MIRI Coronagraphy of GJ 758 b

Example Science Program #21

This article discusses a high contrast imaging science use case using MIRI coronagraphy.

Introduction

In this science use case, we will observe the brown dwarf companion GJ 758 B, one of the coldest sub-stellar mass companions imaged to date. Ground based near-IR photometry and spectroscopy have confirmed an effective temperature of ~700K, and identified a methane rich atmosphere. Its host, GJ 758, is within close proximity (~19pc) and is a G9 spectral type star. Multi-epoch coronagraphic imaging indicates an edge-on eccentric orbit, with the companion moving towards the star at a projected ~100 mas/year. While cooling-track-derived masses place this object above the deuterium-burning limit, it is an important benchmark since its orbit is favorable for the future determination of its dynamical mass using astrometry or radial velocity. A thorough characterization of its atmospheric properties will provide a key reference point to compare to field substellar objects of similar temperatures. Moreover, understanding its composition will answer fundamental questions regarding the formation of such rare objects (using "metallicity" as a proxy).

The goals of this program are to:

- Characterize the atmosphere of this cool benchmark brown dwarf at long wavelengths.
- Measure effective temperature and atmospheric ammonia absorption.
- Compare to atmospheres of field brown dwarfs and combine with existing shorter wavelength data to retrieve atmospheric properties in detail.

Characterizing The Brown Dwarf GJ 758 b

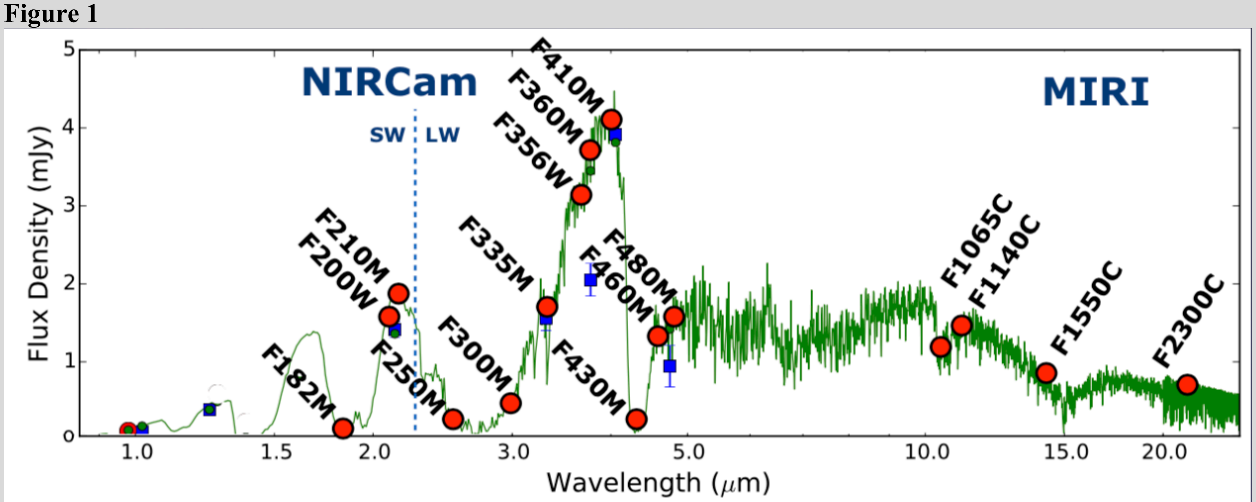
In planning any high-contrast imaging (HCI) investigation with JWST users should follow the steps provided in the JWST High Contrast Imaging Roadmap. The following worked example has been structured in accordance with these planning considerations.

Becoming familiar with the HCI capabilities and instrument-specific modes of JWST

The high-contrast imaging (HCI) capabilities of JWST will enable imaging and characterization of brown dwarfs and other high-contrast scenes at near- and mid-infrared wavelengths. Three of the JWST instruments provide specialized high-contrast imaging modes: MIRI, which offers high-contrast coronagraphic imaging in wavelength bands from 10 to 23 µm; NIRCam, which offers coronagraphic imaging in the wavelength range 2-5 µm; and NIRISS, providing JWST's highest resolution imaging in four filters between 2.8 and 4.8 µm using aperture masking interferometry (AMI). The achievable inner working angles (IWAs) vary with wavelength and type of mask (0.14–0.9" for NIRCam, 0.34–2.2" for MIRI and 0.089–0.15" for NIRISS).

JWST's unique combination of high sensitivity and broad wavelength coverage will make it a powerful platform for studying brown dwarfs. Relative to ground-based facilities, JWST has a dramatically greater raw sensitivity due to its cold temperature and location far above atmospheric and terrestrial thermal emission. The filter compliment of the available HCI modes spans a tremendous amount of richness of spectral features that can be used to characterize the atmospheres brown dwarfs. Figure 1 shows the predicted spectrum of a brown dwarf with the spectral coverage of JWST's NIRCam and MIRI coronagraphic modes annotated.

Figure 1



Showing a model Brown Dwarf spectrum (Teff = 1000 K, log(g) = 3.5 model from Barman et al.), with MIRI and NIRCam spectral features annotated.

Identifying the parameter space

Selecting which instrument to use for a given observational program depends on many parameters, including the characteristics of the target(s), the capabilities of the instruments, and the scientific goals of the observation.

What are the wavelength range(s) of interest for our intended science and how does this influence (or limit) our choice of science instrument(s), mask(s) and filter(s)?

The 1.8 to 23 µm wavelength range available with JWST contains a wealth of spectral features that can be used to characterize the atmospheres of brown dwarfs (*see Figure 1*) and the working wavelength range is determined by the selected bandpass filter. As mentioned earlier, the goal of our investigation is to measure GJ 758 B at long (mid-IR) wavelengths, to complement existing NIR data obtained from the ground; with MIRI, we are able to overcome the limited sensitivity of ground-based observatories and extend its characterization to 11-23 µm. This wavelength range is key for both determining the bolometric luminosity of the cool known exoplanets and for accessing the strongest ammonia bands. In conjunction with shorter wavelength observations, these measurements will enable better constraints on a range of planetary parameters (such as the effective temperature, chemical equilibrium state and gravity).

For cool exoplanet atmospheres, ammonia (NH_3) is the main spectral feature between 5-20 µm. Among its various capabilities, MIRI's coronagraphic mode was specifically conceived to detect the ammonia feature and to measure its intensity; the first 4QPM filter is centered on the ammonia absorption band (at λ = 10.65 µm), while the second filter is strategically placed beside the first to give the level of the continuum. By measuring the adjacent continuum at 11.4 µm and the longer wavelength continuum at 15.5 µm, we can infer a the effective temperature of the planet from the resulting slope. However, since brown dwarfs become very dim and their spectra contain little information beyond 20 µm, we will not attempt observations in the 23 µm filter. By comparing our measurements with field brown dwarf atmospheres, we hope to develop our understanding of the astrophysics behind these objects and support their comprehensive modeling.

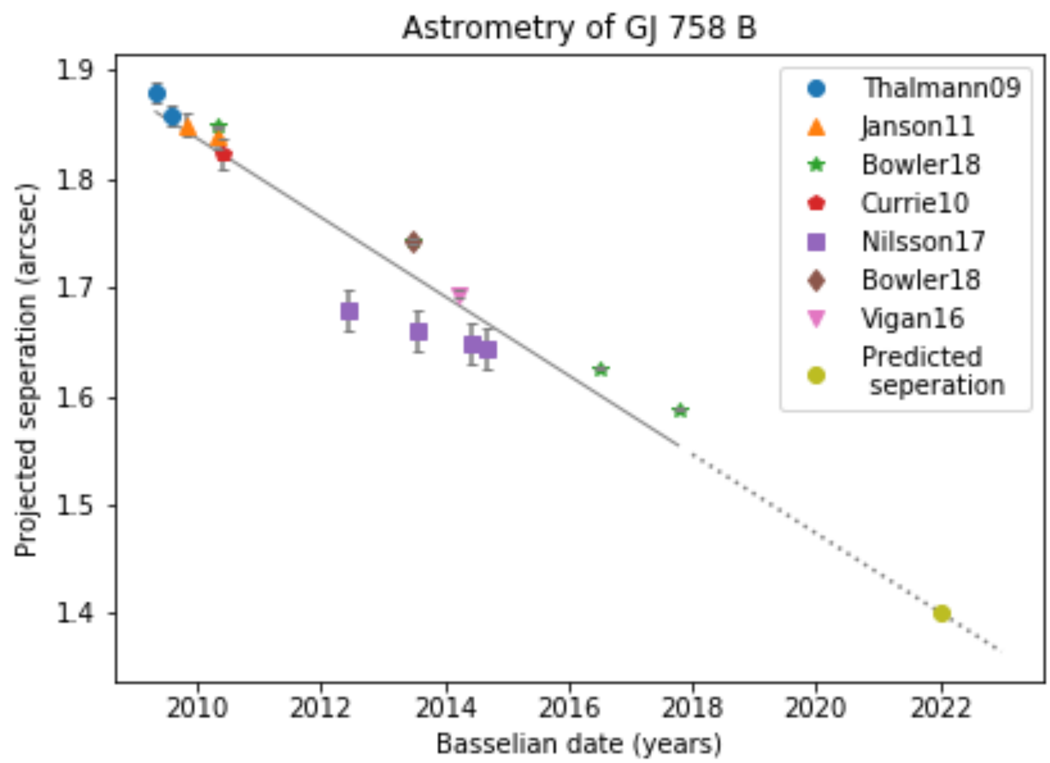
What is the predicted companion contrast at the wavelength(s) of interest?

Using atmospheric models to extrapolate the available NIR data of GJ 758 B to MIRI wavelengths we can infer that the contrast is moderate (~10^{-4} at 10.65 µm), making it a reasonable target to observe given the predicted contrast performance of MIRI.

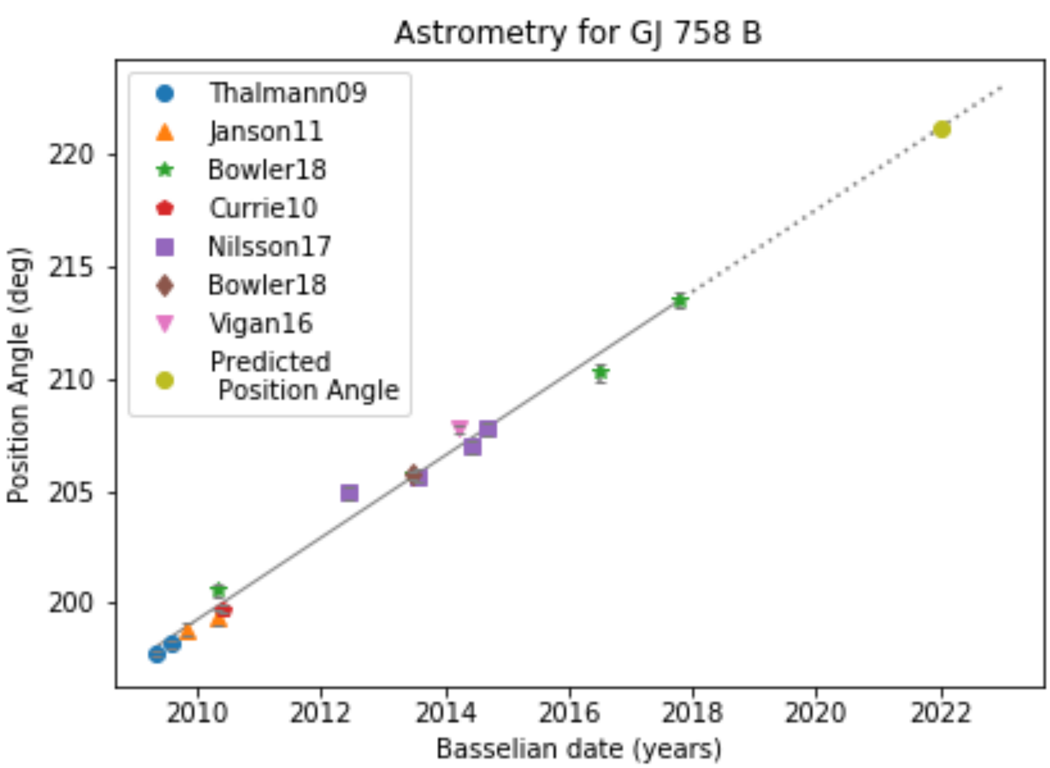
What is the required inner working angle?

One aspect that imposes a challenge on the observation of GJ 758 B is its edge-on orbit, which will move it inward to a projected separation of 1.4" by the time of observation, placing it at the inner-edge of 4QPMs' IWA. This necessitates the need for the highest possible suppression of our target star and motivates our decision to invoke the JWST Small Grid Dither

Technique (allowing us to recover near-optimal contrast in the speckle limited regime around the mask).



Astrometry of GJ 758 B
Projected seperation (arcsec)
1.9
1.8
1.7
1.6
1.5
1.4
2010
2012
2014
2016
2018
2020
2022
Basselian date (years)
Thalmann09
Janson11
Bowler18
Currie10
Nilsson17
Bowler18
Vigan16
Predicted
seperation



Astrometry for GJ 758 B
Position Angle (deg)
220
215
210
205
200
2010
2012
2014
2016
2018
2020
2022
Basselian date (years)
Thalmann09
Janson11
Bowler18
Currie10
Nilsson17
Bowler18
Vigan16
Predicted
Position Angle

Relative astrometry of Gl 758 B. The companion is approaching Gl 758 at a rate of ≈34 mas yr^{-1}. Astrometry are from Thalmann et al. 2009, Janson et al. 2011, Currie et al. 2010, Nilsson et al. 2017 and Bowler et al. 2018. Using a linear fit, we predict a sepsration of ~1.4" and companion PA of ~221º by 2022.

How important is the azimuthal coverage of the occulter in our investigation?

Because it is a known companion, and we are able to make predictions on the position angle of GJ 758 B at the time of observation, we do not require complete azimuthal coverage (as could be offered by the NIRCam round masks, for instance). We will, however, be cognizant of the placement of our companion relative to the boundaries of the 4QPMs, where it signal can become partly attenuated (reducing the sensitivity by up to a factor of 10 in a field of width ~1λ/D along the four edges of the mask).

Stage 3 – Selecting a PSF calibration strategy and suitable PSF calibrator

While the coronagraph suppresses the stellar PSF effectively (resulting in a gain of about 2 orders of magnitude in contrast), the raw contrast remains many orders of magnitude above the fundamental limits set by photon and detector read noise. Typically, stellar PSF photon noise dominates in the inner few arcseconds, then background noise will dominate further out (that background consisting of detector noise, zodiacal light, and observatory thermal emission, with their relative proportions depending on wavelength). PSF subtraction is then needed to improve beyond the raw contrast.

What factors might limit the effectiveness of our PSF calibration and subtraction?

Key factors that may limit the coronagraph performance include ***target acquisition residuals***, ***fundamental photon*** & ***background noise***, and perhaps most challenging, ***wavefront variations*** on multiple timescales.

Any single science observation or PSF reference will have some residual offset, expected to be around 5 mas, 1σper axis, due to imperfect TAs. The 4QPMs are very sensitive to misalignments between science and PSF calibrator observations relative to the coronagraphic spot. To mitigate ***TA residuals***, the Small Grid Dither (SGD) Technique may be used. A SGD pattern assembles a small PSF reference library of with sufficient pointing diversity to encompass the true target positioning. From this basis the KLIP algorithm can be used to generate a synthetic PSF matched precisely to the target pointing. While it can cost more in terms of time to build the dithered reference library, it provides a tremendous gain in contrast (~10x) at the 4QPM coronagraphs' inner working angle.

The coronagraphic contrast is also degraded by wavefront error variations. Changes in the observatory attitude with respect to the sun can cause small thermal deformations, leading to slow changes in the wavefront and thus changes to the point spread function (degrading our ability to calibrate and subtract it). In order to minimize the changes to the PSF between science and PSF reference star observations, they should be scheduled as close in time as possible (ideally back-to-back). Furthermore, observing the science target at two rolls (as specified in the standard coronagraphic sequence) allows for PSF subtraction at nearly the same spacecraft attitude, conserving wavefront stability.

What is our PSF Subtraction Strategy?

For each FQPM filter, we will follow the recommended coronagraphic standard observing sequence: executing two rolls on the science target (i.e a roll-dither) and one observation of the PSF reference star, scheduled together in time (to minimize wavefront errors). Because the companion is moving closer to the star in projected separation, with an expected separation of 1” (~2 λ/D at 15 μm) by 2021, we want to recover the highest possible suppression of the target star the speckle limited regime around the coronagraph. Thus, we will invoke the small grid dither (SGD) technique in each of our observations in combination with the KLIP algorithmto improve the contrast close in to the occulted star.

Stage 4 – Assessing target visibilities and allowed position angles

For our science case, we will use the Coronagraphic Visibility Tool (CVT) to ensure that the requested orientations on the coronagraph mask avoid placing the companion along any FQPM quadrant boundaries and that the desired roll angle is a possibility over the visibility period. (See also: JWST Position Angles, Ranges and Offsets).

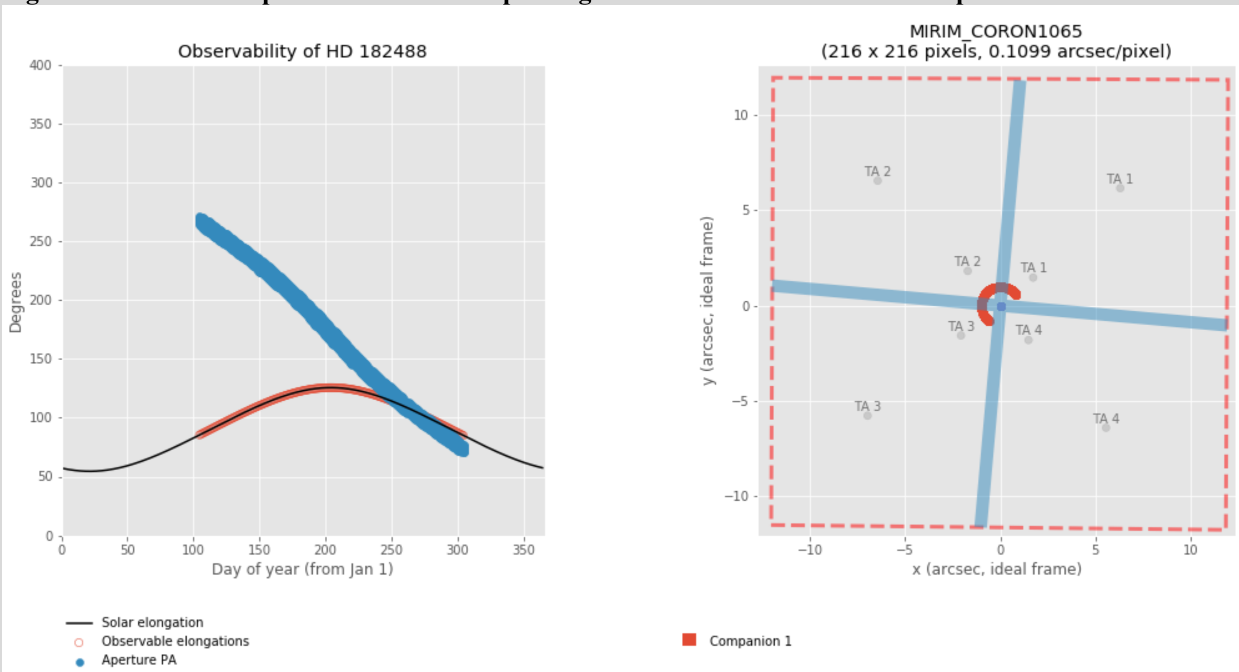
What is our target's ecliptic latitude?

The ecliptic coordinates of are target, GJ 758 are: longnitude, latitude = 300.8658°, 54.4451° (RA, Dec [J2000] = $19^h23^m34.01^s$, +33°13'19.07")

What are the available visibility windows and allowed position angles of our target, versus time?

The companion's PA in the middle of cycle 1 (epoch 2020.0) will be ~222°. Following the CVT step-by-step guide, within the control panel: we resolve GJ 758 with SIMBAD (and cross-reference the SIMBAD ID, RA and Dec) and specify our brown dwarf companion at a PA and separation of 222° and 1.38", respectively. We specify that we'll be using the MIRI instrument with the **MIRIM_CORON1065** mask and ask the CVT to plot the **Aperture PA**.

Figure 1. The CVT output for GJ 578 when plotting the detector location of the companion GJ 758 B



The left plot shows the target's visibility windows. The red highlights on the solar elongation line indicate the valid windows. The blue tracks show the allowed position angles for the selected instrument and mask over those windows. The right plot shows the selected mask's field of view (red dashed line), whereas the shaded blue regions indicate the locations at which the companion could be obscured by the 4QPMs. The plot shows the companion's positions as a function of time within the visibility window(s).

Should we restrict the placement and orientation of our target?

The CVT indicates three scheduling windows (near days 110, 200 and 290 of the year) in which the companion is positioned well away from the boundaries of the 4QPM. These scheduling windows place the companion in three different detector quadrants. We have chosen the middle scheduling window (near day 200 of the year and positioning the target in quadrant 2) because we can achieve a 12° roll there, whereas at the extremes of the visibility period, the achievable roll angle is reduced to ~9°. We will set up the program to use that scheduling opportunity. In particular, this means that we will:

1. Define our range of PA to be between 175°–185° for our first observations in each filter, which positions the companions in quadrant 2 well away from the 4QPM boundaries. This 10° range yields about a 10 day scheduling window.
2. Set our aperture PA offset between the two observations in each filter to the range 11°–12°, which is near the maximum available roll.
3. Because we have decided to use a scheduling window that places the the companion in quadrant 2, we can leave the TA in the default quadrant within the APT (i.e., 1).

How does the JWST background vary over the observability periods?

Click on the thumbnails below to view an enlarged image of the figure.

Stage 5 – Using the Exposure Time Calculator

See the ETC Step-by-Step Guide for MIRI Coronagraphic Imaging of GJ 758 B for instructions on using the Exposure Time Calculator (ETC) for this program.

A pre-defined **Example Science Program Workbook** for this program can be retrieved in the **Available Workbooks** pane of the ETC.

See JWST ETC Using the Sample Workbooks

Stage 6 – Selecting a suitable PSF calibrator

What is our choice of PSF reference star?

Our science target, GJ 758, is a spectral type G9 star with a K magnitude of 4.49 and celestial co-ordinates of RA: $19^h\ 23^m\ 34.01^s$ and Dec +33° 13′ 19.07″

Obtaining matched PSF calibrators is a crucial ingredient to reach high contrast. This directly motivates the JWST standard science policy to require all coronagraphic observations to be paired with at least one PSF calibrator observation. Following the MIRI Coronagraphic Recommended Strategies and steps in the JWST High Contrast Imaging Roadmap, we are looking for a PSF reference calibrator that is: 19 23 + 33 13.

1. Preferably, a ***known*** **good** PSF reference star, observed previously coronagraphically and found to be single.
2. In **closeproximity** to the science target (to ensure **scheduability** and minimal slew time – which in turn minimizes thermal changes to the telescope and thus changes to the PSF)
3. Closely matched in **spectral type** to the science target (which is less critical at MIRI wavelengths because the FQPM filters are relatively narrow, but still good to have)
4. Close **in magnitude** to the science target (to achieve the same signal-to-noise ratio in comparable exposure times)
5. Is **non-binary** (and so will appear optically single at JWST resolution)

Our target is particularly bright and so difficult to match, leaving a small set to choose from. However, we find that **HD 190360 (=GJ 777 A)** will serve as a good reference as it is:

Relatively **nearby** (RA: $20^h\ 03^m\ 37.41^s$Dec: +29° 53′ 48.5″): ~9 degrees separation

from our science target, requiring a small amount of time to slew between them.
It is **schedulable** at the same time as the GJ 758, according to the CVT.

Close in **spectral type** (G7)

0.4 magnitudes **brighter** (K mag = 4.08), allowing for shorter exposure times, which

is helpful in reducing the cost of taking 9 individual PSF observations in a small-grid dithering pattern.
A **known** RV planet host star with extensive observations that rule out (stellar)

binarity.
Non-binary[1].

[1] It does have a suspected co-moving companion red dwarf GJ 777 B, but at a very wide separation that places it outside of the MIRI coronagraphic field of view entirely. We also note that HD 190360 is itself a known exoplanet host star, with a 1.6 MJup planet in a 4AU orbit and is an inner Neptune-mass planet. Neither planet can be spatially resolved by JWST, with projected separations <1 lambda/D at MIRI wavelengths. Furthermore, the estimated age of this star is > 6–7 Gyr, putting the Jovian planet below MIRI's detection floor.)

Step 5 – Designing your observing strategy

What is our observation strategy?

For our overall program, we'll be making observations in the three 4QPM filters: **F1065C**, **F1140C** and **F1550C**. We note that there is a degree of freedom involved in the ordering of activities in programs that constitute of observations of the same target in multiple filters: for our program we will be choosing to sequentially expose in each filter between spacecraft maneuvers (slews and rolls) in order to minimize overheads (according to the optimal efficiency strategy). Note that this re-ordering of visits can (slightly) trade efficiency against temporal proximity of the PSF calibrators and science targets in the same filter (see JWST Coronagraphic Sequences and MIRI Coronagraphic Recommended Strategies).

1. Slew to the target (1800s)
2. Observe Science target in ***F1065C*** (576 s science exposure, total time 2218 s)
3. Observe Science target in ***F1140C*** (576 s science exposure, total time 1935 s)
4. Observe Science target in ***F1550C*** (863 s science exposure, total time 2155 s)
5. Roll observatory ~10°
6. Observe Science target in ***F1065C*** (576 s science exposure, total time 2984 s)
7. Observe Science target in ***F1140C*** (576 s science exposure, total time 1935 s)

8. Observe Science Target in ***F1550C*** (863 s science exposure, total time 2155 s)
9. Slew to PSF star (830 s)
10. Observe PSF star using a SGD in ***F1140C*** (1773 s science exposure, total time 3850 s)
11. Observe PSF star using a SGD in ***F1065C*** (1773 s science exposure, total time 3723 s)
12. Observe PSF star using a SGD in ***F1550C*** (2655 s science exposure, total time 4632 s)

Step 6 – Implementation into the Astronomer's Proposal Tool

See the APT Step-by-Step Guide for MIRI Coronagraphic Imaging of GJ 758 B for instructions on how to implement this program into the Astronomers Proposal Tool (APT).

The associated APT File for this program can be downloaded from the following link:

GJ_758_MIRI_Coronagraphy.aptx

Acknowledgements

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References

Special thanks to the investigators of the JWST program 1413: "MIRI

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