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Time series observations with the Mid-Infrared Instrument (MIRI) on JWST

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ABSTRACT

Time-variable phenomena such as transiting exoplanets will be a major science theme for the James Webb Space Telescope (JWST). For Guaranteed Time and Early Release Science Observations, over 500 hours of JWST time have been allocated to time series observations (TSOs) of transiting exoplanets. Several dedicated observing modes are available in the instrument suite, whose operations are specifically tailored to these challenging observations. MIRI, the only JWST instrument covering the wavelength range longwards of 5 μm on JWST, will offer TSOs in two of its modes: the low resolution spectrometer, and the imager. In this paper we will describe these modes for MIRI, and discuss how they differ operationally from regular (non-TSO) observations. We will show performance estimates based on ground testing and modeling, discuss the most relevant detector effects for high precision (spectro-)photometry, and provide some guidelines for planning MIRI TSOs.

Keywords: JWST, space telescopes, time series, exoplanets, mid-infrared

1. INTRODUCTION

1.1 Time series observations (TSOs)

A wide range of astrophysical sources display time-variable observational characteristics. Observing this variability is necessary for identifying the physical processes at work. Exploration of the time domain is a fast growing research area in astrophysics; numbers of known time-variable sources of all types have increased hugely in recent years due to dedicated large surveys in space and on the ground: the Kepler Space Observatory,¹ WASP,² CoRoT,³ and many more. For JWST too time-variable phenomena will take up a significant fraction of the observatory's mission.

The goal of time series observations is to detect and characterise flux modulations; the metrics of interest are (spectro-)photometric precision, repeatability and stability. These modulations may be very small - of the order of $1:10^4$ or less (≤ 100 parts per million) for transiting exoplanets. The highest achievable precision is to reach the photon noise floor, i.e. where the noise budget of the observation is limited by Poisson noise from source and

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background. This requires a very detailed understanding of the noise sources in the data and their correlations, and careful treatment of the data in analysis. In addition to instrumental noise, confounding noise can arise from the astrophysical source itself, such as stellar flux variability from starspots that can mask variability due to transiting exoplanets.

Experience with the Hubble and Spitzer Space Telescopes - observatories that were designed and built when the field of exoplanet research was virtually non-existent - has given important insights into the calibration and data analysis requirements for these challenging observations. We distinguish between time series observations (TSOs) and targets of opportunity (ToOs): the latter, whilst also presenting as time variable phenomena, require different observational approach from the regularly-occurring, predictable time variability as is displayed by exoplanet host stars, eclipsing binaries, variable stars, amongst others. There may be some overlap between the categories, e.g. some types of supernovae may benefit from time series-type follow-up.

1.2 MIRI: the Mid-Infrared Instrument for JWST

The James Webb Space Telescope (JWST) is a 6.5-m diameter infrared space observatory, under development by NASA, ESA and CSA. The observatory is entering its final stages of assembly, integration and testing. Its suite of 4 science instruments will cover a spectral range from 0.7 to 28 μm with a wide variety of observing modes: imaging, slit and slitless spectroscopy, integral field spectroscopy, coronagraphic imaging and aperture masking interferometry. The Mid-Infrared Instrument, MIRI,^{4,5} is the only instrument to cover the wavelengths beyond 5 μm , providing imaging, coronagraphy and medium resolution integral field spectroscopy from 5-28 μm ($R \sim 1500$ -3500), and low resolution slit and slitless spectroscopy from 5-12 μm (LRS; $R \sim 100$).

MIRI has 3 Si:As Impurity Band Conductor (IBC) detectors, one for the imager module (covering imaging, low resolution spectroscopy and coronagraphy), and two for the short- and long-wavelength channels of the medium resolution spectrometer (MRS). Each detector has a 1024×1024 pixel format with 25 μm pixel pitch. The detectors have 4 columns of “reference pixels” on either side of the detector, giving a total of 1032 columns (see Fig. 1). MIRI is the only instrument that has an active cooler where the detectors operate around 6 Kelvin. This is an extreme cryogenic environment, well below the temperature at which the conductivity of the silicon components freezes out, which presents unique challenges in terms of data reduction and calibration.

In this paper we focus on the capabilities of MIRI for time series observations (TSOs). Two of MIRI’s modes are available for TSOs:

1. low resolution slitless spectroscopy;
2. imaging.

The low-resolution slitless spectroscopy mode is *exclusively* dedicated to TSOs; imaging can be performed for “regular” (non-TSO) observations or TSOs. Low resolution spectroscopy is available for non-TSO observations, in this case the source is positioned in a fixed slit.

1.2.1 Detector readout scheme

The MIRI detectors use the MULTIACCUM readout scheme that is common to all JWST instruments.^{6,7} Pixels can be read out while signal continues to accumulate in a non-destructive way. Each detector read is termed a *group*, and each sequence of up-the-ramp sampled reads between detector resets is an *integration*. In the general MULTIACCUM scheme, a group can consist of multiple frames averaged together. For MIRI however a group contains a single frame only, i.e. the terms *group* and *frame* may be used interchangeably. An *exposure* is defined as a number of sequential integrations carried out within a single command.

Two read modes are available: FAST mode, where each frame (and thus each group) represents a single read of the detector pixels (readout time of 2.77 s), or SLOW mode, where pixels are sampled 8 times to combine into a single frame (read time 23.88 s). The latter will not be available for use with TSOs, and will not be further discussed in this context. Within an integration, the main purpose is to gather as much signal as possible without saturating the detector. The signal-to-noise ratio can be increased by performing multiple integrations within a single exposure, whose signals can be co-added to produce the final image or spectrum. In Section 2.4 we provide specific exposure setup recommendations for TSOs, as these may differ somewhat from the general recommendations captured in the JWST documentation⁸ and in García Marín et al (2018).⁹

2. TIME SERIES OBSERVATIONS WITH JWST AND MIRI

The infrared coverage of JWST is particularly well suited to time series observations of exoplanet host stars and their planet families, via imaging and spectroscopy*. The mid-infrared wavelength regime contains numerous molecular features that will allow us to probe the structure and measure abundances in the atmospheres of transiting exoplanets, such as CO, CO₂, H₂O and CH₄. Contrast ratios between planets and their hosts become more favourable in the mid-infrared, as the stellar spectral energy distribution tails off from its optical/near-IR peak, and the thermal emission from planets peaks at longer infrared wavelengths.

The broad wavelength coverage of JWST avoids the need for stitching spectra from different instruments taken non-simultaneously, which can introduce hard to calibrate noise. For spectroscopy, the broadest instantaneous wavelength coverage with JWST is provided in the near-infrared by the NIRSpec prism mode, and by the MIRI LRS (5-12 μm) in the mid-IR - though several modes are available across the instrumentation suite.

The goal of these observations is to detect flux variations of ≤ 100 ppm. To do so, a detailed understanding of noise sources in both the spacecraft and the instrument over long temporal baselines, and how they combine, is needed.

2.1 JWST spacecraft considerations

The spacecraft itself can be a source of noise in long time series observations. Beichman et al (2014)¹⁰ give a good overview of such noise sources in data from other space observatories, their effect and mitigation strategies. For JWST we identify the following effects:

- Pointing drifts and instability (jitter);
- Jitter arising from the repointing of the high-gain antenna (HGA), on timescales of $\sim 10,000$ seconds;
- Time variability of the thermal background from the different observatory components.

The JWST Documentation system provides the most up-to-date information on the spacecraft's performance in these areas.¹¹⁻¹³ How these noise sources affect the data at the focal plane further depends on instrument properties, such as the sampling of the point spread function (PSF).

2.2 TSO Capabilities of MIRI

In addition to the sources of noise originating in the spacecraft, instrumental systematics contribute to the overall noise budget in the data. For MIRI, the most important sources of noise are inter- and intra-pixel detector gain variations, detector reset effects and response drifts. Dedicated tests and measurements will be carried out during the JWST commissioning period to characterise these effects. In addition, a ground test campaign has been led by NASA JPL; these tests are further described in Section 3.

TSOs with the imager and the low resolution spectrometer have the follow common attributes:

Dithering is disabled. Because of the difficulty of calibrating intra-pixel gain variations and the sensitivity to pointing errors, and the stringent requirements on calibration, the target should be kept fixed in position on the detector, so that the same amount of flux ideally falls on the same pixels throughout the observation.

Target acquisition is highly recommended. A target acquisition procedure is required to place targets at the nominal pointing locations if more accurate placement is required than is possible with the telescope's blind pointing,¹² for example for optimal wavelength calibration. For TSOs this is particularly important where multi-epoch observations are performed for a given target, e.g. multiple exoplanet transits. In such cases the target should be placed onto the same pixels with high accuracy. For MIRI LRS spectroscopy (slitless as well as with slit) the accuracy of the wavelength calibration depends on the placement of the target. With target acquisition, we expect a pointing accuracy of < 0.1 px.

*We note that the coronagraphic modes of JWST will provide direct imaging capability of stellar companions; we do not discuss such observations in this paper.

Subarray name	Size (rows $\times$ columns)	Size (arcsec)	Frame time (s)	F560W Saturation limit (mJy)
FULL	1024 $\times$ 1032	74 $\times$ 113	2.775	4.1
BRIGHTSKY	512 $\times$ 512	56.3 $\times$ 56.3	0.865	13
SUB256	256 $\times$ 256	28.2 $\times$ 28.2	0.300	38
SUB128	128 $\times$ 136	14.1 $\times$ 14.1	0.119	96
SUB64	64 $\times$ 72	7 $\times$ 7	0.085	134

Table 1. Overview of MIRI Imager subarrays, sizes, frame times and saturation limits in the F560W filter. Saturation limits assume an unresolved point sources observed with a 5-group integration, and represents the pixels reaching 70% of their full-well capacity. Saturation is further discussed in Section 2.4.2.

Exposures can extend beyond 10,000 s. Regular JWST exposures are limited to 10,000 s to allow repositioning of the HGA. TSO's, whose exposure duration is driven by the duration of the time-variable event, can expose through the HGA repositioning. This will cause a small pointing disturbance in the data.

Integrations of 2-4 groups are permitted. The minimum recommended integration length for MIRI for optimal calibration consists of 5 groups. As TSO's are mainly concerned with *relative* measurements to a baseline, the calibration difficulties associated with short integrations have a lesser impact for TSOs than observations requiring robust absolute calibration.

We provide here a short description of each MIRI TSO-enabled mode. For a general description of these instrument modes, we refer to Bouchet et al (2015)¹⁴ for the MIRI imager and Kendrew et al (2015)¹⁵ for the MIRI LRS, as well as the JWST Documentation System.

2.2.1 MIRI Time Series Imaging

The MIRI imager covers a maximum field of view of 74 $\times$ 113 arcsec, and offers 9 broadband filters from 5.6 to 25.5 μm . Image quality is diffraction limited in all filters, and with pixel sampling of 0.11 arcsec/pixel the PSF is undersampled only in the shortest-wavelength filter (F560W); from the F770W filter onwards the PSF is Nyquist sampled or better. To increase the dynamic range of the instrument, four smaller subarrays are offered with square field sizes from 56.3 to 7 arcsec on a side; these are listed in Table 1 and their locations are shown in Figure 1.

Time series support for MIRI imaging is not fully implemented in the JWST proposal tools suite at the time of writing. In particular, target acquisition is not yet available, however it is expected to be offered for JWST Cycle 1.

2.2.2 MIRI Time Series Spectroscopy

The LRS default operation modes uses a fixed slit. However a spectrograph slit can exacerbate the effect of pointing drifts or positioning errors, causing differential slit losses over the course of an observation, or between different observation epochs. Therefore, for TSOs a dedicated slitless mode was created for high-precision spectrophotometry. Both LRS modes share a focal plane with the MIRI imager and coronagraphs (see Figure 1).

The MIRI LRS covers a wavelength range of 5-12 μm in a single exposure with a resolving power R of ~ 100 at 7.5 μm . R varies linearly from ~ 40 at 5 μm to ~ 160 at 10 μm . The spectrum is dispersed by a double prism mounted in the filter wheel; the resulting trace falls vertically on the detector with little measurable spatial distortion (Fig. 1). The dispersion relation produced by the prisms contains a folding over of the spectrum around 4.5 μm . Although the throughput of the prisms is low in this region, some flux contamination can occur due to the shorter wavelengths being dispersed back onto the longer region.

Given the brightness of many TSO targets, the dynamic range of the slitless LRS is increased by using a dedicated subarray called SLITLESSPRISM with a read time of 0.159 s, a factor ~ 17 times faster than the full array. As the absence of the slit allows more background radiation to be dispersed into the region of the science spectrum, the LRS is a factor 10 less sensitive in slitless compared with slit mode. Hence the slitless mode is not implemented for general (non-TSO) observing.

TSO's with the Medium Resolution Spectrometer, an integral field unit design, are not currently supported. This facility may become available in later observation cycles.

Figure 1. Diagram of the MIRI Imager focal plane, showing the locations of the imager subarrays, all of which are available for time series imaging. The SLITLESSPRISM subarray is used for high-precision spectrophotometry with slitless low-resolution spectroscopy.

2.3 Performance of MIRI TSO modes

Figure 2 shows the saturation limits of the MIRI Imager and slitless LRS for reference, as well as the limiting fluxes for a SNR of 10 in 10,000 seconds. These numbers were generated with the JWST Exposure Time Calculator (ETC; Pontoppidan et al 2016¹⁶) v. 1.2, and assume the target is an unresolved point source.

The JWST Exposure Time Calculator reports saturation when a pixel reaches 70% of its full well capacity. It should be considered a relatively conservative estimate of when saturation may occur. We provide further guidance on saturation in Section 2.4.2 below.

The imaging saturation limits in the F560W filter (central wavelength $5.6 \mu\text{m}$) are 4.1 mJy and 134 mJy for the FULL and SUB64 array configurations, respectively. Assuming an M5V star with $T \sim 3500 \text{ K}$, this corresponds to limiting K-band magnitudes of 11.7 in FULL array and 7.8 in the SUB64 subarray. For the slitless LRS, a saturation limit of 558 mJy corresponds to a K-band magnitude of 6.4 assuming the same M5V spectral type.

The numbers quoted here and shown in Fig. 2 assume integrations of 5 groups, which is the minimum recommended number for good quality calibration. For TSOs the dynamic range may however be further increased by reducing the number of groups below 5, with the caveat that detector reset effects (see Section 3) will not be fully corrected, which will affect the data quality.

2.4 User recommendations

In this section we provide user recommendations for two important aspects of setting up TSOs with MIRI, which apply to both imaging and spectroscopy mode: setting up the exposure, and how to manage saturation.

2.4.1 Exposure setup

When proposing observations with JWST, users are required to calculate the required exposure time using the JWST ETC. In the Astronomer's Proposal Tool, they are asked to specify how the exposure time should be configured into exposures, integrations and groups, and what readout mode should be selected. Generic recommendations for MIRI are provided in García Marín et al (2018).⁹

Figure 2. Saturation limits (left panel) and sensitivities (right panel) for the MIRI TSO modes, showing the brightest and faintest sources respectively that can be detected with the MIRI TSO modes. The saturation limits assume an integration of 5 groups. Saturation is defined as a pixel reaching 70% of its full well capacity, as is implemented in the JWST Exposure Time Calculator (ETC). For the MIRI Imager, we show the values for the full array and the smallest subarray (SUB64), representing the lowest and highest limits, respectively. The sensitivity values are plotted as the limiting fluxes that can be detected in 10,000 seconds to a signal to noise ratio (S/N) of 10. All numbers were calculated with the ETC v. 1.2.

For TSOs, the duration of an observation is typically determined by the period of the event being observed (e.g. the transit duration) rather than, or in addition to, being driven by SNR requirements. Phase curve observations for transiting exoplanets, for example, may require exposure times of 24 hours or more. We recommend that lengthy observations are performed as single exposures for optimal detector stability and time tracking; the exposure time limit waiver listed above was implemented for this purpose.

The long-duration exposure should be broken down into multiple integrations, with the length of each integration set by a trade off between SNR requirement and saturation management (see Section 2.4.2). In this scheme, each integration represents an individual observation of the source. A dedicated branch of the JWST pipeline is available for TSOs, which returns data products at the level of each individual integration, as well the “standard” reduced image or spectrum with all integrations co-added. For faint targets that are not at risk of saturation, the maximum recommended duration of an integration is approximately 1000 seconds, to avoid excessive cosmic ray hits to the detector.⁹

We note that the JWST ETC calculates an effective overall SNR for a multi-integration exposure, assuming the integrations will be co-added. We recommend that the ETC therefore only be used to estimate the SNR or saturation in a single integration. For more comprehensive SNR simulations for transiting exoplanet science, Batalha et al (2017)¹⁷ developed the PandExo tool[†]. PandExo is a “value-added” application that uses the ETC calculation engine Pandeia¹⁶ to perform more detailed noise calculations and provide exposure setup recommendations.

2.4.2 Managing saturation

Many likely TSO targets are bright, and several of the most interesting exoplanetary systems are at the limit of what is observable in the mid-IR with MIRI. Managing saturation is therefore a major concern for such obser-

[†]<https://pandexo.emac.gsfc.nasa.gov/>

uations. We describe in this section some background on saturation for the MIRI detectors and considerations for users planning time series observations of bright sources.

The JWST ETC currently reports that saturation has occurred when the number of electrons produced in a pixel exceeds 70% of its full well capacity; the 30% margin was included to account for uncertainties in the full throughput of the system prior to launch. An ETC report of saturation does therefore not necessarily mean that the pixels *will* be saturated, however it does signal a risk of data quality being compromised. As the integration approaches saturation, detector artefacts may occur along the rows and columns of the (near-) saturated pixels, which add to the systematics to be accounted for in the data processing and analysis.

Despite this, saturation does not need to be avoided at all costs. For integrations of 5 or more groups, the JWST calibration pipeline disregards the final group because of detector reset effects (see Section 3); if saturation occurs within this final group, this will not affect the resulting data quality. In fact, having some degree of saturation can be beneficial for extracting information from the brightest possible targets. For time series spectroscopy with MIRI, allowing some degree of saturation at the short wavelength end of the spectrum ($\sim 5\ \mu\text{m}$) can still allow unsaturated data to be collected at longer wavelengths, albeit with potential systematics from the row/column artefacts.

The information presented here represents our pre-launch understanding of these effects. Recommendations will be updated as further ground tests are performed, and following commissioning and initial calibration activities. The user should always reference the JWST documentation system and call for proposals documents for up-to-date information.

3. DETECTOR CHARACTERIZATION FOR TSO

To maximise the performance and scientific results from the MIRI detectors the instrument team is engaged in a program of tests with flight spare detectors and flight clone electronics led by NASA JPL. The aim of these tests is to improve our knowledge of the characteristics of the arrays ahead of the mission to improve observation strategies as well as the data reduction pipeline.

TSO science requires a different philosophy in detector testing compared to the other instrument science cases. For example, TSO requires 1 single pointing and exposure; therefore it cannot benefit from the pixel redundancy of dithered data used for other observations. Stability is also hugely important to TSO observations where observations will be taken over several hours or even on the time scale of a day, e.g. the phase curve observations described in Section 4. Therefore, in our test program we have designed tests to monitor stability and sensitivity when configured in a TSO observation-like setting i.e. 1 exposure with many integrations over several hours. Additionally, we have performed TSO-specific tests where we introduce a "transit" by reducing the current through our test source by a very small increment.

From these tests the MIRI team is investigating the following list of TSO specific characterisation issues :

Reset effects: The MIRI detectors have a number of known reset effects⁶ that are corrected in the JWST pipeline. For example the last group of an integration before reset is affected by signal coupled through the reset of the adjacent row pair. Additionally there is an effect known as Reset Switch Charge Decay (RSCD), which is seen as a non-linear hook in the first groups of an integration and is a product of charge injection and clock feed through. These reset effects may present problems for absolute flux calibration. The challenge for TSO science is to understand the magnitude and stability of the effects across long time scales (hours) and plan observation strategies accordingly.

Stability and Response Drift: Drifts in the detector response were seen in the Spitzer mission.¹⁸ These have also been observed in our ground test data with MIRI. Preliminary results show that they are flux-dependent, both in the shape of the drift function and the time scale of the drift. Ongoing work is designed to identify the origin of these drifts and the time scale it takes to reach stability.

Pre-flashing: Spitzer detectors benefited from the technique of "pre-flashing" where slewing to a bright target before the observation improved the stability.¹⁹ This technique is a challenge for JWST, which has longer slew time overheads than the Spitzer telescope. The team is investigating to see if there are benefits and methods to perform pre-flashing that might improve response drifts in TSO observations with MIRI.

Bright targets: TSO does not require absolute flux calibration, which is an advantage for observations of bright objects as it allows observers to make full use of the dynamic range of the detectors and include shorter than the recommended minimum of 5-group integrations in their observations. The team is investigating low numbers of groups specifically for TSO observations, principally to find out when and how the above reset effects dominate over the signal in short-timescale integrations.

Overall, and importantly for TSO science, ground tests indicate that MIRI detector are extremely sensitive and easily match and exceed their design requirements. In particular the detectors show excellent repeatability both across the arrays and from test to test. The detailed results of the MIRI detector tests campaigns are to be published in future work, but it is important to note that the tests have found no unforeseen issues with detector stability or sensitivity.

4. CASE STUDY: A 30-HOUR PHASE CURVE OBSERVATION WITH MIRI LRS

As part of the JWST Early Release Science (ERS) program, the Space Telescope Science Institute approved an allocation of 80 hours of JWST Director's Discretionary Time to the Transiting Exoplanet Community Early Release Science Program (PI: N. Batalha, Co-PIs: J. Bean and K. Stevenson).¹⁸ The program aims to accelerate the acquisition and diffusion of technical expertise for transiting exoplanet observations with JWST, in line with the top-level goals of the ERS program. Given the very specific demands of TSOs on the instruments and data processing and analysis procedures, this campaign will provide important information on how to get the best scientific results from such observations with MIRI.

With MIRI the program will construct a full phase curve of the short-period hot Jupiter WASP-43b by observing the star-planet system for 29.4 hrs with the slitless LRS. The observation will thus record the flux of the star-planet system throughout an entire orbital period. It will begin just before the secondary eclipse and end after the following secondary eclipse, including one primary transit. The scientific goals of the program are:

- Characterize the global climate of the planet, e.g. determine the temperature-pressure profile to 30 K precision and measure the planet's Bond albedo to <1%;
- Constrain the dominant cloud species and particle sizes;
- Retrieve the abundance of several major absorbing species in the planetary atmosphere, e.g. H₂O, CH₄, CO, and measure the abundance variation with longitude.

Simulations of the expected data from WASP-43 in comparison with the expected performance of MIRI are shown in Figure 3, from Bean et al (2018).¹⁸

The observations will form a unique dataset providing insight into a number of technical questions for MIRI. They will allow us to study the hour-to-hour stability of the telescope and MIRI LRS, and the measurement repeatability over day-long timescales, as well as identify drift behaviour (and other systematics) of the detectors, and variability of the thermal backgrounds of telescope over > 24 hours.

From the lessons we expect to learn from these observations, the best practices for TSOs with MIRI will be refined. The ERS team will provide a data analysis toolkit showing worked data analysis examples using the JWST calibration pipeline, and make code contributions to the pipeline based on the hands-on experience with TSO data. These "science enabling products" will be of great value to the exoplanet community and to other research fields requiring long-duration TSOs with JWST and MIRI.

The MIRI phase curve observations are one of six planned observation types in the ERS program, each prototyping TSOs with one of the JWST instrument TSO modes. Description and proposal files of this program are publicly available[‡].

[‡]<https://jwst.stsci.edu/observing-programs/approved-ers-programs>

Figure 3. Simulated dayside and nightside thermal emission spectra for WASP-43b in the wavelength range of MIRI LRS, from a range of General Circulation Models (solid and dashed lines, respectively), compared to simulated MIRI observations (points with 1σ uncertainties). Figure from Bean et al (2018).¹⁸

5. SUMMARY

A significant fraction of JWST observing time will be dedicated to time series observations of transiting exoplanets or similar time-variable targets. As the observatory's only mid-infrared instrument, MIRI is critical for extending such observations beyond $5\text{ }\mu\text{m}$, with time series capabilities for both imaging and low resolution slitless spectroscopy. The possibility exists of extending the TSO capability to MIRI's MRS, to provide time series spectrophotometry with the integral field spectrometer; this will be decided in the interim period to launch. The instrument teams as well as the scientific community are working to get maximum scientific return from these challenging observations. The instrument team is performing specifically-designed ground tests at NASA JPL to understand detector systematics and their stability over long timescales. The exoplanet community has put together an exciting Early Release Science observing program that will measure a full phase curve of the hot Jupiter WASP-43b with MIRI LRS. The ERS observations will return valuable science products and data analysis cookbooks for MIRI TSOs, to complement the commissioning and calibration measurements planned by the instrument team post-launch.

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