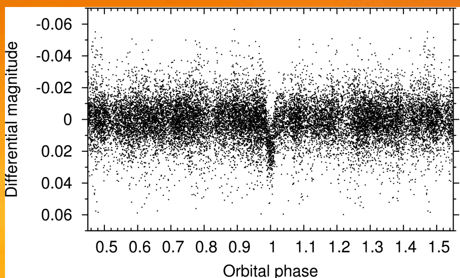
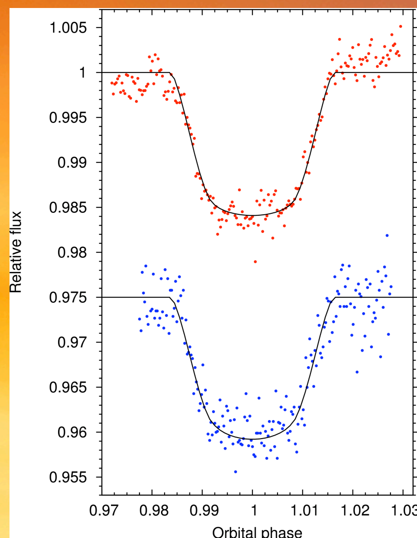
WASP-31b: a bloated, short-period, giant planet orbiting a sub-solar metallicity F-type star

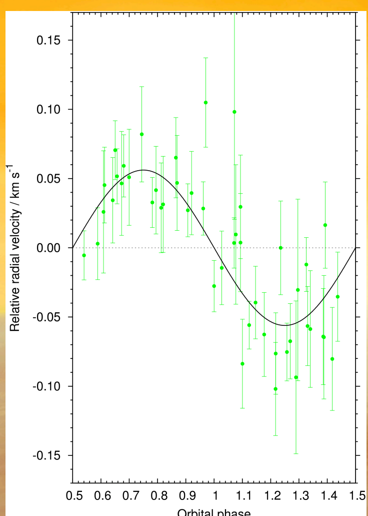
David R. Anderson, Keele University, SuperWASP Consortium



WASP discovery light curve



FTS & Euler transits



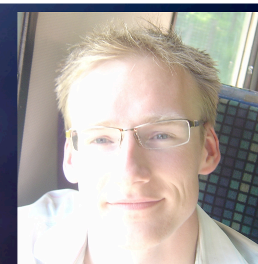
CORALIE radial velocities

Period ~ 3.5 days

Mass ~ 0.5 M_{Jup}

Radius ~1.6 R_{Jup}

Density ~0.12 ρ_{Jup}

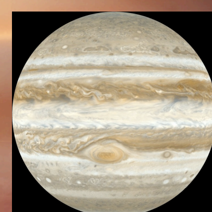


Current research interests

Discovery and characterisation of exoplanets

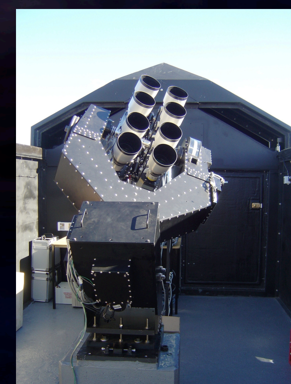
Ground- & spaced-based occultations

Spectroscopic transits



Jupiter

WASP-31b



Nahks Tr'Ehnl

Overcoming The Challenges in the Discovery of Exoplanet Candidates with Radial Velocity Method:

Discriminating Different Velocity Fields By Using Bisectors of Cross Correlation Functions:

Ozgur BASTURK
Ankara University

Radial Velocity Variations in Cool Stars' Spectra

There is a variety of phenomena that cause radial velocity variations in cool stars' spectra (Gray 2005). Most important of such variations are rotation, granulation, pulsation, chaotic mass movements in stellar atmospheres, surface spots caused by magnetic activity of the star and component(s) physically attached to the star of interest. Discriminating these phenomena from one another is crucial in studying a cool star or its component(s).

In order to study all these different velocity fields in a cool star's spectrum, attentive analysis of radial velocity variations and line profiles is needed. The best way to study and quantify line profile variations is to study line bisectors (Gray 1990). A line bisector is defined as the locus of midpoints on the horizontal lines connecting the wings of a line profile (Figure 1).

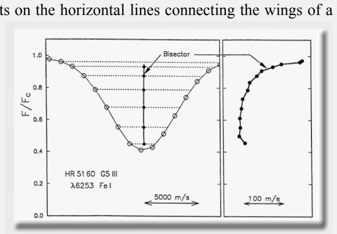


Figure 1. Spectral Line Bisector (Gray 1992)

The shape of the bisector is the indicator of a line asymmetry. Bisector of a symmetric profile should be a straight line passing through the line center. Any effect causing asymmetry will lead to a deviation from this straight line. Because different sections of spectral lines form in different depths in a stellar atmosphere, a line asymmetry indicates phenomena leading to velocity difference between these depths.

High resolution, high signal/noise (S/N) spectra are needed in order to study line profile asymmetries. Although it is possible to obtain high resolution spectra with the use of high technology telescope-spectrograph configurations, in order to achieve high S/N required, either long exposure times are needed or many short exposure spectra are combined. However, short-term profile variations will not be observed in both of the solutions.

Since the velocity fields vary with the depth in stellar atmosphere, different lines with different line strength will have different asymmetries and hence different bisectors. Therefore, "average bisectors" of classes of lines with close line parameters such as the oscillator strength, excitation potential and ionization level can be more trustworthy than a single line bisector.

CCF Bisectors as Tools to Discriminate Velocity Fields

In order to overcome this difficulty, cross-correlation functions (CCF) are employed. These are formed by cross-correlating observational stellar spectra with synthetic or observational spectra of stars whose parameters are well known, or masks constructed using binary or delta functions. These can be thought as near-optimal "average spectral lines" because cross-correlation procedure relies on lines of many different elements.

They are advantageous because

- They have intrinsically high S/N
- They represent an average line of a specifically selected group of lines
- Weak, strong and blended lines are avoided so they will be free from blends
- By selecting different groups of lines for the mask, different volumes in stellar atmospheres can be targeted

Bisector of a CCF profile is defined in the same way as a single line bisector and it is sensitive to variations in the lines used in cross-correlation procedure (Queloz et al. 2001)

Dall et al. (2006) showed that CCF profiles can be employed in much the same way as single line profiles in order to study profile variations. It is crucial to determine and to understand the relationships between the shape of the CCF bisectos, profile variations and mechanisms that cause these variations. Dall et al. (2006) questioned the relations between CCF bisectors and other observational evidences of such mechanisms.

As distinct from mechanisms intrinsic to stars, unseen companions do not cause line asymmetries but radial velocity jitter. Hence, lack of correlation between the variations in the CCF bisectors and radial velocity is interpreted as an indicator of an orbiting exoplanet (Queloz et al. 2001). In some cases, while radial velocity variations thought to be resulting from an orbiting exoplanet before, turned out to be originating from the variations intrinsic to the star in later analyses (Huélamo et al. 2008). In some others, the exact opposite is the case (Melo et al. 2007).

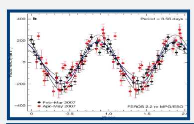


Figure 2. Radial velocity observations of TW Hya by Setiawan et al. (2008)

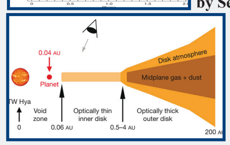


Figure 3. Model based on RV observations (Setiawan et al. (2008)

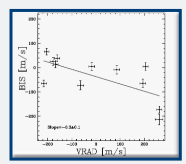


Figure 4. Clear correlation between the bisector inverse slope (a measure of bisector shape) and radial velocity variation showing that the cause of the variation is magnetically induced surface spots (Huélamo et al. 2008)

What we aim to do?

My PhD thesis project aims at combining the properties of a large sample of stars, observed with the HARPS spectrograph attached on the 3.6 m. ESO telescope in La Silla, in terms of (a) their line profile variations and radial velocity time series; (b) fundamental stellar parameters derived from spectral synthesis; (c) newly derived as well as already published asteroseismic parameters; (d) known planets; (e) magnetic activity indices and their variation with time. Mapping out this parameter space will allow us to place in the proper context dedicated studies of selected targets showing solar-like pulsations and strong magnetic activity.

With this aim, we will investigate in greater detail how bisectors of CCFs can be used as diagnostic tools for different velocity fields in a stellar atmopshere. We aim to establish an empirical calibration of the variation in RV caused by stellar activity and other intrinsic effects, so that these different physical effects may be properly separated and studied. From our HARPS data we will derive RV, CCF bisectors, and activity parameters.

"Designer-CCF" Concept

Our focus will be mainly on what can be learned about the stellar structure through employing a number of specially designed CCF masks which we are developing in collaboration with HARPS instrument experts. Form of CCF bisectors and bisector measures in parallel, depend heavily on the synthetic or observational spectra, or binary or delta functions used in cross-correlation procedure (Figure 5).

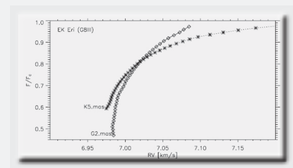


Figure 4. CCF bisectors obtained by the cross-correlation of observational spectra of EK Eri with two masks constructed for two different spectral types. (Dall et al. 2006).

Since the "original" HARPS CCF-masks are designed with the aim of detecting planets, they have been fine-tuned to contain as little variability signal from the stellar atmosphere as possible. Hence, in order to extract the maximum amount of information about the oscillations and the magnetic field, a completely different set of spectral lines, and hence new masks are needed. Thus, we are going to study different aspects of the "average spectral line" in a completely new way, by investigating what one might call "designer-CCF's"

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Queloz, D. et. al, 2001, "No Planet for HD 166435", A&A, 379, 279
Setiawan J. et al., 2008, "A young massive planet in a star-disk system", Nature, 451, 38

Supervisors: Dr. Selim O. Selam (Ankara University) , Thomas H. Dall (ESO)

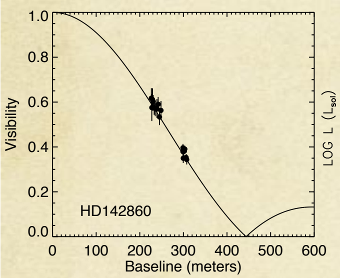
SIZING UP THE STARS

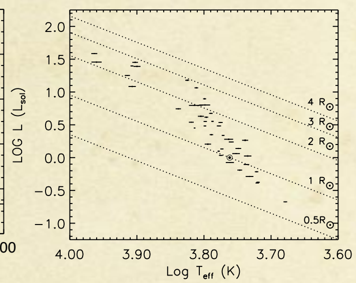
ANGULAR DIAMETERS WITH THE CHARA ARRAY

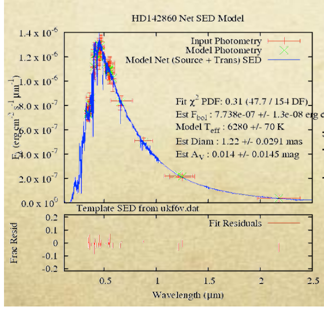
Tabetha Boyajian
GSU / CHARA (Hubble Fellow)

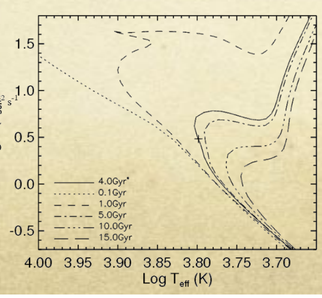
Fundamental properties of stars with long-baseline optical/IR interferometry

•Survey of nearby, 'normal', main-sequence, A, F, and G type stars out to a maximum distance of ~30pc (A stars) and ~15pc (G stars). Average precision on the angular diameter, $\sigma\,\theta$, is ~1.4% !
•Empirically determined values of linear radius, bolometric flux, and effective temperature
•Fitting isochrones to these quantities constrain masses and ages of these stars
(see also K. von Braun ePoster for exoplanet host stars and K-M dwarfs)



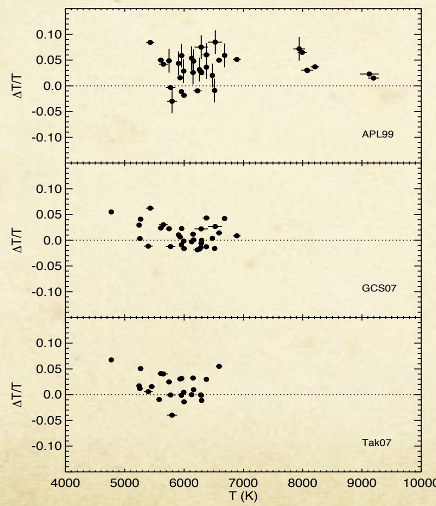






Temperature compared to less direct methods

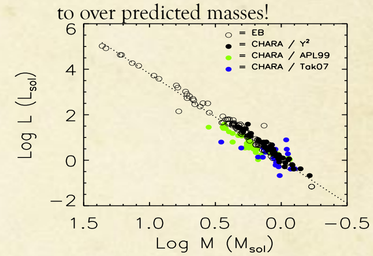
•Works which utilize less direct methods tend to overestimate T_{eff} by ~1.5-4% (below) when compared to our directly measured values with no apparent correlation to the star's metallicity or color index. These less direct methods also predict smaller radii, while the luminosities are in agreement.



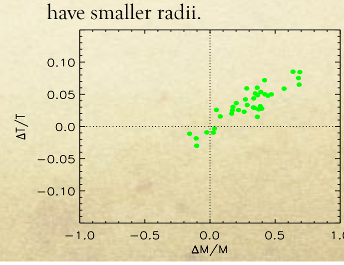
References: Allende Prieto & Lambert 1999 (APL99), Holmberg, Nordström & Andersen 2007 (GCS07), Takeda 2007 (Tak07)

Model masses compared to eclipsing binaries

•Masses found by isochrone fits to our data are in excellent agreement with eclipsing binaries (below, black)
•Log *g* used in combination with interferometrically measured radii (below, green and blue points) lead to over predicted masses!

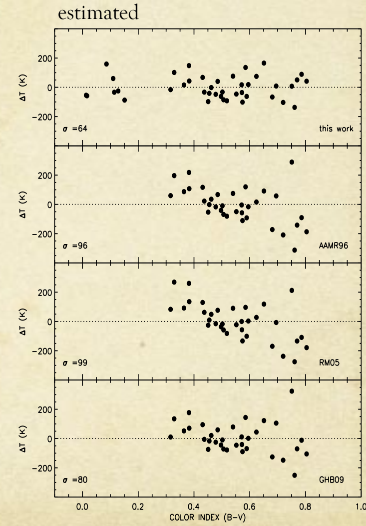


•Overestimated log *g* is likely associated with overestimates of T_{eff} used in the spectral templates used to measure the log *g* of the stars (see below example), also making stars appear younger and have smaller radii.



Color-temperature-metallicity relation

•Empirically derived solution
•For solar metallicity, stars bluer than the sun are typically overestimated in T_{eff}, while T_{eff} of redder stars are under estimated



References: Alonso, Arribas & Martinez-Roger 1996 (AAMR96), Ramírez & Meléndez 2005 (RM05), González Hernández & Bonifacio 2009 (GHB09)

Spectral Properties of Cool Stars

Planet Search Stars

Radial velocity planet surveys collect thousands of high resolution (R > 50,000) spectra in the hunt for planet signals. Most of these spectra have reference lines imprinted on them, obscuring any additional information. The California Planet Survey (CPS), which uses an iodine cell to imprint a reference spectrum, also takes clean template spectra of each star to help to help model the doppler shift. Using Spectroscopy Made Easy (SME, Valenti 2009), we have analyzed more than 1,600 spectra of almost 1,000 stars to determine properties such as temperature, metallicity, surface gravity, mass and age. We will be publishing this analysis as an addition to the catalog, 'Spectral Properties of Cool Stars (SPOCS I, Valenti & Fischer 2005).

John M. Brewer
Yale University
john.brewer@yale.edu

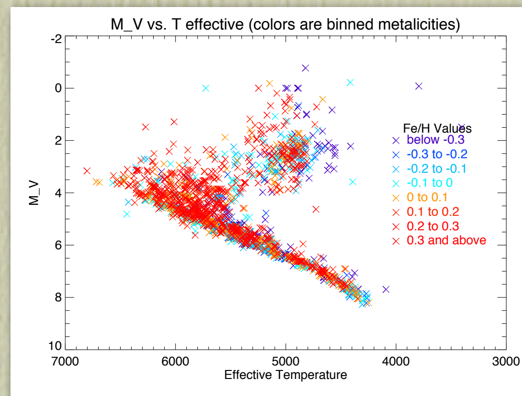


Figure 1 - Entire sample of template spectra from 2005 to present. Fits for stars below ~4700 K are poor due to the increase in atomic lines.

Challenges

Several of the parameters involved in modeling the spectra are degenerate. The new version of SME compensates for this degeneracy by finding a best fit model, then using the resulting temperature, metallicity, and alpha element abundances to find a Yonsei-Yale isochrone. The gravity from the isochrone is compared to the gravity obtained by modeling the spectrum and if they differ, a new model is found using the isochrone gravity. The process is repeated until the gravities from each method agree.

Next Steps

We have analyzed all of our spectra and determined a new relation between rotational broadening and effective temperature. We are now finishing up a re-analysis with this new relation and will be publishing the catalog in the coming months.

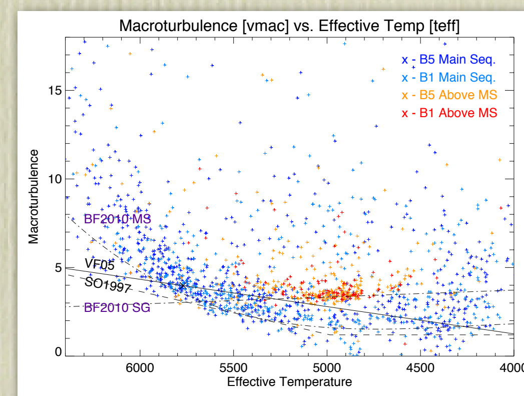


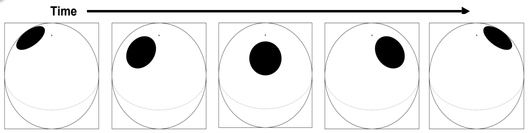
Figure 2 - Macroturbulence and v sini are degenerate. Here we allowed all rotational broadening to be absorbed into one parameter and fit a lower bound to find a relation between v_{mac} and T_{eff}.

Brown Dwarfs and Giant Planets Around Young Stars

Christopher J. Crockett[1], Naved Mahmud[2],
Lisa Prato[1], Christopher M. Johns-Krull[2], Patrick Hartigan[2], Daniel T. Jaffe[3], Charles A. Beichman[4]
[1]Lowell Observatory, [2]Rice University, [3]UT, Austin, [4]JPL

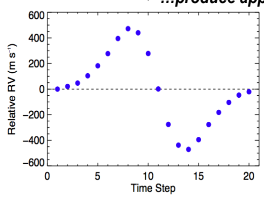
Overview An RV survey of ~150 1-3 Myr old stars in the Taurus-Auriga star forming region to identify the giant planet population around young stars and explore the origins of the brown dwarf desert.

1 Star spots introduce velocity noise

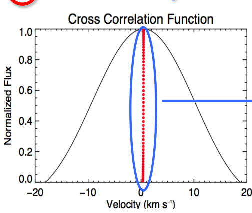


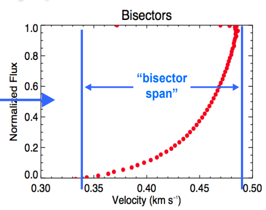
Rotating star spots…

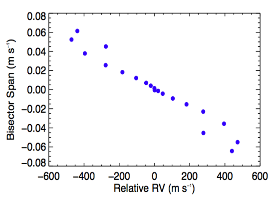
…produce apparent RV modulation



2 Bisector analysis can identify spots



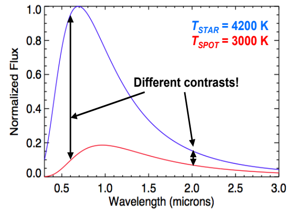


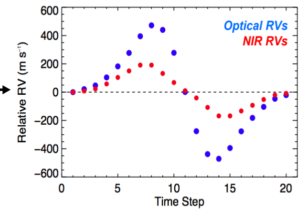


Spotted stars exhibit an RV-bisector span correlation.

But not always…

3 Multiwavelength behavior of star spots

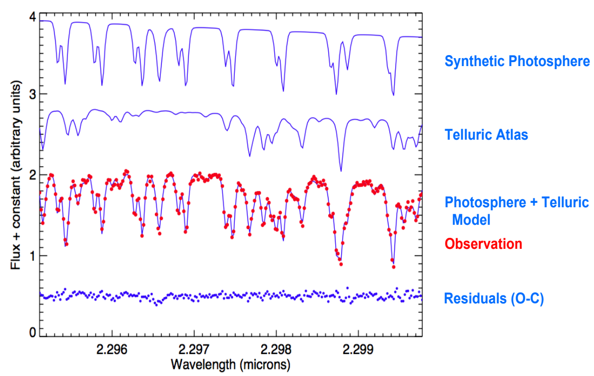




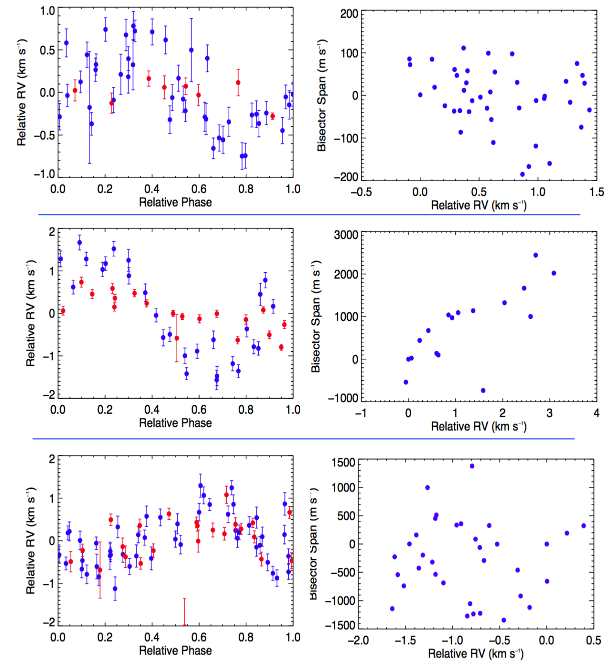
Spots exhibit wavelength-dependant RV amplitudes; planets do not!

4 NIR RV Determination

A two component model is used…



5 Results from a sample of our targets



Acknowledgements

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New Worlds

Detecting Bio-signatures on an Evolving Earth-like Atmosphere

Julia DeMarines

Webster Cash, Giada Arney, Phil Oakley, Eric Schindhelm (University of Colorado)

And the New Worlds Team (newworlds.colorado.edu)

Introduction:

New World Observer is a mission designed to search for terrestrial exoplanets, specifically planets that may harbor life.

The mission will consist of a 4 meter telescope and a starshade 50 meters across (a 16 petal occulter) that will be in orbit at L2 (Lagrange point 2).

The star shade will diffract light in such a way that the light will deconstructively interfere with itself allowing the faint light, reflected off of the planets, to be imaged and analyzed.

My research:

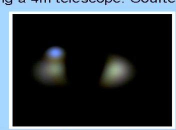
Oxygen seems to be the hot topic in the detection of biosignatures of an exo-atmosphere, but I wanted to know if pre-photosynthetic life was detectable. I was specifically interested in the rise in methane due to anaerobic bacteria in the early years of Earth (methanogens).

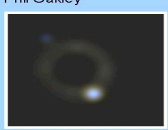
Collaborating with the Virtual Planetary Lab (VPL) at the University of Washington, I used their simulated spectra of the Archean atmosphere based on current data, produced by Shawn Domagal-Goldman et al. We lowered the resolution of the spectra to that of observing the light of a planet at a distance of 10pc away. Then I overploteed the results of an Archean atmosphere to that of one without methane.

See preliminary results to the right!

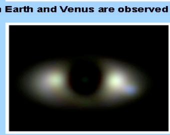
-Parameters located bottom right-

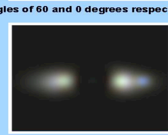
Simulated images: Earth (blue dot) and Venus (white dot) as viewed through the Starshade, at a distance of 10 parsecs using a 4m telescope. Courtesy of Phil Oakley





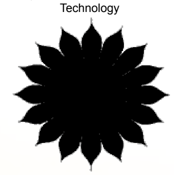
Both Earth and Venus are observed at angles of 60 and 0 degrees respectively



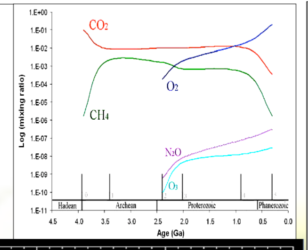


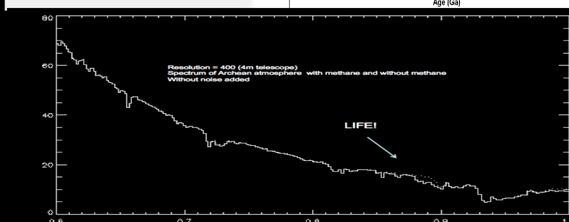
Just the Earth observed at angles of 60 and 90 degrees respectively

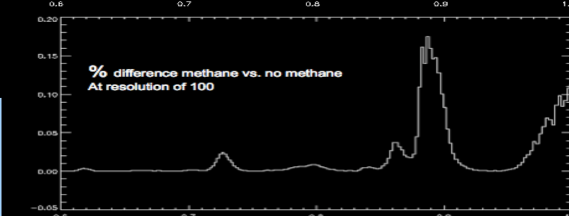
Courtesy of Northrop Grumman Space Technology

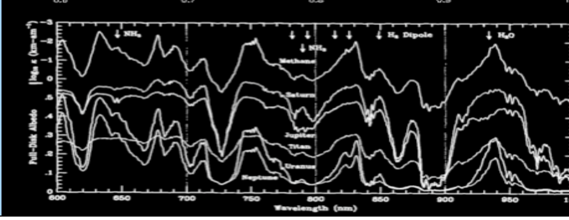


16 petal starshade

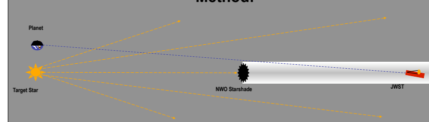








Method:



Once we have identified a target star (one with planets in the habitable zone) we will then take long exposures to be able to gather enough light from the planet to analyze the data.

Spectroscopic analysis from the starlight, reflected off the planets, will give insight on the composition of the atmosphere.

We have the capability to detect as little as 2% oxygen and 0.2% methane in an atmosphere, which means we can detect a primitive as well as complex forms of life!

What we may discover:

New Worlds has the capability to detect molecular **oxygen** (at 761 nm), **water** and **water vapor** (at 960 nm), as well as biological methane (at 725 nm) in an exo-atmosphere.

Detection of the O_2 A band is a very probable indication of plant life! Detection of H_2O indicates the presence of water, and possibly water worlds, another place where life could exist! Detection of CH_4 in a small rocky planets atmosphere is indicative of biological production!

The first life on Earth was thought to be Methanogens, which produce methane as a waste product. "The major influence of methane on the atmosphere may have begun almost as soon as life originated more than 3.5 billion years ago (Kasting & Siefert 2002; Ueno et al. 2006; Canfield 2006)".

Mission Status:

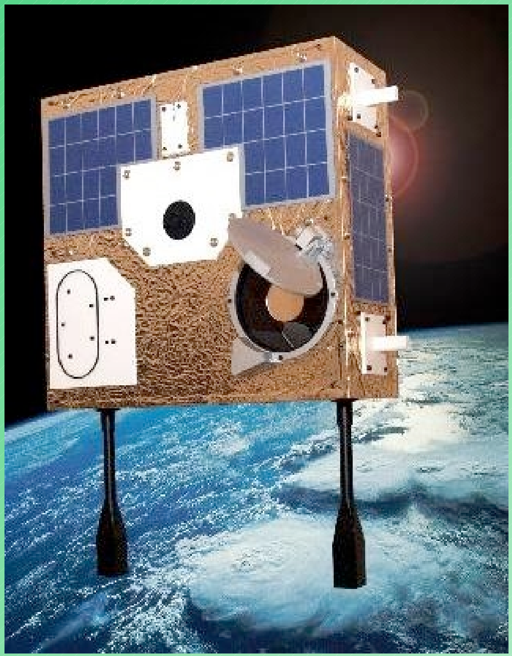
Dr. Cash and his team have completed the Astrophysics Strategic Mission Concept Study in April 2009 and have submitted a pending white paper to NASA's Decadal Review.

urrent Parameters for NWO:
Telescope D = 4m, or JWST
angular resolution = 0.026"
spectral resolution= 100
starshade separation= 72,000km
outer diameter= 50m
# of petals = 16
inner working angle= 0.058"

Substantial contributions have been made by Northrop Grumman, Goddard Space Flight Center and Ball Aerospace.

Hunting for super-Earths with the MOST space telescope

Diana Dragomir
Ph.D. student @ the University of British Columbia



I am currently working on a search for transits among previously identified radial velocity candidates, with minimum masses of 2 – 20 M_{earth}.

The goal is to enlarge the currently known sample of transiting super-Earths and to characterize their interior structure.

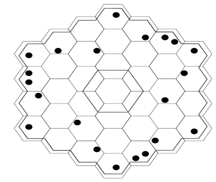
The search is conducted using the MOST telescope, a Canadian suitcase-sized microsatellite which houses a 15-cm optical telescope. It can monitor stars almost continuously for up to 8 weeks.

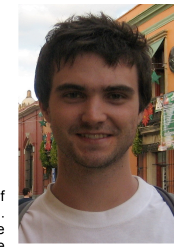
MOST can achieve a photometric precision of a few parts per million (~μmag).

Searching for Substellar Companions Below the Telescope Diffraction Limit

Tom M. Evans, Michael J. Ireland, Adam L. Kraus, Peter G. Tuthill, Frantz Martinache

We are using aperture masking interferometry to conduct a survey for faint companions to 73 members of the nearby young stellar associations AB Dor, Beta Pic, TWA, Tuc-Hor, and Her-Lyr. Making use of aperture mask facilities installed on ~5-10m telescopes at the Keck, VLT and Palomar observatories, we routinely achieve contrast ratios of ~10^2 at angular resolutions below the formal diffraction limit, corresponding to orbital separations ~3-30AU. This is a region of orbital separation space that is currently inaccessible to other techniques, with radial velocity searches losing sensitivity beyond around 5AU, and coronographic direct imaging searches losing sensitivity within around 30AU. As part of this survey, we have identified three companions with masses in the range 0.3-0.5$M_\odot$ and our detection limits are reaching down to 20M_J for 35% of our sample. Despite being sensitive to companions below the hydrogen burning limit, including even gas giant planets, we have not detected any such objects.

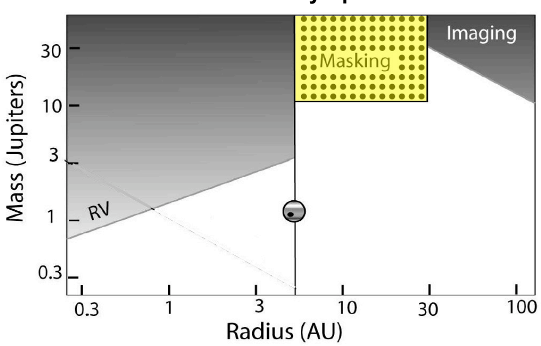




THE UNIVERSITY OF SYDNEY

Our group consists of researchers at The University of Sydney, The University of Hawaii, Cornell University, and the National Astronomical Observatory of Japan. We make use of aperture mask facilities installed on ~5-10m telescopes at the Keck (*pictured*), VLT, and Palomar observatories. The illustration above shows the subapertures of a 21-hole mask projected onto the segmented mirror of the Keck II telescope. Each pair of holes is an interferometric baseline.

Discovery Space



Target is assumed to be a 2.5$M_\odot$ star in the 5Myr old Upper Sco association at ~145pc. Radial velocity precision of 20m/s is assumed, typical for a star of this mass. Imaging limits assume no speckle suppression.

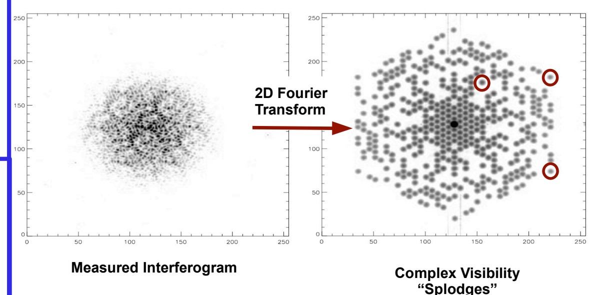
Young, nearby stellar associations provide ideal targets to detect the light from faint substellar companions such as brown dwarfs and gas giant planets:

- Companions will still be glowing strongly in the infrared following **recent formation**.
- Assumed common birth removes the difficulty of estimating the ages individually for each sample member.
- **Proximity** provides favorable projected separations between primary and companion.

For our targets at distances <100pc, we achieve our deepest limits within the 3-30AU observational blind spot between RV surveys and coronographic direct imaging surveys. From a planetary perspective, this range is especially interesting because it is where giant planets are predicted to form. Probing these separations will also allow us to quantify the extent of the well-established brown dwarf desert that exists at separations <3AU.

Our current detection limits allow us to place meaningful constraints on the frequency of >20MJ companions in this separation range, however, by improving the data reduction pipeline and targeting younger stars, we hope to improve our limits down to ~5MJ for the majority of our targets in the near future.

The Technique



Each pair of holes in the aperture mask generates a set of interference fringes on the chip. The figure on the left shows a single-exposure interferogram, consisting of the superposition of fringe sets from each pair of holes in the mask. To extract information about the source brightness distribution, we take the 2D Fourier transform of the interferogram to get the **complex visibilities**. Each visibility "splodge" corresponds to a single complex-valued point in the spatial frequency plane as sampled by a pair of holes in the aperture mask.

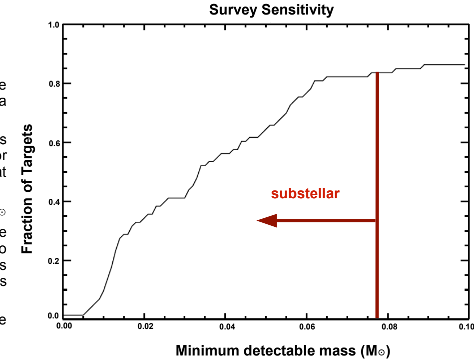
By adding the measured visibility phases around a triangle of baseline pairs (*red circled*), we obtain a quantity called the **closure phase** which is largely independent of atmospheric and instrumental effects. If we measure multiple closure phases, we can accumulate enough spatial information to constrain simple brightness distributions such as binaries.

Using this technique, we can achieve dynamic ranges ~10^2 in brightness at angular resolutions ~λ/2B, where B is the longest hole-pair baseline in the mask. Given that the longest baseline is typically ~90% of the full aperture diameter, this corresponds to sub-diffraction resolution.

Survey Status

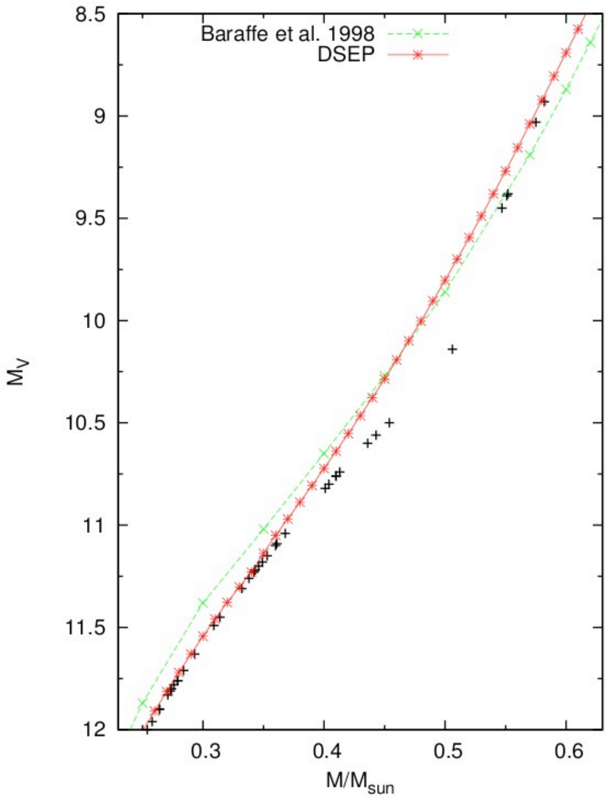
- We have obtained usable data for 73 stars in the J, H, K, and L bands.
- For each target, we use a χ^2 minimization algorithm to determine if the closure phase measurements are more consistent with a single star or a binary system.
- The figure on the right shows the fraction of stars in our survey sample as a function of the minimum companion mass to which we are sensitive. For ~35% of our sample, we are sensitive to companions down to ~20M_J at projected separations typically in the range 3-30AU.
- We have identified 3 new companions with masses in the range 0.3-0.5$M_\odot$
- However, we have not identified any companions with masses in the range ~20-80M_J (i.e. "brown dwarfs" loosely speaking). This null result appears to be consistent with the well-known brown dwarf desert at semimajor axes <3AU, and the apparent paucity of brown dwarf companions at separations >30AU revealed by direct imaging surveys in the past few years.
- The next step is to use our null result to estimate an upper limit for the frequency of brown dwarf companions with semimajor axes 3-30AU.

Survey Sensitivity

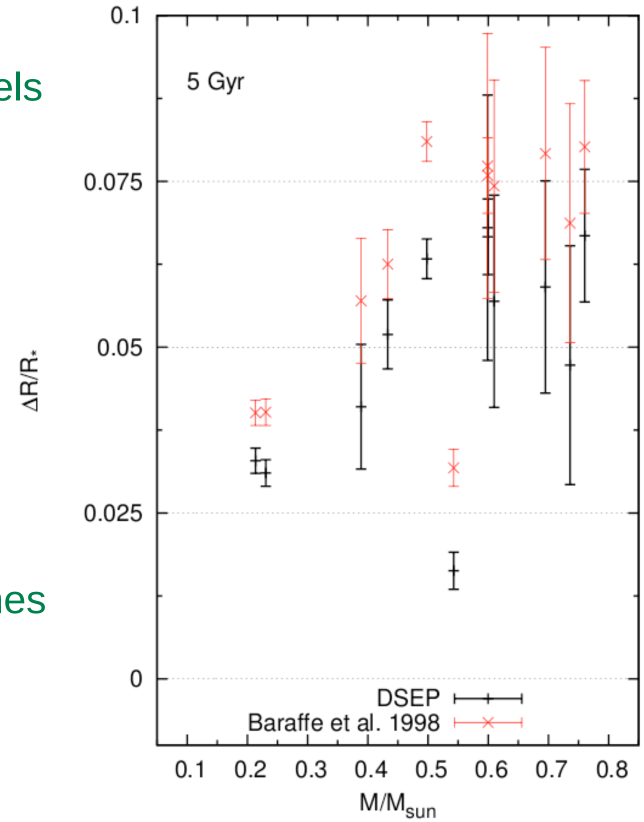


Modeling Low Mass Stars

Gregory Feiden
Dartmouth College



- Need for accurate stellar models
- Mass-Radius Relation
  - Baraffe et al. 1998
    - 5 - 8% discrepant
  - Dartmouth Code
    - 1 - 7% discrepant
- Future of Dartmouth Code
  - Magnetic field effects
  - Improved convection routines
  - Improved surface BCs



Investigating surfaces of earth-like exoplanets via scattered light

Yuka Fujii[1] (yuka.fujii@utap.phys.s.u-tokyo.ac.jp)

collaborators: H. Kawahara[6], Y. Suto[1,2,3], A. Taruya[1,2,4], S. Fukuda[5], T. Nakajima[5] & E. L. Turner[3,4]

1. Department of Physics, The Univ. of Tokyo, 2. RESCEU, The Univ. of Tokyo, 3. Department of Astrophysical Sciences, Princeton University, 4. IPMU, The Univ. of Tokyo, 5. Center of Climate System Research, The Univ. of Tokyo, 6. Tokyo Metropolitan University

CHARACTERIZING EARTH-LIKE EXOPLANETS WITH SCATTERED LIGHT

Light scattered by a planet carries an important piece of information because the scattering properties depends on of the details of the surface and atmosphere. It is also intriguing from the view point of astrobiology--- it may also let us probe the existence of ocean. Additionally, vegetation's "red edge", dramatic increase in reflectivity at $\lambda \sim$750nm which is related to the system of photosynthesis, may be a potential indicator of exo-life.

▶ Reconstruction of planetary surface from multi-band photometry

In decomposing the scattered light to extract the information of surface, the total scattered light is modeled with simplifying assumptions into a linear expression. Assumptions are that surface are classified into a few surface types each of which consists of surface with known albedo and an atmosphere, and that they are Lambertian.

$$I(\lambda) = R_p^2 I_*(\lambda) \iint f_{\Phi,\Psi}(\theta_0,\phi_0;\theta_1,\phi_1)\cos\theta_0\cos\theta_1\sin\Theta d\Theta d\Phi$$

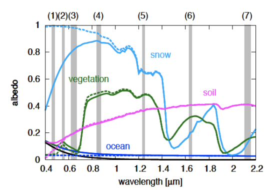
◇ 4 surface types

- ocean/soil/vegetation/snow + atmosphere

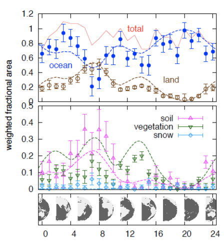
◇ Lambertian

$$I_j(t_i) = \sum_k \alpha_{jk} A_k(t_i) \qquad A_k(t_i) \equiv R_p^2 \int_{s_k} \cos\theta_0\cos\theta_1 ds$$

reflection intensity — Incident flux — reflection property — weighted area fraction



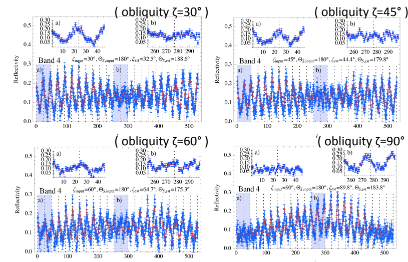
↑ Typical reflection spectra of representative surface type on the Earth (dashed: from ASTER spectral library, solid: including the effect of atmosphere by single scattering approx.)



Left figure is the result of solving the above matrix equation in terms of A_k using a mock diurnal light curves I_i of a cloudless Earth at 10 pc away seen at quadrature. The error bars come from the Photon shot noise only.

Main features such as Pacific ocean and the Amazon forest are recovered. Although ocean is mirror-like and the specular spot is fairly localized, the combination of ocean + atmosphere is a more Lambertian-like scatterer and it helps us to reliably estimate the weighted fraction of ocean.

▶ Orbital and the diurnal variation of mock cloudless Earth



variation of reflectivity in band 0.81-0.91um with different obliquity starting from winter solstice
(solid lines: predicted light curves with the best-fit parameters)

[Input]

- Reflection property
  - Atmosphere : Rayleigh scattering
  - Ocean : model (Nakajima & Tanaka 1983)
  - Land : MODIS dataset (Rossi-Li model)
- cloudless, no atmospheric absorption, no aerosols
- Face-on circular orbit

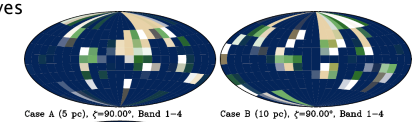
[Error estimation]

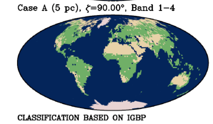
- O3-like mission with 1.1m aperture
- 5 pc-away system
- read noise, dark noise, exozodi noise included
- stack data for 14 days and fold the light curves to obtain diurnal light curves

▶ 2-dimensional mapping by combining orbital and the diurnal variation

The illuminated and visible region sweeps the planetary surface as the planet rotates around its spin axis and the host star (obliquity~90° is the most favorable for face-on orbit). Thus, in principle, one can obtain 2-dimensional information of planetary surface from overall variation.

Using 4 bands (centered at 0.47um, 0.56um, 0.64um, 0.86um) photometric data, we first decomposed the components of the surface and then mapped the pixelized surface by solving linear inverse problem with BVLS (Bounded-Variable Least-Squares) algorithm.





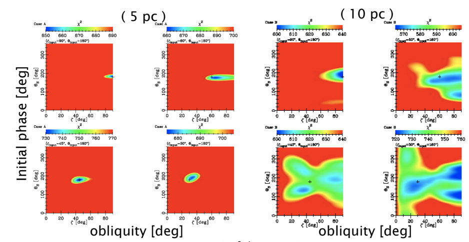
(obliquity ζ=90°)

←↑ "Soil" and "vegetation" are blended with yellow and green, respectively

▶ Obliquity dependence

The overall shape of the light curves depends on the planetary obliquity (and orbital parameters). (e.g., on face-on orbit, no phase variation will be seen if the obliquity is 0.)

Assuming that the planetary orbit is known, the obliquity is measured by optimizing the mapping in principle. This methodology reasonably works in the case of cloudless Earth 5pc away. for 10pc away case, it is marginal.



χ^2 of the mapping
(left: 5pc cloud-free case, right: 10pc cloud-free case, cross point: input values)

ONGOING ISSUES

- Effect of Clouds and decomposition of it from surface signal
- More realistic computation with radiative transfer
- Beyond the Earth model

REFERENCES

- Y Fujii et al. 2010, ApJ, 715, 866
- Kawahara and Fujii 2010, submitted to ApJ, arXiv: 1004.5152