NIRCam and MIRI Coronagraphy of the Beta Pictoris Debris Disk

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Example Science Program #35

This Example Science Program presents an application of the JWST High Contrast Imaging Roadmap, demonstrating how to create a cross-instrument MIRI/NIRCam observing program to observe the Beta Pictoris Debris Disk.

Introduction

Main article: JWST High Contrast Imaging Roadmap
See also: Step-by-step guides

The JWST High Contrast Imaging Roadmap guides readers through the process of designing a high-contrast imaging (HCI) observing program with JWST. Here we demonstrate this process, walking the user through the decisions made at each step, for an example science program that uses the NIRCam and MIRI coronagraphs to observe the Beta Pictoris debris disk.

Science Motivation

The debris disk around Beta Pictoris (Beta Pic) is famous for being the first circumstellar disk to be spatially resolved. Since its discovery in 1984, generations of observations have delivered insights into its complex structure, composition of its constituent particles and physical processes that shape the disk. As one of the brightest and largest disks on the sky, it remains a compelling target for detailed investigations at unprecedented sensitivities with JWST.

The science case we describe here is based on the "Coronagraphy of the Debris Disk Archetype Beta Pictoris" GTO Program. Their goal is to characterize the archetypical debris disk around Beta Pic with deep imaging in multiple filters across JWST's entire wavelength range. Specific objectives include:

- Measure the disk structure, composition and interactions with planets.
- Test for the presence of water and CO_2 ices and organic tholins (such as those on Titan).
- Measure color variations and asymmetries across the disk.
- Probe the thermal emission from both the warm inner belt and outer cooler main disk.
- Obtain a comprehensive legacy dataset on this target, for analysis alongside similar data and/or on other debris disks studied using JWST.

Step-by-Step Guide

Main article: JWST High Contrast Imaging Roadmap

Below we follow the workflow outlined in the JWST High Contrast Imaging Roadmap to design an observing program for this example science case.

Stage 1 – Becoming familiar with the HCI capabilities of JWST

Main article: JWST High-Contrast Imaging
See also: Contrast Considerations for JWST High-Contrast Imaging, JWST High-Contrast Imaging Inner Working Angle

JWST and its suite of instruments, modes and high contrast capabilities will open a dramatic new era in the study of debris disks. JWST offers an unprecedented raw sensitivity, orders of magnitude beyond what can be achieved from the ground, and a wavelength coverage that adds significantly to that covered by the Hubble Space Telescope (HST). JWST will provide resolved scattered light and thermal emission imaging of hundreds of debris disk systems.

Debris disks are circumstellar disks composed of dust created by the collisions of plants and/or minor bodies such as asteroids. They are very faint compared to their central star and so the ability to reject starlight at extreme levels is essential. The high performance coronagraphs on JWST will enable us to resolve many of these disks. There are 5 coronagraphs of different types in NIRCam and 4 in MIRI, collectively usable with various filters spanning 1.8 – 23 μm. This filter complement spans a wealth of spectral features that can be used to characterize the compositions of dust and ice particles present in debris disks.

Stage 2 – Comparing your parameter space to the performance limits and capabilities of the HCI observing modes

Main articles: MIRI Coronagraphic Imaging, NIRCam Coronagraphic Imaging

Achieving the science goals of this program requires multi-wavelength imaging from the near- to mid-infrared of the Beta Pic debris disk with high-spatial resolution. Resolved images at multiple wavelengths are powerful when it comes to characterizing debris disks: images provide independent measurement of the spatial distribution of the dust, while the variation of its brightness with wavelength allows the size distribution and composition of the dust to be constrained (e.g. Debes et al 2008; Rodigas et al 2015). For this observing program, we will employ the NIRCam and MIRI coronagraphs, which cover nearly the full wavelength range of JWST.

NIRCam Coronagraphic Imaging will provide images of Beta Pic at HST-like resolution at near-IR wavelengths, with great sensitivity. We will use NIRCam's F182M, F210M, F250M, F300M, F335M and F444W filters, which are sensitive to the presence of water and CO ices and organic tholins, to study the composition and spatial variation of the disk. We want to use the round coronagraphic masks (MASK210R and MASK445R) to obtain full azimuthal coverage of the disk, allowing us to study the vertical structure. With the F444W filter, we will also be able to search for unknown wide-separation (>10AU) planetary companions, reaching well below the mass of Saturn. We note, the known planet (Beta Pic b) will be at a small projected angular separation from the star at this time, after its near transit in front of the star in 2017—observing Beta Pic B is not a goal of this program.

With MIRI, Coronagraphic imaging at 15.5 and 23 μm will allow us to image faint disk structures close to the star that have been unresolvable until now. We will use the F1550C and F2300C coronagraphic filters to probe the warm inner asteroid belt and cooler outer main disk, respectively. For MIRI, the coronagraphic imaging filters are associated directly with each coronagraph and are not interchangeable—selecting the filter selects the coronagraph.

Stages 3 & 6– Selecting a PSF calibration strategy and reference PSF calibrator

Main article: Selecting Suitable PSF Reference Stars for JWST High-Contrast Imaging
See also: NIRCam Coronagraphic PSF Estimation

In order to draw out the best contrast and achieve the smallest inner working angles of each coronagraph, we will observe a nearby and color- and flux-matched PSF reference source, using contemporaneous and identically executed observation sequences. We will employ the standard coronagraphic sequence for every instrument, mask and filter combination: an initial observation orientated at a desired nominal aperture position angle (i.e. one that maximizes the spatial coverage of the disk); followed by a second observation with an aperture position angle ~10 degrees relative to the first observation; followed by an observation of the PSF reference star. Furthermore, all observations will be linked in a non-interruptible sequence to ensure the PSF calibrator is observed close in time to the science target. Lastly, because of the brightness of Beta Pic, we do not foresee the need to employ the small grid dithering technique.

Beta Pic, is a spectral type A6 star with a K magnitude of 3.48 and celestial co-ordinates of 05 47 -51 03. Following the guidelines provided in Selecting Suitable PSF Reference Stars for JWST High-Contrast Imaging, we are looking for a PSF reference calibrator that is:

- Relatively nearby (to ensure scheduability and minimal slew time – which in turn minimizes thermal changes to the telescope and thus changes to the PSF)
- Closely matched in spectral type (less critical at MIRI wavelengths, because the FQPM filters are relatively narrow, but has a stronger impact for NIRCam as the wavelengths shorten and as the spectral bandwidth widens)
- Close in magnitude (allowing shorter exposure time on PSF star – especially helpful given our choice to use SGDs)
- Is non-binary (and so will appear optically single at JWST resolution)

Successfully used as a PSF calibrator for Beta Pic in many HST observations and a known single star, Alpha Pictoris appears a good candidate as our PSF reference target. It is located ~19° from the target star (at 06 48 11.4516; -61 56 28.8060) and therefore is expected to have an overlapping visibility window with Beta Pic (see Stage 4). The difference in K mag between Alpha Pic (K=2.57) and Beta Pic (K=3.48) is ~0.9. Furthermore, Alpha Pic (A8V) is fairly close in spectral type to Beta Pic (A6V), which provides a more than adequate color match (given previous estimates of the impact of color mismatch on NIRCam coronagraphy contrast) to minimize chromatic differences between the reference PSF and target PSF. For the MIRI observations, color match is even less important.

Stage 4 – Assessing target visibilities and allowed position angles

Main article: JWST Coronagraphic Visibility Tool Help
See also: JWST Position Angles, Ranges, and Offsets, JWST Target Viewing Constraints, JWST General Target Visibility Tool Help

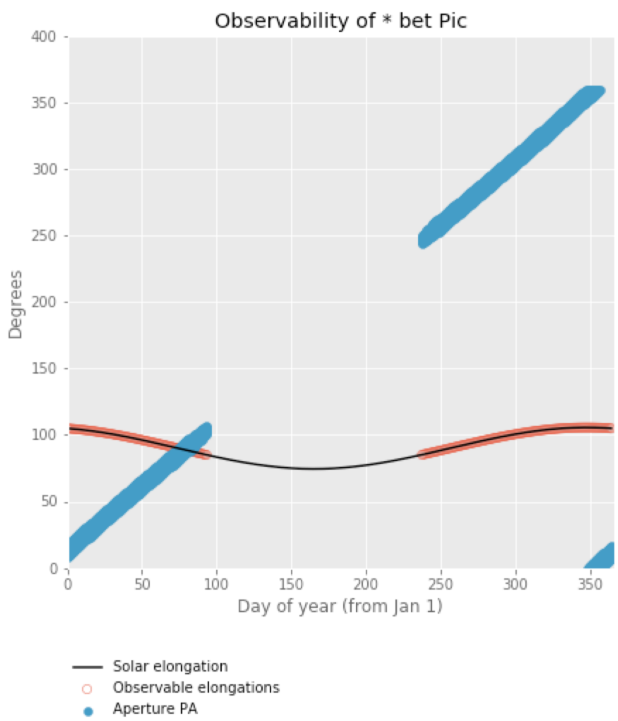
While the Astronomers Proposal Tool (APT) assesses individual observation requests in detail—checking all constraints, links, and guide star availability—it does not provide much "overview" information on a targets visibility versus time, or the position angles (PAs) available. Because coronagraphic observations have additional constraints that go beyond target visibility, such as the placement and orientation of known sources on the coronagraphic masks or offsets between multi-roll observations, it is advantageous to understand the overall scheduability and PA flexibility for a given target prior to performing detailed scheduability checks in the APT. The JWST Coronagraphic Visibility Tool (CVT) is a GUI-based tool developed specifically for pre-planning and strategizing coronagraphic observations with NIRCam and MIRI; in addition to overall target visibility information, the CVT provides information on location of assumed companions relative to instrumental structures—such as occulting bars in NIRCam or boundaries in the MIRI 4QPM coronagraphs—as a function of time, and shows how the instantaneous roll flexibility changes (from approximately ±3.5° to ±7° from nominal) over the visibility period. Indeed, some preplanning may save significant time and possibly wasted effort downstream, in the event that certain desired angles or offsets are not available due to observatory level constraints.

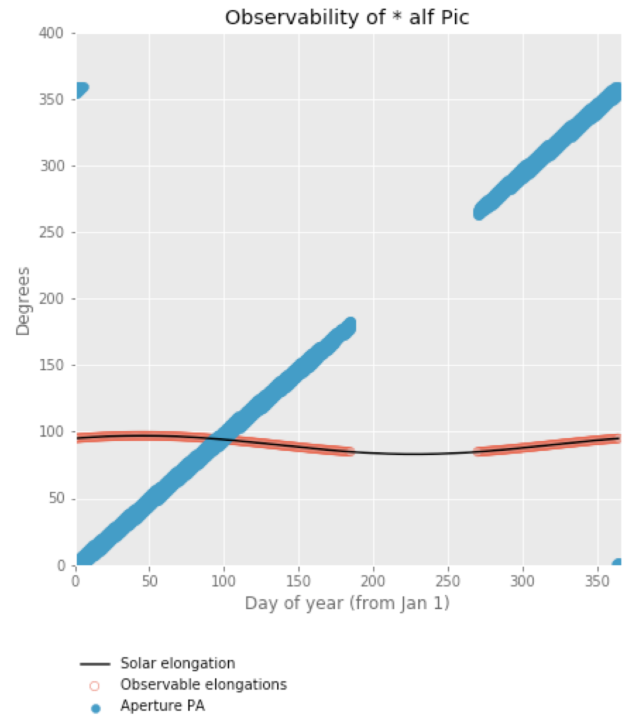
For this example science program, we will use the CVT in the following ways:

1. to check and verify that our target star and PSF reference star are both observable and determine the periods over which their visibility windows overlap.
2. to determine the optimal orientation(s) of the disk on the coronagraphic masks in relation to instrumental obscurations.
3. to determine the ideal roll angles and offsets for our multi-roll observations (supporting our PSF calibration strategy, see Stage 3).

After installing and opening the CVT, we first use the CVT to determine the visibility of Beta Pic (target star) and Alpha Pic (reference PSF star) and determine periods over which the visibility windows of the targets necessarily overlap. In the control panel, we begin by using the **SIMBAD Target Resolver** to generating Beta Pic's **RA**, **Dec** and **Ecliptic coordinates**, and then click **Update Plot** to calculate the target's visibility. The plot generated on the left shows the target's visibility windows, with the red highlights on the solar elongation line indicating the valid windows. Computing the same plot for Alpha Pic, we are then able to determine the periods over which the visibility windows of Alpha and Beta Pic overlap; in doing so, we find that the two visibility periods over which the source's visibility windows overlap: Jan 1st–Apr 4th and Sept 27th–Dec 31st (*see Figure 1*).

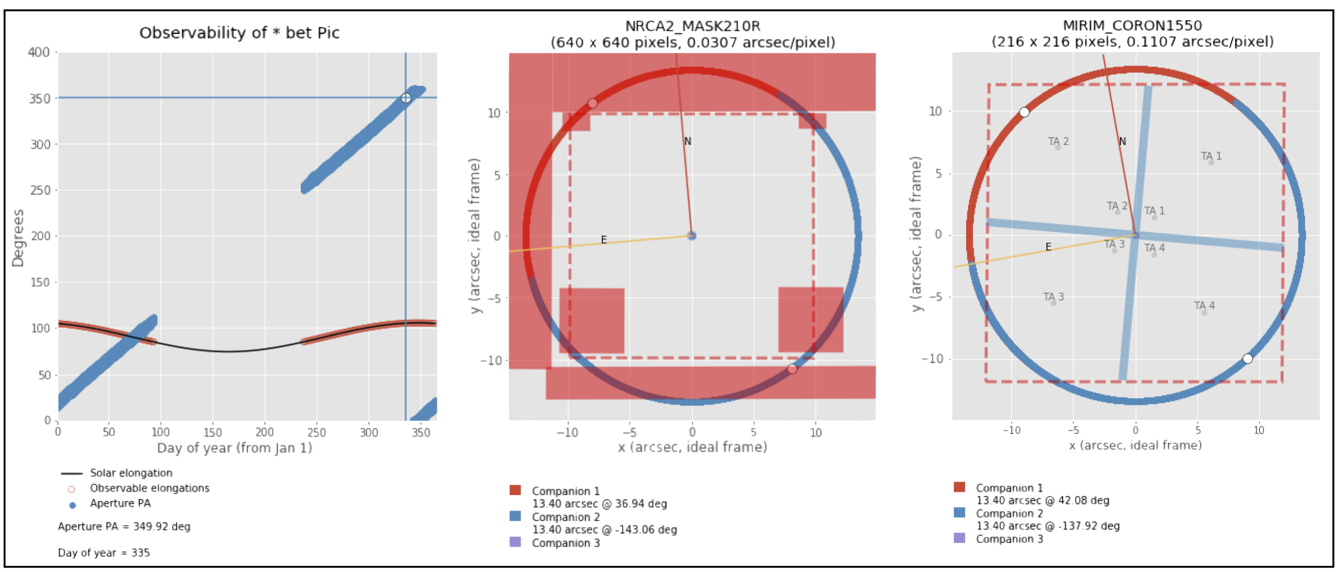
Figure 1. Observability plots of Beta and Alpha Pic produced by the Coronagraph Visibility Tool





Next we will use the CVT to judge the extent of the disk in the coronagraphic fields of view. Beta Pic's mid-plane is at a PA of ~`30°`, with inner and outer radii of ~`1.2`" and `11`", respectively (Apai et al. 2015). The CVT allows the placement of up to 3 companions relative to the primary target, so we define a companion **PA** of `30°` and **Sep** of `1.2`" (to represent the inner radius of the disk); a second companion with a **PA** of `32°` and **Sep** of `11`" (to represent the outer radius of the disk); and a third companion, diametrically opposed to the second, with a **PA** of `210°` and **Sep** of `11`" (representing the other side of the disk). For each of our planned observations, we select the corresponding instrument and mask (*see Figure 2*).

Figure 2. CVT output for Beta Pictoris



Because our observations are split into two separate groups/ sequences, we can chose slightly different orientations for the MIRI and NIRCam observations. Our aim is to determine orients that maximize the spatial coverage of the disk, but that are not coincident with any obscurations in the coronagraphic fields of view.

For the NIRCam observations, because the disk is edge-on, we will chose an orientation that places the disk mid-plane near the diagonal of the NIRCam coronagraph subarray to maximize spatial coverage, but avoid the ND spots. We find that the ideal orientation would be at an aperture position angle (APA) of ~350°, and other orientations would sacrifice some of the science. Consequently, we determine that an APA range of 345°–360° will be suitable for our NIRCam observations.

For MIRI, we will orient the disk at an angle of ~45° from the 4QPM axes, which corresponds to an APA of ~345°. Note that this orientation also avoids the two supporting struts in the mounting bracket of the Lyot coronagraph, which themselves block light in the FOV. We will define a corresponding APA range of 340°–355°.

We note that while we plan to define these specific PA range requirements, they are not completely rigid. In the event of a target acquisition issue or other scheduling problem, we could consider alternative orientations. For the MIRI observations in particular, we only require the disk mid-plane is oriented near ~45 deg from the 4QPM axes-- there are several orientations acceptable, but we can only program one into APT. For NIRCam, the orientation we request is ideal however alternative orientations could be considered if absolutely necessary.

Here's a summary of the corresponding observing restrictions that have determined for our program, using the CVT:

1. We will define an APA Range of 345° to 360° for our NIRCam observations, specifically placing the disk near the diagonal of the coronagraphic subarray, maximizing spatial coverage but avoiding the ND spots.
2. We will define an APA Range of 340° to 355° for the MIRI observations, placing the disk midplane ~45° from the 4QPM axes.
3. The selected orientation of our MIRI observations places the disk in quadrants 2 and 4 of the 4QPM; thus we will specify that TA is performed in quadrant 1.
4. We will adopt a relative roll angle between observations of 10° to 14°.

Stage 5 – Using the Exposure Time Calculator

Main article: JWST Exposure Time Calculator Overview
See also: JWST Coronagraphy in ETC

Once target visibility is confirmed and a PSF calibration strategy adopted, we use the JWST Exposure Time Calculator (ETC) to determine the optimal exposure specifications for our program. Step-by-step ETC calculation instructions can be found in the ETC Step-by-Step Instructions for Beta Pictoris article.

Stage 7 – Deciding on an observing strategy

Main article: JWST Coronagraphic Observation Planning
See also: JWST Coronagraphic Sequences

Now that we have made a series of technical decisions for our program (such as our PSF calibration strategy, exposure specifications, etc.), we now need to identify an observing strategy that incorporates each of these components, whilst also minimizing observing overheads and performance degradation.

We find there are two strategies in which to schedule our set of observations. In the first approach, the observations made in each instrument are scheduled together in a non-interruptible sequence, at the orient in which the spatial coverage of the disk is maximized. Alternatively, by making a slight sacrifice in orientation and requiring that the NIRCam and MIRI observations be scheduled together in one long non-interruptible sequence (with the PSF reference observations placed between them) it is possible to save on overheads. However, this second approach puts very tight restrictions on the schedulability of the observations, resulting in a single two-day scheduling window. This is potentially problematic: if any observation failures were to occur that were not caused by the program itself (e.g., caused by an instrument or telescope operational problem, malfunction or safing event), there would not be another opportunity in which to repeat this sequence of observations within that observing cycle—the program would need to be deferred for at least another year. Thus, we will go with the first scheduling approach. This increases the schedulability of the observations from ~2 days per year to ~2 weeks and allows us slightly more ideal instrument orientations, at the expense of slightly longer overheads. We note that if there is a target acquisition issue or something that prevents scheduling of the observations, there are other possible orientations that are available other than those provided.

The order in which the two sets of observations will be scheduled is as follows:

Table 1. Beta Pictoris observation techniques with NIRCam and MIRI coronagraphs

Observing Beta Pictoris with the NIRCam coronagraphs	Observing Beta Pictoris with the MIRI Coronagraphs:

Observing Beta Pictoris with the NIRCam coronagraphs	**Observing Beta Pictoris with the MIRI Coronagraphs:**
1. ***Slew to PSF reference star*** 2. **Observe PSF reference star with NIRCAM LW filters** 3. **Observe PSF reference star with NIRCAM LW filters** 4. ***Slew to science target*** 5. **Observe science target with NIRCAM SW filters** 6. ***Roll Observatory ~12°*** 7. **Observe science target with NIRCAM SW filters** 8. **Observe science target with NIRCAM LW filters** 9. ***Roll Observatory ~12°*** 10. **Observe science target with NIRCAM LW filters**	1. ***Slew to science target*** 2. **Observe science target with MIRI F2300C** 3. **Observe science target with MIRI F1550C** 4. ***Roll observatory ~12°*** 5. **Observe science target with MIRI F1550C** 6. **Observe science target with MIRI F2300C** 7. ***Slew to PSF reference star*** 8. **Observe PSF reference star with MIRI F2300C** 9. **Observe PSF reference star with MIRI F1550C**

This order was chosen in order to minimize overheads while also minimizing time between reference PSF observations and science target observations.

Stage 8 – Using the Astronomers Proposal Tool

> *Main article: APT Step-by-Step Instructions for Beta Pictoris*
> *See also: JWST Astronomers Proposal Tool Overview*

Once we have completed all other steps in the proposal planning process, we can write, validate and submit our proposal in the JWST Astronomers Proposal Tool Overview (APT). A step-by-step guide for entering this example science program into the APT is provided in the APT Step-by-Step Instructions for Beta Pictoris article.

Links

"Coronagraphy of the Debris Disk Archetype Beta Pictoris" GTO Program

Simbad entry for Beta Pic

References

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