From Hot Jupiters to Habitable Planets: Optimizing Atmospheric Characterization Methods

Cam Buzard, Danielle Piskorz, Björn Benneke, and Geoff Blake

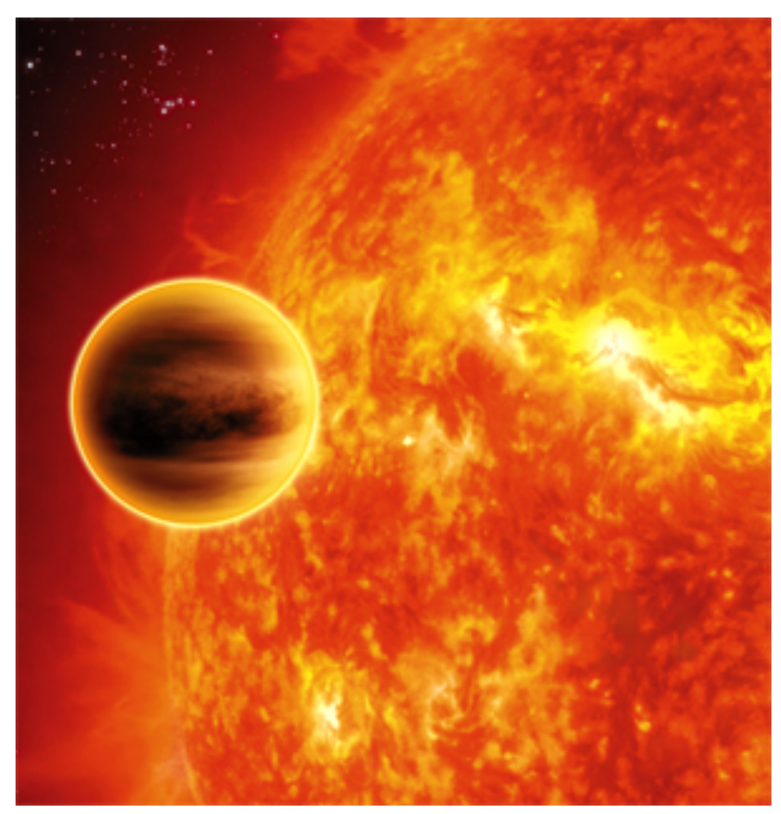
Abstract

A big question in the search for life elsewhere in the universe asks *where* to look. Since the first exoplanet orbiting a main sequence star was discovered in 1995, a new era of astrobiological research begun. If life can exist on Earth, chances are that it can exist on another planet orbiting another star. With astronomers now estimating that every star in the galaxy has at least one bound planet, the possibilities are endless. How we can actually study these potentially habitable, if not inhabited, planets, however, is a distinct and challenging task that our research hopes to address. We are working to optimize an observational pipeline that is currently used to detect molecules in and characterize the atmospheres of hot Jupiters. In combination with the much higher resolution spectroscopy provided by the next generation of telescopes (Keck-NIRSPEC2.0, LUVOIR), our method will be able to characterize the much fainter Earth-like planets around other stars, many of which will be discovered by the TESS mission, scheduled to launch in 2018.

Hot Jupiters: First step to habitable planets

- Gas giant planets that orbit their host stars at extremely close orbital distances–within the orbit of Mercury in our solar system
- Planet-to-star contrast:
  - Hot Jupiters ~ 10^{-6}
  - Earth-like planets around Sun-like stars ~ 10^{-10}

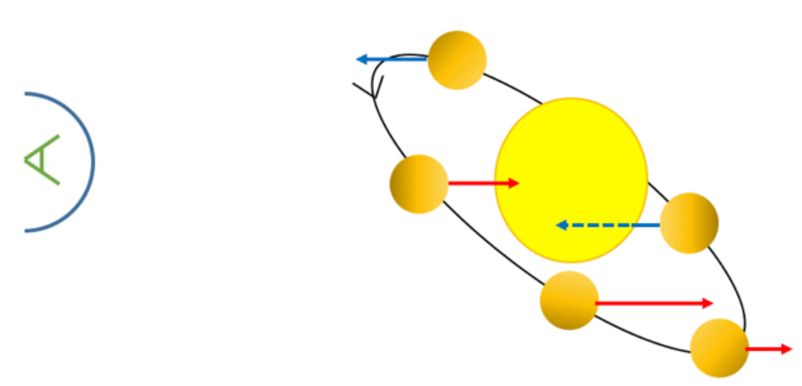
We can therefore optimize techniques for characterizing hot Jupiter atmospheres to be able to characterize atmospheres of potentially habitable planets.



Characterization Technique: Direct Detection Method

Basic steps:

- Obtain spectra with the planet at multiple orbital locations
- Subtract out features from the Earth's atmosphere (telluric lines), so only signals from the planet and the star are left
- Use cross correlation to separate planet and star signal and detect molecules in the planet's atmosphere (e.g. Piskorz et al. 2016; Lockwood et al. 2014)!



Doppler shifting of nontransiting hot Jupiter spectrum at different orbital locations.

Benefits of the direct detection technique:

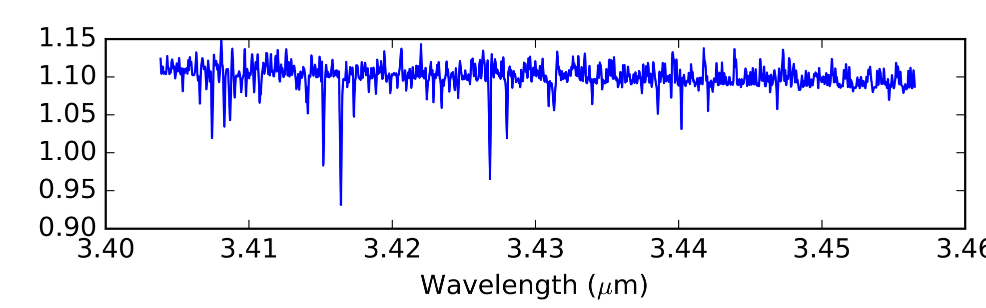
- Can detect spectra of *nontransiting* exoplanets. This will be critical for characterizing habitable zone planets because statistically, far more planets do not transit their host stars as viewed from Earth, than do.
- *Multi-epoch* data also allows us to look at planets further out from their stars. With multiple Doppler shifted spectra, it's easier to get full planet spectra without features obscured by either stellar or telluric lines.

Pushing the limits: Habitable Planets, Here we come!

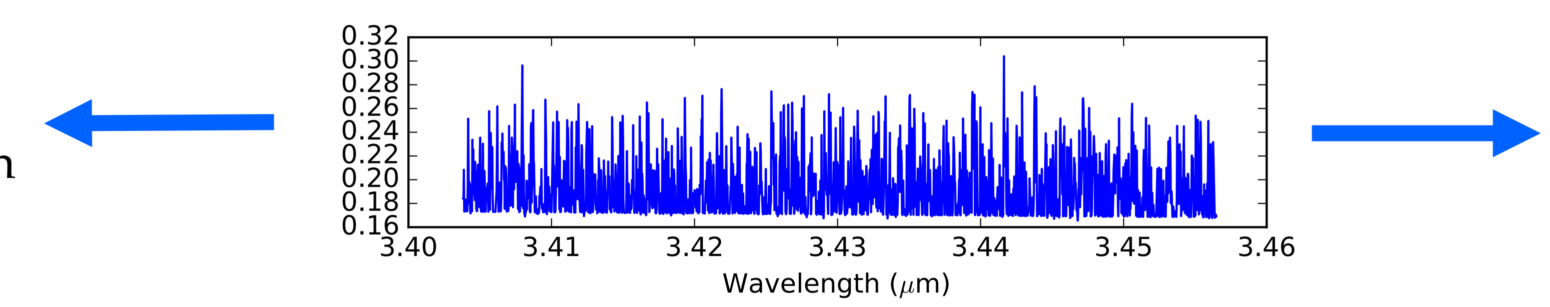
What to optimize…

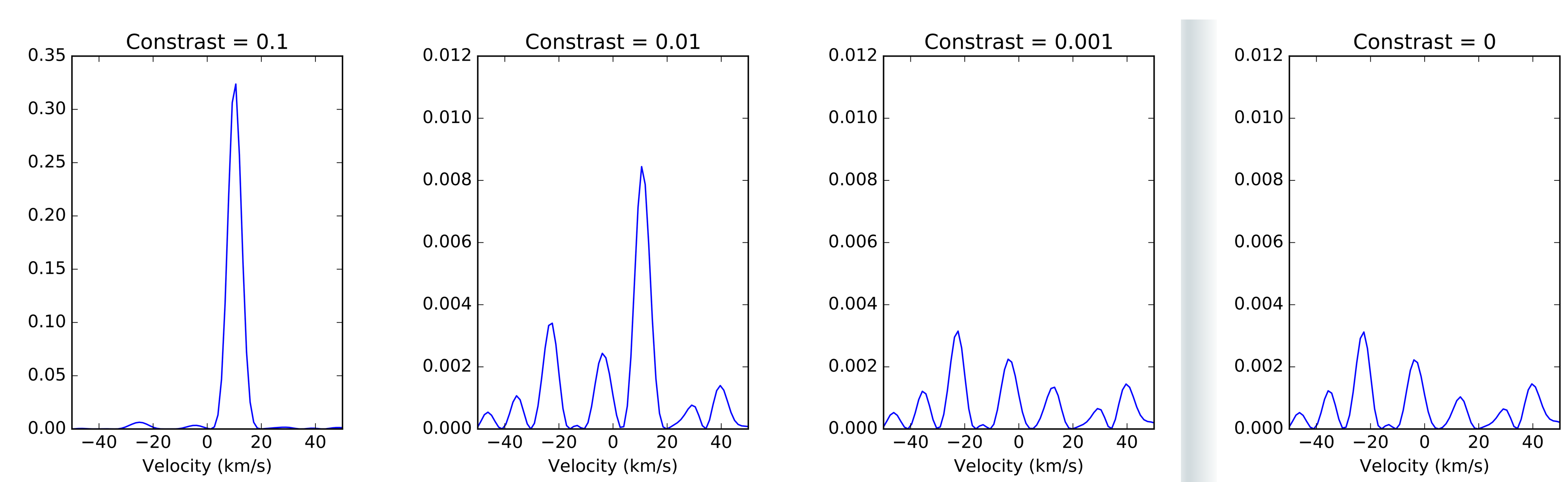
Our spectra are from the Near-Infrared Spectrometer (NIRSPEC) on Keck. In order to perfectly isolate planet spectra, we need to find wavelength regions with **small unintended star/planet cross correlation.** We start by testing the cross correlation of model spectra to see when unintended correlation between spectrum of the star and the planet will be larger than intended correlation.

Model of "real" spectrum:
Stellar spectrum + Planet spectrum at 10 km/s Doppler shift and contrast of 0.01



Model of planet spectrum:
Shift and cross correlate with "real" spectrum





At high enough contrast, cross correlation can easily find the planet signal in the "real" spectrum.

10^{-6} Contrast: Typical Hot Jupiter Contrast

0 Contrast: All correlation is unintended

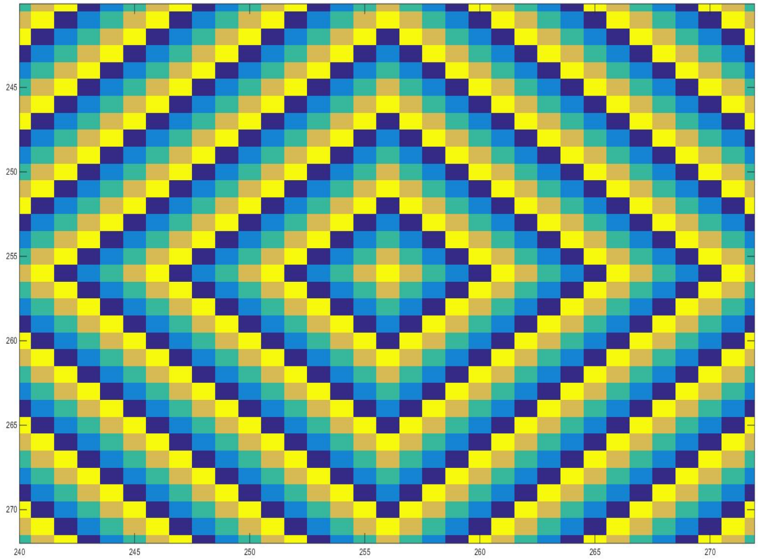
10^{-10} Contrast: Typical Earth-size planet

Future work

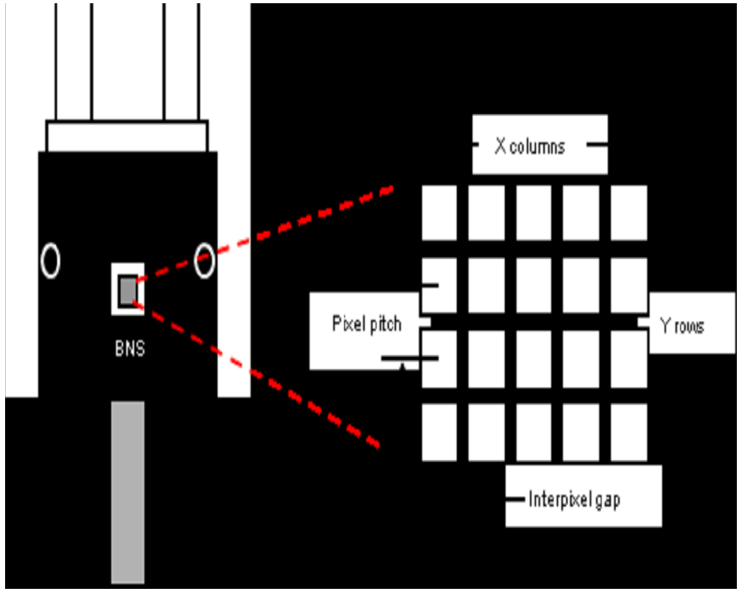
- Find wavelength regions where unintended star/planet correlation is minimized. Moving to longer wavelengths (obtainable by TMT/ELT or a large aperature space telescope such as LUVOIR or the OST) will also optimize planet/star contrast for habitable planets.
- Investigate methods to remove stellar signal from data, so planet signal is retrievable down to lower contrasts

Development of a Pyramid Wavefront Sensor Using a Spatial Light Modulator

Robert Broadfoot, Deqing Ren - California State University, Northridge

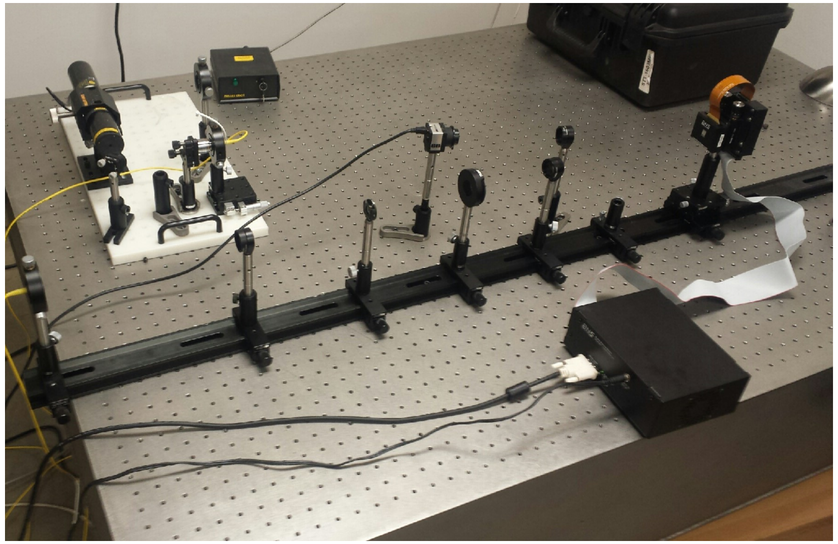


- Research focuses on replacing pyramid prism and mechanical component with a Spatial Light Modulator (SLM)
- Each different color on the phase map represents a voltage that will be addressed to the SLM



- The voltages cause the pixel to deform into the desired shape.
- Due to the fast response time of the SLM, the shape of the phase map can be quickly altered to simulate the prism vibrating

- Instead of transmitting through a prism, the source reflects off of the surface of the SLM to the CCD camera



Distinguishing the Effects of Photoelectric Instability from Embedded Planets in Debris Disks

Areli Castrejon[1], Wladimir Lyra[1,2]

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Introduction

- Debris disks are structures formed of gas and dust around other star systems. They are the extrasolar analogies of our own Kuiper and asteroid belt. They are the remnants of planet formation around other stars. Their usual radius is between 10 to 100 AU in diameter. They are optically thin and emit radiation in the infrared. Advances in imaging thanks to ALMA and others have allowed for more detailed images of these disks. The more structure we see in disks, the more claims there are that there are planets in these systems.

Objectives

- Many of these disks show structures such as rings, arcs, and gaps. These structures are interpreted to be the effects of one or more perturbers within the system. In our research, we try to show that while planets are the more extravagant solution, there are also other mechanisms at work within these disks that can cause the same structures. We do simulations involving Photoelectric Instabilities (PEI) alongside embedded planets to show the effects of each and how we could be able to tell the two apart.

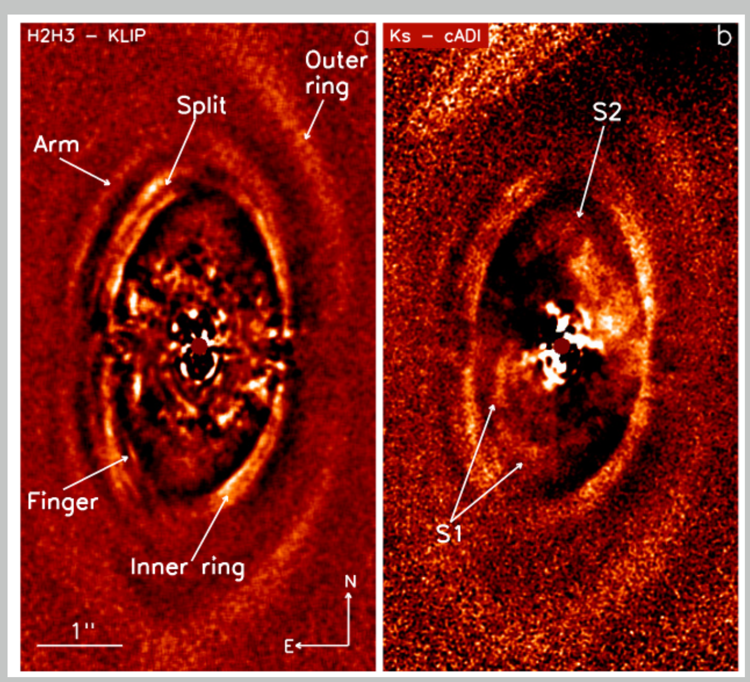

Figure 1: Rings and gaps in HD 141569

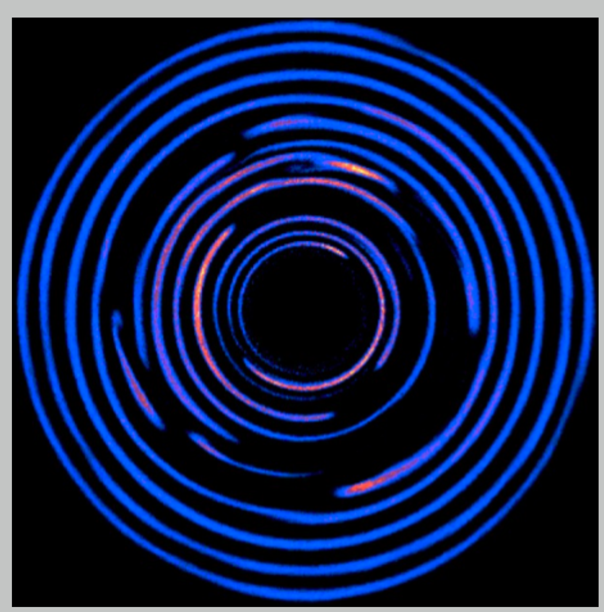

Figure 2: Simulations from PEI, Lyra and Kuchner 2013

Methods

- We do our global disk simulations in two dimensions. These are done using The **Pencil Code**, a magnetohydrodynamic code, referenced in over 400 papers. We start with a stationary star, and the disk rotates around the star. 200,000 Keplerian particles at inserted at random to simulate the dust in the disk. The disk is assumed to have a dust to gas ratio of unity. Planets of both a Jupiter and Neptune mass are added, depending on the run being conducted. The disk is assumed to be isothermal, meaning it is in radiative equilibrium. The grid size resolution is 528 x 528. The

Mathematical Section

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$$\mathbf{X} \rightarrow \mathbf{r}(\mathbf{X}) = \arg\max_{c} \left\{ \max_{n} \left\{ \sum_{x_i \in \mathbf{X}} \delta(\mathbf{x_i}, \mathbf{Y_{n,c}}) \right\} \right\}$$

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Results: Global Disk Plots:Top(Neptune) Bottom(Jupiter)

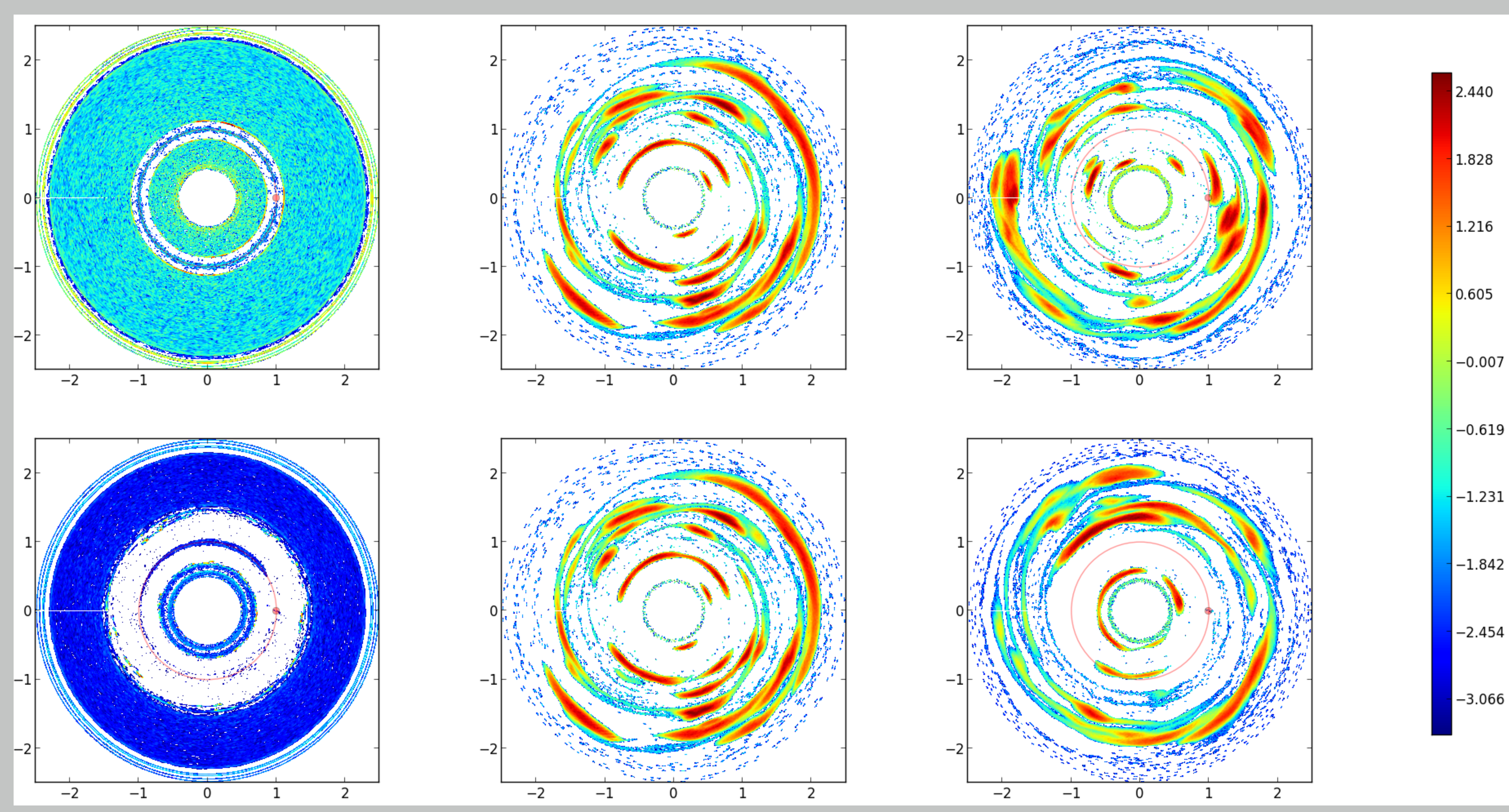

Figure 3: Comparison of PEI and planets

Results: Density Profiles (Neptune) Right(Jupiter)

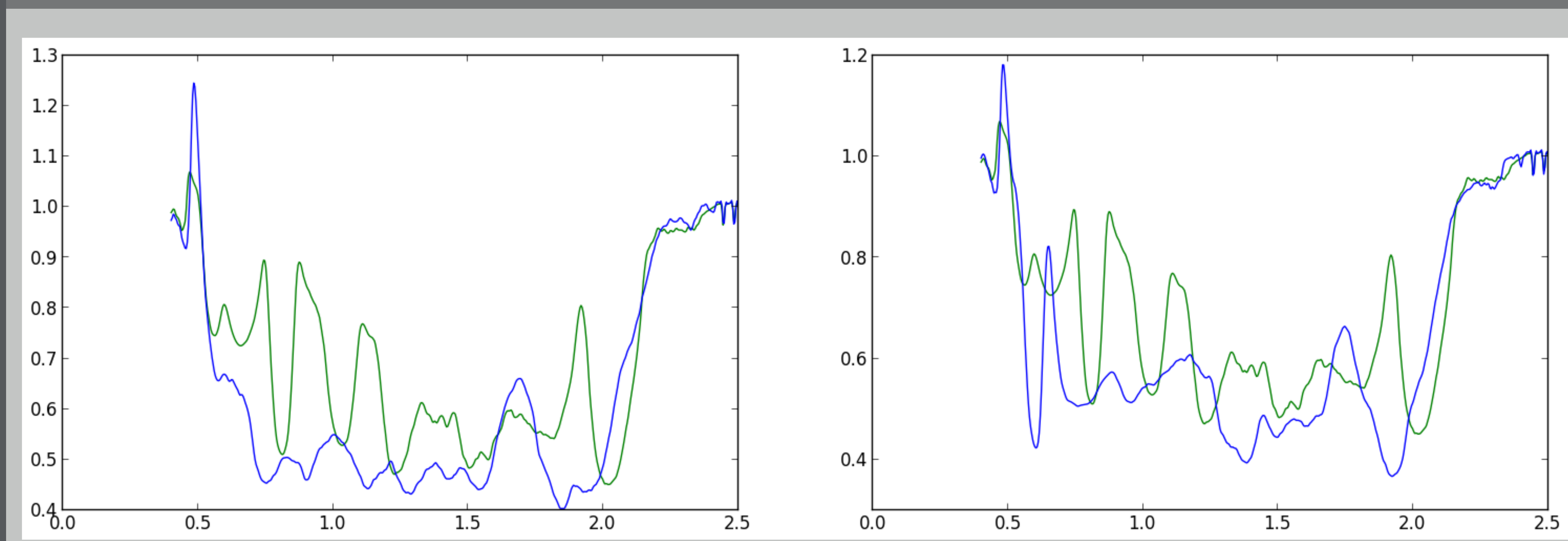

Figure 4: Comparison of gas profiles

Conclusion

- Comparing the effects of PEI on a disk, versus the effects of a Neptune-mass planet along with PEI, we see no discernable differences in the shape of the arcs, or a noticeable gap where the planet orbits.
- The effects of a Jupiter-sized planet are evident on the plot for the dust. We see a huge gap being carved out at 1, which is were the planet is located.
- If we look at the density profiles that belong to a neptune planet, we see that the PEI in green has higher densities than the PEI and planet simulation.
- When looking at the Jupiter density profiles in the gas, we see that the change in the densities is much more pronounced. On average the dust density is lower because some of the gas has been accrued onto the planet, leaving the disk wit less gas.

References

- Lyra, W.: Kuchner, M. (2013) Formation of sharp eccentric rings in debris disks with gas but without planets. Nature 499, 18.
- De Val-Borro et al. (2006) A comparitive study of disc-planet interaction.

Acknowledgments

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Contact Information

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The Kepler Follow-Up Observation Program

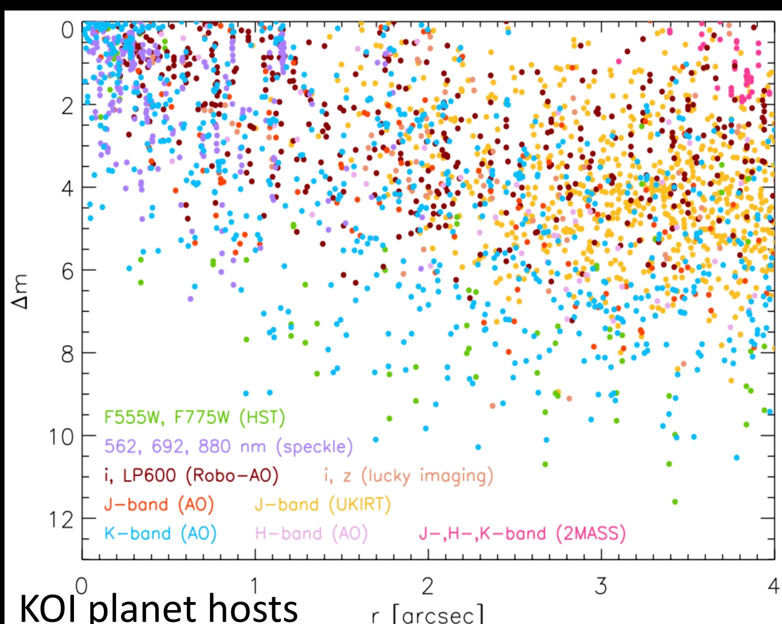
6 years (2009-2015)

confirm and validate planet candidates

➜ need accurate stellar properties of KOI host stars

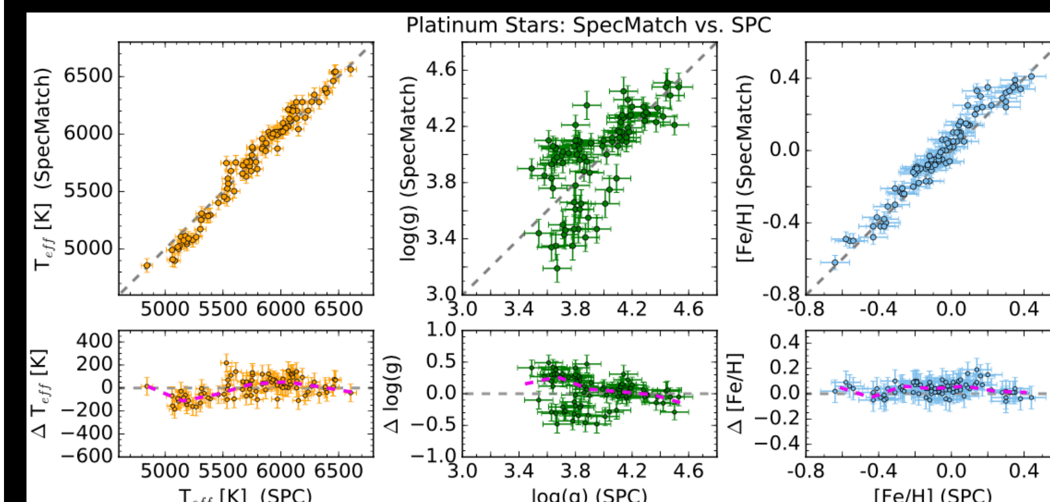
High-resolution imaging:

- determine stellar companions within Kepler aperture (bound companions or background objects)
- for blended stars: derive true sizes of planet candidates



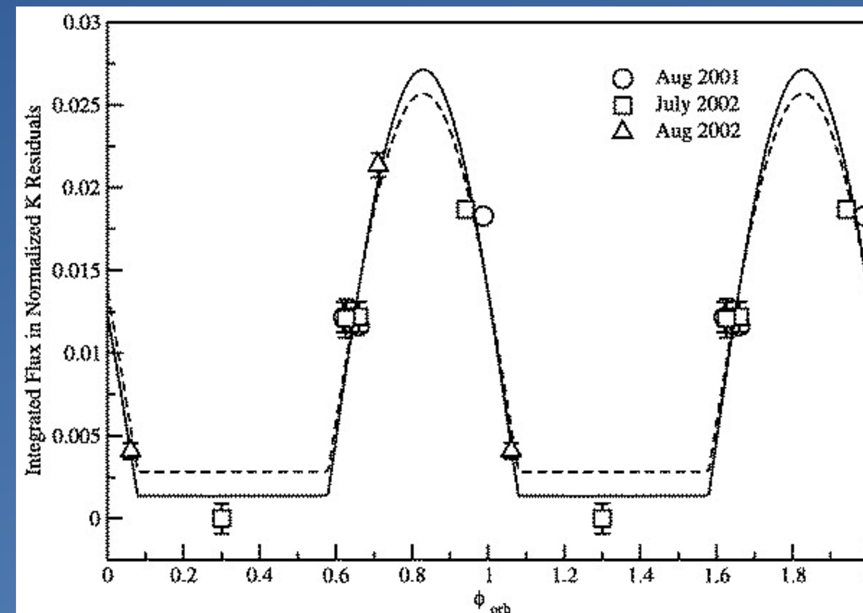
Medium- and high-resolution spectroscopy:

- determine stellar parameters
- detect stellar companions
- determine radial velocity curves
- set of standard stars and KOI host stars

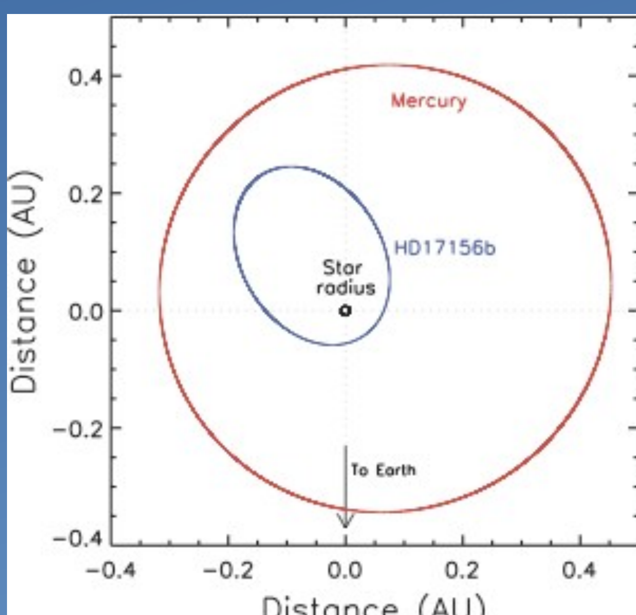


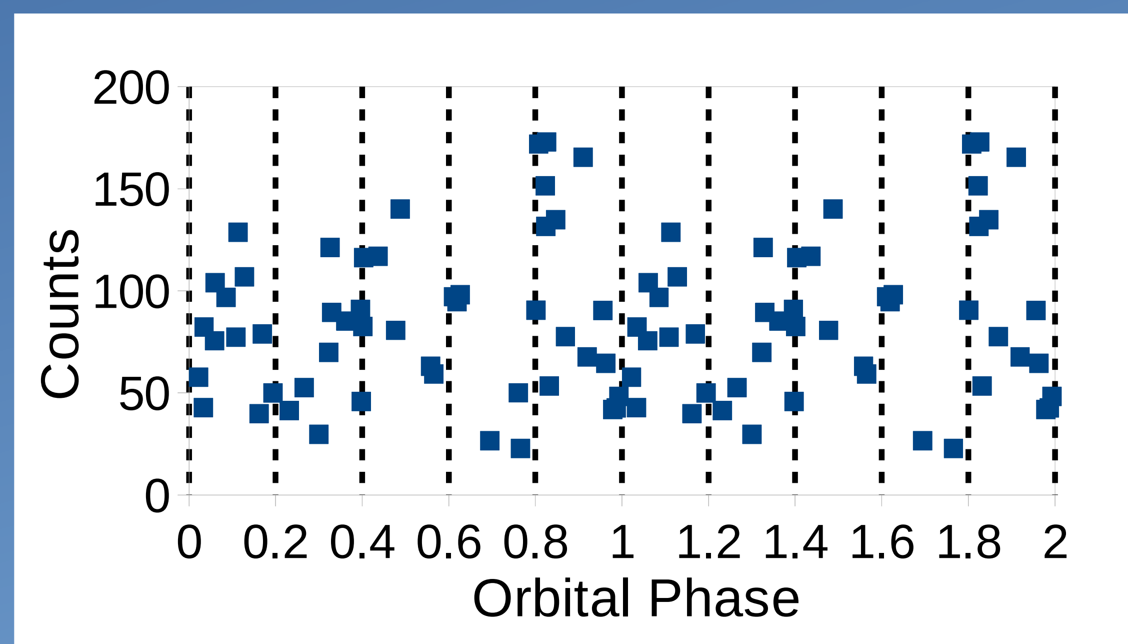
Using exoplanet systems with highly elliptical orbits to search for star-planet interactions

Jesse Lopez[1], John Hodgson II[1], Damian Christian[1], Suzanne Hawley[2]
1. California State University, Northridge 2. University of Washington



Looking for changes in the Ca II H&K lines via tidal, magnetic, and stellar wind interactions





THE AGN-PROTOPLANETARY DISK ANALOGY: BUILDING BLACK HOLES IS LIKE BUILDING PLANETS.

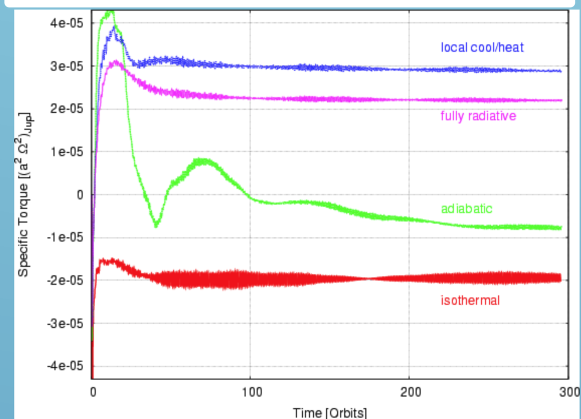
WLADIMIR LYRA, JOSHUA SHEVCHUK

Accrete ← Accrete ← Accrete

BACKGROUND

- AGNs can be thought of as scaled-up versions of protoplanetary disks.
- Planets interact with the parent disk gas which leads to angular momentum exchange, in a process called migration

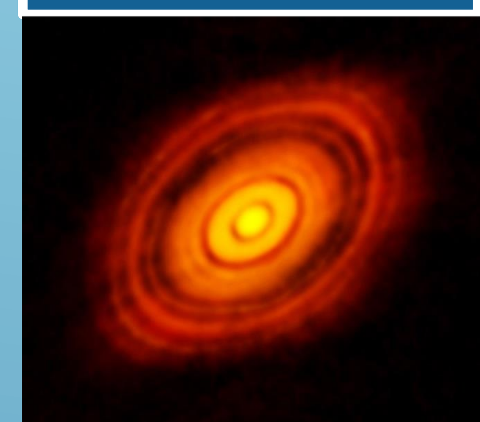
MIGRATION



Rule of thumb: Migration is outwards in steep temperature gradients,

inwards in isothermal regions.

PROTOPLANETARY DISK

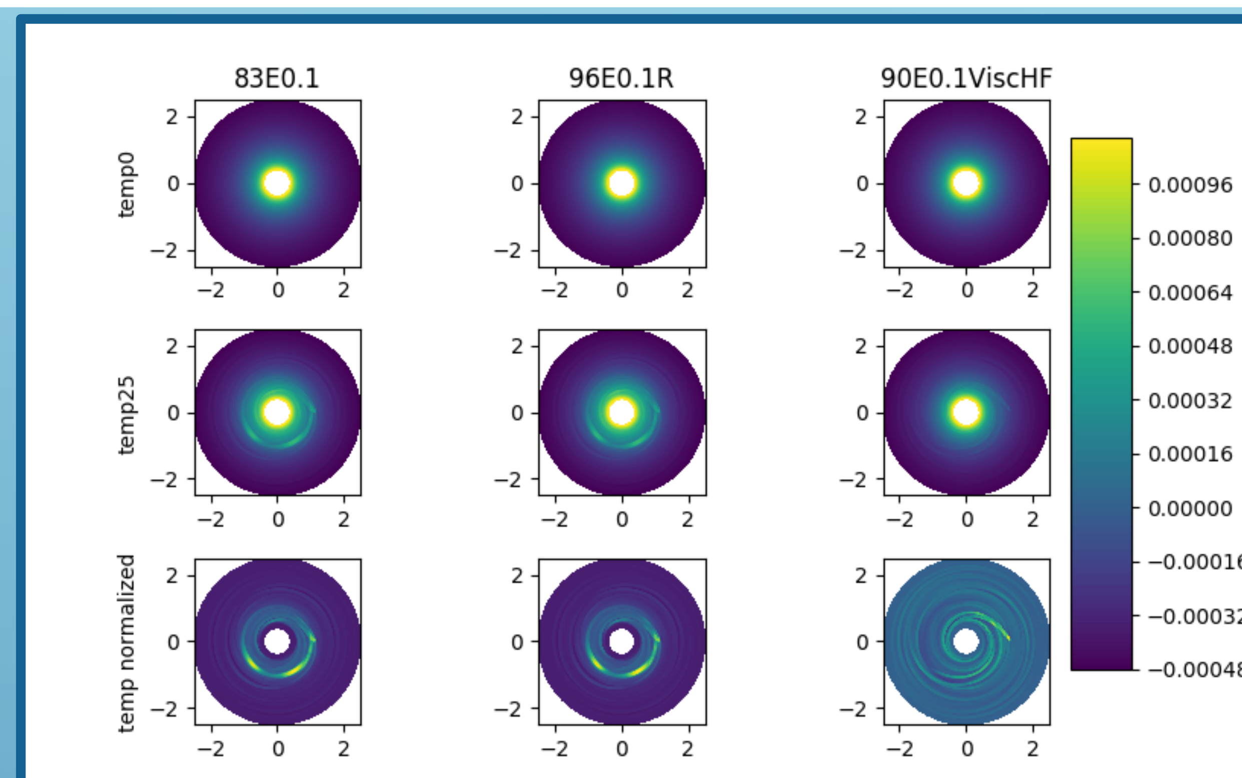


Atacama Large millimeter array image of HL Tauri

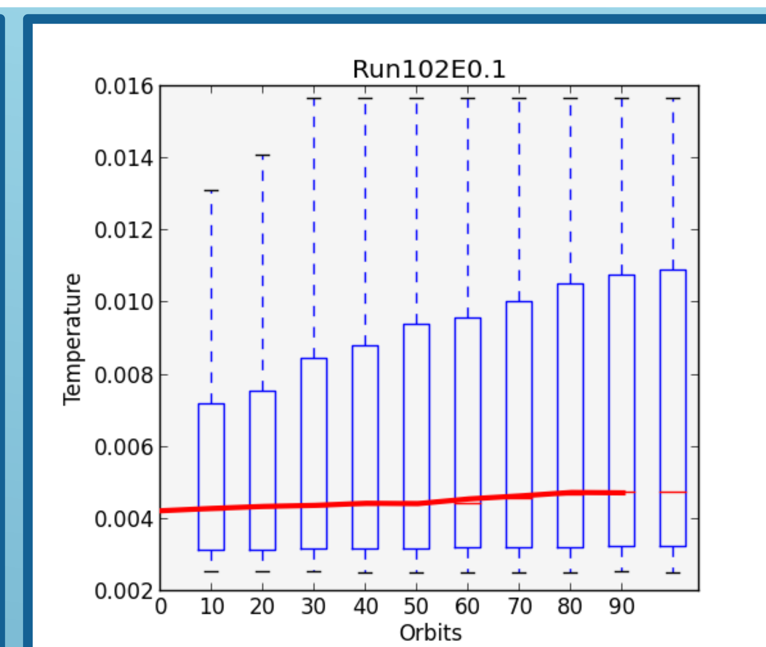
Notice the gaps carved in the disk.

- Migration can be either inwards or outwards. In locations where the migration torque vanishes, a planetary embryo stalls and growth ensues in a safe environment.
- The mass ratio between a star and planetesimals in a protoplanetary disk is similar to that between the central supermassive black hole and the masses of the nuclear compact objects (NCOs; white dwarfs, neutron stars, stellar mass black holes) that orbit in the AGN.
- Analogous to core accretion building planets, agglutinating these compact objects in an AGN should lead to objects of mass ratio q=1e-4 and q=1e-3, which in an AGN means the masses of intermediate-mass black holes

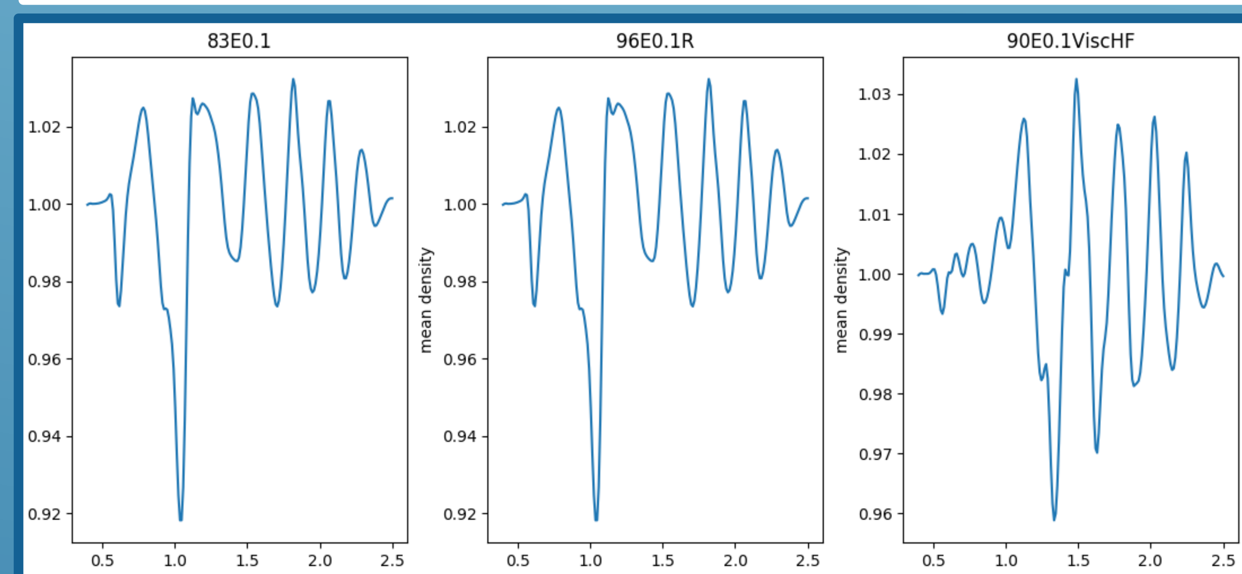
DATA AND CURRENT RESULTS



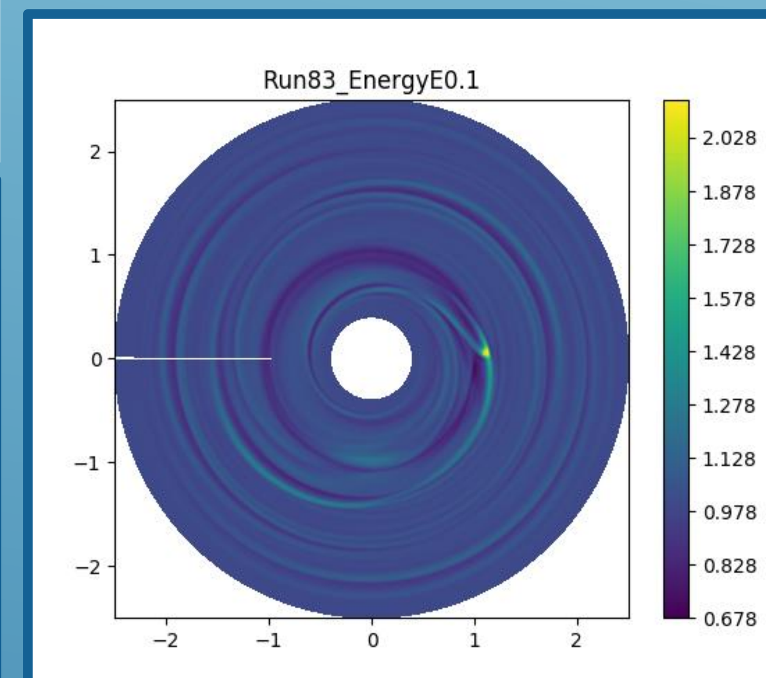
- **(Fig 1),** Temperature Contour plots, columns represent prograde, retrograde and prograde without viscous heating. Rows 1-2 represent orbits at 0 and 25 intervals. Row 3 represents normalized values between the two orbits.



- **(Fig 3),** Evolution of temperature within the disk. Median plotted in red.



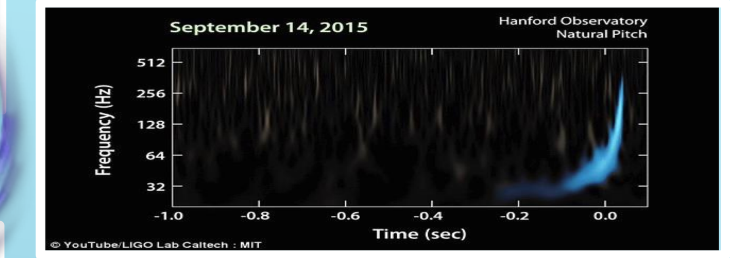
- **(Fig 2),**Mean density vs radius. There is a difference in maximum average density when viscosity heating is false.



- **(Fig 4),**Radial density of an AGN disk. Low density gaps are carved by the Orbiter.

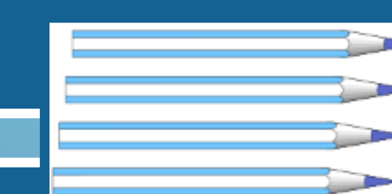
- All simulations are performed on a cylindrical grid with a radial range of 2 AU and resolution of 256x768
- **NCOs orbiting in the AGN can have different eccentrics and different inclinations** .The orbits of eccentric and retrograde NCOs has not been too well studied, so we need to characterize them. One of the first things to consider is that they lead to **shocks** as they cross the disk, and these shocks may lead to **disk heating**, orbital decay, and circularization. **We are measuring the amount of heating from the shocks.**
- The result of the **non-viscous heating** simulations and the normalized temperature allows us to tell the **amount of heating** that is received from the **shocks**.

WHY THE RESEARCH?



LIGO BH Masses:
GW150914: 36 and 29 M8
LVT151012: 23 and 13 M8
GW151226: 14 and 7 M8
GW170104: 31 and 19 M8

- ***We need a new theory.***
- Think of AGN disks as scaled up protoplanetary disks.
- The LIGO event is akin to collisions between planetary embryos in core accretion
- The problem with the LIGO observation is the mass of the black holes involved in the merger, which are heftier than expected from stellar evolution.
- These merging black holes themselves should be the result of previous mergers. Just like planetary embryos.
- We need to build AGN equivalent of the core accretion model.



BUILDING THE NUMERICAL MODEL

- We use pencil-code to build 2D global hydro-dynamical simulations of gas disk with planets substituted as an IMBH
- To measure shock heating in the disk we change the eccentricity of the binary while keeping the mass ratio constant.
- Pencil code can Solve for the dynamical and thermodynamical evolution

REFERENCES

- Paardekooper & Mellema (2006),Kley & Crida (2008)
- Alexander J. W. Richert, Wladimir Lyra,, Aaron Boley, Mordecai-Mark Mac Low, Neal Turner(2015)
- Lyra, Paardekooper, & Mac Low (2010), Lyra, Paardekooper, & Mac Low (2010),, Sandor, Lyra & Dullemond (2011), Sandor, Lyra & Dullemond (2011),
- Horn, Lyra, Mac Low & Sándor (2012), Sirko & Goodman 2003, Thompson, Quataert & Murray 2005
- *Johnathan Webb (2014-11-06). "Planet formation captured in photo". BBC.*

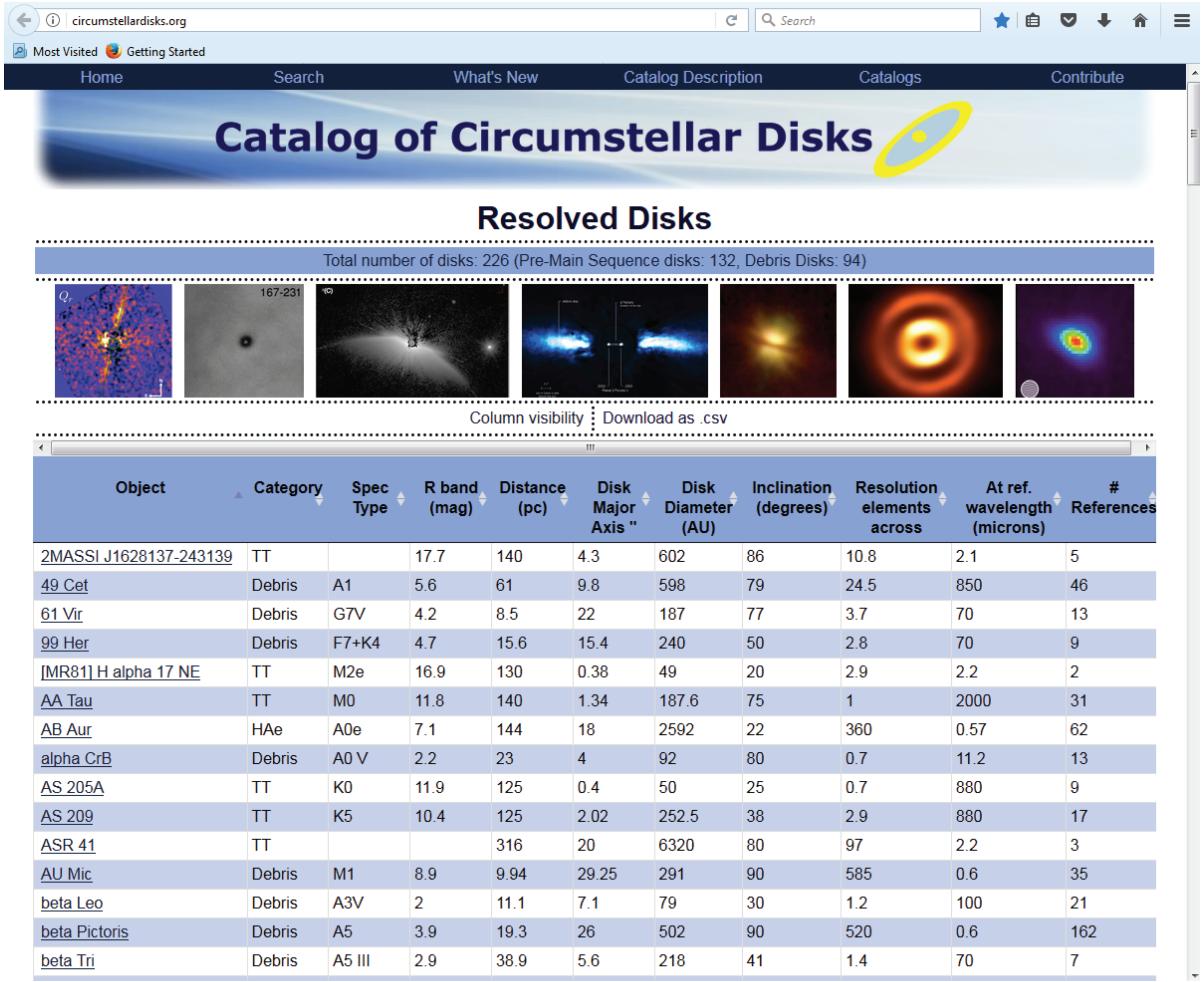
JPL CL #17-4260

circumstellardisks.org

An Online Catalog of Spatially Resolved Disks

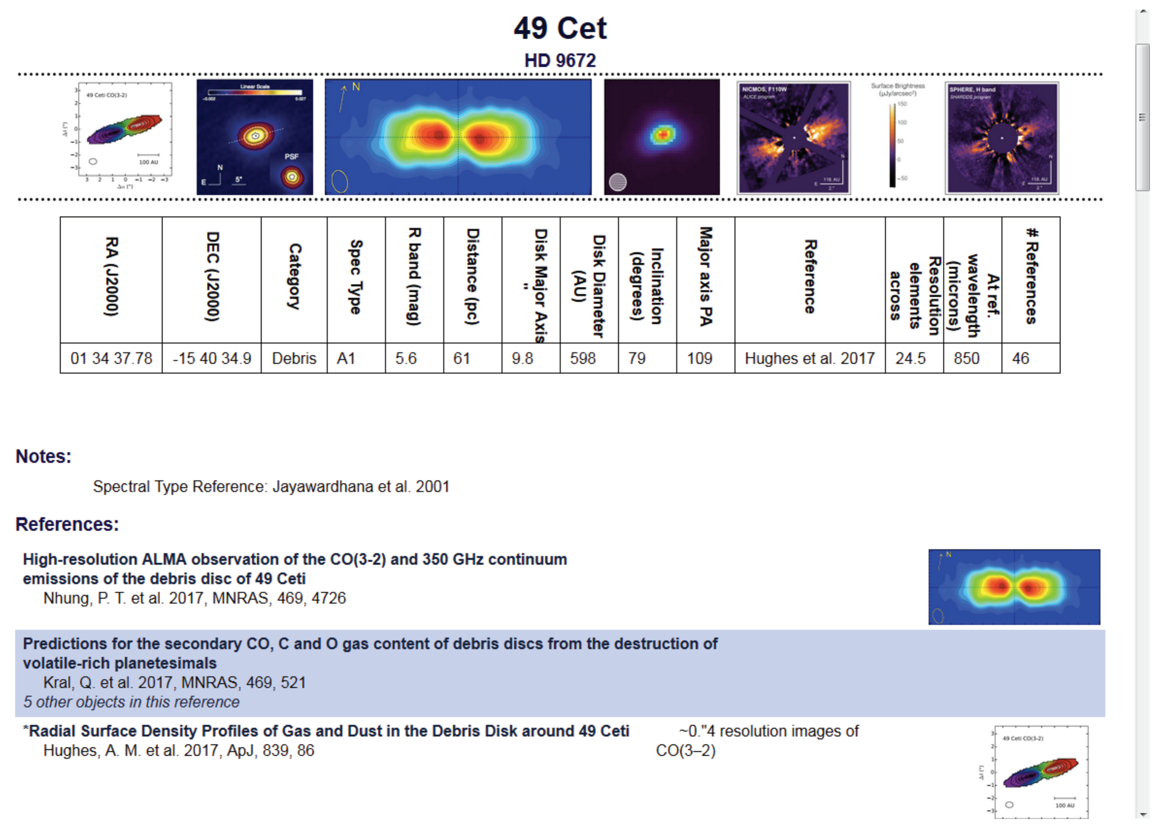
K. R. Stapelfeldt (JPL/Caltech), C.-E. McCabe, C. Gould (JPL & UC Berkeley), I. Jansen (General Electric)

Circumstellar disks are the builders of worlds and tracers of mature planetary systems. Originally discovered merely as far-infrared photometric excess, more than 200 disks are now spatially resolved in scattered light, dust thermal emission, or gas emission lines. Since 2005 https://circumstellardisks.org has been the largest online compendium of resolved disks. The site tracks recent research results in disk observations and disk modeling. Holdings include disk sizes, disk orientations, host star properties, and links to key references. Users can sort the database, perform search queries, and export the main table as a .csv file. A special emphasis is put on disk images, a different assortment of which is presented to the user each time they visit the front page. Clicking on an image takes the user to its parent reference in the refereed literature.



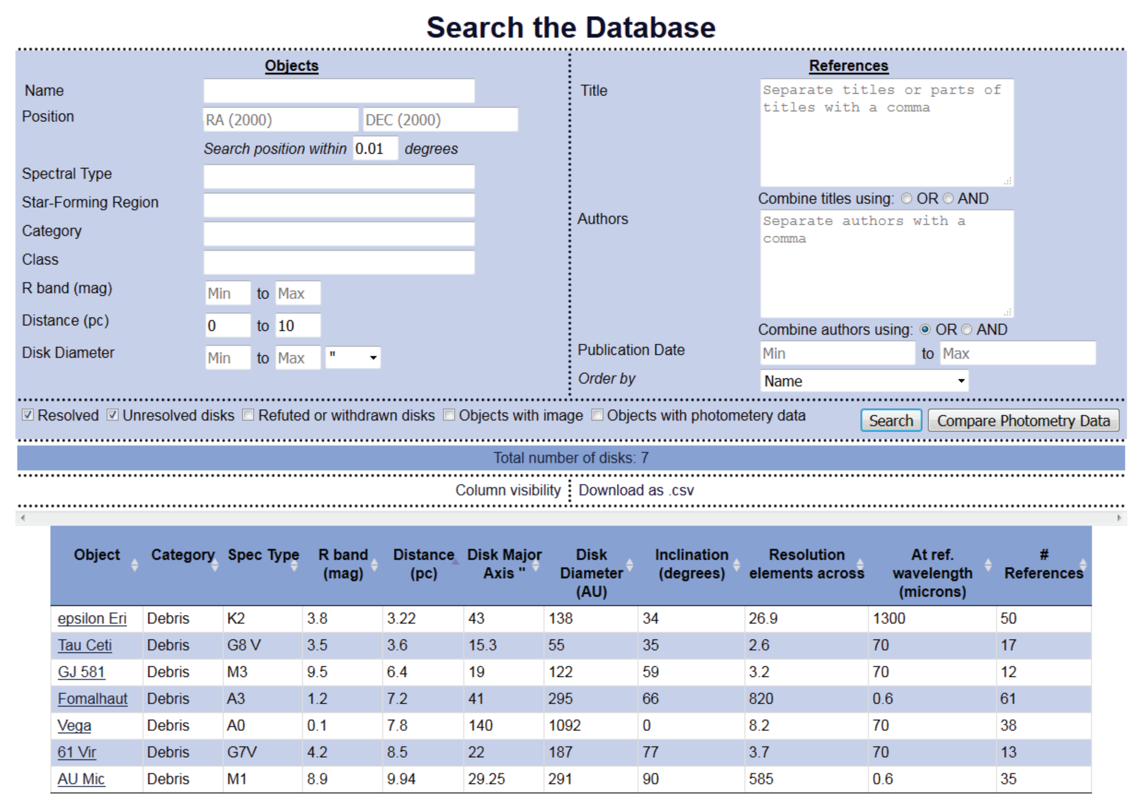
Object	Category	Spec Type	R band (mag)	Distance (pc)	Disk Major Axis "	Disk Diameter (AU)	Inclination (degrees)	Resolution elements across	At ref. wavelength (microns)	# References
2MASSI J1628137-243139	TT		17.7	140	4.3	602	86	10.8	2.1	5
49 Cet	Debris	A1	5.6	61	9.8	598	79	24.5	850	46
61 Vir	Debris	G7V	4.2	8.5	22	187	77	3.7	70	13
99 Her	Debris	F7+K4	4.7	15.6	15.4	240	50	2.8	70	9
[MR81] H alpha 17 NE	TT	M2e	16.9	130	0.38	49	20	2.9	2.2	2
AA Tau	TT	M0	11.8	140	1.34	187.6	75	1	2000	31
AB Aur	HAe	A0e	7.1	144	18	2592	22	360	0.57	62
alpha CrB	Debris	A0 V	2.2	23	4	92	80	0.7	11.2	13
AS 205A	TT	K0	11.9	125	0.4	50	25	0.7	880	9
AS 209	TT	K5	10.4	125	2.02	252.5	38	2.9	880	17
ASR 41	TT			316	20	6320	80	97	2.2	3
AU Mic	Debris	M1	8.9	9.94	29.25	291	90	585	0.6	35
beta Leo	Debris	A3V	2	11.1	7.1	79	30	1.2	100	21
beta Pictoris	Debris	A5	3.9	19.3	26	502	90	520	0.6	162
beta Tri	Debris	A5 III	2.9	38.9	5.6	218	41	1.4	70	7

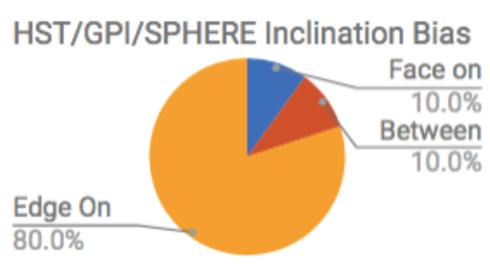
Individual Object Page

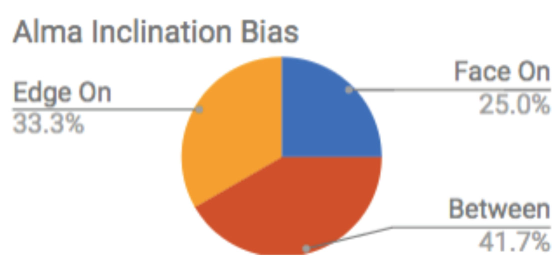


Search Page

with example output







Average debris disk diameter is 330 AU, about twice that inferred for our Kuiper Belt

Acknowledgements

The webpage was first established by JPL NRC postdoc Caer McCabe in 2005. NASA GSFC intern Isabelle Jansen redesigned the site in 2012 and made major coding imrpovements in 2016. JPL Interns Carlotta Pham (2009) and Cee Gould (2017) updated the site contents. Deborah Padgett (IPAC, GSFC, and JPL) and Geoff Bryden (JPL) have provided important advice over the years. Bill Adler has maintained the host computers since the site's inception. Karl Stapelfeldt curates the site and is responsible for any errors. Send suggested updates or corrections to Karl.R.Stapelfeldt@jpl.nasa.gov.