R_\lambda \sim 54$) between 1.00 and 1.65 μm provided by *VLT/SPHERE-IFS* (Chauvin et al. 2017), *VLT/SPHERE-IRDIS* H_2 (1.58 μm), H_3 (1.66 μm), K_1 (2.11 μm), and K_2 (2.25 μm) photometry (Cheetham et al. 2019), and our new *JWST* NIRC*am* and MIRI photometry. The NaCo data are not used for the reasons described in Section 4.4. We first adapted the BT-SETTL synthetic spectra to our data, by reducing their spectral resolution to that of SPHERE-IFS and calculating the synthetic photometric flux at each bandpass using throughputs as obtained from *spaceKLIP* for the *JWST* data, and from the SVO filter service for all other data¹⁵ (Rodrigo et al. 2012; Rodrigo & Solano 2020). We then defined flat priors on the T_{eff} and the $\log(g)$ according to the limits of the grid, and applied nested sampling to estimate the posterior distributions of these two parameters. We also add the radius, R , to the list of the parameters explored by the nested sampling. At each iteration, a radius is picked randomly (uniform prior), and a dilution factor $C_K = (R/d)^2$ is calculated and multiplied to the model, where d is the distance to the object (107.49 pc).

The best fit models to our data combined with the existing SPHERE data are displayed in Fig-

ure 9, alongside posteriors in Figure 11. We estimate $T_{\text{eff}} = 1667^{+25}_{-24}$ K, $\log(g) = 4.07^{+0.19}_{-0.19}$ dex, and $R = 0.92^{+0.04}_{-0.04} R_{\text{Jup}}$. From the T_{eff} and the radius, we apply the Stefan-Boltzmann law and estimate a bolometric luminosity of $\log(L_{\text{bol}}/L_\odot) = -4.23^{+0.02}_{-0.02}$, and from the $\log(g)$ and R we estimate a mass of $M = 3.95^{+2.23}_{-1.16} M_{\text{Jup}}$. By comparing the integrated flux of the best fit model across all wavelengths, and the integrated flux between the shortest and longest wavelength observations, we determine that these observations span $\sim 97\%$ of HIP 65426 b’s luminous range. These results are also in agreement with a similar BT-SETTL model fitting procedure to *VLT/SINFONI* data of HIP 65426 b (see Petrus et al. 2021). Finally, the uncertainties of all parameters are given at 3σ , however, we emphasise that they do not necessarily describe our confidence in the true planetary properties and are better considered as the model phase space that best fits our data.

The precision on these measurements is primarily driven by the SPHERE/IFS data, however, we do note some differences that result from the addition of the *JWST* data. Specifically, when fitting just the SPHERE data in isolation, we obtain $T_{\text{eff}} = 1642^{+33}_{-27}$ K, $\log(g) = 3.89^{+0.17}_{-0.13}$ dex, $R = 1.02^{+0.11}_{-0.14} R_{\text{Jup}}$ and $\log(L_{\text{bol}}/L_\odot) = -4.10^{+0.07}_{-0.09}$, again with uncertainties given at 3σ . Therefore, the *JWST* data improve the precision of the radius and bolometric luminosity by a factor of ~ 3 , but do not significantly improve the precision on the temperature and surface gravity. We also note offsets between the best fit values between these two fits of up to 3σ (using the uncertainties from the combined fit), which suggests that the selected models do not accurately capture these two regions of wavelength space simultaneously.

The atmospheric forward model fit yields a luminosity within the bolometric luminosity range of -4.21 to -4.35 that was found from combining SED measurements with models in the regions not covered by

¹⁵ <http://svo2.cab.inta-csic.es/theory/fps/>

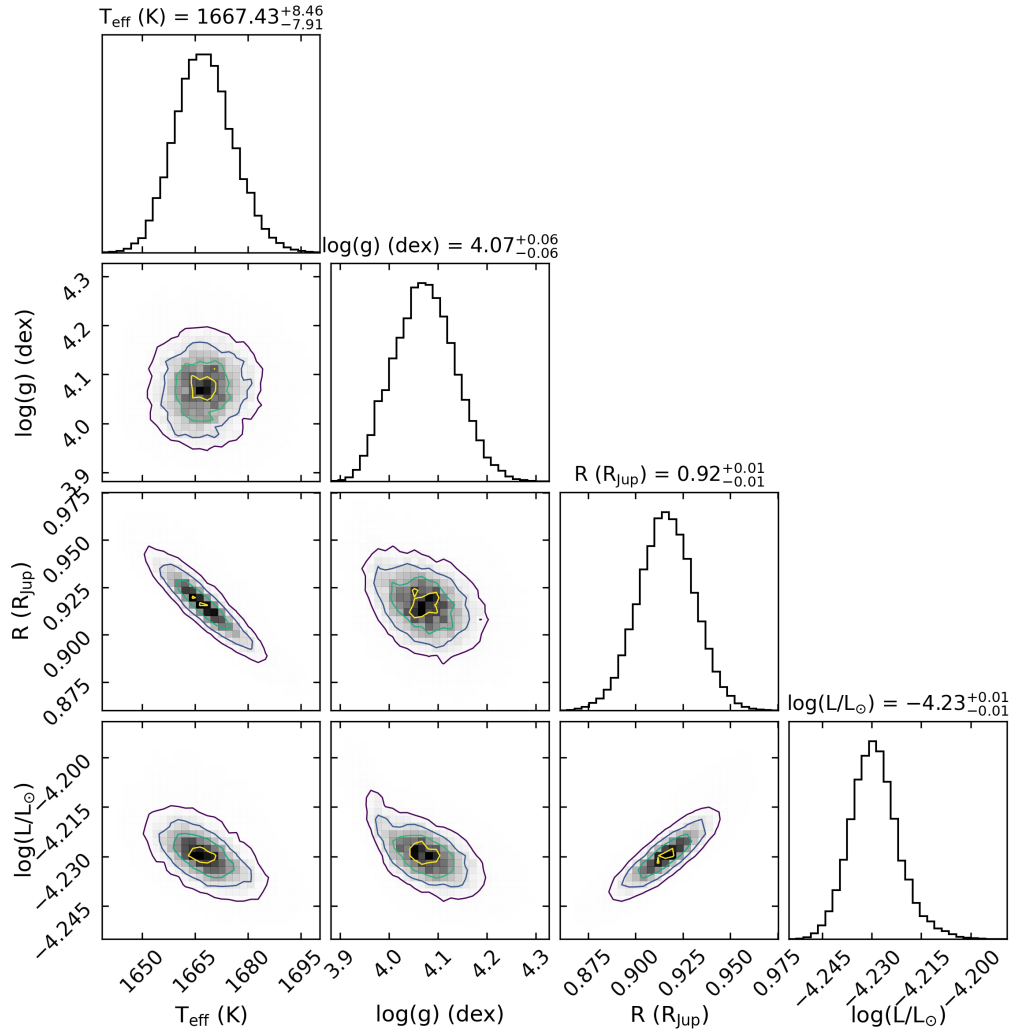


Figure 11. Posterior distributions for the BT–Settl atmospheric model fitting to both *JWST* and *VLT/SPHERE* observations of HIP 65426 b. Best fit values and 1σ uncertainties are indicated, however, these should be interpreted as the model phase space that fits these data, and not the precision to which these properties can be empirically measured.

the SED. However, the effective temperatures and radii found using the atmospheric forward model are considerably in tension with predictions from evolutionary model fits to the measured bolometric luminosity range (see Section 4.6). In particular, to obtain similar bolometric luminosity values, the forward models favour higher effective temperatures (~ 1700 K) and smaller radii ($\sim 0.90 R_{\text{Jup}}$) compared to the evolutionary models (~ 1300 K, $\sim 1.48 R_{\text{Jup}}$). In fact, the atmospheric forward model used here predicts an unphysically small, sub-Jupiter radius for an exoplanet which may still be contracting at these young ages. Thus, we consider the effective temperature and radius predictions from the evolutionary models to be more robust here. The tension we find between the atmospheric models and evolutionary models is well-documented in the community; atmospheric models have a long history of requiring un-

physically small radii and high effective temperatures to fit spectroscopy (see e.g., Marois et al. 2008; Patience et al. 2012).

4.8. Future Work

There is a range of additional investigation that can be performed on the data presented here that is worth highlighting, but ultimately falls outside the scope of this work.

Most importantly, it is possible to perform the atmospheric forward model fitting procedure shown here in Section 4.7 with a wide range of state-of-the-art models (e.g., ATMO, Tremblin et al. (2015); Phillips et al. (2020); Exo-REM, Charnay et al. (2018); Sonora, Karalidi et al. (2021)), each with their own treatment for the effects of clouds and atmospheric chemistry. Additionally, atmospheric fitting can also be performed using

retrieval techniques (e.g., Mollière et al. 2020; Gonzales et al. 2021). Divergences in the measured planetary properties between these models are expected, and a more complete analysis in the context of the relative assumptions of each model will greatly improve our understanding of the true properties of HIP 65426 b.

The precision of the 3–5 μm data may be sufficient to provide constraints on the relative atmospheric abundances of CH_4 and CO , which can be impacted by disequilibrium chemistry (Zahnle & Marley 2014; Miles et al. 2020). The F1140C photometry falls slightly under the best fit model at $\sim 1.5\sigma$, and may be indicative of absorption by small silicate dust grains (Cushing et al. 2006; Suárez & Metchev 2022, Miles et al. submitted). Finally, while the F1550C photometry is relatively insensitive to the choice of atmospheric model, it may be sensitive to circumplanetary disk emission (Sterzik et al. 2004; Stolker et al. 2020a).

5. CONCLUSION

In this work we present the first ever scientific observations using the *JWST* high contrast imaging modes of both NIRCcam from 2–5 μm , and MIRI from 11–16 μm . The known exoplanet companion, HIP 65426 b, is clearly detected in all seven observational filters, representing the first ever direct detection of an exoplanet beyond 5 μm . These observations provide a variety of insights into: a) the performance and best practices of *JWST* high contrast imaging, and b) the properties of the HIP 65426 b system, which we summarise below:

- **Contrast:** *JWST* is exceeding its anticipated contrast performance for both NIRCcam and MIRI coronagraphy by up to a factor of 10 in the contrast limited regime (see Section 4.1). For the contrasts achieved, we are sensitive to sub-Jupiter companions with masses as small as $0.3M_{\text{Jup}}$ beyond separations of ~ 100 au. Furthermore, for more optimal targets such as young, nearby M stars it is highly likely that both NIRCcam and MIRI will be sensitive to sub-Saturn mass objects beyond ~ 10 au (Carter et al. 2021a).
- **Subtraction Strategy:** For these data at small separations $< 2''$, the best contrast is obtained using a small-grid dither RDI subtraction strategy for both NIRCcam and MIRI. Additionally, an ADI+RDI subtraction does not significantly improve the measured contrast compared to RDI. For the MIRI F1550C observations in particular, we were unable to recover HIP 65426 b using ADI alone. At wider separations however, the observational efficiency of ADI may make it preferable to

RDI. These conclusions may aid future observers in selecting their PSF subtraction strategy, although we emphasise that a clearer understanding of whether they apply under all circumstances will require the analysis of a broader range of *JWST* coronagraphic observations.

- **Photometry:** These photometric observations of HIP 65426 b provide exquisite sensitivity at a precision of $\sim 7\%$ for NIRCcam and $\sim 16\%$ for MIRI. Furthermore, prior to propagation of the uncertainty in the stellar flux ($\sim 5\%$), and the current absolute flux calibration accuracy (5/15% for NIRCcam/MIRI), the uncertainty in the measured relative flux is even smaller at $\sim 2\%$ for both NIRCcam and MIRI. These measurements are a significant step forward from ground-based observations from 3–5 μm , which have comparative sensitivities of $\sim 13\text{--}32\%$ for HIP 65426 b, and are restricted to particular wavelength regions due to telluric contamination. With this improved precision we will be able to constrain directly imaged exoplanet atmospheres in much greater detail, in addition to more complex effects such as variability, disequilibrium chemistry, and the emission of circumplanetary material.
- **Atmospheric Model Fitting:** Using a BT-SETTL atmospheric forward model we are able to fit all data, in addition to the majority of ground-based observations to within 2σ . This agreement provides precise constraints on the $T_{\text{eff}} = 1667_{-24}^{+25}$ K, $\log(g) = 4.07_{-0.19}^{+0.19}$ dex, $R = 0.92_{-0.04}^{+0.04} R_{\text{Jup}}$, and $\log(L_{\text{bol}}/L_{\odot}) = -4.23_{-0.02}^{+0.02}$. Compared to a fit excluding the *JWST* data, this corresponds to a factor of ~ 3 improvement in the precision of the radius and bolometric luminosity. Despite the excellent model agreement, both the temperature and unphysically small radius are in disagreement with the values obtained from the evolutionary models, further emphasising a long standing tension for this class of objects.
- **Empirical Bolometric Luminosity:** As *JWST* offers a uniquely broad spectral coverage in comparison to ground-based instruments, we are able to obtain a very precise measurement of the bolometric luminosity of HIP 65426 b that is constrained between a $\log(L_{\text{bol}}/L_{\odot}) = -4.21$ to -4.35 , irrespective of the model atmosphere adopted for the wavelengths not covered by observations. In combination with evolutionary models, this provides tight constraints on the prop-

erties of HIP 65426 b with $M=7.1\pm 1.1 M_{\text{Jup}}$, $T_{\text{eff}}=1282^{+26}_{-31}$ K, and $R=1.45\pm 0.03 R_{\text{Jup}}$. Given the achieved sensitivity, similar *JWST* observations will facilitate this analysis for a broader range of PMCs than ever before and provide comparable constraints on their bolometric luminosities, and therefore mass.

In conclusion, the observations reported here from our ERS program (ERS-01386, [Hinkley et al. 2022a](#)) demonstrate that *JWST* provides an transformative opportunity to study exoplanets through high contrast imaging. Beyond this work, we look forward to further results from our program of: 3–16 μm NIRC*am* and MIRI coronagraphy of the circumstellar disk HD 141569 A (Millar-Blanchaer et al. in preparation, Choquet et al. in preparation); NIRSpec and MIRI spectroscopy from 1–28 μm of the PMC VHS J1256 b (Miles et al. submitted); and NIRISS AMI observations of HIP 65426 at 3.8 μm (Ray et al. in preparation, Sallum et al. in preparation).

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APPENDIX
A. SUBTRACTED IMAGES

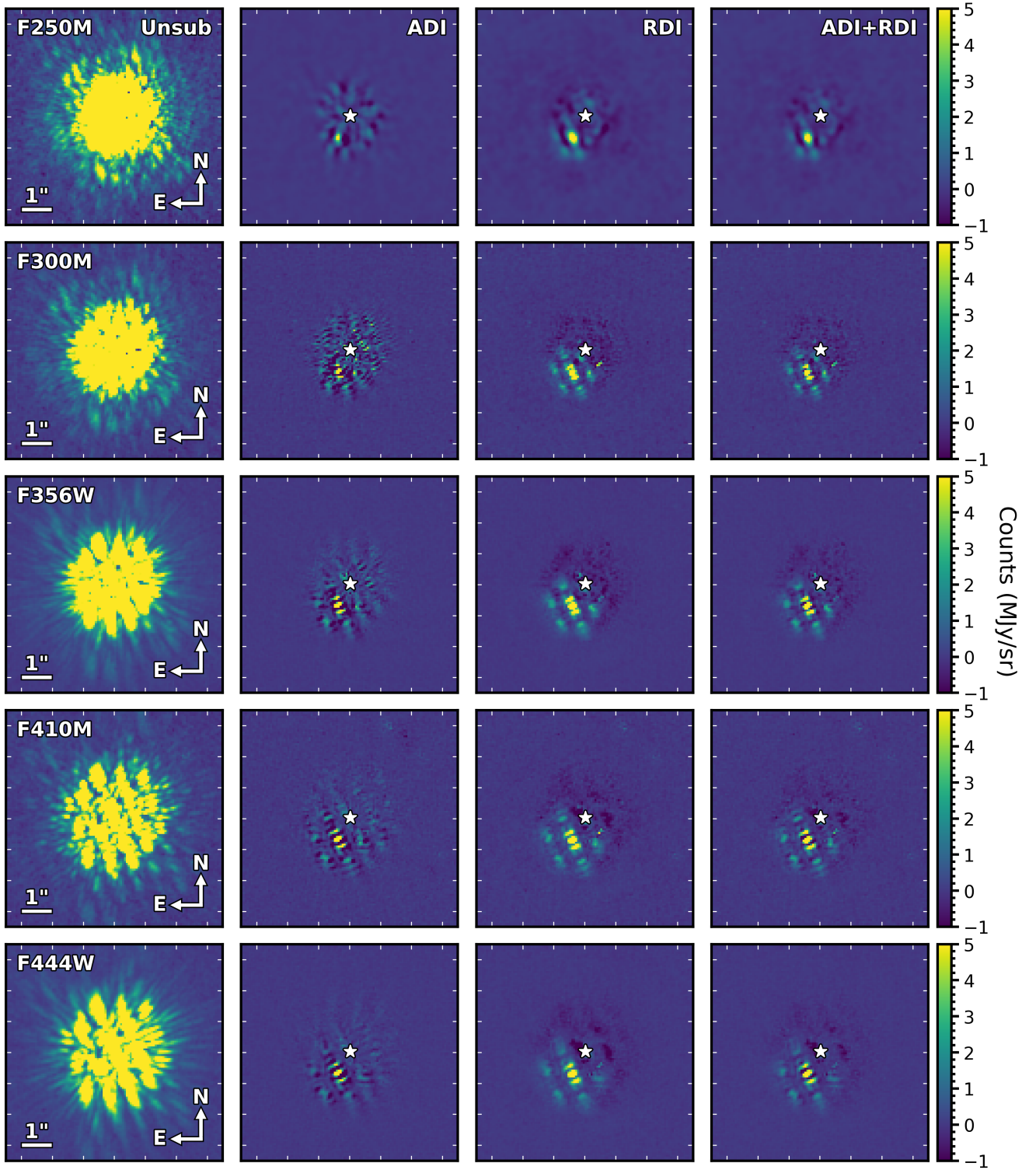


Figure 12. As in Figure 3, except for the NIRCcam F250M, F300M, F356W, F410M, and F444W filters. Here we show subtractions using the maximum number of PCA modes for ADI, RDI, and ADI+RDI, respectively. The F250M subtracted images have been smoothed as described in Section 2.

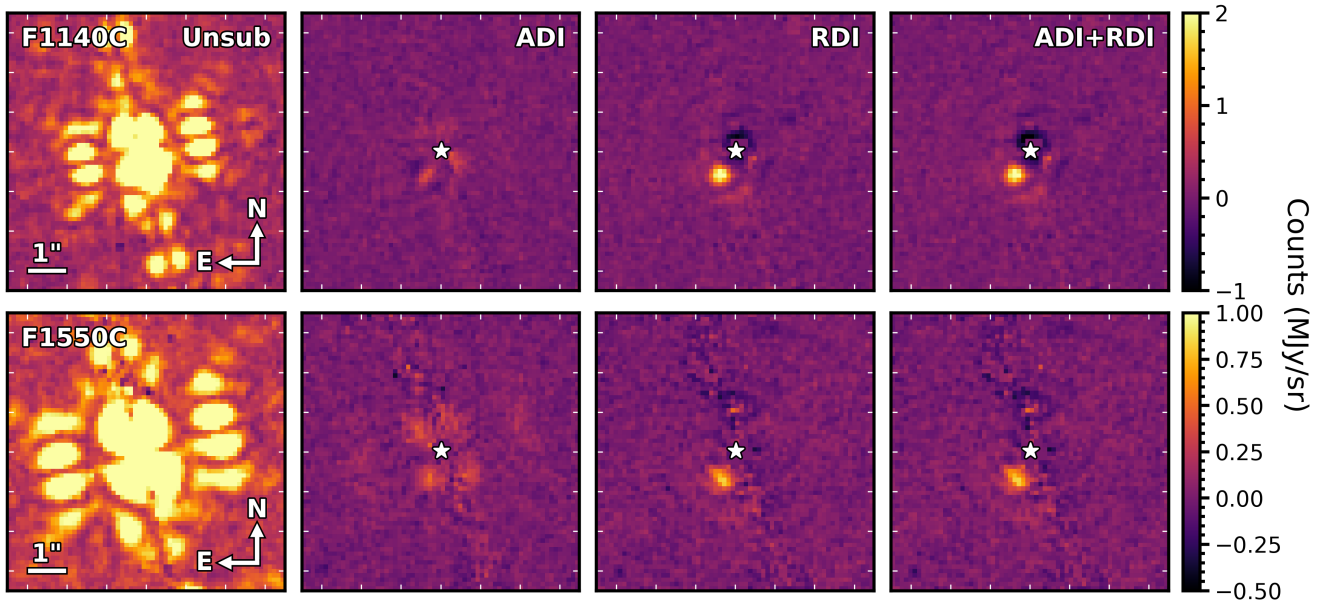


Figure 13. As in Figure 3, except for the MIRI F1140C and F1550C filters. Here we show subtractions using the maximum number of PCA modes for ADI, RDI, and ADI+RDI, respectively. To aid visual clarity, the subtracted F1550C images are shown with a peak image intensity five times smaller than the unsubtracted image.

B. CONTRAST PERFORMANCE

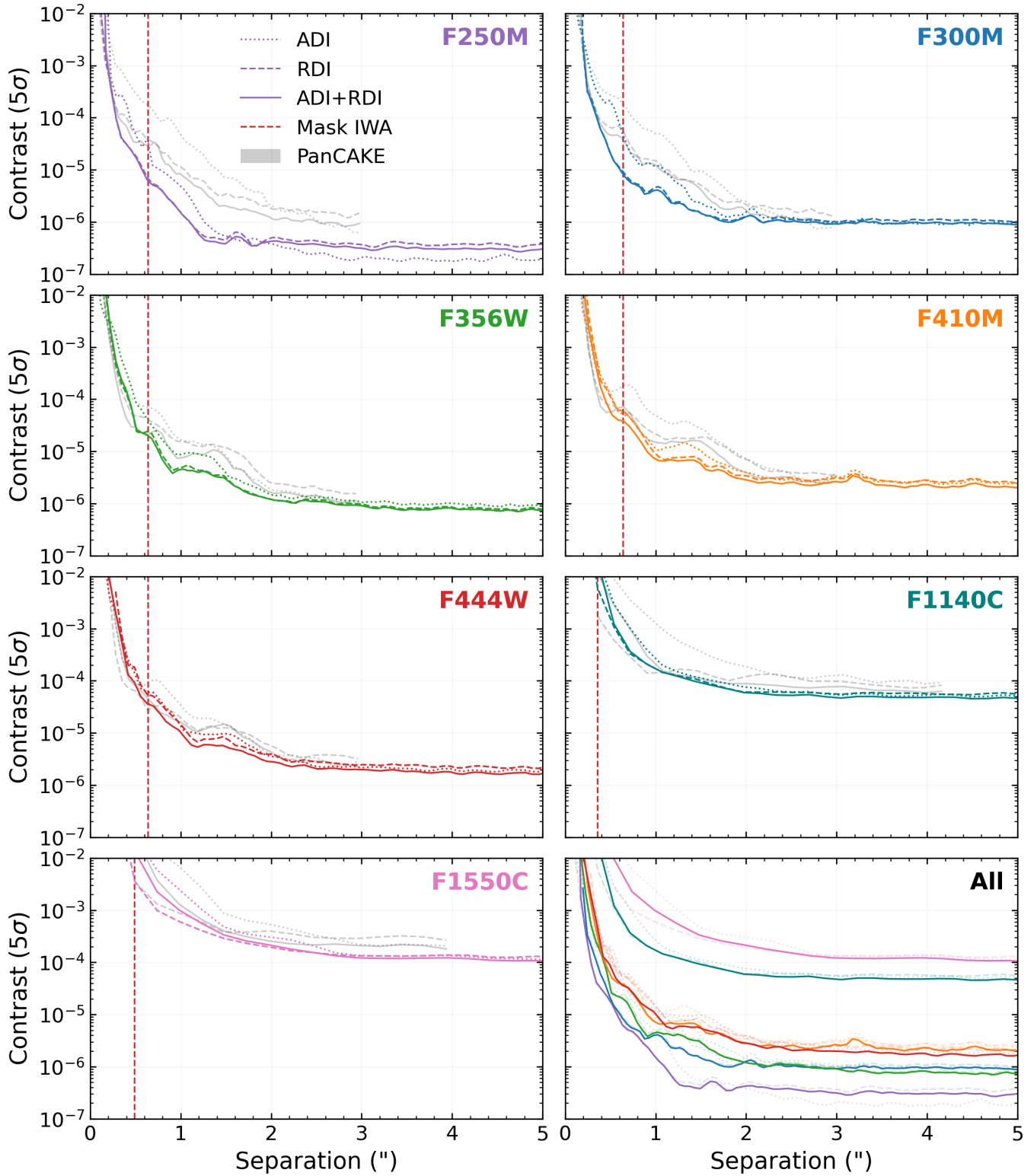


Figure 14. As in Figure 5, but for all used filters. We also plot the equivalent predicted contrast curves for these observations from PanCAKE (grey lines) following (Carter et al. 2021b). In every filter *JWST* is exceeding its predicted performance.

C. PSF FITTING

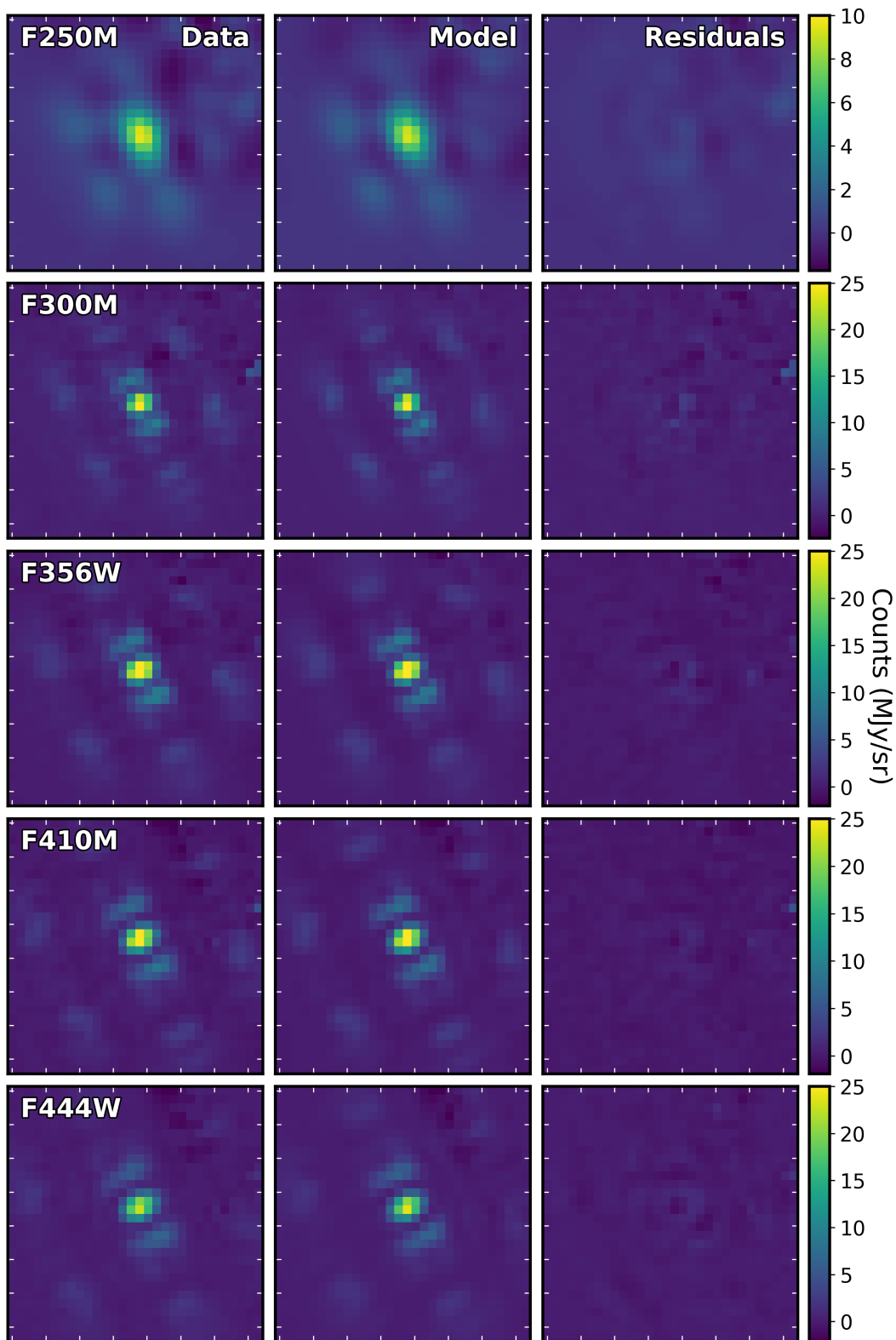


Figure 15. The data (left column), model PSF (middle column), and residuals (right column) for the `spaceKLIP` PSF fitting of the NIRCcam observations of HIP 65426 b. Pixel counts are in MJy/sr and are indicated by the colour bar on the right hand side.

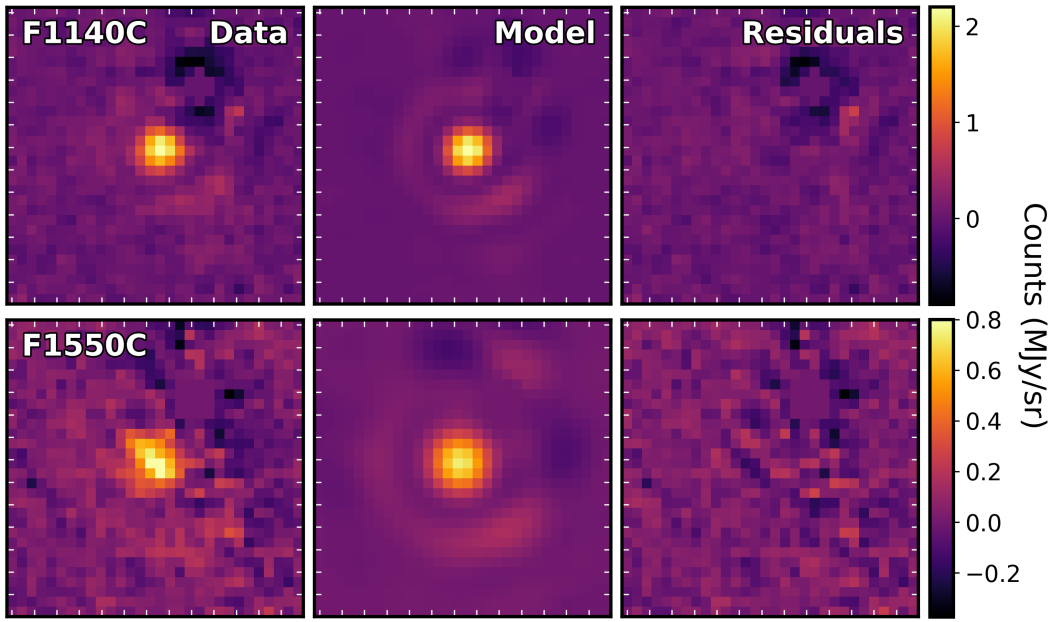


Figure 16. As in Figure 15, but for the MIRI observations.

D. COMPLEMENTARY PHOTOMETRIC MEASUREMENTS OF HIP 65426 B

Table 3. Additional photometric measurements of HIP 65426 b considered in this work.

Wavelength (μm)	Bandwidth (μm)	Instrument	Band	Flux ($\text{W m}^{-2} \mu\text{m}^{-1}$)	Ref.
1.002	0.011	SPHERE/IFS	YJ	$(2.434 \pm 0.569) \times 10^{-17}$	1
1.011	0.011	SPHERE/IFS	YJ	$(3.155 \pm 0.670) \times 10^{-17}$	1
1.021	0.011	SPHERE/IFS	YJ	$(3.564 \pm 0.575) \times 10^{-17}$	1
1.030	0.011	SPHERE/IFS	YJ	$(3.199 \pm 0.428) \times 10^{-17}$	1
1.040	0.011	SPHERE/IFS	YJ	$(4.095 \pm 0.482) \times 10^{-17}$	1
1.050	0.011	SPHERE/IFS	YJ	$(3.829 \pm 0.435) \times 10^{-17}$	1
1.060	0.011	SPHERE/IFS	YJ	$(4.154 \pm 0.489) \times 10^{-17}$	1
1.070	0.011	SPHERE/IFS	YJ	$(4.456 \pm 0.521) \times 10^{-17}$	1
1.081	0.011	SPHERE/IFS	YJ	$(4.679 \pm 0.432) \times 10^{-17}$	1
1.091	0.011	SPHERE/IFS	YJ	$(5.143 \pm 0.483) \times 10^{-17}$	1
1.102	0.011	SPHERE/IFS	YJ	$(4.746 \pm 0.543) \times 10^{-17}$	1
1.112	0.011	SPHERE/IFS	YJ	$(5.127 \pm 0.576) \times 10^{-17}$	1
1.123	0.011	SPHERE/IFS	YJ	$(4.775 \pm 0.641) \times 10^{-17}$	1
1.133	0.011	SPHERE/IFS	YJ	$(5.228 \pm 0.682) \times 10^{-17}$	1
1.144	0.011	SPHERE/IFS	YJ	$(4.982 \pm 0.609) \times 10^{-17}$	1
1.154	0.011	SPHERE/IFS	YJ	$(4.821 \pm 0.519) \times 10^{-17}$	1
1.165	0.011	SPHERE/IFS	YJ	$(5.324 \pm 0.486) \times 10^{-17}$	1
1.175	0.011	SPHERE/IFS	YJ	$(4.739 \pm 0.453) \times 10^{-17}$	1
1.186	0.011	SPHERE/IFS	YJ	$(5.709 \pm 0.477) \times 10^{-17}$	1
1.196	0.011	SPHERE/IFS	YJ	$(5.291 \pm 0.415) \times 10^{-17}$	1
1.206	0.011	SPHERE/IFS	YJ	$(6.155 \pm 0.471) \times 10^{-17}$	1
1.217	0.011	SPHERE/IFS	YJ	$(6.586 \pm 0.490) \times 10^{-17}$	1
1.227	0.011	SPHERE/IFS	YJ	$(6.431 \pm 0.500) \times 10^{-17}$	1
1.237	0.011	SPHERE/IFS	YJ	$(6.203 \pm 0.483) \times 10^{-17}$	1
1.247	0.011	SPHERE/IFS	YJ	$(6.409 \pm 0.477) \times 10^{-17}$	1
1.257	0.011	SPHERE/IFS	YJ	$(7.100 \pm 0.483) \times 10^{-17}$	1
1.266	0.011	SPHERE/IFS	YJ	$(7.289 \pm 0.502) \times 10^{-17}$	1
1.276	0.011	SPHERE/IFS	YJ	$(7.344 \pm 0.504) \times 10^{-17}$	1
1.285	0.011	SPHERE/IFS	YJ	$(7.315 \pm 0.499) \times 10^{-17}$	1
1.294	0.011	SPHERE/IFS	YJ	$(8.215 \pm 0.543) \times 10^{-17}$	1
1.303	0.011	SPHERE/IFS	YJ	$(8.701 \pm 0.543) \times 10^{-17}$	1
1.312	0.011	SPHERE/IFS	YJ	$(8.731 \pm 0.580) \times 10^{-17}$	1
1.321	0.011	SPHERE/IFS	YJ	$(7.450 \pm 0.594) \times 10^{-17}$	1
1.329	0.011	SPHERE/IFS	YJ	$(7.073 \pm 0.583) \times 10^{-17}$	1
0.987	0.019	SPHERE/IFS	YJH	$(1.556 \pm 0.312) \times 10^{-17}$	1
1.002	0.019	SPHERE/IFS	YJH	$(1.791 \pm 0.355) \times 10^{-17}$	1
1.018	0.019	SPHERE/IFS	YJH	$(2.855 \pm 0.510) \times 10^{-17}$	1
1.034	0.019	SPHERE/IFS	YJH	$(2.615 \pm 0.305) \times 10^{-17}$	1
1.051	0.019	SPHERE/IFS	YJH	$(3.394 \pm 0.442) \times 10^{-17}$	1
1.068	0.019	SPHERE/IFS	YJH	$(4.239 \pm 0.456) \times 10^{-17}$	1
1.086	0.019	SPHERE/IFS	YJH	$(3.472 \pm 0.407) \times 10^{-17}$	1
1.104	0.019	SPHERE/IFS	YJH	$(3.802 \pm 0.415) \times 10^{-17}$	1
1.122	0.019	SPHERE/IFS	YJH	$(4.403 \pm 0.504) \times 10^{-17}$	1

Table 3 *continued*

Table 3 (*continued*)

Wavelength (μm)	Bandwidth (μm)	Instrument	Band	Flux ($\text{W m}^{-2}\mu\text{m}^{-1}$)	Ref.
1.140	0.019	SPHERE/IFS	YJH	$(3.906 \pm 0.397) \times 10^{-17}$	1
1.159	0.019	SPHERE/IFS	YJH	$(4.132 \pm 0.422) \times 10^{-17}$	1
1.178	0.019	SPHERE/IFS	YJH	$(4.641 \pm 0.452) \times 10^{-17}$	1
1.197	0.019	SPHERE/IFS	YJH	$(5.368 \pm 0.544) \times 10^{-17}$	1
1.216	0.019	SPHERE/IFS	YJH	$(6.356 \pm 0.573) \times 10^{-17}$	1
1.235	0.019	SPHERE/IFS	YJH	$(6.763 \pm 0.602) \times 10^{-17}$	1
1.255	0.019	SPHERE/IFS	YJH	$(7.107 \pm 0.622) \times 10^{-17}$	1
1.274	0.019	SPHERE/IFS	YJH	$(7.228 \pm 0.630) \times 10^{-17}$	1
1.294	0.019	SPHERE/IFS	YJH	$(7.599 \pm 0.668) \times 10^{-17}$	1
1.314	0.019	SPHERE/IFS	YJH	$(7.296 \pm 0.648) \times 10^{-17}$	1
1.333	0.019	SPHERE/IFS	YJH	$(6.046 \pm 0.577) \times 10^{-17}$	1
1.353	0.019	SPHERE/IFS	YJH	$(5.400 \pm 0.649) \times 10^{-17}$	1
1.372	0.019	SPHERE/IFS	YJH	$(5.523 \pm 0.872) \times 10^{-17}$	1
1.391	0.019	SPHERE/IFS	YJH	$(5.875 \pm 0.729) \times 10^{-17}$	1
1.411	0.019	SPHERE/IFS	YJH	$(5.285 \pm 0.550) \times 10^{-17}$	1
1.430	0.019	SPHERE/IFS	YJH	$(4.516 \pm 0.460) \times 10^{-17}$	1
1.449	0.019	SPHERE/IFS	YJH	$(4.768 \pm 0.439) \times 10^{-17}$	1
1.467	0.019	SPHERE/IFS	YJH	$(5.374 \pm 0.484) \times 10^{-17}$	1
1.486	0.019	SPHERE/IFS	YJH	$(5.888 \pm 0.506) \times 10^{-17}$	1
1.504	0.019	SPHERE/IFS	YJH	$(5.927 \pm 0.498) \times 10^{-17}$	1
1.522	0.019	SPHERE/IFS	YJH	$(6.259 \pm 0.519) \times 10^{-17}$	1
1.539	0.019	SPHERE/IFS	YJH	$(6.778 \pm 0.561) \times 10^{-17}$	1
1.556	0.019	SPHERE/IFS	YJH	$(7.318 \pm 0.605) \times 10^{-17}$	1
1.573	0.019	SPHERE/IFS	YJH	$(7.560 \pm 0.624) \times 10^{-17}$	1
1.589	0.019	SPHERE/IFS	YJH	$(8.037 \pm 0.665) \times 10^{-17}$	1
1.605	0.019	SPHERE/IFS	YJH	$(8.497 \pm 0.706) \times 10^{-17}$	1
1.621	0.019	SPHERE/IFS	YJH	$(8.579 \pm 0.715) \times 10^{-17}$	1
1.636	0.019	SPHERE/IFS	YJH	$(9.011 \pm 0.762) \times 10^{-17}$	1
1.593	0.055	SPHERE/IRDIS	H2	$(8.569 \pm 0.383) \times 10^{-17}$	1
1.667	0.056	SPHERE/IRDIS	H3	$(10.129 \pm 0.564) \times 10^{-17}$	1
2.110	0.102	SPHERE/IRDIS	K1	$(7.500 \pm 0.600) \times 10^{-17}$	1
2.251	0.109	SPHERE/IRDIS	K2	$(7.100 \pm 0.600) \times 10^{-17}$	1
3.800	0.620	NACO	L'	$(4.010 \pm 0.542) \times 10^{-17}$	2, 3
4.051	0.020	NACO	NB4.05	$(3.220 \pm 0.780) \times 10^{-17}$	3
4.780	0.590	NACO	M'	$(2.549 \pm 0.820) \times 10^{-17}$	2, 3

References—(1) Chauvin et al. (2017); (2) Cheetham et al. (2019); (3) Stolker et al. (2020b).

NOTE—For the L' and M' -band photometry, we considered the average of the measurements reported in Cheetham et al. (2019) and Stolker et al. (2020b), but kept the largest error bars.