The Hunt for Sirius "Ab"

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Using MagAO+Clio2 to learn how to analyze MagAO-X data

The forthcoming MagAO-X instrument design incorporates a vector apodizing phase plate coronagraph (vAPP). The currently operational Clio2 instrument (used with MagAO) incorporates a similar vAPP element (Otten et al., 2017), allowing us a head-start on developing the sort of algorithms and pipelines we will need to analyze MagAO-X vAPP data.

This work made use of data taken at the extreme brightness limit of the vAPP element in Clio2. In 2015, Males and collaborators obtained deep imagery of Sirius (m_V = -1.46). Calibrating this data required modifications to standard data reduction techniques. For example, we had to estimate sky background levels without the luxury of interleaved sky images (due to detector persistence from the bright source).

Additionally, the core of the PSF was saturated, requiring the development of a model that could reproduce the saturated PSF for alignment and estimate the true integrated flux from the unsaturated wings of the PSF.

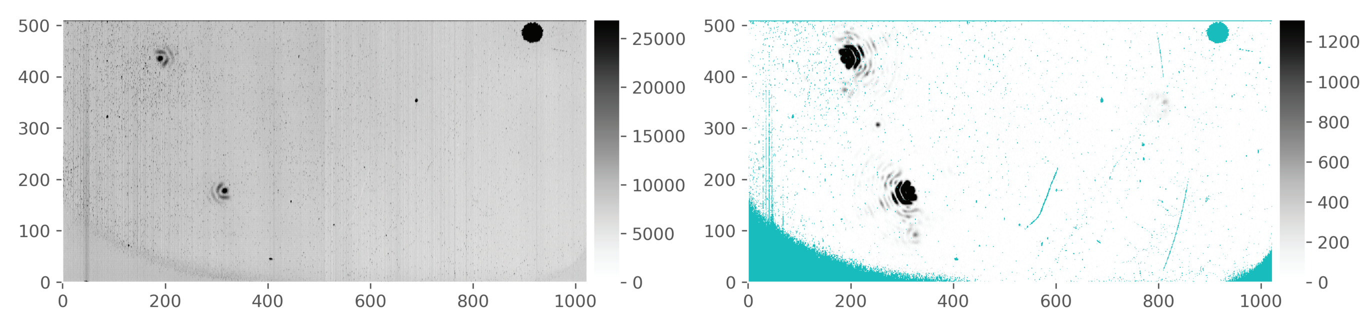

Figure 1: Raw data (left) and calibrated pipeline output (right) from Clio2 + vAPP showing the dual PSF structure with complementary dark holes detailed in Figure 4. (Linear scale from 0 to 99.5%ile.)

The development of software for the analysis of vAPP data also, of course, has scientific applications. The data used for this project represent the deepest images, with the smallest coronagraphic inner working angle, ever taken of Sirius. Since Benest & Duvent (A&A, 1995) asked "Is Sirius a triple star?", attempts have been made to find a companion within the Sirius system motivated by dynamical arguments. Most recently, Thalmann and collaborators observed the system with Subaru IRCS and AO188 (ApJ, 2011). Their search found no companions down to 6–12 M_{jup} and 1"–2" separation, but they were unable to probe masses and separations under these limits—where MagAO and Clio2+vAPP potentially reach—to high completeness in their observations.

Estimating background flux from partial data

Clio2 and MagAO are optimized for operation in the thermal-IR wavelength range, meaning data are subject to a rapidly varying thermal background signal. Observers typically interleave background frames with science frames by "nodding" the telescope to displace the star on the detector (or off of it). Sirius' extreme brightness means background frames taken this way would be compromised by detector persistence, leading us to develop a technique to estimate frame-by-frame background illumination from a PCA basis derived from the set of sky frames (inspired by Hunziker et al. 2018, A&A) taken at longer intervals in the observation sequence.

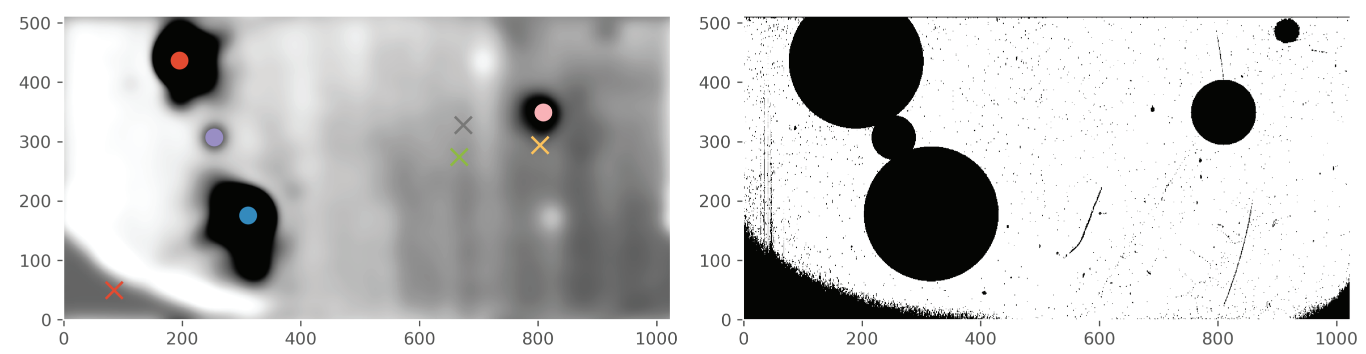

Figure 2: (left) Peak locations on a smoothed image. The calibration pipeline performs coarse peak finding using search boxes around an initial guess. This results in PSF location estimates for left and right nod positions, as well as glints within the instrument that need to be masked. Successfully found peaks are indicated with a circle; fits that did not converge are marked "x". (right) Mask used to estimate background signal. The regions around the science PSFs and any glints are masked out, along with known bad pixels, to get an estimate of the background illumination.

As shown above (Figure 2), estimating the background from regions of the detector without starlight requires knowledge of where the starlight falls. This creates a bit of a circular dependency, which we break by doing an initial rough background subtraction and peak finding with a median sky frame, followed by a PCA-based sky reconstruction using the pixels that are not masked.

The RMS error of the resulting background reconstruction is within tens of counts for sky frames not used in the PCA basis construction, and under 100 counts for the background regions of science exposures. Further refinement of the masking technique and alternative dimensionality reduction algorithms may be able to improve performance further.

The current pipeline (Figure 3) is written with an eye to future cluster parallelization, with current performance bottlenecks being caused by the PCA computation (inherently non-parallelizable). Future work will explore approximate algorithms (e.g. IPCA) to remove this constraint.

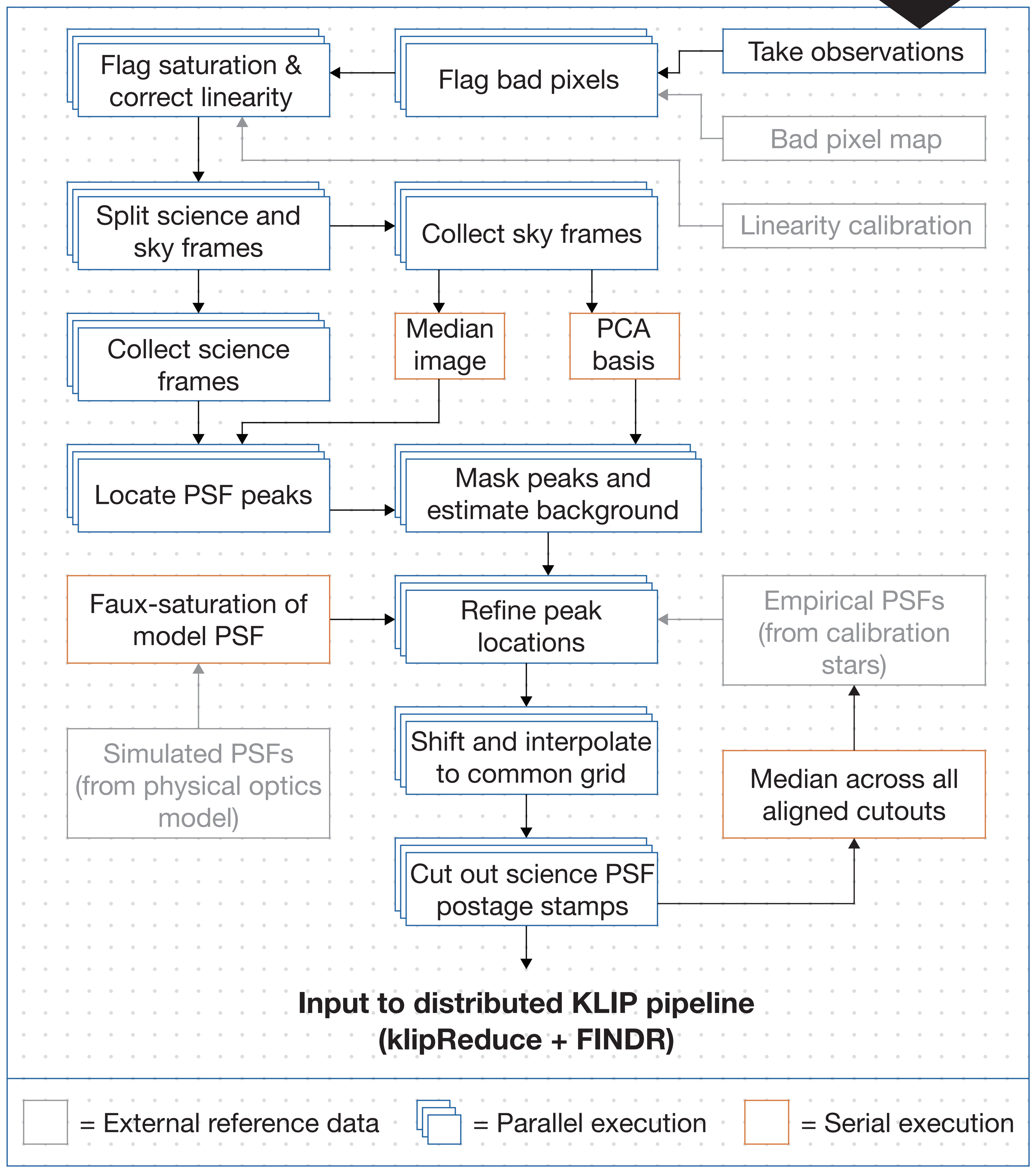

Figure 3: Flow-chart representation of the data reduction pipeline (up to PSF subtraction). "Parallel execution" indicates that the algorithm to perform this task is a so-called "embarrassingly parallel" algorithm that can be distributed over many different computers, so long as the inputs are available. "Serial execution" tasks may be parallelized across multiple cores, but will not scale across multiple nodes easily.

Physical and empirical PSFs

To successfully align the science frames for PSF subtraction and planet-finding, sub-pixel precision locations for the science PSFs are needed. This is accomplished with Fourier transform cross-correlation with a physical optics based simulated PSF, but the code generalizes to empirical models provided as FITS images (Figure 4).

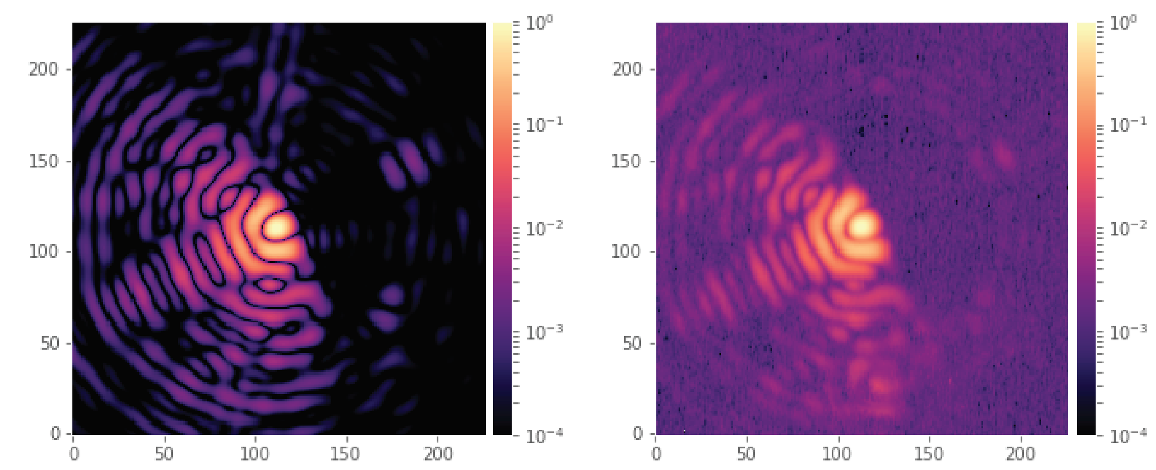

Figure 4: (left) Model PSF computed from vAPP phase pattern design using POPPY. (right) Empirical PSF recovered by shifting and combining HR3188 3.9 micron calibration data.

Acknowledgements

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References

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