Precision interferometry with MIRC-X/MYSTIC for exoplanets

John D. Monnier[a], Tyler Gardner[b], Linling Shuai[a], Emily Rauscher[a], Hayley Beltz[a], Isaac Malsky[a], Jean-Baptiste le Bouquin[c], Gail Schaefer[d], Stefan Kraus[b], Benjamin Setterholm[a], Narsireddy Anugu[d], Theo ten Brummelaar[d], Sorabh Chhabra[b], Isabelle Codron[b], Claire Davies[b], Jacob Ennis[a], Mayra Gutierrez[a], Noura Ibrahim[a], Aaron Labdon[b], Cyprien Lanthermann[d], and Daniel Mortimer[b]

[a]University of Michigan, Ann Arbor, MI USA
[b]University of Exeter, Exeter UK
[c]IPAG, Grenoble, France
[d]CHARA, Georgia State University, GA USA

ABSTRACT

We report progress on Project Prime (PRecision Interferometry with MIRC for Exoplanets) to detect exoplanets using precision closures using MIRC-X and MYSTIC at CHARA. Our investigations include modeling systematics caused by OPD drifts, differential dispersion, beamtrain birefringence, and flatfielding errors. Injection tests suggest we can recover hot Jupiter companions as faint at 1/5000 of the host star brightness with 4 nights of observing and we will present some results of our recent searches for the hot Jupiters. Our upper limits are starting to constrain current-generation Global Circulation Models (GCMs). We propose the addition of modest nulling (10:1) to today's interferometers in order to vastly increase the ease of this work and to open up many more targets for detections.

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1. INTRODUCTION

Exoplanets are difficult to study due to their close proximity to their host star and the large flux ratio between planet and star. Most of what we know about exoplanets are from transit observations where we can measure their sizes (primary transit), their dayside temperatures (secondary eclipse), and often probe their atmospheres (transmission spectroscopy). Most exoplanets do not transit their host star and we develop here a method to directly detect planets throughout their orbit using infrared interferometry.

With the high angular resolution of interferometry, we can resolve separations as small as 1 milliarcecond, thus opening up the possibility of measuring orbit separations, inclinations, and exoplanet spectra as a function of orbital phase. Further, by opening up investigations of non-transiting exoplanets, we can peer into the polar regions of giant planet atmospheres for the first time.

These science goals are challenged by the high contrast between star and planet, with exoplanets >3000× fainter than their host stars even in the best cases. The star not only produces a huge amount of photon noise that hides the faint planet signal, but worse there are subtle systematics in the data that limit the attainable dynamic range in actual observations.

Our team at the University of Michigan has been working toward a definitive first detection of an exoplanet at CHARA for more than a decade.[1] With recent upgrades of the MIRC-X instrument,[2] introduction of the new MYSTIC instrument,[3] and new adaptive optics systems,[4] we have revived this effort[5] and provide a progress report here. A more detailed investigation with full science results will be published elsewhere.

Further author information: (Send correspondence to J.D.M.)
J.D.M.: E-mail: monnier@umich.edu

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2. BASIC IDEA

The primary science driver for the construction of CHARA[6] interferometer was to study binary stars. With over 300meter baselines and operating in the visible and infrared, CHARA has the highest angular resolution in the world, resolving binaries with separations smaller than 1 mas.[7]

We can think of a star+exoplanet as a high contrast binary system from the point of view of CHARA. For a binary star, the interferometer measures a complex visibility $\tilde{\mathcal{V}}$:

$$\tilde{\mathcal{V}} = (1-\alpha)\tilde{\mathcal{V}}_\star + \alpha e^{-2\pi i \vec{u}\cdot\vec{\rho}} \tag{1}$$

where $\tilde{\mathcal{V}}_\star$ is the visibility of the star (accounting for its finite size), α is the flux ratio of planet over star, $\vec{u}$ is the (u,v) coverage which is related to the baseline vector between telescopes divided by the observing wavelength ($\frac{\vec{B}}{\lambda}$), and ρ is the angular separation of the star and planet.

Note that $\tilde{\mathcal{V}}_\star$ is a complex variable with an amplitude and a phase. For typical $\alpha \sim 10^{-4}$, we see that the we expect tiny visibility and phase changes, specifically $\Delta V \sim 10^{-4}$ and $\Delta\Theta \sim 10^{-4}$ radians $= 0.006°$. Such small changes are very difficult to measure in the presence of atmospheric turbulence, but we can measure the closure phase which is independent of atmospheric turbulence.[8]

The closure phase is the sum of 3 phases around a closed triangle in an interferometer.[9] This value is independent of phase delays at each telescope and thus can be a robust observable in spite of terrible turbulence in the optical and infrared. When a binary system is resolved, the typical closure phase values are comparable to α thus presenting a promising method of detecting an exoplanet.

In short, we want to measure precise closure phases for planet-hosting stars to search for deviations from zero that would indicate an exoplanet. For more information on the background of this experiment, see the recent summaries.[1,5]

3. TARGETS

CHARA has excellent angular resolution but only small 1-m telescopes. Thus, we need to seek targets with the most flux and with most favorable planet-to-star contrast.

Table 1 contains a list of known hot Jupiters systems that are resolvable by CHARA. We have so far collected extensive data on υ And, with some data on τ Boo and 51 Peg. We will be summarizing recent results here on υ And.

Table 1. Priority Targets for Hot Jupiter Project PRIME (limited to H mag< 5.5)

Planet Name	R.A.	Dec.	V	H	M_*	R_*	T_*	$M_{pl} \sin i$	Period	Semimajor axis		T^a_{pl}	
			mag	mag	$M_\odot$	$R_\odot$	K	M_{jup}	day	au	mas	K	
υ And b	01 36 48	+41 24 38	4.09	2.957	1.31	1.625	6212	0.69	4.6171	0.060	4.410	1572	
τ Boo b	13 47 17	+17 27 22	4.5	3.546	1.3	1.331	6387	3.9	3.3125	0.048	3.079	1657	
51 Peg b	22 57 27	+20 46 07	5.49	4.234	1.11	1.266	5787	0.468	4.2308	0.053	3.376	1377	(*)
55 Cnc b	08 52 37	+28 20 02	5.95	4.265	0.96	1.15	5235	0.84	14.6513	0.116	9.393	795	
HD 217107 b	22 58 15	-02 23 42	6.16	4.765	1.11	1.08	5704	1.40	7.1269	0.075	3.780	1044	
HD 179949 b	19 15 33	-24 10 45	6.25	5.101	1.18	1.19	6170	0.90	3.0925	0.045	1.633	1530	
HD 185269 b	19 37 12	+28 30 00	6.67	5.4	1.28	1.88	5980	0.94	6.838	0.077	1.532	1425	

Reference: The Extrasolar Planets Encyclopaedia: http://exoplanet.eu; SIMBAD; the Exoplanet Orbit Database at exoplanets.org;;[10,11]

(a) Equilibrium temperature of the planet, assuming zero albedo and full heat redistribution: $T_p = T_*(1-A_B)^{\frac{1}{4}}\sqrt{\frac{R_*}{2a}}$, where A_B is the bond albedo ($A_B = 0$), a is the semi-major axis of the planet[12]

4. METHODOLOGY

When we observe a hot Jupiter system at CHARA, we request 4 or 5 nights which is comparable to the typical orbital periods for hot Jupiters. In order to maximize the time on source, we generally only observe one calibrator per night and spend as much time as possible on target. Since the planet is so faint compared to star, we can use the target itself as calibrator and attempt to model slow changes in closure phases due to instrumental effects using target data itself.

These long data sets have let us explore how closure phases can be affected by spectral resolution, changes in the linear polarization through the CHARA system, differential air path in delay lines, and fringe tracking errors. We also investigated fringe crosstalk between baselines.

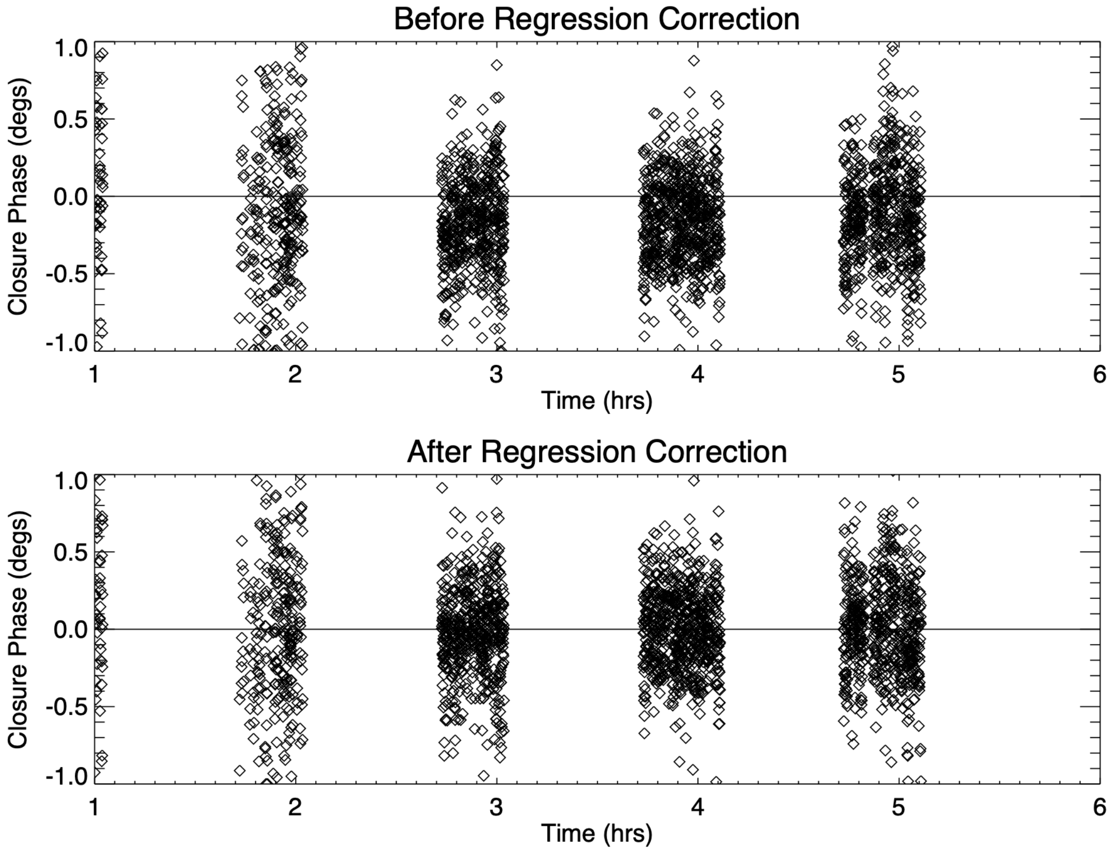

Figure 1. Here we show one particular closure phase measured υ And during a night of observing. We see the raw values (top panel) are systematically non-zero with some drifts through night. When apply a simple regression model using the fringe tracking information and the measured differential dispersion, we improve our calibration (bottom panel). More advanced machine learning algorithms are also being explored.

Figure 1 shows an example of raw closure phases before and after applying a regression to remove drifts correlated with tracking errors, differential dispersion, flux variations, and parallactic angle changes.

Once we have removed systematic trends, we search for the exoplanet by fitting a full orbit to the multi-night data set. We generally fix the period, eccentricity, ω, and time of periastron from the known radial velocity orbit. We then carry-out an extensive grid search in Ω, inclination, and constant flux ratio.

We recognize the flux ratio will change as a function of wavelength and phase but expect that this first search will be sensitive to the correct orbit parameters. With sufficient signal-to-noise ratio, we could then add more parameters to our fit, such as a phase curve variation and wavelength dependence.

We also carry out injection tests to set our upper limits. We can add the expected closure phases for a candidate set of orbital parameters and flux ratios, and then verify if we can recover the planet.

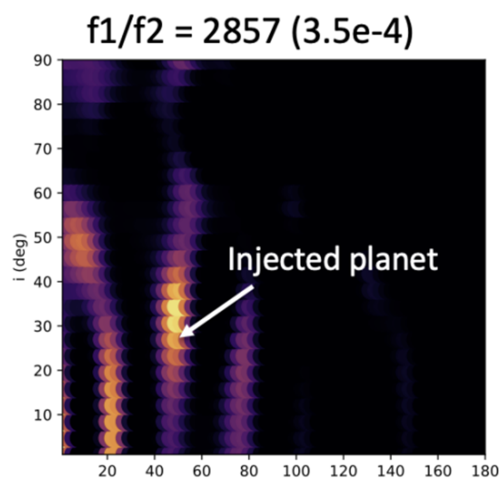

Figure 2. We inject artificial planets to determine upper limits. Here we show and example for 2900:1 contrast where we easily recover thet planet using MYSTIC.

Figure 2 shows an example of grid search with an injected planet marked.

5. RECENT OBSERVATIONS

In 2019 and 2021, the team (led by Tyler Gardner) conducted observations that yielded possible detections in the H-band with a contrast ratio of approximately 5000:1. The two separate detections agreed on the flux ratio, Ω, inclination, and semi-major axis. Intuitively, this felt like a strong and meaningful detection, however we held off publishing as we were not able to recover the planet using the newly-commissioned K-band instrument MYSTIC which was used in the 2021 observing run. Figure 3 shows the promising preliminary detections in 2019 and 2021.

In order to quiet our remaining doubts, we sought confirming data of our 2019 and 2021 detections. The most recent data from October 2023 did not show detections above the 5000:1 contrast limit in either the H or K-band. This outcome suggests that the previous tentative detections might have been false positives, highlighting the challenges in achieving reliable detections as such deep constrasts.

In any event, our injection tests show that our data are constraining models of υ Andromeda. Figure 4 show a recent set of model spectra from a global circulation model (GCM) from the Rauscher group, compared with our current contrast limits. Our K-band limits seem to challenge this class of models and work is on-going to verify.

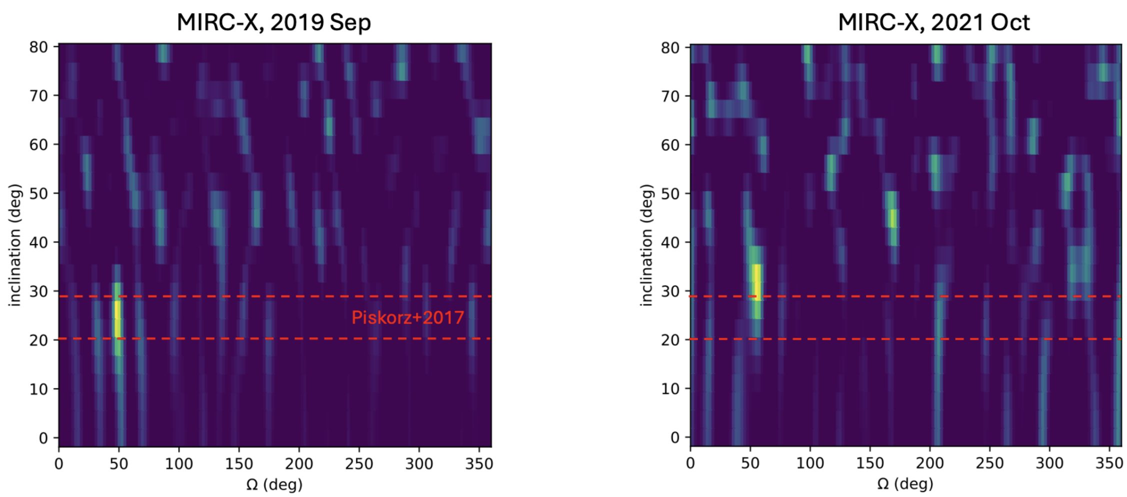

Figure 3. Here we see the result of a grid search where a promising candidate comes up with $\Omega \sim 50^\circ$ and inclination $\sim 28^\circ$, while agreeing on the correct semi-major axis (not shown). Using this preliminary analysis, we are not sure sure if this is a real detection or false positive yet. More statistical analysis is underway.

6. CONCLUSIONS

While the direct detection of hot Jupiters remains elusive, project PRIME has made significant progress in pushing the limits of contrast sensitivity and challenging existing GCM models. Based on models, we seem close to reporting reliable detections.

Directions we are taking to continue improvements:

- Apply novel machine learning methods to correct for systematics
- Explore new integrated optics combiners available on MIRC-X and MYSTIC that may prove more robust to systematics

- Observe other exoplanets beyond υ And b, that may prove to have better contrast, especially τ Boo b
- Expand PRIME beyond CHARA to the VLTI. The new 200m baseline will make this practical.
- Seek facility improvements at CHARA to increase throughput, such as improved adaptive optics systems and better live centroid tracking to keep starlight focused on fiber for longer dwell periods.
- Polarization modeling of the system is underway to eliminate birefringence effects from our systematics budget.
- Develop nulling instrumentation for CHARA to boost the contrast. Even a crude 10:1 nuller would vastly boost the SNR and make detections possible with only hours of integration instead of days.

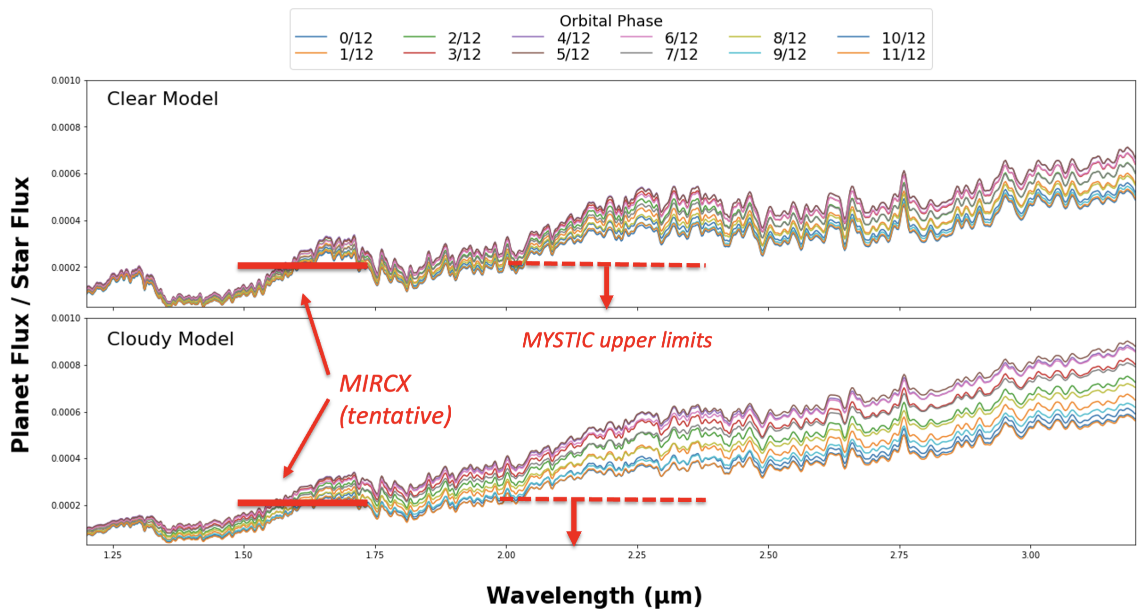

Figure 4. Here we see a recent GCM model calculation specifically for υ And, with the tentative upper limits / marginal detections from our current CHARA interferometer program.

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