101. KEPLER MISSION AND EXOPLANET STATISTICS

THE KEPLER MISSION AND EXOPLANET STATISTICS.
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ABSTRACT: Data from the Kepler Mission are profoundly expanding what is known about the galactic planetary census. The catalog of planets and high-quality planet candidates now numbers in the thousands, and large regions of orbital and physical parameter space (such as the zone harboring short-period planets with masses greater than Neptune's mass) are statistically well-described. Substantial numbers of planets with masses in the super-Earth range, or periods substantially longer than a year, have been detected. Planets are being discovered using transit photometry, Doppler spectroscopy, microlensing, astrometry, and direct imaging.

In this talk, I will attempt to delineate the salient feautres of the overall distribution. Of particular interest is a possible tension between the results of the Kepler Q0-Q3 data releases and the results of high-precision Doppler velocity surves such as the Geneva Observatory's HARPS GTO program. The HARPS radial velocity survey suggests that the occurrence fraction of planets with P<100 days and $M<M_{Neptune}$ is of order 50% among chromospherically quiet nearby stars, whereas a straightforward interpretation of the Kepler data suggests a substantially smaller occurrence rate for planets having these properties. I will discuss how these results can be brought into concordance, and I will outline the interesting possible consequences for planet formation theory. Also of interest is the distribution of orbital mean-motion resonances within extrasolar planetary systems. The Kepler Mission, with its accurate timing measurments of systems that contain multiple transiting planets, directly infers the distribution of low-order resonances, and confirms that a subdominant fraction of multiple-planet systems have planets that are deeply in resonance. This finding also has important consequences for planetary formation theories, and I will try to make the implications clear. Finally, with the planetary distribution that is currently in hand, it is possible to make (marginally) informed speculations regarding the frequency of analogs of solar system planets such as Earth and Jupiter. At the risk of going on record with statements that will be revealed in time as hopelessly naïve, I will make predictions (with error estimates) regarding the number of Earth-mass planets, and the frequency of systems that are true solar-system analogs.

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COROT EXOPLANET SEARCH. C. Moutou[1], M. Deleuil[1], A. Baglin[2] and the CoRoT Exoplanet Science Team
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Introduction: The CoRoT instrument is in operations since February 2007, searching for transiting planets and recording stellar oscillations. From light curve analyses to ground-based complementary observations, the team reports hundreds of candidates and a large family of confirmed planets. Figure 1 shows the present satisties of CoRoT planetary candidates as a function of the stellar magnitude. More than half of the candidates brighter than 14 are solved by the aid of follow-up observations, whereas faint stars are less well characterized.

We will discuss the status of the CoRoT program, the major breakthroughs, the recent findings, the small-planet statistics [1], and future prospects.

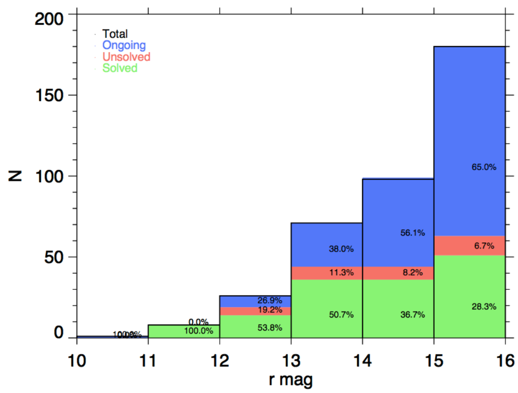

Figure 1: statistics of CoRoT planetary candidates known in the beginning of 2011. The bottom green area shows the proportion of solved configurations.

Planet population: The CoRoT field of view crosses the Galactic Plane towards two opposite directions, a major difference from the Kepler mission, since the stellar populations may strongly differ from one pointing to the next. The potential impact on the characteristics of planets is discussed.

Figure 2 shows a recent planet discovered by CoRoT and characterized by HARPS, CoRoT-20 b [2]. It is a short-period eccentric massive giant planet, which characteristics bring new constraints into the global picture of tidal history and orbital evolution.

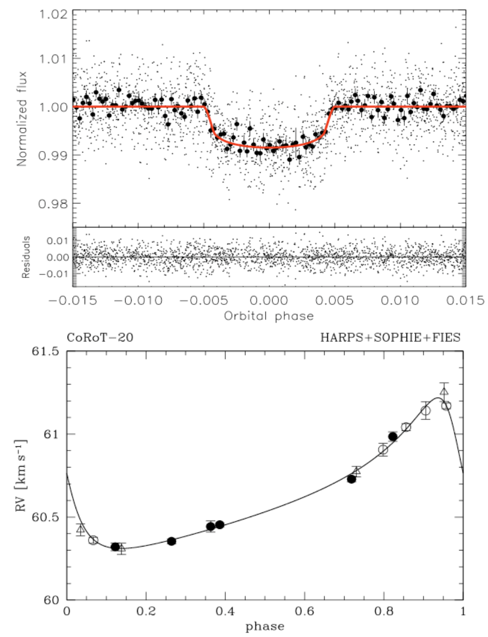

Figure 2: the transit light curve and radial-velocity curve of CoRoT-20 b [2].

Prospects: CoRoT will complete soon 5 years of observations, accompanied since the beginning by heavy ground-based observational effort. The objectives for extending the operations in the context of Kepler will be presented.

References::

[1] Bonomo A. et al, 2012, A&A subm
[2] Deleuil M. et al, 2011, A&A in press

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W. J. Borucki[1] and D. G. Koch[2], ([1]NASA Ames Research Center, Mail Stop 244-30, Moffett Field, CA 94035, William.J.Borucki@nasa.gov), ([2]NASA Ames Research Center, Mail Stop 244-30, Moffett Field, CA 94035, dkochx@gmail.com)

Kepler got its start more than a decade before the first 'exoplanets' were discovered around main-sequence stars when Audry Summers and I published a paper in 1984 that discussed the requirements for detecting exoplanets via transit photometry. [1] This simple – but technically challenging – technique requires detecting patterns of dips with amplitudes as low as 80 ppm in the presence of stellar variability many times higher. The requirements include high precision CCD detectors not yet demonstrated, space-borne observations, and the need to monitor many thousands of quiescent stars. That same year, the first NASA Ames Workshop on high-precision photometry was organized. A year later, a second published paper discussed the photometric limitations imposed by stellar variability. [2]

In 1987 a second NASA Ames Workshop on high-precision photometry, co-sponsored by the National Institute of Standards and Technology was organized. Workshop attendees mapped out a plan to operate a robotic telescope to assess the precision achievable from ground-based observations, to test CCDs, and to evaluate new-generation silicon diode detectors.

In 1992, NASA issued a solicitation for mission concepts that could be developed for moderate cost. The transit idea was favorably reviewed scientifically, but rejected for requiring detectors then thought not to exist. The first proposal to the newly created Discovery Program, in which a spacecraft would operate from a Lagrange point, was rejected for cost reasons in 1994. In 1995, Robinson et al [3] published the first results from a laboratory demonstration of detectors with the required precision to detect Earth-size planets. A less expensive mission proposed for solar orbit was rejected in 1996 because automated photometry of thousands of stars had not been demonstrated. During 1997 a fully automated photometric telescope was built and installed in the Crocker Dome at Lick Observatory. It communicated to NASA Ames by radio link where a pipeline had been installed to analyze the data. Team members did follow up observations of the discovered candidates. The successful operation of this facility demonstrated multi-target photometry with pipeline processing and follow up. A third Discovery proposal in 1998 was rejected because the anticipated on-orbit noise and performance had not been fully addressed. By this time, exoplanets were known to exist and HQ was sufficiently intrigued by the science potential to provide funding to develop a testbed facility to demonstrate the ability to generate and detect 80 ppm transits and to accommodate anticipated on-orbit noise.

The fourth attempt, in 2001, was successful and the Kepler mission began development. During development, many obstacles had to be overcome such as detector and filter problems, delays in delivery of the optics due to competing military programs, and unexpected cost increases. Compromises, such as removing onboard compensation for energetic particle hits, and the articulated antenna, were made as necessary.

Prior to the Kepler launch in March 2009, team members observed and classified 4.4 million stars in Kepler FOV to generate the Kepler Input Catalog (KIC) that was used to select those stars most suitable for planet detection. Since the launch, Kepler has been operating superbly, yielding data of phenomenal quality. A critical element in the scientific productivity of the Mission is the worldwide network of hundreds of scientists using many of the world's largest telescopes to conduct crucial follow-up observations to confirm planets. In addition, newly-developed theoretical models that interpret the transit timing variations are elucidating the structure of planetary systems and their planets.

Ongoing follow-up spectroscopic observations and their analyses are providing improved values of stellar temperatures, sizes, and metallicities for the stars that host planetary candidates. These new values contribute to better estimates of candidate size and association with stellar characteristics. Improvements to the data analysis pipeline now allow data taken during all quarters to be stitched together to form a contiguous time series that enhance the detection of small planetary candidates in long-period orbits. Intrinsic distributions of the candidates are being derived that allow estimates of the frequency distributions of planet size with semi-major axis and orbital period and to associate the results with stellar characteristics. Updated distributions are presented as well as a preliminary estimate of the frequency of Earth-size planets in the habitable zone based on the current candidate discoveries.

References:

[1] Borucki W. J. and Summer A. L. (1984) *Icarus., 58,* 121–134. [2] Borucki W. J. et al. (1985) *ApJ, 291,* 852-854. [3] Robinson L. et al (1995) *P ASP 107,* 1094–1098.

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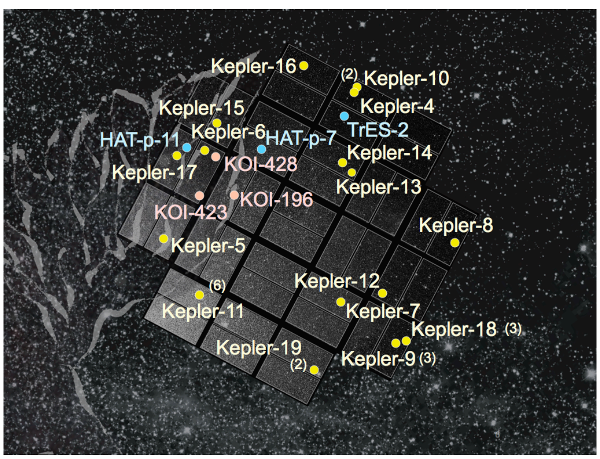
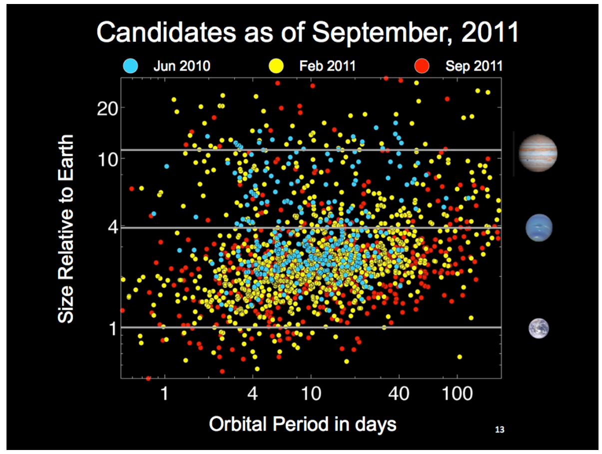
KEPLER'S EXOPLANET SURVEY: HONING IN ON ETA-EARTH N.M Batalha[1] and The Kepler Team, [1]San Jose State University (Department of Physics and Astronomy, One Washington Square, San Jose, CA 95192) Natalie.Batalha@sjsu.edu

Introduction: In the 2.5 years since launch, the Kepler Mission has changed the landscape of both exoplanet science and stellar astrophysics owing to its long-baseline, continuous, part-per-million precision. This contribution is a retrospective of exoplanet science from the Kepler science team, a look forward at the final year of the baseline mission, and prospects for an extended mission.

Planet Confirmations: The number of confirmed and characterized transiting planets has more than doubled this year. Major milestones include: our first rocky planet, Kepler 10-b[1], a six planet system, Kepler-11, characterized with the aid of transit timing variations[2], an unseen planet inferred from the transit time variations of Kepler-19b[3], and our first circumbinary planet, Kepler-16ABb[4]. Previously unexplored regions of the mass-radius diagram are now being studied, and the potential for measuring the masses of sub-Neptunian size planets via transit timing measurements is being fully exploited.



KOI Catalogs: Arguably the most important contribution of the Kepler Mission is the ever-growing catalog of viable planet candidates and the statistical information it contains. The team has scrutinized tens of thousands of transit events identified by the data analysis pipeline, has improved upon the suite of statistical tests used to assess the viability of the planet interpretation, and has collated the data products that speak to planet candidate properties and viability[5,6]. As of Feb 2011, 1,235 planet candidates associated with 997 stars had been identified from analysis of the first five quarters of data (May 09 - Jun 10). Planet frequency increases with decreasing size down to at least 2 R_e[7]. Future work will determine whether or not this trend continues down to 1 R_e.



Before year's end, the team will provide a catalog of new candidates identified from the analysis of six quarters of data (May 09 - Sep 10). We report the results of that effort here, including an update to the number of stars harboring earth-size, HZ, and multiple candidates. Larger than expected growth in the number of candidates is a byproduct of pipeline improvements such as the ability to join data from different quarters to identify longer-period and smaller planet candidates. It is exactly these niches of the parameters space that have seen the largest gains.

Future Direction: We focus on strategies that lead toward the determination of eta-Earth, namely: 1) pipeline improvements which yield the largest numbers of earth-size transit detections, 2) knowledge of pipeline detection efficiency, and 3) determination of the rate of astrophysical false positives. Instrument noise and intrinsic stellar variability on the 6.5-hr timescale have been quantified[8]. The data reveal that the Sun is quieter on this time scale than most solar-type stars in the Kepler sample. Pre-launch estimates of the detectability of earth-size planets based on extrapolations from solar data can now be recomputed using the observed distributions. The results drive planning for the remainder of the baseline mission and beyond in which the determination of eta-Earth is our continued priority.

References:

[1] Batalha, N.M. et al. (2011) *ApJ, 729,* 27.
[2] Lissauer, J.J. et al. (2011) *Nature, 470,* 53.
[3] Ballard, S. et al. (2011) *arXiv:1109.1561*.
[4] Doyle, L. (2011) *Science, 222, 1602,*.
[5] Borucki, W.J. (2011) *ApJ, 728, 117.*
[6] Borucki, W.J. (2011) *ApJ, 736, 19.*
[7] Howard, A. et al. (2011), *arXiv:1103.2541*
[8] Gilliland et al. (2011) *ApJS, 197, 6*

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Overview of the Kepler Science Operations Center Pipeline. J. M. Jenkins[1] and the Kepler SOC/SO Teams, [1]SETI Institute, M/S 244-30, NASA Ames Research Center, Moffett Field, CA 94035; Jon.Jenkins@nasa.gov.

Introduction: The *Kepler* Science Operations Center (SOC) processes the ~160,000 Long Cadence (29.4 min) and 512 (per month) Short Cadence (58.8 Sec) data downlinked by the *Kepler* spacecraft each quarter to produce calibrated pixels (from the CAL pipeline), and for each target star, several time series products:

1) simple aperture photometric flux time series and brightness-weighted centroids from the Photometric Analysis (PA) pipeline, systematic error-corrected flux time series from the Presearch Data Conditioning (PDC) pipeline.

The Transiting Planet Search (TPS) pipeline scours the PDC lightcurves for signatures of transiting planets using a wavelet-based, adaptive matched filter [1], and stars with signatures >7.1σ are subjected to a series of diagnostic tests by the Data Validation (DV) pipeline which also extracts physical parameters for the planet using a general least-squares approach, and then searches for additional transit signatures in the residual light curves.

SOC 8.0: A Brand New Pipeline: The SOC has recently completed testing a new codebase and has deployed it to operations. We are processing all new data sets with this code base and are reprocessing all existing data sets with SOC 8.0 as quickly as practical and estimate that quarters Q0 – 3 will be reprocessed and archived by March 2012 and we expect to complete reprocessing Q4 – 9 in July 2012.

We highlight the most important improvements to the data products for the astrophysicist in this talk.

The most striking improvement in SOC 8.0 is the correction of systematic errors by PDC, as illustrated by Fig. 2. Other improvements include better handling of 1-D black corrections to account for known scene-dependent artifacts in CAL, higher robustness against transient artifacts through the use of a robust detection statistic in TPS. Pixel Response Function-based centroiding and centroid offset analysis were also added to DV to help discriminate between real transiting planets and astrophysical false positives.

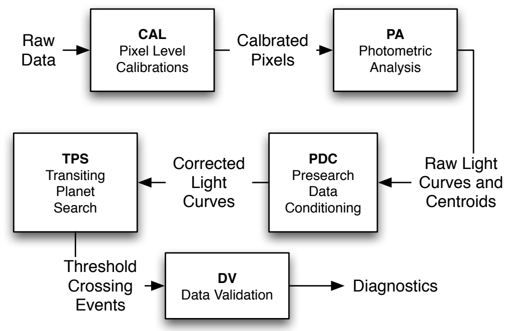

Figure 1: Data flow through the SOC Pipeline

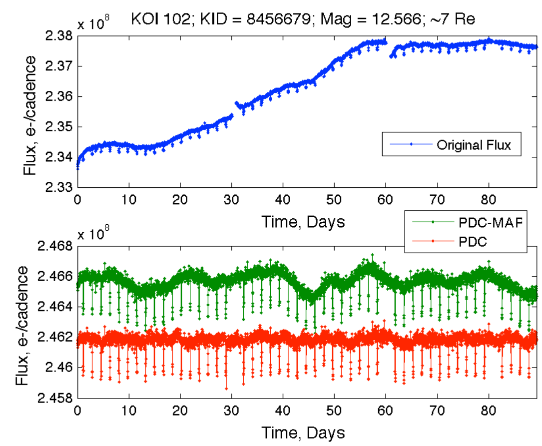

Figure 2: Example of the Bayesian Maximum A Posteriori (MAP) approach in SOC 8.0 to correcting systematic errors. KOI 102 is a planet candidate with a 7 R_e radius. The original Presearch Data Conditioning over-fitted the data, removing intrinsic stellar variations on timescales longward of days and introduced additional short timescale noise. The new MAP approach does a beautiful job of preserving the intrinsic stellar variations due to spots that were completely wiped out by the original PDC software.

References:

[1] Jenkins, J. (2002) *ApJ*, 575, 493.

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OVERVIEW OF THE TRANSITING PLANET SEARCH SOFTWARE IN THE KEPLER ANALYSIS PIPELINE. P. Tenenbaum[1], J.M. Jenkins[2] and S. Seader[3], [1]SETI Institute, NASA Ames Research Center, Mail Stop 244-30, Building N244 R301, Moffett Field, CA 94035; peter.tenenbaum@nasa.gov. [2]SETI Institute, jon.jenkins@nasa.gov. [3]SETI Institute, shawn.seader@nasa.gov.

Introduction: The Kepler dataset includes flux time series from almost 200,000 stars. Each flux time series includes samples taken every 29.4 minutes, and most of the flux time series cover the full duration of the Kepler mission (about 2.5 years so far). The Transiting Planet Search (TPS) module performs an automated search of each light curve for periodic transit-like signals with durations from 1.5 hours to 15 hours and periods from 0.5 days to the full duration of the dataset.

Quarter Stitching: TPS is the first stage of the pipeline which receives flux time series from multiple seasonal orientations ("quarterly rolls") of the Kepler spacecraft. The different CCDs can have significantly different properties, and additionally the corrected light curves from different quarters can also have different behaviors. TPS needs to combine the data from multiple quarters into a contiguous flux time series.

The first step in "quarter stitching" is to median-correct the flux time series from the individual quarters. Each quarter's flux is divided by the median flux value for that quarter, and 1 is subtracted. This converts from absolute flux in photoelectrons to fractional deviation from median flux, thus eliminating scale variations from the time series.

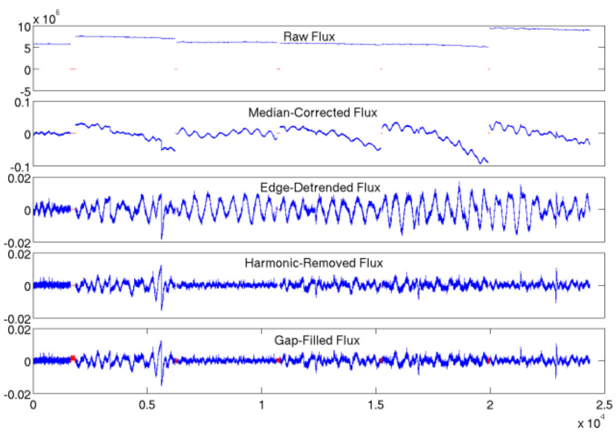

Figure 1. Steps in the quarter stitching of a flux time series. Horizontal axis is sample number; vertical axis is photoelectrons for the top plot and fractional deviation from median for all others.

The second step corrects trends at the leading and trailing edges of a quarter. The data from each quarter is fitted with a detrending function composed of a straight line plus two exponentials (one for the leading edge, one for the trailing). The detrending function is subtracted from the data. This allows the edges of the time series to be connected without severe discontinuities.

The third step removes highly-sinusoidal oscillations (narrow band harmonics) from each quarter of the flux time series. These highly-harmonic signatures cause confusion in subsequent stages of analysis if not removed.

Finally, the gaps between quarters are filled in a manner which minimizes the impact on the power spectral density of the flux time series. The resulting contiguous and well-conditioned time series can now be subjected to the subsequent analysis steps.

Figure 1 illustrates the steps in quarter stitching of a flux time series.

Wavelet Analysis: Detection of small transit-like features within the non-stationary, non-white stellar variability is made possible by performing a joint time-frequency decomposition of the light curve. This is accomplished using a wavelet-based whitening filter [1,2]. This analysis allows us to determine the Combined Differential Photometric Precision (CDPP) and the single event detection statistic at all sample times in the time series.

Folding in Time: The Single Event Statistic time series is analyzed for evidence of a periodic transit-like signature. This is accomplished by taking the Single Event Statistics and "folding" them over one another at periods from 0.5 days to the mission duration to date. At each period a Multiple Event Statistic is computed, which specifies the SNR for a transit detection at the given period. Stars which have a Multiple Event Statistic greater than 7.1 sigmas are then subjected to additional tests designed to identify false positives [3]. Targets which pass that test are then sent to the Data Validation (DV) pipeline module [4,5] for additional automated study.

Acknowledgements: Funding for the Kepler Mission is provided by the National Aeronautics and Space Administration (NASA) Science Mission Directorate.

References: [1] Jenkins, J.M (2002) *ApJ,575,* 493-505. [2] P. Tenenbaum et al, these proceedings (2011). [3] S. Seader et al, these proceedings (2011). [4] J. Li et al, these proceedings (2011). [5] J. Twicken et al, these proceedings (2011). [6]

Uniform Modeling of the Kepler Objects of Interest Catalog. J.F. Rowe[1] the Kepler Team, [1] The SETI Institute/NASA-Ames, NASA-Ames Research Park, MS-244-30, Moffett Field, CA 94035-1000, Jason.Rowe@nasa.gov

Introduction: We present the first catalog of uniform state-of-the-art lightcurve modeling for Kepler's list of planetary candidates using tested and validated algorithms. This process involved modeling planetary transits, phase curves and orbits. We used observables obtained from Kepler-photometry and ground-based follow-up to determine key planetary parameters such as the radius and mass. More importantly, we deter-mined posterior probability distributions for the fitted parameters by employing a Markov chain Monte Carlo algorithm.

We have measured with uncertainties: stellar parameters, orbital periods, planet radii, inclinations. When sufficient groundbased radial velocities are available we have modeled orbital solutions and planetary densities. We also model multi-planet, transiting systems by fitting for each planet-candidate simultaneously.

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Kepler Completeness Study. J. L. Christiansen[1], C. J. Burke[1], and the Kepler Completeness Team [1]SETI Institute/NASA Ames Research Center, M/S 244-30, NASA Ames Research Center, Moffett Field, CA, 94035; jessie.l.christiansen@nasa.gov

Introduction: We describe the ongoing efforts in the Kepler Science Office to characterize the completeness of the Kepler results, which is fundamental to measuring the frequency of Earth-size planets in the habitable zone.

We present the first results from an initial test of the detection completeness of the pipeline. For each target, for a set of trial durations (from 1.5 to 15 hours), the pipeline generates a Combined Differential Photometric Precision (CDPP) time series (see Figure 1 for an example). The time series is a cadence-by-cadence measure of the depth of a signal of that duration that would produce a 1-sigma detection [1].

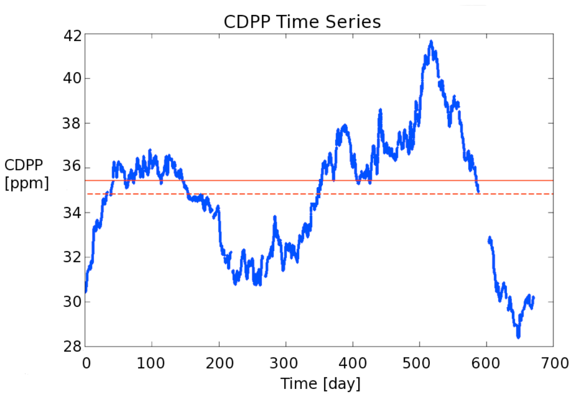

Figure 1: The 6-hour CDPP time series for a typical 12th magnitude Kepler target. The red lines are the mean (dashed) and median (solid) CDPP values over the time series.

We consider the full set of Kepler targets as a large number of independent statistical tests for calibration of the CDPP time series, and use those time series to measure the overall detection efficiency. For each target, we select a set of planet parameters from a prior distribution, and inject the resulting signal train into the calibrated pixels. We choose to space the transits at a higher cadence than the orbital period of the injected planet in order to maximise the number of independent tests per target (see Figure 2 for an example of such a signal). We then investigate any systematic changes to the signal through the pipeline. We expect the most shallow (and therefore, most interesting) signals, to be the least perturbed by the pipeline.

We then determine a set of completeness metrics over a grid of planet radii and periods. For a given detection threshold (7.1 sigma in our case), we can use the CDPP time series to determine whether a transit signal produced by a planet of a particular size, period and orbital inclination would produce a detection (see Figure 3). Working towards a complete end-to-end measurement of the pipeline detection completeness will enable characterization of the underlying planet population with Kepler.

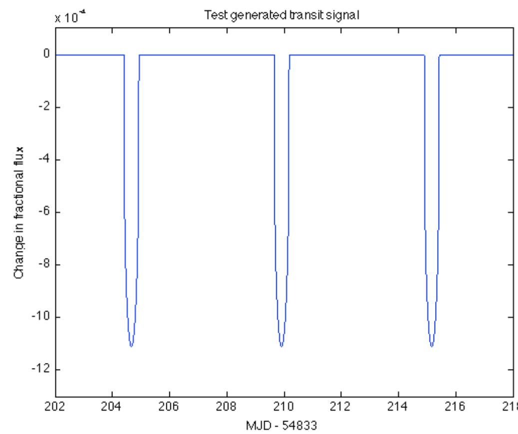

Figure 2: A sample transit signal for injection. The transit shape is defined by the orbital period of the test planet, however the spacing is reduced to maximize the number of tests.

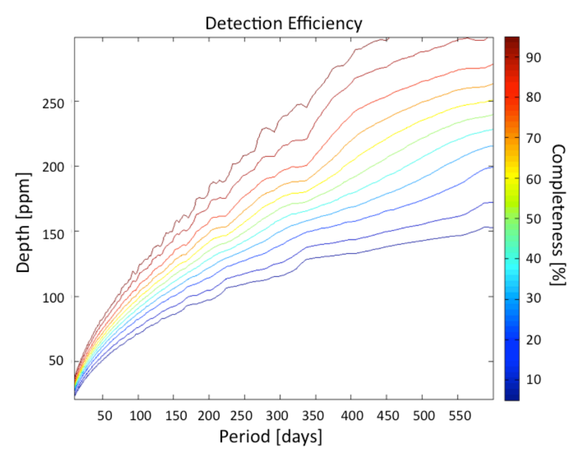

Figure 3: The detection efficiency of a typical 12th magnitude Kepler target as a function of completeness, from 5% complete in blue (very few planets could have been detected) to 95% complete (nearly all planets could have been detected)

References:

[1] Jenkins J. M. et al. (2010), *SPIE*, 7740, 10

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Noise Sources Impacting *Kepler's* Photometry and Mission Goals. D. A. Caldwell[1], E. W. Dunham[2], Vic S. Argabright[3], W. J. Borucki[4], W. J. Chaplin[5], J. L. Christiansen[1], T. N. Gautier III[6], R. L. Gilliland[7], J. M. Jenkins[1], J. J. Kolodziejczak[8], and J. E. Van Cleve[1]; [1]SETI Institute, MS 244/30, NASA ARC, Moffett Field, CA 94035, [2]Lowell Observatory, [3]Ball Aerospace and Technologies Corp., [4]NASA Ames Research Center, [5]University of Birmingham, [6]Jet Propulsion Laboratory, [7]Space Telescope Science Institute, [8]NASA Marshall Spaceflight Center

Introduction: The pre-eminent scientific goal of the *Kepler Mission* is to determine the frequency of Earth-size and larger habitable zone planets. The science requirements of the mission were designed to support this goal. Two related key requirements are the photometric precision for 12th magnitude dwarf stars and mission lifetime. The precision requirement was necessarily set without knowledge of typical levels of stellar variability. We find the noise for Kp=12 dwarf stars is dominated by stellar variability and the overall noise is ~50% higher than the required value. The increased noise substantially reduces Kepler's ability to achieve its scientific objectives within the 3.5 year baseline mission, but extending the duration of the mission to allow averaging of more transits will regain Kepler's initially envisioned capability.

Noise Measurements: Kepler's ability to detect transits by small planets in habitable-zone orbits depends on the total noise on transit timescales, called Combined Differential Photometric Precision (CDPP). CDPP includes intrinsic stellar variability, Poisson + readout noise, detector noise, and the mitigations included in the processing software. Measured CDPP from Quarter-4 is shown in Figure 1. The mode of the distribution for dwarf targets at Kp=12 is 30ppm. Only ~1% of the dwarfs meet the 20 ppm requirement. We investigated several different approaches for photometry and none makes a significant improvement in CDPP. Gilliland et al. [1] demonstrate that larger than expected stellar variability (19.5 ppm vs 10 ppm allocated) is responsible for the bulk of the increase in CDPP over predictions and that there are only modest increases in Poissson + readout noise (16.8 vs 14.1 ppm) and intrinsic detector noise (10.8 vs 10.0 ppm).

Planet Yield Predictions: In order to quantify the impact of increased CDPP on projected mission results, we calculate the detection probability –including geometric alignment probability– for a variety of planet sizes following the approach given in [2]. Our predictions depend strongly on the stellar parameters as determined in the Kepler Input Catalog[3]. We are especially sensitive to stellar radius as transit S/N ~ $(R_p/R_*)^2$. The distribution of dwarf targets in R_*, T_{eff} space is shown in Figure 2. We will present the expected number of Earth-size habitable zone planet detections under the assumption that each star has such a planet and explore the sensitivity to uncertainties in the stellar parameters and the length of the mission.

The current Kepler Objects of Interest (KOIs) with $R_p < 2\ R_{Earth}$ are overlayed on Figures 1&2. The Earth-size planet candidates are biased to bright stars, but span the distribution of R_* and T_{eff}. While these KOIs tend to be short period candidates –well inside the habitable zone- they give us an indication that there is not a significant undetected bias in our stellar parameters.

References: [1] Gilliland R. L., et al. (2011) accepted by *ApJ* (2011arXiv1107.5207G). [2] Borucki, W. J., et al. (2011) *ApJ* 728, 117. [3] Brown, T. M., et al. (2011) *AJ*, 142, 112

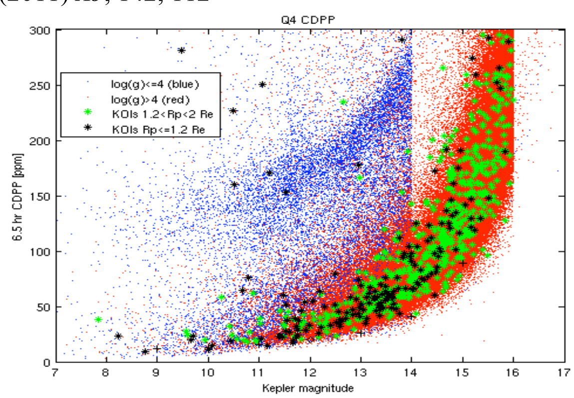

Figure 1: 6.5 hr CDPP for all targets. Stars with log(g)>4 are shown in red, evolved stars in blue. The clear breaks in the distribution at Kp=14 & 16 result from target selection. KOIs with $R_p < 2\ R_{Earth}$ are overlayed. Terrestrial-size candidates span the entire magnitude range of the Kepler planetary target set.

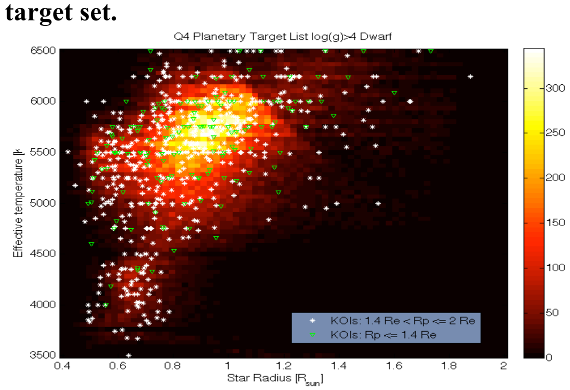

Figure 2: T_{eff} versus R_* for Q4 dwarf targets. The 2-D histogram shows the number of targets per bin in R_*, T_{eff} space (bin sizes ~ 0.02 R_{Sun} and 45K). KOIs with $R_p < 2\ R_{Earth}$ are overlayed, indicating no strong bias in the location of KOIs relative to the target list.

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USING SPITZER TO ESTIMATE THE KEPLER FALSE POSITIVE RATE AND TO VALIDATE KEPLER CANDIDATES. J. M. Désert[1], D. Charbonneau[1], F. Fressin[1], G. Torres[1], and the Kepler Science Team
[1]Harvard-Smithsonian Center for Astrophysics, Cambridge, MA02138, USA. (jdesert@cfa.harvard.edu)

I present the results from an 800 hour campaign with the Spitzer Space Telescope to gather near-infrared photometric measurements of Kepler Objects of Interest (KOI). Our goals are (1) to validate the planetary status of these Kepler candidates, (2) to estimate observationally the false positive rate, and (3) to study the atmospheres of confirmed planets through measurements of their secondary eclipses. Our target list consists of 34 candidates ranging in size from 15 to 1.6 Earth radii, orbiting stars which range in spectral type from F8V to MIV, with orbital periods up to 100 days.

Our Spitzer observations provide two constraints on the possibility of astrophysical false positives resulting from stellar blends, including eclipsing binaries and hierarchical triples: First, true planetary transits should be achromatic, whereas stellar blends will show a difference in transit depths between Kepler and Spitzer (see Figure 1). Second, the color (*Spitzer*$_{4.5\mu m}$ - *g*) also provides a strong constraint on the presence of a second star.

A substantial effort in this project resides on obtening precise stellar characterization for the stars of interest. This is done using spectroscopic reconnaissance. The Spitzer results and the knowledge of the star allows to set limits on the stellar properties of potential blend scenarios. Since, the number of stars within the Kepler photometric apertures vary with the position of the KOI on the field of view, the number of possible blends vary for each candidate. This number is estimated using stellar population synthesis models and observational probes of the KOI close environements from direct imaging (e.g. Adaptive Optics, Speckle images, Kepler centroids). Combining all the above information, we compute odd ratios for all the 34 candidates in order to determine their false positive probability. Our results suggest that the Kepler false positive rate in this subset of candidates is extremely low.

We also anticipate validating several of the candidates and presenting these new planets during the conference.

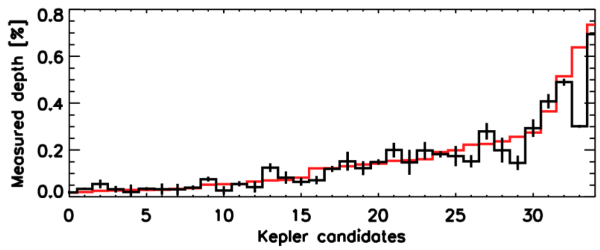

Figure 1: Transit depths measured with Kepler (in red) and with Spitzer (in black) for the 34 Kepler candidates that we followed-up for this large program on Warm-Spitzer. The target are ordered with increasing transit depths towards the right. For 32 of the 34 targets, the depths measured with Spitzer are in agreement with those from Kepler. For the remaning two, the disagreements are explained by the larger PSF of Kepler which include a known nearby star, and hence the planet interpretation is valid.

111. EARTH ANALOG AND SUB-NEPTUNE-SIZE PLANETS

Patterns of Low-mass Planet Occurrence from *Kepler* and Doppler Planet Searches. A. W. Howard[1], G. W. Marcy[1], and the *Kepler* Team. [1]Department of Astronomy, University of California, Berkeley, CA 94720; howard@astro.berkeley.edu, gmarcy@berkeley.edu.

Introduction: The distribution of planets as a function of their size, orbital period, and host star spectral type offers key probes of planet formation, migration, and evolution. We measured these distributions using *Kepler* data [1] and compare the occurrence patterns with Doppler planet searches from Keck/HIRES [2] and HARPS [3].

Patterns of Planet Occurrence from *Kepler*: Planet occurrence varies by three orders of magnitude for planets having orbital periods shorter than 50 days, with smaller and more distant planets being the most common (Figure 1). Summing over these orbital periods, the planet radius function (Figure 2) increases in logarithmic planet radius bins as a power law with exponent -2.01 ± 0.09. The rapid increase with decreasing planet size agrees with core-accretion, but disagrees with population synthesis models.

Planet occurrence versus orbital period has a more complicated dependence. Occurrence falls off steeply for periods shorter than a cut-off of ~2-10 days, perhaps owing to star-disk-planet interactions. For periods longer than the cutoff, planet occurrence increases modestly as a power law with increasing period.

The occurrence of close-in planets smaller than Neptune (2-4 Earth-radii) increases by a factor of seven from the hottest stars in the *Kepler* sample (~F2 dwarfs, T_{eff} = 6600-7100 K) to the coolest (~M0 dwarfs, 3600–4100 K).

This talk will emphasize how planet occurrence can be reliably measured in *Kepler* data, the occurrence trends from the Feb. 2011 data release [4], and will show how planets from the Sept. 2011 data release [5] can be used to probe planets smaller than 2 Earth-radii and beyond 50-day orbits.

Concurrence between *Kepler* and Doppler Occurrence Measurements: Planet occurrence has also been measured by Doppler surveys using Keck/HIRES [2] and HARPS [3]. The qualitative patterns of increasing occurrence with decreasing planet radius/mass and increasing orbital period are seen in each data set. The HIRES and HARPS measurements agree with each other to within ~1-σ for their overlapping region of high completeness ($M\sin i$ > 3 M_e, P < 50 days). Comparisons with *Kepler* are complicated because *Kepler* measures planet radius, not $M\sin i$. Nevertheless, for reasonable lower bounds on planet radius and $M\sin i$, the three results are at least approximately consistent. A more detailed comparison [1] has shown that the HIRES and *Kepler* occurrence measurements are compatible for a physically plausible planet density function.

References: [1] Howard, A. W. et al. 2011. *ApJ* (submitted, arXiv: 1103.2541). [2] Howard, A. W. et al. 2010. *Science*, 330, 653. [3] Mayor, M. et al. 2011. *A&A* (submitted, arXiv: 1109.2497). [4] Borucki W. J. et al. 2011. *ApJ*, 736, 19. [5] Batalha, N. M. 2011. *Extreme Solar Systems II meeting*, Jackson Lake Lodge, Wyoming, abstract #01.01.

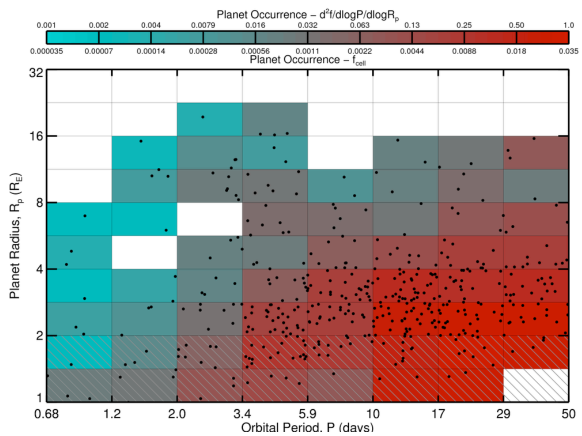

Figure 1. Close-in planet occurrence versus orbital period and planet radius, as measured by *Kepler* [1]. Planet occurrence is highest for smaller planets and longer orbital periods (red tiles in lower right), and is corrected for non-uniform transit probability and detection completeness over this plane.

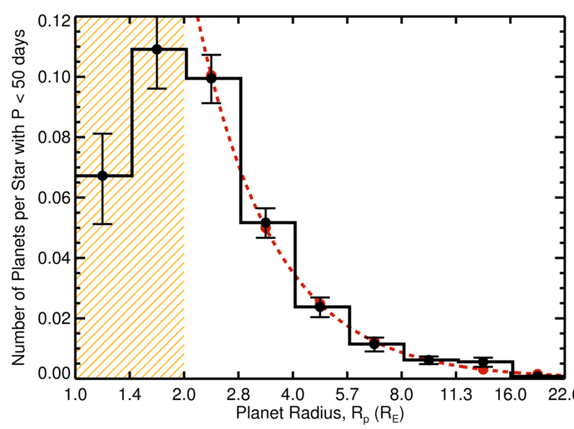

Figure 2. Intrinsic close-in planet occurrence as a function of planet radius, as measured by *Kepler* [1]. Only high signal-to-noise transits of planets orbiting bright, GK dwarf stars were used to compute occurrence. For planets smaller than 2 Earth-radii, *Kepler* occurrence measurements are likely incomplete.

112. EARTH ANALOG AND SUB-NEPTUNE-SIZE PLANETS

OCCURRENCE, MASS DISTRIBUTION AND ORBITAL PROPERTIES OF SUPER-EARTHS AND NEPTUNE-MASS PLANETS FROM THE HARPS SURVEY. C. Lovis[1], M. Mayor[1], M. Marmier[1], S. Udry[1], D. Ségransan[1], F. Pepe[1], W. Benz[2], J.-L. Bertaux[3], F. Bouchy[4], X. Dumusque[1], G. Lo Curto[5], C. Mordasini[6], D. Queloz[1], N.C. Santos[7,8], [1]Geneva Observatory, University of Geneva (christophe.lovis@unige.ch), [2]Physikalisches Institut, Universität Bern, [3]LATMOS, CNRS/UVSQ Université de Versailles, [4]Observatoire de Haute-Provence, [5]European Southern Observatory, [6]Max-Planck-Institut für Astronomie, [7]Centro de Astrofísica, Universidade do Porto, [8]Departamento de Física e Astronomia, Faculdade de Ciências, Universidade do Porto.

Introduction: We report on the results of an 8-year survey carried out at the La Silla Observatory with the HARPS spectrograph to detect and characterize planets in the super-Earth and Neptune mass regime. The size of our star sample and the precision achieved with HARPS have led to the detection of a sufficiently large number of low-mass planets to study the statistical properties of their orbital elements, the correlation of the host-star metallicity with the planet masses, as well as the occurrence rate of planetary systems around solar-type stars.

Results: A robust estimate of the frequency of systems shows that more than 50% of solar-type stars harbor at least one planet of any mass and with period below 100 days. Different properties are observed for the population of planets less massive than about 30 $M_\oplus$ compared to the population of gaseous giant planets. The mass distribution of Super-Earths and Neptune-mass planets (SEN) is strongly increasing between 30 and 15 $M_\oplus$. The SEN occurence rate does not exhibit a preference for metal-rich stars. Most of the SEN planets belong to multi-planetary systems. The orbital eccentricities of the SEN planets seems limited to 0.45. At the opposite, the occurence rate of gaseous giant planets is growing with the logarithm of the period, and is strongly increasing with host-star metallicity. About 14% of solar-type stars have a planetary companion more massive than 50 $M_\oplus$ on an orbit with a period shorter than 10 years. Orbital eccentricities of giant planets are observed up to 0.9 and beyond.

Conclusions: The precision of HARPS-type spectrographs opens the possibility to detect planets in the habitable zone of solar-type stars. Identification of a significant number of super-Earths and Neptunes orbiting solar-type stars in the vicinity of the Sun has been achieved by Doppler spectroscopy. The detected planet population, corrected from instrumental biases, can be compared to the population detected by Kepler with the goal of constraining the bulk composition and orbital architecture of low-mass planetary systems.

FORMATION AND STRUCTURE OF NEPTUNE-SIZE EXOPLANETS. Peter Bodenheimer[1], Leslie A. Rogers[2], Jack J. Lissauer[3], and Sara Seager[4]. [1]UCO/Lick Observatory, Department of Astronomy and Astrophysics, University of California, Santa Cruz, CA 95064, peter@ucolick.org. [2]Massachusetts Institute of Technology, larogers@mit.edu. [3]NASA-Ames Research Center, Jack.J.Lissauer@nasa.gov. [4]Massachusetts Institute of Technology, seager@mit.edu.

Introduction: Transit measurements by *Kepler* have revealed hundreds of planet candidates with radii between 2 and 6 Earth radii within 0.5 AU from their stars. For most of these objects, the masses, and therefore the mean densities, have not been measured. By using numerical simulations of planet formation, structure, and evolution, we explore the range of possible masses for these objects, with an emphasis on determining their minimum plausible masses. The models focus on highly irradiated exoplanets with equilibrium temperatures of 500 K or above. The main question to be investigated is the formation mechanism for these objects. We consider two possible formation mechanisms for low-mass planets with low-density envelopes of hydrogen and helium: core-nucleated accretion, and outgassing of hydrogen from dissociated ices.

Core-nucleated accretion models: Core accretion models in the past [1] have emphasized the formation of Jupiter- or Saturn-like objects with heavy-element cores of 5-15 Earth masses and light-element envelopes of 100 or more Earth masses. In this study we consider a new regime of parameter space. Models of protoplanetary disks are chosen with surface densities of solid material at 4 to 5 AU low enough so that cores of only 2-4 Earth masses are able to form on a time scale of 2-4 Myrs. The nebular gas dissipates before the planet has a chance to collect a high-mass envelope. The planets then are assumed to migrate inwards until they reach equilibrium temperatures of 500 to 1000 K. After accretion stops, the evolution is calculated at constant mass up to times of 1 to 4 Gyrs, at which times the outer radius is determined. Models are also considered in which the planet forms at smaller distances, from 0.5 to 2 AU. In these cases the disk surface densities are high enough so that a core of about 2.2 Earth masses forms, and the disk temperatures are high enough to preclude the formation of a high-mass envelope. The models calculated here include the settling and coagulation of grains for the determination of the opacity of the gaseous envelope [2]. Plausible models with radii in the observed range are found, having heavy-element core masses in the range 2-3 Earth masses and gaseous envelope masses of order 0.1 Earth masses.

Formation by outgassing of hydrogen: For the cases of rocky planets with outgassed hydrogen envelopes, we consider the mechanism in which water reacts with metallic iron to form molecular hydrogen [3] during planet formation. We consider the limiting case in which the iron and the water react to the maximum extent possible, leaving the planet with no excess surface water. This assumption leads to the maximum radii possible for planets with outgassed atmospheres. The derived limiting mass-radius relation shows that radii are typically well below 3 Earth radii for masses in the range 4-30 Earth masses. Thus outgassing of hydrogen from planets formed mainly from rocky material is unlikely to account for the planets observed by *Kepler* to have radii in the range 3 to 6 Earth radii.

Equilibrium models: For both formation mechanisms we employ equilibrium models of planets [4,5]. Such models allow the exploration of a much larger range in parameter space than is possible by the use of detailed formation models. For cases with the same parameters, the radii of the equilibrium models agree well with those derived from the full core-accretion calculation. We determine the range of the parameters (planet mass, envelope mass, equilibrium temperature) that is consistent with the range of observed radii. Atmospheric mass loss is considered in order to eliminate some portions of this parameter space. The results show that the *Kepler* candidates with radii of 2 to 6 Earth radii could plausibly have masses of 4 Earth masses or less, although masses a few times higher are also possible. For example, a model planet with a mass of 5 Earth masses and a radius of 4 Earth radii must have a gaseous envelope mass in the range 5 to 15 percent of the total planet mass for an equilibrium temperature of 500 K, and only 2-6 percent of the planet mass for 1000 K. Thus warm exoplanets of Neptune size can have masses substantially smaller than that of Neptune itself. Although the numerical results depend on several assumptions, this qualitative conclusion is robust.

Acknowledgements: P. B. and J. L. acknowledge support from the NASA Origins program. P. B. acknowledges support from NSF grant AST-0908807,

References: [1] Pollack, J. B. et al. (1996), *Icarus, 124*, 62–85. [2] Movshovitz, N. et al. (2010), *Icarus, 209*, 616-624. [3] Elkins-Tanton, L. T., and Seager, S. (2008). *ApJ, 685*, 1237-1246. [4] Rogers, L. A., and Seager, S. (2010), *ApJ, 712*, 974-991. [5] Rogers, L. A., and Seager, S. (2010), *ApJ, 716*, 1208-1216.

114. EARTH ANALOG AND SUB-NEPTUNE-SIZE PLANETS

RV FOLLOW-UP OF SMALL PLANETS FROM *KEPLER*: VERIFICATION, MASSES, AND DENSITIES

G. Marcy[1], H.Isaacson[1], A.Howard[1], L.Rogers[2], S.Seager[2], D.Sasselov[3], and the *Kepler* Team. [1]Department of Astronomy, University of California, Berkeley, CA 94708, [2]Department of Physics, Massachusetts Institute of Technology, Cambridge MA 02139, [3]Department of Astronomy, Harvard University, 60 Garden St., Cambridge, MA 02138; gmarcy@berkeley.edu, hisaacson@berkeley.edu; howard@astro.berkeley.edu, larogers@mit.edu, seager@mit.edu, dsasselov@cfa.harvard.edu.

Introduction: All KOIs remain "candidate planets" until a verification is carried out that provides strong (>99%) confidence that the transit signature in the photometry is actually caused by an orbiting planet. If so verified, the masses of the planets remain unknown until some dynamical technique measures the gravitational effect of that planet on other objects, either the star (with RV measurements) or other planets (with TTVs). Measuring planet masses is particularly important as, when combined with the transit-based planet radii, they yield the bulk density of the planets, constraining conditions in the interior, notably the amount of metal, rock, water, and gas. For planets much smaller than 4 Earth-radii, the transition between Neptune-like and rocky planets is particularly intriguing, bearing on formation, evolution, and habitability.

The RV Data: We provide precise (~2 m/s) Doppler RVs for 15 KOIs having planet radii considerably smaller than 4 Earth radii (sub-Neptune) to probe the transition toward rocky planets. New techniques are employed to obtain RV measurements for faint stars of ~13th mag, notably real-time, long-slit sky subtraction and statistical priors for PSF and wavelength scale in the Doppler analysis. The RV observations are timed at moments near orbital quadrature to maximize the RV differences. We obtained 10-20 RVs for each of 15 KOIs, with typical exposure times of 30 min.

The Orbital Models: The RVs are first fit with circular orbit, Keplerian models that include all transisting planets and their known ephemerides from the *Kepler* photometry. The free parameters are only the masses of the planets (and RV zero point). Both random and systematic errors will not be correlated with orbital phase, ensuring that the RV signal-to-noise improves as the square root of the number of RV observations. Orbital fits provide planet mass, density, and in some cases contraints on eccentricity. For RV non-detections, MCMC analyses provide upper limits to planet mass and density. Some of the RV non-detections may be false positives, the probability of which requires a BLENDER analysis to anticipate possible eclipsing binary scenarios that reproduce the light curve without a planet. Detailed analysis of the spectrum of a KOI can rule out (or in) the presence of such an eclipsing binary. For the multi-planet systems, the false-positive probability is normally under 1%.

The Results: Figure 1 shows measured RV versus phase for a representative KOI having a planet radius of 2.4 Earth-radii. This KOI exhibits RVs that are high and low as predicted by the ephemeris from the transit photometry, supporting the planet hypothesis. The RV amplitude is K = 2.6 m/s, implying a planet mass of 9.8 Earth-masses and density of 3.8 g/cc. With a density intermediate between that of a purely rocky planet and a Neptune-like planet, it may represent the transition object between the two types. The planet mass and radius constrain its interior structure (see presentation by L.Rogers, this meeting.) The formation and evolution of such planets remain to be explained.

Summary: We will present RV orbital results for some 15 KOIs having small planet candidates, offering support for the planet hypothesis, as well as masses and densities, or upper limits thereto. Some have densities clearly less than 2 g/cc rendering them composed in part of water or gas while others are apparently solid. Companion presentations will be given by Leslie Rogers, Sara Seager, and Dimitar Sasselov offering interpretations for interior structure and formation.

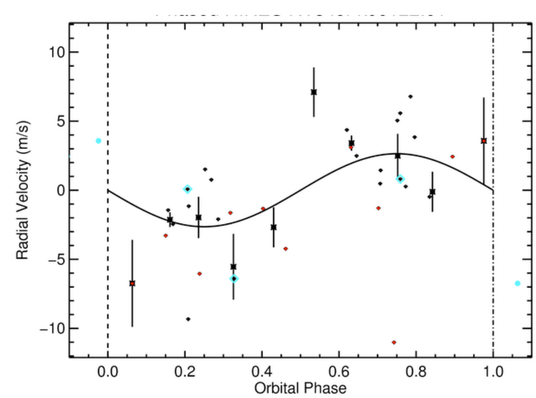

Figure 1. RV measurements vs. orbital phase, from Keck Observatory for a KOI having a radius of 2.4 Earth-radii. Bold dots are RVs binned in 1/10 phase bins. The planet mass is 9.8 Earth-masses and the density is 3.8 g/cc, a new regime for exoplanet interiors.

Acknowledgements: Funding for the Kepler Mission is provided by the National Aeronautics and Space Administration (NASA) Science Mission Directorate. Observations were made possible by the Keck Observatory.

115. EARTH ANALOG AND SUB-NEPTUNE-SIZE PLANETS

RV Follow-Up of Small Planets from *Kepler*: Planet Bulk Composition and Interior Structure

L. Rogers[1], S. Seager[1], D. Sasselov[2], G. Marcy[3], H. Isaacson[3], A. Howard[3], and the *Kepler* Team. [1]Department of Physics, Massachusetts Institute of Technology, Cambridge MA, 02139, [2]Department of Astronomy, Harvard University, Cambridge MA, 02138, [3]Department of Astronomy, University of California, Berkeley, CA 94708. larogers@mit.edu, seager@mit.edu, dsasselov@cfa.harvard.edu, gmarcy@astro.berkeley.edu, hisaacson@berkeley.edu, howard@astro.berkeley.edu.

Introduction: The *Kepler Space Telescope* has discovered hundreds of small transiting planet candidates with radii smaller than Neptune (R_p<$4R_\oplus$) [1, 2]. To determine the planet mass, the gravitational influence of the planet candidate must be observed, either through radial velocities (RVs) or transit timing variations (TTVs). Constraints on the planet interior structure are possible for the valuable subset of exoplanets with measurements for both the planet mass and the planet radius. The resulting planet average densities can be used for both a compositional interpretation of individual planets and a statistical interpretation of the ensemble exoplanet properties.

Observational Data: In a companion presentation, G. Marcy et al. will unveil new Keck HIRES RV orbital solutions for 15 sub-Neptune size *Kepler* planet candidates. A mean velocity precision of ~2m/s was achieved for the KOIs, which have *Kepler* magnitudes ranging from 10th to 13th. Orbital fits and MCMC analyses were employed to derive planet masses and mass upper limits from the Doppler RVs.

In addition to the new Keck RV orbital solutions, *Kepler* has previously announced 10 confirmed planets with radii smaller than $4R_\oplus$. Of these, 2 have RV-measured masses (Kepler-10b [3] and Kepler-4b [4]), 4 have TTV-measured masses (Kepler-11b, c, d, and f [5]), and 4 have mass upper limits (Kepler-9d [6], Kepler-10c [7], Kepler-11g [5], and Kepler-19b [8]).

Model and Approach: We constrain the bulk compositions of *Kepler's* small planet candidates using planet interior structure models. Our model (based on [9]) considers fully differentiated planets comprised of up to four layers: a metal core, a silicate mantle, a water mantle, and a gas envelope. We calculate the planet interior structure by integrating the coupled differential equations describing a self-gravitating body in hydrostatic equilibrium, employing modern equations of state for the metal, silicates, water, and gas.

For any individual planet candidate, a wide range of compositions is consistent with the measured mass and radius. We consider the planet candidates as an ensemble, and categorize each candidate according to whether it may be purely rocky, it may harbor a vapor-rich (high mean molecular weight) envelope, or its mean planet density is low enough to demand a voluminous hydrogen-rich envelope.

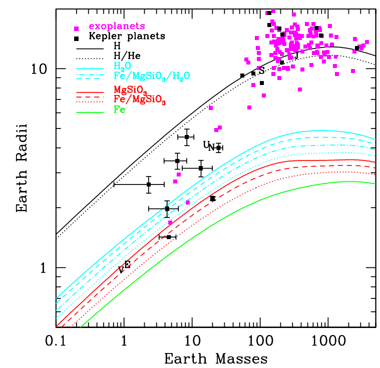

Figure 1: Mass-radius distribution of exoplanets (current as of 09/28/11). Mass-radius relations for cold solid planets [10] are shown. Solar System planets are indicated by their first initial.

Goals: We will frame our presentation in context of the exoplanet mass-radius distribution (Figure 1). We will present an updated distribution including the 15 new small *Kepler* planet candidates with Keck RV-measured masses (or mass upper limits). From the observed planet mass-radius distribution, we will theorize about why parts of the distribution are unpopulated and about whether this could be a signature of planet formation and evolution.

We will also focus on the intriguing transition between rocky exoplanets and exo-Neptunes. The threshold between predominantly rocky planets and planets with voluminous gas layers has implications for planet formation, evolution, and habitability. We will explore whether the current census of sub-Neptune size exoplanets yet constrains this transition.

Finally, we will look to the future and describe the methods and prospects for constraining the demographics of small planet bulk compositions from an ensemble of *Kepler* plane candidates with RV follow-up.

Acknowledgements: Funding for the Kepler Mission is provided by the National Aeronautics and Space Administration (NASA) Science Mission Directorate. Observations were made possible by the Keck Observatory.

References: [1] Borucki W. J. et al. (2011) *ApJ, 728,* 117–136. [2] Borucki W. J. et al. (2011) *ApJ, 736,* 19–30. [3] Batalha et al. (2011) *ApJ, 729,* 27–47. [4] Borucki et al. (2010) *ApJL, 713,* L126–L130. [5] Lissauer et al. (2011) *Nat., 470,* 53–58. [6] Torres et al. (2011) *ApJ, 727,* 24–41. [7] Fressin et al. (2011) *ApJ,* accepted. [8] Ballard et al. (2011) *ApJ,* accepted. [9] Rogers L. A. and Seager S. (2010) *ApJ, 712,* 974–991. [10] Seager et al. (2007) *ApJ, 667,* 1279-1297.

116. EARTH ANALOG AND SUB-NEPTUNE-SIZE PLANETS

LIMITS FROM *KEPLER* AND THE MEARTH PROJECT ON THE OCCURRENCE RATE OF SUPER-EARTHS AND NEPTUNES AROUND M DWARFS.

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Introduction: The *Kepler* target list contains 5252 stars cooler than 4000K [1] but previous work on the *Kepler* data has focused on the occurrence rate of planets around FGK stars [1,2,3,4,5]. Results from Kepler show that the occurrence rate of 2-4 $R_\oplus$ planets (with periods < 50 days) rises sharply toward lower mass stellar hosts, with roughly 1/4 of M0 dwarfs hosting such a planet [2,6]. Because the stellar mass function peaks at M3-M4 dwarfs [7], how far this trend extends to later type stars is of paramount importance to the Galactic exoplanet census. To answer this question we investigate the occurrence rate of planets around the coolest *Kepler* target stars and compare our results to preliminary statistical limits from the MEarth Project, a ground-based transit survey of M3-M6 dwarfs.

Early M Dwarfs from *Kepler*: We use the photometry provided by [8] in the *Kepler* Input Catalog (KIC) to improve the radius and temperature estimates for the cool stars in the *Kepler* target list and refine the estimates of the planet candidate radii. We estimate the completeness of the current *Kepler* Objects of Interest (KOI) list for cool stars by simulating the likelihood of detecting a transit of a planet with a given radius and period around each of the stars (see Fig. 1). We investigate the dependence of the occurrence rate on stellar and planetary parameters by assigning planets from a variety of underlying distributions to the cool stars listed in the KIC and comparing the populations of detected simulated planets to the population of KOIs.

Mid-Late M Dwarfs from MEarth: We present preliminary statistical limits on the occurrence rate from observations of 1,000 very nearby M dwarfs observed by the MEarth Project. MEarth has published only one planet, the super-Earth GJ1214b [9], but is sensitive to 2-4 $R_\oplus$ planets in the two-week habitable zones of its cool target stars. We simulate the end-to-end sensitivity of the survey so far and discuss the implications for the occurrence rate of Super-Earth to Neptune-sized exoplanets as cool as 300K.

In addition to the ramifications for the sheer number of 2-4 $R_\oplus$ planets in the Galaxy, these results bear upon the potential yield from proposed all-sky space-based transit surveys such as TESS or ELEKTRA and on our prospects for characterizing the atmospheres of habitable worlds with JWST or immense ground-based telescopes in the coming decade [10,11].

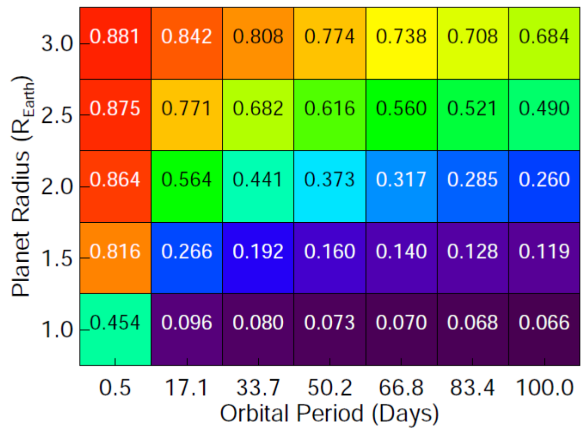

Fig 1. *The fraction of cool stars in the Kepler target list for which a central transit of a planet with the indicated radius and period could have been detected in the first four months of observation.*

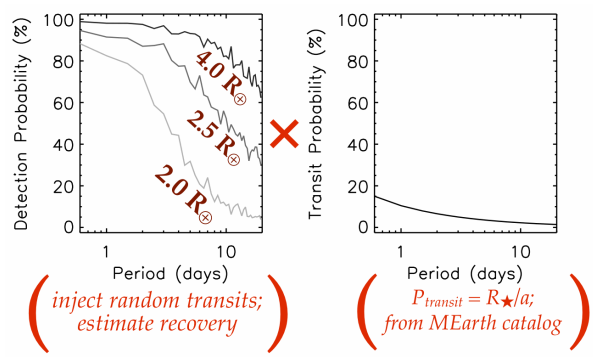

Fig 2. *An example calculation of the planet discovery sensitivity of 1 of the 1,000 M dwarfs that have been observed by the MEarth survey, combining simulations of transits running through the MEarth pipeline (left) with the estimated stellar properties for this well-characterized, nearby sample of stars (right).*

References: [1] Borucki W. et al. (2011), *ApJ, 736*, 19. [2] Howard et al. (2011), submitted to *ApJ*, (arXiv:1103.2541). [3] Youdin (2011), submitted to *ApJ* (arXiv:1105.1782). [4] Catanzarite & Shao (2011), *ApJ, 738*, 115. [5] Traub (2011), accepted by *ApJ* (arXiv:arXiv:1109.4682). [6] Gaidos et al. (2011), submitted to *ApJ*, (arXiv:1108.5686). [7] Bochanski, J. et al. (2010), AJ, 139, 2679-2699. [8] Brown et al. (2011), *AJ, 142*, 112. [9] Charbonneau, D. et al. (2009) Nature, 462, 891-894. [10] Deming, D. et al. (2009) PASP, 121, 952-967. [11] Pallé, E. et al. (2011) ApJ, 728, 19.

Kepler transit frequency statistics in the presence of statistical false positives. P. Nutzman[1], K. Schlaufman[2], J. Mulder[3], G. Laughlin[4], and J. Fortney[5]. [1] UCSC Dept. of Astronomy & Astrophysics, 1156 High St., 275 Interdisciplinary Sciences Building, Santa Cruz, CA 95064, pnutzman@ucolick.org. [2] UCSC, kcs@ucolick.org. [3] UCSC, jmulder_xf@hotmail.com. [4] UCSC, laugh@ucolick.org. [5] UCSC, jfortney@ucolick.org.

Introduction: Kepler has been enormously successful in detecting hundreds of super-Earth/mini-Neptune size planets. However, the transit signal/noise thresholds necessary to minimize the number of false positive exoplanet candidates may limit Kepler's ability to accurately quantify the frequency of small radius planets. Reducing the transit significance threshold, while precisely quantifying the false positive rate, may provide a better estimate of the true frequency of small planets. We argue that reducing the significance threshold will improve frequency estimates until the rate of false positives is comparable to the rate of real signals. A modest reduction in the signal/noise threshold spoils our ability to confidently distinguish real signals from statistical flukes, but may open up a significant population of small-radius candidates for statistical studies. We also investigate whether the rate of periodic "anti-transits" may be used as a proxy for the rate of false positives. This possibility relies on the up/down symmetry of most Kepler photometric noise, and the fact that many forms of stellar variability (e.g., pulsations, granulation noise) are also symmetrical about the mean stellar flux.

118. EARTH ANALOG AND SUB-NEPTUNE-SIZE PLANETS

The validation of Earth-size planets.

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The Kepler Mission is subtitled "a search for Earth-size planets". Kepler observations have already demonstrated that we can detect very shallow signals that may be interpreted as transits by Earth-size planets. However, confirming the planetary nature of those signals by spectroscopic means through detection of the reflex motion of the parent star is extremely challenging. The Kepler team has developed ways of "validating" these candidates statistically by modeling the photometry to place constraints on the wide range of false positives ("blends") that can mimic the transit light curves. I will describe our updated "BLENDER[1,2,3]" methodology that allows us to further tighten those constraints for planets as small as the Earth, or even smaller, and makes use of additional constraints from follow-up observations including spectroscopy, high-resolution imaging, and centroid motion analysis. This presentation will illustrate how we estimate the frequency of blends, and ultimately the probability that a candidate is a bona-fide Earth-size planet.

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[1] Torres G. (2004), *ApJ*, 614, 979
[2] Torres G. (2011), *ApJ*, 727, 24.
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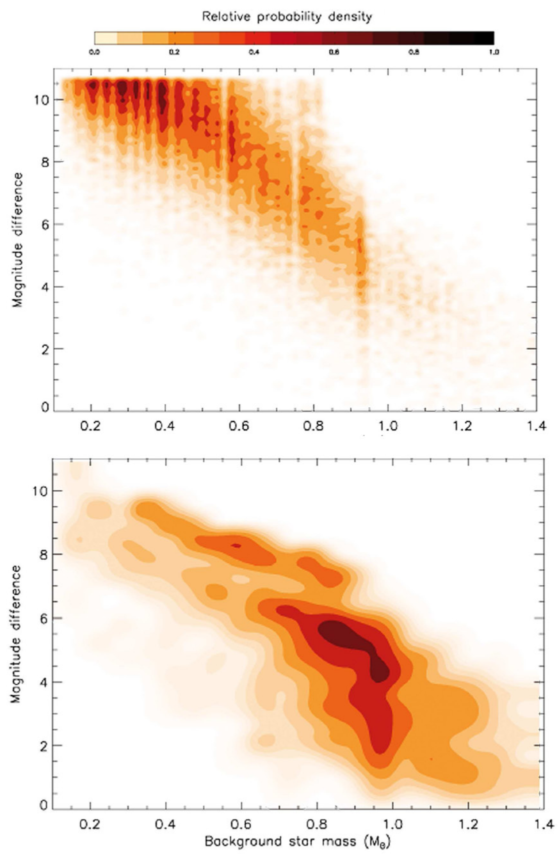
[4] Robin A. (2003), *A&A*, 409, 523.



Top: Density contours (stars per square degree) for background stars around one of our targets, taken from the Besancon[4] model of the galaxy. **Bottom**: Contours indicating the density of background stars orbited by a larger transiting planet that could be mimicking the transit light curve for an Earth-size planet, and that are allowed by BLENDER. Note that the peak in the density distribution is displaced compared to the maximum stellar density in the top panel, a result of BLENDER that depends on the properties of this particular target. This means that only a small fraction of background stars are able to match the signal for this candidate, which reduces the frequency of possible blends.

119. EARTH ANALOG AND SUB-NEPTUNE-SIZE PLANETS

Kepler-11: Super-Earths or Mini-Neptunes? Constraints from Mass Loss. E. D. Lopez[1], J. J. Fortney[2], & N. Miller[3], [1]University of California Santa Cruz, Department of Astronomy and Astrophysics, 1156 High St. Santa Cruz, CA 95064, edlopez@ucsc.edu, [2]University of California Santa Cruz, jforney@ucolick.org, [3]University of California Santa Cruz, neil@astro.ucsc.edu

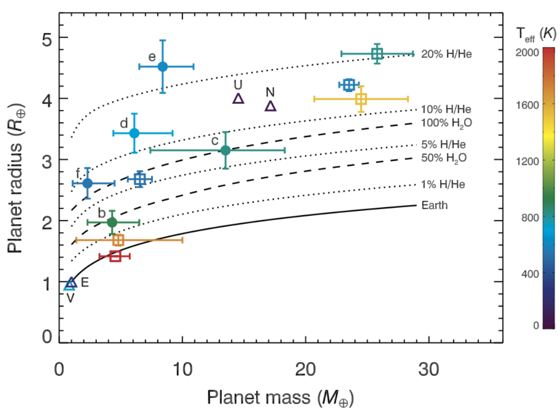
Introduction: Low-density Super-Earths, like those in Kepler-11[1], represent members of a new class of planets. Basic questions about their structure and bulk composition still need to be addressed. Are they, in fact, scaled up rocky planets with thick hydrogen-rich atmospheres; or are they instead miniature Neptunes, with much of their mass in water?

Formation models[2,3] show that Neptune-like planets must form beyond the snow-line and migrate inward to reach ~10 day orbits. Given the closely packed, coplanar, circular obits in Kepler-11[1], if we can rule out Super-Earth compositions, then the system likely formed beyond the snow line a type I migrated in.

Using interior structure models[4,5], we constrain the present-day compositions for the five inner planets in Kepler-11. Using thermal evolution models[6] coupled with XUV driven mass loss[7,8], we then explore the mass, radius, and composition history of each planet. By comparing to planet formation models, we put constraints on the composition and formation of the system.

Results:

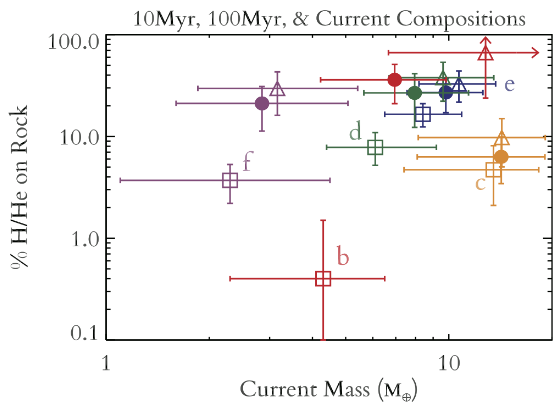
Mass-Radius Diagram.



Above are mass-radius curves that we produced for the Kepler-11 discovery paper[1]. Solar and extra-solar low mass planets are plotted in radius vs. mass and colored by their effective temperatures. In general, there is a degeneracy between models with large amounts of water and models with small amounts of hydrogen and helium.

We propose using mass loss models to break this degeneracy. Super-Earths with hydrogen dominated atmospheres are much more vulnerable to mass loss than water planets. In particular Kepler-11b, is highly vulnerable to mass loss since it is both low gravity and highly irradiated.

Current and Initial Compositions.



Here we plot composition vs. mass for the five inner planets in Kepler-11, assuming a super-Earth scenario, i.e., H/He on a rock/iron core without any water. The squares indicate the current mass and composition, while the circles show the results of our model when the system was 100 Myr old. Colors indicate each planet. Kepler-11b is extremely vulnerable to mass loss; although only ≈ 0.5% H/He today it would have had to be ≈ 30% H/He when it formed.

We compare to planet formation models[2] with different values for the proto-planetary dust opacity, which regulates the amount of atmosphere a given planetary core can accrete. We conclude that Kepler-11 can only be a system of Super-Earths if both dust grain opacity and a mass loss efficiency are very low.

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[1] Lissauer J. J. et al. (2011) *Nat., 470,* 53–58. [2] Alibert Y., Mordasini C., & Benz, W. (2011) *A&A, 526,* 63A. [3] Ida S. & Lin D.N.C. (2010) *ApJ, 719*, 810-830. [4] Miller N., Fortney J.J., & Jackson B. (2009) *ApJ*, *702*, 1413-1427. [5] Nettelmann N. et al. (2011) *ApJ*, *733*, 2N. [6] Fortney J.J., Marley M.S., & Barnes J.W. (2007) *ApJ*, *659*, 1661-1672. [7] Erkaev N.V et al. (2007) *A&A*, *472*, 329-334. [8] Murray-Clay R.A., Chiang E.I., & Murray N. (2009) *ApJ*, *693*, 23-42.

120. EARTH ANALOG AND SUB-NEPTUNE-SIZE PLANETS

THE CHEMISTRY OF PLANET FORMATION: DETAILED ABUNDANCES OF STARS WITH LOW-MASS PLANETS DISCOVERED BY KEPLER. S.C. Schuler[1], V.V. Smith[1], S.B. Howell[2], and K. Cunha[1,3,4] [1]National Optical Astronomy Observatory, 950 N. Cherry Ave., Tucson, AZ 85719 USA, sschuler@noao.edu, vvsmith@noao.edu, kcunha@noao.edu; [2]NASA Ames Research Center, steve.b.howell@nasa.gov; [3]Steward Observatory/University of Arizona; [4]Observatório Nacional, Brazil

Introduction: Initial results of a detailed abundance analysis of solar-type stars with low-mass planets discovered by Kepler are presented. Recent studies suggest that planet formation, possibly terrestrial planet formation in particular, leaves an observable signature in the compositions of the planet host stars. The signature is manifested as a decreasing trend in the abunances of refractory elements as a function of increasing condesation temperture (T_c) of the elements [1,2]. It has been suggested that the refractory elements depleted in stars displaying such trends may be locked inside terrestrial planets. Our group has shown that the refractory element abundances may also be sensitive to the dynamical evolution of planetary systems [3]. We have expanded our study of planet host star abundances to solar-type dwarfs in the Kepler field. These stars have an increasing planet occurrence with decreasing planet size [4] and are an ideal sample with which to determine if terrestrial planet formation alters the bulk composition of the host stars. Here we present the results of a detailed abundance analysis (abundances of up to 18 elements have beed derived for each star) of the first few Kepler stars from our study.

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When Is an Earth-analog Really an Earth-analog?

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In terms most commonly used within the Kepler community, an Earth-analog would be an Earth-sized planet orbiting a solar-type star at a distance of ~1 AU. The authors of *Rare Earth: Why Complex Life is Uncommon in the Universe* might add to the requirements for analog status, a large moon, a Jovian counterpart at ~5AU, at least one asteroid belt or reservoir, the absence of close companion stars, a terrestrial-scale planetary magnetic field, a density ~ 5 gm cm^{-3}, a 2:1 ratio of ocean to continental area, an age of several billion years and other things that allowed the improbable (in their view) evolution of complex animal life. Those of us working on the search for extraterrestrial intelligence (SETI) have yet another definition of what makes an Earth-analog, and that is the existence of some technology on that planet that we here on Earth can detect remotely. That technology bespeaks the presence (at least at some time) of intelligent technologists. From our point of view, the origin and evolution of an intelligent species on an exoplanet is what uniquely qualifies that body as an Earth-analog.

This paper will present a summary of the SETI observations with the Allen Telescope Array and other radio and optical facilities that have been conducted over the past three years that have focused on exoplanets and the initial Kepler list of 1235 candidate exoplanets.

201. KEPLER MISSION AND EXOPLANET STATISTICS

KEPLER EXOPLANET CANDIDATE HOST STARS ARE PREFERENTIALLY METAL RICH.

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ABSTRACT

We find that *Kepler* exoplanet candidate (EC) host stars are preferentially metal-rich, including the low-mass stellar hosts of small-radius ECs. The last observation confirms a tentative hint that there is a correlation between the metallicity of low-mass stars and the presence of low-mass and small-radius exoplanets. In particular, we compare the *J-H---g-r* color--color distribution of *Kepler* EC host stars with a control sample of dwarf stars selected from the ~150,000 stars observed during Q1 and Q2 of the *Kepler* mission but with no detected planets. We find that at *J-H* = 0.30 characteristic of solar-type stars, the average *g-r* color of stars that host giant ECs is 4σ redder than the average color of the stars in the control sample. At the same *J-H* color, the average *g-r* color of solar-type stars that host small-radius ECs is indistinguishable from the average color of the stars in the control sample. In addition, we find that at *J-H* = 0.62 indicative of late K dwarfs, the average *g-r* color of stars that host small-radius ECs is 4σ redder than the average color of the stars in the control sample. These offsets are unlikely to be caused by differential reddening, age differences between the two populations, or the presence of giant stars in the control sample. Stellar models suggest that the first color offset is due to a 0.2 dex enhancement in [Fe/H] of the giant EC host population at M_star ≈ 1 M_Sun, while Sloan photometry of M 67 and NGC 6791 suggests that the second color offset is due to a similar [Fe/H] enhancement of the small-radius EC host population at M_star ≈ 0.7 M_Sun. These correlations are a natural consequence of the core-accretion model of planet formation.

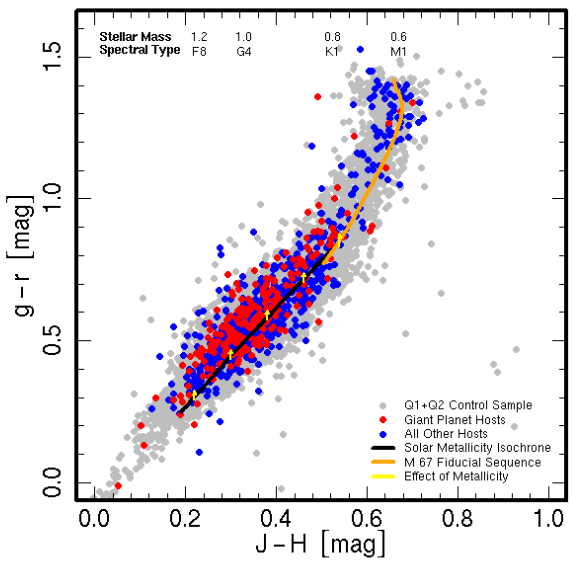

Figure 1. *Kepler* EC host stars in a *J-H---g-r* color--color plot. We plot in red stars that host at least one giant EC (i.e., R_p > 5 R_Earth), while we plot in blue stars that host an EC system with no giant planets. We plot in gray a control sample of 10,000 stars randomly selected from the ~150,000 stars observed in Q1 and Q2 of the *Kepler* mission that have no detected ECs. The black curve is a 2 Gyr, solar metallicity Padova isochrone, and the orange curve is the M 67 fiducial sequence from. We indicate with yellow arrows the affect of increasing metallicity 0.2 dex in [Fe/H] on *g-r* at constant *J-H*. Note though that the yellow arrows do not connect stars of constant mass, as a metal-enriched star will be about 5% more massive than a solar metallicity star at constant *J-H* color. We give approximate stellar mass and spectral type as a function of *J-H* color at the top of the plot. At *J-H* ≳ 0.6 (typical of late K dwarfs), giant ECs become very rare relative to smaller ECs. In other words, the *Kepler* ECs confirm the correlation between host stellar mass and frequency of giant planet occurrence. Moreover, at *J-H* ≈ 0.62 characteristic of late K dwarfs, the effect of metallicity moves metal-rich stars to redder *g-r* at constant *J-H*. At that color, the population of K dwarfs that host ECs has a redder *g-r* color than the control sample.

Jerome Orosz

We have measured accurate eclipse times in a sample of 1040 eclipsing binaries (EBs) observed by Kepler. A large number of EBs show significant eclipse timing variations (ETVs) which indicate the presence of a third body. In many cases the inferred mass of the third (circumbinary) body is relatively small and is a strong planet candidate. We will give an update on the status of the follow-up observations and modeling efforts on these systems.

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VALIDATION OF HABITABLE-ZONE SUPER EARTH KEPLER CANDIDATES WITH WARM SPITZER. Sarah Ballard[1], Jean-Michel Desert[1], Francois Fressin[1], David Charbonneau[1], [1]Harvard-Smithsonian Center for Astrophysics (60 Garden St. MS-10, Cambridge MA 02138; sballard@cfa.harvard.edu)

Beginning in August 2011, we initiated a new 600-hour campaign with Warm *Spitzer* to measure transits of habitable-zone super Earths. This program is distinct from our earlier 800-hour campaign, the results of which will be presented separately at this conference (see abstract by J.-M. Desert et al.). Our new campaign exclusively targets planets ranging in radius from 1.5-3 Earth radii and orbiting in or near their stellar habitable zones. By comparing the transit depth at infrared wavelengths as observed with *Spitzer* with that at visible wavelengths as observed by *Kepler*, we address the alternate hypothesis that the light curve results not from a transiting planet, but from a blend containing an eclipsing binary star.

We have already demonstrated this use of *Spitzer* to validate the planets Kepler-10c [1] and Kepler 19b [2, see Figure 1], among others. We will present the *Spitzer* light curves for the first habitable-zone super Earth candidates observed as part of our new program. The small masses and large orbital distances of these candidates preclude their traditional confirmation with radial velocity measurements.

We developed a novel reduction technique of *Spitzer* photometry [3] which resulted in demonstrably improved precision. The higher-order intrapixel sensivity features that we identified in that work are visible in Figure 2. We discuss the use of this technique, as well as other alternative methods [4][5] to treat the systematics inherent in Warm *Spitzer* observations.

References: [1] Fressin, F. et al. (2011) *ApJ accepted* (arXiv:1105.4647). [2] Ballard et al. (2011) *ApJ accepted* (arXiv:1109.1561). [3] Ballard et al. (2010) *PASP,* 122, 897, 1341-1352. [4] Stevenson, K. et al. (2011) *ApJ submitted* (arXiv:1108.2057). [5] Demory, D. et al. (2011) *A&A*, 533, A114.

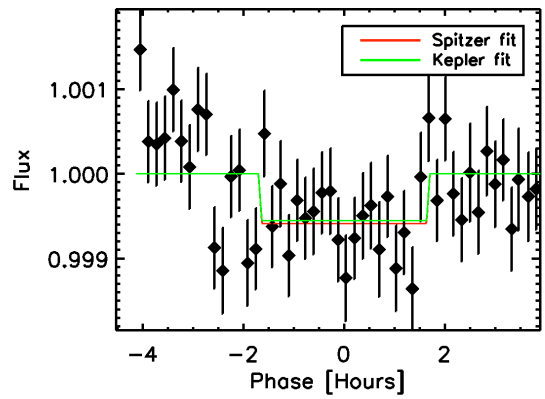


Figure 1: The binned *Spitzer* observations of Kepler-19b, with the best-fit transit depths independently derived from *Kepler* (green) and *Spitzer* (red) overplotted. By combining these data with additional constraints from adaptive optics imaging, high-resolution spectroscopy, and photometric blend models, we validated Kepler-19b as a 2 R_{Earth} planet [2].

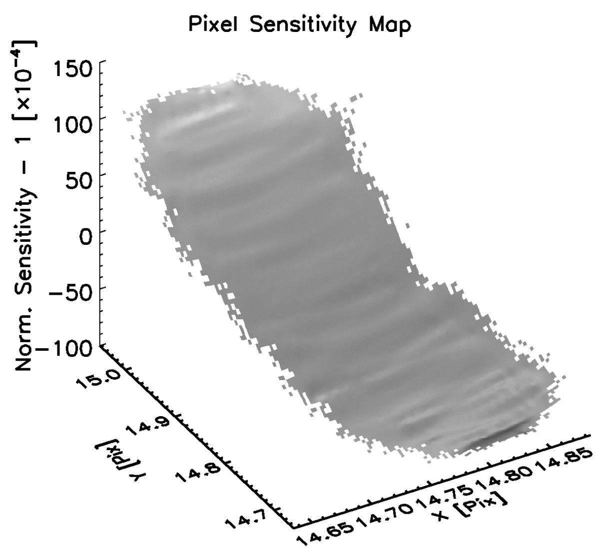
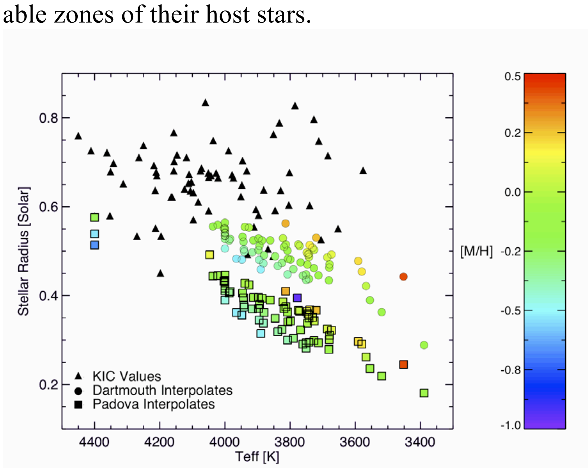


Figure 2: Intrapixel sensitivity map of the Spitzer Infrared Array Camera (taken from [3]). Our novel technique accounts for higher-order features (seen here as ripples), which are not corrected with a traditional treatment.

ACCURATE STELLAR PARAMETERS OF LOW-MASS KEPLER PLANET HOSTS. P. S. Muirhead[1], K. Hamren[2], E. Schlawin[3], B. Rojas-Ayala[4], K. Covey[3], and J. P. Lloyd[3], [1]California Institute of Technology, 1200 California Blvd, MC 249-17, Pasadena, CA 91125, [2]Department of Astronomy and Astrophysics, University of California Santa Cruz, 1156 High Street, Santa Cruz, CA 95064, [3]Department of Astronomy, Cornell University, 122 Sciences Drive, Ithaca, NY 14853, [4]Astrophysics Department, American Museum of Natural History, Central Park West at 79th Street, New York, NY 10024

Introduction: We report stellar parameters for low-mass planet-candidate host stars recently announced by the Kepler Mission [1]. We obtained medium-resolution, K-band spectra of 84 low-mass Kepler Objects of Interest (KOIs) [2]. We identified one KOI as a giant; for the remaining dwarfs, we estimated effective temperatures by comparing measurements of K-band regions dominated by H_2O opacity with predictions of synthetic spectra for low-mass stars. We measured overall metallicities ([M/H]) using the equivalent widths of Na I and Ca I absorption features and an empirical metallicity relation calibrated with nearby stars [3]. With effective temperatures and metallicities, we estimate the masses and radii of the low-mass KOIs by interpolation onto two sets of evolutionary isochrones [4,5]. The resultant stellar radii are significantly less than the values reported in the Kepler Input Catalogue and, by construction, correlate better with effective temperature. Using either set of isochrones, our results significantly reduce the sizes of the corresponding planet candidates, with many less than 1 Earth radius. We report recalculated equilibrium temperatures for the planet-candidates and the implications for Kepler's yield of terrestrial exoplanets in the habitable zones of their host stars.



References:

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205. KEPLER MISSION AND EXOPLANET STATISTICS

The Masses and Metallicities of Kepler's Planet-hosting M Dwarfs

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While much attention is focused on Kepler's Sun-like target stars, there are many target stars that reside at the bottom of the main sequence. Thus, Kepler provides valuable information about planet formation around the Galaxy's most numerous denizens, the M dwarfs. I will present recent advances in understanding the fundamental physical properties of M dwarfs using both broadband photometry and optical spectroscopy. These techniques provide revised estimates of stellar masses and radii, thereby elucidating the radius distribution of planets orbiting low-mass stars. We will present the specific case studies LHS6343C and KOI-254.01, a transiting brown dwarf and hot Jupiter, respectively, orbiting two of Kepler's least massive and most proximate target stars.

Assessing the Kepler Inventory with Planet Hunters M.E. Schwamb[1,2], C. J. Lintott[3], D. A. Fischer[4], M. J. Giguere[4], S. Lynn[5], J. M. Brewer[4], M. Parrish[5], K. Schawinski[1,2], R. J. Simpson[3], A. Smith[5], J. Spronck[4], [1]Yale Center for Astronomy and Astrophysics, Yale University, P.O. Box 208121, New Haven, CT 06520 (megan.schwamb@yale.edu), [2]Department of Physics, Yale University, [3]Department of Physics, University of Oxford, [4]Department of Astronomy, Yale University, [5]Adler Planetarium

Introduction: The human brain is well suited to picking out most transits that cannot be detected in periodograms and may be missed by the automated search algorithms. With Planet Hunters(http://planethunters.org), part of the Zooniverse collection of citizen science projects [2,3], we enlist members of the general public, via the World Wide Web, to visually inspect the 150,000 publicly released Kepler light curves for exoplanet tranits. Planet Hunters is a novel and complementary technique to the automated transit detection algorithms, providing an independent assessment of the completeness of the Kepler exoplanet inventory.

Planet Hunters: Since launch in December 2010, ~45,000 volunteers have made over 3.6 million classifications, with the average Planet Hunters user contributing more than 50 classifications. For each of the ~150,000 Kepler-monitored stars, approximately 10 users examine 30-day segments of the star's light curve, identifying potential transits. Planet Hunters classifications are processed through a pipeline which uses simulated short-period planet transit light curves to assess the capabilities of individual volunteers. Weightings are assigned to individuals and an iterative process is used to converge on final classifications and identify planet candidates.

Summary: We present the first results from Planet Hunters with an analysis of the detection efficiency of human classifiers to identify planetary transits. We present the planet candidates identified by Planet Hunters comparing to the Kepler team's published lists of planet candidates [1]. In particular, we discuss the abundance of large planets (> 2 earth radii) on short period (< 15 days) orbits based on Planet Hunters detections for the first 33.5 days of the Kepler mission.

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207. KEPLER MISSION AND EXOPLANET STATISTICS

WHAT WILL GAIA DO FOR KEPLER? A. Sozzetti[1], [1]INAF-Osservatorio Astronomico di Torino, Via Osservatorio 20, I-10025 Pino Torinese, Italy (email: sozzetti@oato.inaf.it)

Abstract: With a nominal launch date of May 2013, ESA's Gaia global astrometry mission will soon herald us into the era of micro-arcsecond-level (μas) precision positional astronomy. The wealth of information in the Gaia catalogue of exoplanets [1] will constitute a fundamental contribution to several areas of exoplanet science.

I will briefly address some of the relevant technical issues (choose your preferred algorithm, make sure your solution is robust, then double-check using a completely different approach!) associated with the precise and accurate determination of astrometric orbits of planetary systems using Gaia data (see e.g., [2], and references therein, for details).

I will then highlight some of the important synergies between Gaia high-precision astrometry and other ongoing and planned, indirect and direct planet-finding and characterization programs, both from the ground and in space, and over a broad range of wavelengths. I will particularly focus on the potential for improved understanding of planetary systems orbital architecture and physical properties when Kepler's exquisitely accurate photometry (supported by high-precision ground-based radial-velocity measurements where possible) will be combined with Gaia's superbly precise distance estimates (<1%) for all bright Kepler Objects of Interest (KOIs, V<14.5) in the Kepler field and with the 5-yr time baseline of Gaia astrometry. For example, as a direct consequence of the use of Gaia parallaxes in the Kepler field, the fundamental stellar properties (e.g., masses, radii) of transiting planet hosts in the Kepler field will have to be revised, and this will impact the composition estimates of the planets themselves. Furthermore, being sensitive to giant planetary companions on outer orbits around many of the KOIs, Gaia's astrometric time-series in the Kepler field will help to better the characterization of multiple-planet systems architectures.

The potentially spectacular synergy between Kepler and Gaia will be particularly reinforced if an extension of operations were to be granted to Kepler at least doubling its mission lifetime, thus providing a significant time interval for 'quasi-simultaneous' observations of the Kepler field with both spacecrafts.

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[2] Sozzetti A. (2010) *EAS Pub. Ser., 42,* 55-77.

TRANSITING EXOPLANET SURVEY SATELLITE (TESS).

G. R. Ricker[1], D. W. Latham[2], S. Seager[3], R. K. Vanderspek[4], J. S. Villasenor[5], J. N. Winn[6], and the TESS Science Team. [1]MIT Kavli Institute for Astrophysics and Space Research, Room 37-501, 77 Massachusetts Avenue, Cambridge MA 02139, grr@space.mit.edu [2]Smithsonian Astrophysical Observatory, latham@cfa.harvard.edu [3]MIT, seager@mit.edu [4]MIT, roland@space.mit.edu [5]MIT, jsvilla@space.mit.edu [6]MIT, jwinn@mit.edu

Introduction: The Transiting Exoplanet Survey Satellite (TESS) will discover thousands of exoplanets in orbit around the brightest stars in the sky. In a two-year survey, TESS will monitor more than 500,000 stars for temporary drops in brightness caused by planetary transits. This first-ever spaceborne all-sky transit survey will identify planets ranging from Earth-sized to gas giants, around a wide range of stellar types and orbital distances. No ground-based survey can achieve this feat. A large fraction of TESS target stars will be 30-100 times brighter than those observed by Kepler satellite, and therefore TESS planets will be far easier to characterize with follow-up observations. TESS will make it possible to study the masses, sizes, densities, orbits, and atmospheres of a large cohort of small planets, including a sample of rocky worlds in the habitable zones of their host stars. TESS will provide prime targets for observation with the James Webb Space Telescope (JWST), as well as other large ground-based and space-based telescopes of the future. TESS data will be made public six months after collection, inviting immediate community-wide efforts to study the new planets. The TESS legacy will be a catalog of the very nearest and brightest main-sequence stars hosting transiting exoplanets, thus providing future observers with the most favorable targets for detailed investigations.

Team: TESS Team members include MIT, NASA's Goddard Spaceflight Center, Orbital Sciences Corporation, NASA's Ames Research Center, the Harvard-Smithsonian Center for Astrophysics, Space Telescope Science Institute, Geneva Observatory, the Las Cumbres Observatory Global Telescope Network, as well as additional participants in the USA, China, Denmark, France, Germany, Italy, Japan, and Spain.

Mission: TESS is a low-risk, high-value Explorer-class planet finder, directly in line with U.S. National Space policy and NASA science goals related to the "...search for planetary bodies and Earth-like planets in orbit around other stars" (2010 NASA Science Plan), as well as the highest priorities defined by the NRC Astro2010 Decadal Survey. The TESS mission has been selected for a Phase A study by NASA, with a proposed launch in 2016.

209. KEPLER MISSION AND EXOPLANET STATISTICS

SOFIA: CAPABILITIES FOR STUDYING EXOPLANETS IN THE *KEPLER* ERA AND BEYOND.

Edward Dunham[1], Ian McLean[2], Jürgen Wolf[3], Jeonghee Rho[4], Dana Backman[5], Scott Horner[6], William Reach[4], Erin Smith[6], and the SOFIA team

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With its precise photometry and relentless observing cadence *Kepler* has found a rich variety of planets orbiting stars of various spectral types. The Stratospheric Observatory for Infrared Astronomy (SOFIA) can provide complementary precise multispectral transit observations of *Kepler* planet candidates and similar objects in other parts of the sky. As with *Kepler*, we anticipate that the same precise photometry capability will be valuable in the context of asteroseismic and stellar astrophysics observations. Finally, SOFIA can help advance our understanding of the processes of star and planet formation.

SOFIA is an airborne observatory for infrared and submillimeter astronomy funded by NASA (80%) and the German Space Agency (20%) which began early science operations in late 2010. It is a Boeing 747SP carrying a 2.5-meter telescope flying at 41,000 to 45,000 feet, above most of Earth's atmospheric water vapor, opening most of the far-infrared and sub-mm spectrum to its instrument suite. The photometric stability and low scintillation noise found in airborne data is an important factor for precise photometry.

First generation SOFIA instruments include the High-speed Imaging Photometer for Occultations (HIPO; P.I. Ted Dunham, Lowell Observatory, 0.3-1 µm), the First Light Infrared Test Experiment CAMera (FLITECAM; P.I. Ian MacLean, UCLA, 1-5 µm) with grisms, a mid-infrared camera (FORCAST; PI Terry Herter, Cornell U., 5- 40 µm) with grisms, an infrared Heterodyne Spectrometer (GREAT; PI Rolf Güsten, MPIfR Bonn, 1.2 - 1.9 THz), a far-IR Bolometer Camera, (HAWC; PI Al Harper, Yerkes Observatory, 50-240 µm), an ultra-high resolution mid-infrared Spectrograph (EXES, Echelon-Cross-Echelle Spectrograph, PI Matt Richter, 5-28 µm), and the Field Imaging Far Infrared Line Spectrometer (FIFI-LS, 41-210 µm). SOFIA Second Generation instruments will open new opportunities to study exoplanets.

The SOFIA instruments of primary interest for transit photometry work are HIPO and FLITECAM. In fact these two instruments can be co-mounted to provide simultaneous photometric coverage at two wavelengths from 0.3-1 micron and one in the 1-5 micron range. In the near term the SOFIA tertiary mirror is a dichroic reflector and about half the light in the 0.3-1 micron range is diverted to the focal plane imager (FPI). It is possible to recover this loss by substituting the Fast Diagnostic Camera (FDC) for the FPI, a capability demonstrated by a successful observation of a stellar occultation by Pluto on 23 June 2011. In the longer term an aluminized tertiary will be available.

SOFIA spectroscopy, particularly the FLITECAM grism capability, will allow spectrally resolved observations of extrasolar planets in both transit and occultation to constrain physical and chemical characteristics of these planets. HIPO does not have a grism capability at this time, though one could be added if needed.

In comparison to *Kepler*, SOFIA provides a larger aperture and wide wavelength coverage but short observation durations (3-10 hours). By virtue of SOFIA's stratospheric location we hope to achieve photometric precision comparable to that of *Kepler*. We will be obtaining initial precise photometry test data in the co-mounted HIPO/FLITECAM/FDC configuration in the months leading up to the *Kepler* Science Conference and will present a status report on this work.

At longer wavelengths SOFIA will make unique contributions to the characterization of the physical properties of proto-planetary disks around young stellar objects. This is important for understanding how planets are formed as stars and surrounding disks develop. Does the size of planet depend on the size of stars, initial mass of debris disks or the size of clearency of the hole in the disks? Debris disks and comets have shown various types of dust features such as carbon, water ice, silicates and olivines. HAWC will be able to detect disks with low temperatures. SOFIA will allow study of the more massive analogs to Sun-like stars such as the Herbig Ae/Be stars.

We will present SOFIA's science capabilities together with the sensitivities of instruments and status of SOFIA project. This will include brief discussions of the basic science observations of FORCAST and GREAT and the HIPO and FLITECAM integration and testing experience this year.

210. KEPLER MISSION AND EXOPLANET STATISTICS

ASTROPHYSICS WITH KEPLER DURING AN EXTENDED MISSION. M. Still[1], [1]Bay Area Environmental Research Association/NASA Ames Research Center, Moffett Field, CA 94035.

Introduction: Kepler's primary scientific focus is an exoplanet survey, yet publications from the Kepler community are dominated in number by astrophysics (Figs. 1 and 2). Kepler provides high-precision photometry, a 116 sq. deg, near-monatonic cadence, 3 years of continuous observing and >92% duty cycle. Individually, none of these characteristics are unique, but *collectively* they are a unique and powerful resource.

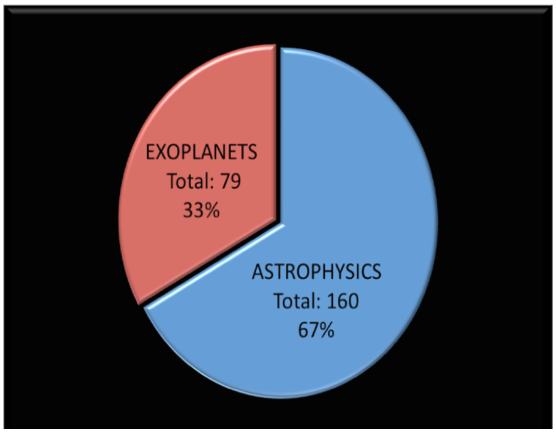

Figure 1: A comparison of the number of refereed non-exoplanet astrophysics papers in press to the number of refereed exoplanet papers in press, as of Sep 28, 2011.

Fundamental questions that can and should be tackled during mission extension are: what are the physical conditions internal and external to stars in our galactic neighborhood? How do those physical conditions drive stellar behavior? Hold old are the stars in our neighborhood? How does stellar behavior and age impact exoplanet physics and the development of ecosystems? Is the sun a typical or atypical star? What impact does this have for solar system phsics and life on Earth?

Kepler's "tool kit" for answering these questions is dominated by asteroseismology, magnetic activity, gyrochronology, and binary stars.

For asteroseismology, a mission extended to 8 years means longer baselines, more targets and greater signal-to-noise. The size of stellar ensembles will increase, the accuracy of stellar parameters will increase. Fainter pulsations will be detectable pushing asteroseismology in the regions of hotter and cooler stars. Asteroseismology will reveal potentially stellar rotation and differential rotation within stellar interiors.

8 years will allow Kepler to monitor complete dynamo cycles in thousands of stars. While the longer baselines and critical innovations in Kepler data analysis will combine to test how typical the sun is over timescales from a few hours to many years (Gilliland et al. 2011, Walkowicz et al. 2011). What are the consequences of quiet or noisy sun for life on Earth?

It is predicted that the Kepler community will be able to age stars using rotation rate as a proxy, calibrated against the 4 open clusters of known age in the field. (Meibom et al. 2011) Longer baselines provide sensitivity to lower levels of spot activity, pushing our ability to age increasingly older stars and their planets.

For binary stars, the Kepler community will extend and the survey to orbital periods > 1 year (Slawson et al 2011). Sensitivity to triple and hierarchical system, and their dynamics will increase dramatically. The long-term effects of binarity on magnetic cycles will be measured. Eclipse timings will indentify new stellar and sub-stellar objects.

The observing community have responded vigorously to the call for multiwavelwength broadband and timing source surveys of the Kepler field. Surveys are required in order to identify the targets of highest observational interest and optimize the target lists for astrophysics content. However these programs have been large and long-term projects. The 3.5 year baseline mission will not benefit from the new surveys greatly. The extended mission phase however will benefit from a greatly more diverse series of target-selection resources.

References:

Basri, G. et al., 2011, AJ, 141, 20
Gilliland, R. et al., 2011, ApJ, in press
Meibom, S. et al., 2011, ApJ, 733, 9L
Slawson, R.W. et al., 2011, AJ, in press

211. MULTIPLE PLANET SYSTEMS

STATISTICAL ARGUMENTS THAT MOST KEPLER MULTI-PLANET CANDIDATES ARE REAL PLANETS J. J. Lissauer[1] and the Kepler Science Team, [1] NASA Ames Research Center (MS 245-3, Moffett Field, CA 94035, Jack.Lissauer@nasa.gov)

Summary: Roughly one-third of Kepler's planet candidates announced by [1] are associated with targets that have more than one candidate planet. Eclipsing binaries shouldn't be correlated with planets, so very few targets should have both a false positive and another signal that would together make them appear as a candidate multi-planet system. The high number of stars with more than one planet candidate compared to the number expected were the candidates distributed randomly implies that the false positive fraction among multiple planet candidates is likely to be quite small. We present and quantify the statistical basis of this conclusion.

References:

[1] Borucki, W. B. et al. (2011) *ApJ, 736,* 19.

212. MULTIPLE PLANET SYSTEMS

DETAILED DYNAMICAL PORTRAITS OF OTHER PLANETARY SYSTEMS. D. C. Fabrycky[1] and the *Kepler* team, [1]Department of Astronomy and Astrophysics, University of California, Santa Cruz (UCO/Lick, University of California, Santa Cruz, CA 95064; fabrycky@ucolick.org).

For the planets of the Solar System, we can measure masses, radii, orbital distance, eccentricity, and inclination. By detecting transiting extrasolar systems, Kepler has made the greatest strides to date in discovering those characteristics for other cases, energizing the fledgling field of comparative planetary *systems*.

Aside from hearty statistics of multiplanet candidates, we now have about a dozen systems in which multiple confirmed planets show transit timing variations due to each other. I take stock of those results, asking what we have learned and what we will learn about them through continued monitoring. Moreover, I discuss what observations are necessary for inverting the transit timing problem to uniquely reveal the characteristics of the planetary system. A key goal is to confirm and measure the mass of planets in the habitable zone, using transit timing alone.

With the discovery of Kepler-16(AB)b and other candidates, Kepler has opened the field of circumbinary planets, worlds with dynamical environments that are much more dramatic than our own. I discuss how the interpretation of timing variations of stellar eclipses is much easier than the planetary transit case, arguing that we can expect unique dynamical models for many of these exotic systems. The results will give fresh input to both the statistics and the formation of planetary systems.

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The Kepler-18 Three Planet System. W. D. Cochran[1] and the Kepler Science Team, [1]McDonald Observatory, The University of Texas at Austin, 1 University Station C1402, Austin TX 78712-0259 (wdc@astro.as.utexas.edu)

Kepler-18b, c and d are three transiting planets orbiting around a Sunlike star. The transit signals were detected in photometric data from the ***Kepler*** spacecraft, and were confirmed to arise from planets orbiting a single star using a combination of large transit-timing variations, radial-velocity variations, Warm-Spitzer observations, and statistical analysis of false-positive probabilities. The host-star star has a mass of 0.97 solar masses, radius 1.1 solar radii, effective temperature 5345K, and iron abundance [Fe/H]= +0.19. The planetary orbits and their physical properties are given in Table 1. Kepler-18c and Kepler-18d are very near a 2:1 mean motion orbital resonance. We have detected transit timing variations (TTVs) in these two planets caused by their mutual gravitational interactions. These TTV signals are shown in Figure 1. We generated a joint solution to the transit times and radial velocities, which gave the masses reported above. This same dynamical model also constrains the mass of the inner planet Kepler-18b, but does not provide a direct confirmation of this planet.

The lack of a clear dynamical confirmation of the nature of Kepler-18b requires us to examine the wide variety of astrophysical false positives (blends) that might mimic the photometric transit, and to assess their *a priori* likelihood compared to that of a true planet. For this we apply the BLENDER technique described by Torres et al. (2004, 2011), with further developments as reported by Fressin et al. (2011). From this BLENDER analysis, the likelihood of a planet is more than 700 times greater than that of a false positive, which we consider sufficient to validate Kepler-18b as a true planet with a high degree of confidence.

Primary transits of Kepler-18c and Kepler-18d were observed with *Warm Spitzer* and the observed transit depths at 4.5μm agree well with the ***Kepler*** photometry. This strongly suggests that the radius-ratios of the candidate Kepler-18c and Kepler-18d to their host star is a wavelength independent function, in agreement with the expectation for a dark planetary object.

Kepler was competitively selected as the tenth Discovery mission. Funding for the ***Kepler*** Mission is provided by NASA's Science Mission Directorate. We are deeply grateful for the very hard work of the entire ***Kepler*** team.

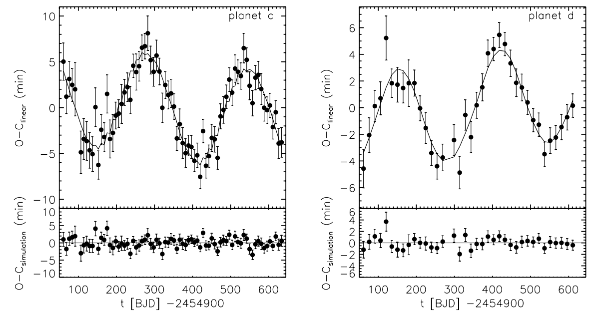

Figure 1: The observed minus calculated (based on a linear ephemeris) values of transit times, for planets c and d. The diamonds are transit times calculated using a dynamical model. The RV variations from this model are plotted along with the RV data.

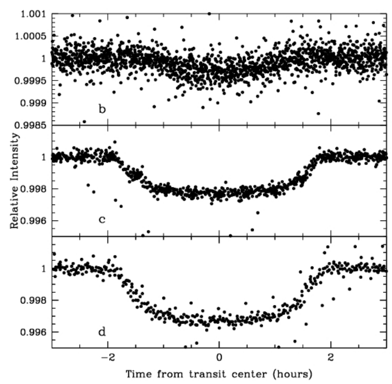

Figure 2: Folded light curves for Kepler-18. The top row is Kepler-18b (K00137.03), the middle row is Kepler-18c (K00137.01), and the bottom row is Kepler-18d (K00137.02). The light curves are folded on the mean period listed in Table 1 (below).

Fressin, F., et al. 2011, ApJ, in press, arXiv:1105.4647
Torres, G., Konacki, M., Sasselov, D. D., & Jha, S. 2004, ApJ, 614, 979
Torres, G., et al. 2011, ApJ, 727, 24

Table 1: Planet Properties

	Kepler-18b	Kepler-18c	Kepler-18d
Period (days)	3.50473±0.00003	7.64159±0.00003	14.85888±0.00004
a (AU)	0.0447±0.0006	0.0752±0.0011	0.1172±0.0017
Radius ($R_\oplus$)	2.00±0.10	5.49±0.26	6.98±0.33
Mass ($M_\oplus$)	6.9±3.4	17.3±1.9	16.4±1.4
ρ (cgs)	4.9±2.4	0.59±0.07	0.27±0.03

The Multiple Planet System Kepler-20.

T. N. Gautier III[1], Steven Bryson[2], David Charbonneau[3], Daniel Fabrycky[3], Francois Fressin[3], R. L. Gilliland[4], Howard Isaacson[5], David W. Latham[3], Jack J. Lissauer[2], Geoffrey W. Marcy[5], Jason F. Rowe[2], Guillermo Torres[3],
[1]Jet Propulsion Laboratory, [2]NASA Ames Research Center [3]Harvard Smithsonian Center for Astrophysics, [4]Space Telescope Science Institute, [5]University of California, Berkeley

Introduction: Initial examination of light curve data obtained with the *Kepler* observatory of the 12.4 magnitude star KIC 6850504 revealed the presence of 4 probable transiting objects. These transit events became Kepler Objects of Interest, and planetary candidates, KOI 70.01 through KOI 70.04 [1]. Further analysis of KIC 6850504 (now KOI 70) revealed a 5th planet candidate, KOI 70.05. Follow-up observations with several ground based telescopes and the Spitzer Space Telescope have been made to assess the likely hood that these KOIs are true planets.

Kepler photometry and astrometry: A search for transits in 484 days of the light curve of Kepler-20 from quarters 1 through 6, 13 May 2009 to 12 September 2010, yielded 5 planetary candidates with the periods given in Table 1. Detailed examination of the light curve provided no indication that any of the transit signals were likely due to transits of stellar companions in binary stars. Analysis of the motion of the photocenter of Kepler 20 during transits [2] showed no indication that a background object was producing any of the transit signals.

Follow-up observations: Moderate signal to noise ratio spectroscopy at several epochs showed no radial velocity variation indicating that any of the transit signals were due to a grazing eclipse by a stellar mass object. Analysis of these same spectra and measurements from the Kepler Input Catalog [3] produced the stellar parameters given in Table 1.

Twenty-eight high SNR spectra taken over a period of 449 days with the Keck HIRES spectrometer and an iodine cell produced a radial velocity curve with an uncertainty of a few meters per second.

Spitzer observations at 4.5μ of transits of KOIs 70.01 and 70.03 were obtained.

Confirmation and validation: A co-analysis of the *Kepler* photometry data and the Keck radial velocity data, assuming an eccentricity of zero for all planetary objects, was made to obtain an estimate of the masses of all candidates.

In addition a detailed analysis of the transit shapes and depths from *Kepler* and *Spitzer* photometry combined with the *Kepler* centroid motion results using the `BLENDER` program [2] was made to estimate the probability that each of the candidates was a true planet rather than a stellar blend mistaken for a planet.

The results of these analyses will be presented.

References: [1] Borucki, W., et al. (2011) *ApJ*, 736, 19. [2] Torres, G. et al. 2011, *ApJ*, 727, 24. [3] Brown, T. M., et al. (2011) *AJ*, 142, 112.

Table 1. Kepler 20 Properties

Mass	Radius	Log g	T_{eff}
(M_{sun})	(R_{sun})	(cgs)	(K)
0.96	0.98	4.43	5456

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In Situ Planet Formation Models of the Kepler-11 Six Planet System

E. V. Quintana[1] and the Kepler Team, SETI Institute/NASA Ames Research Center, M/S 244-30, NASA Ames Research Center, Moffett Field, CA 94035

Introduction:

Kepler-11 is a G dwarf star with a system of six transiting planets that were announced by the Kepler Team in February 2011 [1]. This system is extremely compact, all six planets orbit within 0.5 AU of Kepler-11, providing a remarkable testbed for planet formation theories. The inner five planets are on nearly circular, coplanar orbits within 0.25 AU of the star, and have a combined mass of 34.6 $M_{\oplus}$ indicating that they must have formed from a very massive protoplanetary disk. Most of the mass of these inner five planets is in rock or H_20, but most of the volume is in H/He (or H_20 for Kepler-11b). These significant light gas components imply that the gas was still around in the disk during their formation. Although planet migration cannot be ruled out, the lack of strong orbital resonances argues against against slow migration of the planets. We present results from a suite of numerical simulations of the final stages of planet formation within a massive protoplanetary disk around Kepler-11. We recently modified the Mercury integration package to include eccentricity damping to mimic the presence of small bodies and gas in the disk. We will present the results from our simulations and discuss the feasibility of the *In Situ* formation of this dynamically compact system.

References:

[1] Lissauer, J. J. et al. (2011) *Nat., 470,* 53-58.

216. MULTIPLE PLANET SYSTEMS

DETECTION OF QUASI-PERIODIC TRANSITING PLANETS WITH KEPLER. E. Agol[1] and J. A. Carter[2,3], [1]Dept. of Astronomy, Box 351580, Univ. of Washington, Seattle, WA 98195; agol@astro.washington.edu, [2]Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138; jacarter@cfa.harvard.edu, [3]Hubble Fellow.

Dynamical interactions between transiting extrasolar planets can cause the times of transit to vary significantly. The smallest planets undergo the largest variations when in resonance, and since these have a small transit depth, they can be missed by transit detection algorithms that assume a fixed period for the planet. We present a new solution for detecting these planets, the Quasi-periodic Automated Transit Search (QATS) algorithm, which adapts an existing technique to the transiting planet problem. The algorithm does a global search for transits in continuous photometric light curves, assuming that the spacing between successive transits falls within a specified range of durations. We will show examples of the algorithm applied to simulated and actual Kepler data, discuss the false-alarm probability of the algorithm, and demonstrate its performance in finding nearly periodic transiting planets, as well as other potential applications.

217. MULTIPLE PLANET SYSTEMS

ECCENTRICITIES AND INCLINATIONS IN KEPLER'S PLANETARY SYSTEMS. E. B. Ford[1], A.V. Moorhead[1], R.C. Morehead[1] and the Kepler Science Team, [1]University of Florida (211 Bryant Space Science Center, Gainesville, FL 32611-2055, USA, eford@astro.ufl.edu).

Abstract: NASA's *Kepler* mission has identified over 1200 planet candidates, including hundreds of Earth-size and super-Earth-size planet candidates [1]. While *Kepler* can measure the orbital period and star-planet size ratio precisely, it is considerably more difficult to characterize the orbital eccentricities and inclinations of planets identified by *Kepler*. Both eccentriccities and inclinations can provide clues into the history of planet formation and orbital evolution. We provide an update on the use of transit durations and the frequency of systems with multiple transiting planets to constrain the eccentricity distribution [2] and inclination distributions [3] of Kepler planet candidates. In particular, we revisit whether the distribution of orbital eccentricities is correlated with planet size, number of transiting planets in the system or host star properties. These results are significantly more robust than [2] thanks to improved characterization of host stars by the *Kepler* Follow-Up Observation Program and the Kepler Astroseismic Consortium.

Next, we investigate eccentricities and inclinations in systems with multiple transiting planet candidates. These systems can provide several additional constraints (e.g., orbital stability [3], transit timing variations [4], transit duration variations [5] and the transit duration ratio [5]) that make them fertile ground for testing planet formation models. We summarize the implications of our results for the frequency of planetary systems with small planets on nearly circular orbits like the solar system and the climate of the small planets being identified by *Kepler*. Funding for this mission is provided by NASA, Science Mission Directorate.

References: [1] Borucki, W. B. et al. (2011) *ApJ*, 736, 19. [2] Moorhead, A. V. et al. (2011) accepted to *ApJS,* arxiv:1102.0547. [3] Lissauer, J. J. (2011) accepted to *ApJS,* arxiv:1102.0543. [4] Ford, E. B. (2011) accepted to *ApJS,* arxiv:1102.0544. [5] Holman, M.J. (2011) *Science*, 330, 31.

CONSTRAINING ORBITAL ECCENTRICITY THROUGH TRANSIT PHOTOMETRY ALONE: MULTIBODY ASTERODENSITY PROFILING (MAP). V. P. Manthri[1], D. M. Kipping[2], W. R. Dunn[3] and J. M. Jasinski[4], [1]Department of Physics and Astronomy, University College London, Gower St., London WC1E 6BT, email: zcapd85@ucl.ac.uk, [2]Harvard-Smithsonian Center for Astrophysics, email: kippingdavid@gmail.com, [3]University College London, email: zcapd28@ucl.ac.uk, [4]Mullard Space Science Laboratory, email: jamie.jasinski@ucl.ac.uk

Abstract: The high-calibre photometry of recent transit surveys, like the *Kepler Mission*, has allowed observations of targets that are too faint or too small to be observed by high-precision spectroscopy. This loss of intensive RV follow-up has lead to a loss in information about the orbital eccentricity. Should a planet be on an eccentric orbit, the stellar density, as derived from the transit curve, will deviate from the true density [1]. This deviation contains information on the orbital eccentricity but is inaccessible for a single-planet system without priors on the stellar density.

Multibody Asterodensity Profiling, or MAP, works around this problem by exploiting targets that exhibit multiple transiting systems. In this special, but still rather frequent (406 *Kepler* candidates as of Q2 [2]), case a ratio of the derived densities will eliminate the true density, leaving only the quantity dependent on eccentricity. MAP is a useful technique as it is model-independent; it requires no prior information about the host star and the only assumption is that both (or all) planets orbit the same star. Furthermore, MAP acts as a new observable and opens up the possibility of combination with TTV and RV for an extension of observable constraints.

As well as presenting the theory of this new method, we present the testing of MAP on a synthetic system, as proof of principle, and implementation of MAP on several multibody systems from the *Kepler Mission*, including the three-planet system Kepler-9 and the candidates KOI-209 and KOI-152, which exhibit two and three signals respectively.

References: [1] Kipping, D. M. (2010) *MNRAS, 407*, 301. [2] Lissauer, J. J. et al. (2011) *ApJ,* accepted.

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CONFIRMATION AND CHARACTERIZATION OF MULTITRANSITING EXOPLANET SYSTEMS WITH ANTI-CORRELATED TRANSIT TIMING VARIATIONS . J. H. Steffen, Institution: Fermilab Center for Particle Astrophysics, jsteffen@fnal.gov

The study of anticorrelated transit timing variations in a system with multiple transiting exoplanet candidates can be used to both confirm and to characterize the planets in those systems. Studies of these correlated variations, in conjunction with stability analyses, have been used to confirm several planets in suitable systems using a minimalist criteria for planethood. However, more information is likely to be present in the TTV residuals that was used for this confirmation. The ratio of the TTV amplitudes gives information about the mass ratio of the planets and dynamical interactions that correspond to higher order mean motion resonances may provide insight into the eccentricities of their orbits. I present the results of a TTV correlation analysis of several Kepler systems and discuss some of the insights that can be gleaned from the characteristics of those correlations.

THE SECULAR CHARACTER OF MULTI-PLANET SYSTEMS: KEPLER-10, 11 AND 16. C. Van Laerhoven[1] and R. Greenberg[1], [1]Department of Planetary Science, The University of Arizona, 1629 E University Blvd., Tucson, AZ, 85721-0092, cvl@lpl.arizona.edu

Introduction: In a multi-planet system with no mean-motion resonances, orbital angular momentum, but not energy, is exchanged through secular interactions. Secular interactions cause periodic variations in eccentricities e and arguments of pericenter ϖ (Kepler-discovered systems are likely to be nearly coplanar). The state of a system can be characterized by the amplitudes of the eigenmodes given by classical secular theory. Although classical theory becomes less accurate for planets with large e [1], it is still useful for gaining insight on the qualitative character of a multi-planet system in several ways [2,3]:

Dynamical grouping. Inspection of the degree of sharing of each eigenmode among the planets helps characterize how closely the planets are dynamically linked. If a planet is affected by only one eigenmode that affects no other planet, it is in effect dynamically isolated. At the other extreme, if all modes are shared among all the planets, the planets are strongly interactive. Dynamical grouping revealed in this way is an indication of the degree of planetary packing with implications for a system's formation. The grouping also indicates how strongly the effects of processes like tidal damping are shared among the planets.

Variation of eccentricities. Secular theory can diagnose variability of a planet's eccentricity under a wide range of conditions, without a need to numerically integrate a large number of specific cases, and with application to key issues: The signature of planet-planet scattering can be recognized in the secular constants; and habitability can be challenged where eccentrcities may reach extremes.

Eccentricity damping. If one planet's e is damped (e.g. by tides), the effect is shared among all planets, and secular theory yields the relative damping rate of each eigenmode. The amplitudes of the eigenmodes for an observed system thus constrain its past tidal evolution. When only one eigenmode remains, the pericenters would be aligned.

Kepler-10: Given the best mass values [4], the two planets of Kepler-10 are decoupled: Each of the eigenmodes is strongly concentrated in its own planet. If one planet's e is damped, the other may not be, and even with substantial damping, one would not expect to see pericenter alignment.

Kepler-11: The six planets' e's are unknown [5], but the normalized eigenvectors (Fig. 1) characterize the secular interactions. For $m_g = 0.05 M_J$ (Fig. 1a) the outer planet is dynamically uncoupled from the rest of the system. The other 5 planets are strongly coupled through the other modes. For the the maximum possible m_g (Fig. 1b) the dynamical linking of the outer planet (through mode 6) would be less anomalous.

If the inner planet undergoes tidal damping, mode 1 damps almost as quickly as if this were the only planet, but the other planets would be affected through damping of modes 2, 4, and 5. Eccentricity damping on planet *c* kills the same modes on similar timescales, so one would be unable to differentiate between e-damping on solely *b* versus on both *b* and *c*.

After those shorter-lived modes damp out, Fig. 1 shows planets *d* and *e* would be dominated by mode 3 and thus have aligned major axes, while planet *g* orbits independently with its constant e. If planet *g*'s mass is near its upper limit (Fig. 1b), planet *f* will also be uncoupled from the damping. As e values are determined in the future, they can be interpreted in this context.

Kepler-16: The planet's behavior [6] is dominated by classical secular interaction with the smaller star, and appears to be near the libration/circulation separatrix [7], but the reported small e implies discovery at a improbably special time in the secular cycle.

Consideration of secular interactions can be a powerful tool for interpreting the origin, evolution, and physical character of planetary systems discovered by Kepler.

References: [1] Veras D. and Armitage P. J. (2007) *ApJ*, *661*, 1311 [2] Van Laerhoven C. and Greenberg R. (2011) arXiv:1108.5149 [3] Greenberg R. and Van Laerhoven C. (2011) *ApJ*, *733*, article id 8 [4] Batalha N. M. *et al.* 2011 *ApJ*, *729*, 27 [5] Lissauer J. et al. (2011) *Nat.*, *470*, 53 [6] Doyle L. et al. (2011) *Science*, *333*, 1602 [7] Barnes R. and Greenberg (2006) *ApJ*, *638*, 478

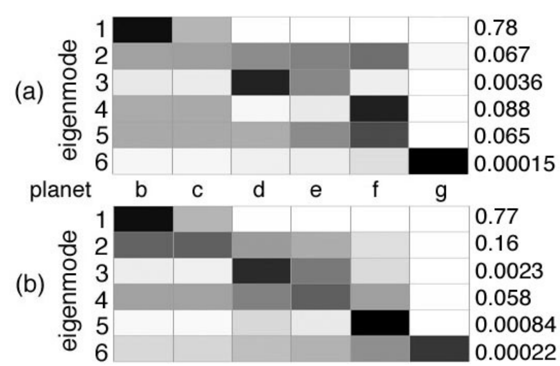

Figure 1: Normalized eigenvectors for Kepler-11 with (a) m_g = 0.05 M_J and (b) m_g = 0.95 M_J. Matrix values are shown by shading (black =1, white = 0). Damping rates for each mode relative to damping of the inner planet are shown at right.

221. MULTIPLE PLANET SYSTEMS

Analysis of 224 Kepler Exoplanets in 93 Multiple Systems. D. R. Ciardi[1], S. B. Howell[2], J. J. Lissauer[3,] M. E. Everett[4] and the Kepler Science Team [1]NASA Exoplanet Science Institute/Caltech, Pasadena, CA USA 91350 (ciardi@caltech.edu), [2]NASA Ames Research Center (steve.b.howell@nasa.gov), [3]NASA Ames Research Center (jack.j.lissauer@nasa.gov), [4]National Optical Astronomy Observatory (everett@noao.edu)

Introduction: We present an analysis of 224 exoplanets in 93 systems in the Kepler field. These systems are all fainter than Kepmag > 14.5 mag and are difficult to confirm with follow-up radial velocity observations from the ground. All of the these planets occur in systems where multiple transiting planetary candidates have been identified. Based upon the work of Lissauer et al. (2011) [1], the false positive probability for each multiple system is significantly lower than that of single planet systems. We have obtained spectra for all of the stars in the sample and determined their effective temperatures, surface gravities and radii, and we have also utilized imaging to assess the blend contamination for each of the Kepler targets. Coupling the derived stellar parameters and the deblended light curves, we have determined the transit and planetary parameters for these systems. We then present a statistical analysis of these multiple systems.

Early Analysis: Analysis is still on-going at the time of this writing, but Figure 1 shows an example of the work performed. The planet candidate sizes appear to be independent of the stellar sizes, although the biggest planets are preferentially found around the larger stars, and large planets in multiple systems do not appear in K and M stellar systems. Additionally, in the multiple systems, there is a strong correlation between the planet size and the orbital period of the planet – the largest planets appear in the longest orbital periods, suggesting that giant planets that migrate into short orbital periods sweep out other planets within the systems (see also [2]). A discussion of the biases in the sample is also presented.

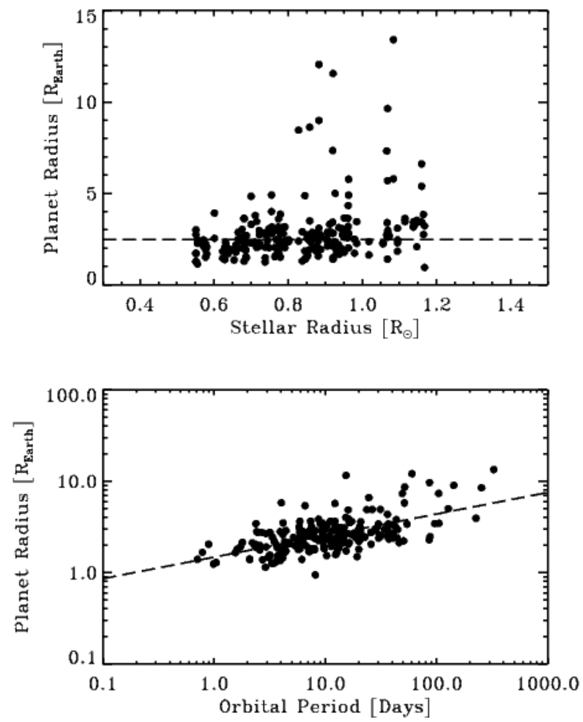

Figure 1: *Top*: Distribution of the planet sizes as a function of stellar size. The dashed line represents the median planet radius of the sample (2.47 Rearth). *Bottom*: Distribution of the planet sizes as a function of the planet orbital period showing a strong correlation; i.e., the largest planets are in the longest orbits.

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Using the composition of super-Earths to track formation processes

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The composition of super-Earths reflects the initial chemical inventory of building blocks during formation, plus any subsequent evolution such as mass loss from evaporation or giant impacts. With measured masses and radii of now several super-Earths, and in combination with internal structure models, it is possible to place constrains on their composition. The results show that both CoRoT-7b and Kepler-10b are rocky planets similarly enriched in iron with respect to Earth. This composition can either have a primordial origin, or be the result of collisional stripping due to giant impacts, or erosion due to atmospheric evaporation. Taken from a sample of stars with and without planets, the Fe/Si ratio of stars cannot account for a primordial composition. In fact, most stars are slightly enriched in Si (a factor of 1.5 in Si/Fe) with respect to solar. Collisional stripping is an effective process to remove part of the silicate mantle of a differentiated planet, and thus, increase its iron content. However, this process is also stochastic and would lead to a wide range of outcomes. On the other hand, erosion of a silicate mantle through atmospheric evaporation is a more systematic process and may also account for iron enrichment. With a simple atmospheric evaporation model, I obtain evaporation tracks that can connect the composition of the solar nebula to the current composition of the high-density exoplanets.

In addition, within the same mass range, there are a handful of low mass planets that have too large a radius to be rocky. In particular, while sharing the same irradiation level than CoRoT-7b and Kepler-10b, 55 Cnc-e is a volatile planet, with a water-vapor envelope. I will present results on the composition of the volatile low-mass planets and focus on GJ1214b. This planet stands out because of the transmission spectra observations that have been taken. While most studies indicate a water-dominated atmosphere, one suggests a H/He composition. With internal structure models, we show that this planet can be fitted with a 100% water-vapor composition. Based on formation arguments, this extreme composition is unlikely, and refractory material, which condenses first from the nebula, is expected. Thus, requiring the presence of lighter abundant gases (such as H/He) as well.

In summary, because of the connection to formation, inferring the composition of super-Earths can help us understand better how planets form and acquire their chemical inventories.

302. EXOPLANET THEORY

ACCUMULATION OF HYDROGEN-RICH ATMOSPHERES OF NEBULAR ORIGIN ON SHORT-PERIOD SUPER-EARTHS: IMPLICATIONS FOR KEPLER-11 PLANETS. M. Ikoma[1] and Y. Hori[2], [1]Department of Earth and Planetary Sciences, Tokyo Institute of Technology, Ookayama, Meguro-ku, Tokyo 152-8551, Japan; mikoma@geo.titech.ac.jp. [2]Division of Theoretical Astronomy, National Astronomical Observatory of Japan, Osawa, Mitaka, Tokyo 181-8588, Japan; yasunori.hori@nao.ac.jp.

Introduction: The space telescope Kepler detected five super-Earths orbiting a Sun-like star named Kepler-11 [1]. The transit measurements revealed that those planets were large in size. This suggests the presence of thick hydrogen-rich atmospheres on the planets. Indeed, according to detailed modeling, the atmospheres of, at least, two of the five, Kepler-11d and 11e, constitute approximately 10-20% of the planetary total masses, provided they are rocky planets [1]. If so, they are a new type of planet that we have never seen in the current solar system. Furthermore, estimates of atmospheric mass loss due to intense stellar-XUV irradiation suggest that they all had such thick atmospheres in the early stages [1, 2].

Those atmospheres, if primordial, came from the protoplanetary disk in which the planets formed. In the framework of the core accretion model [3], solid planetary embryos first form, and then collect the surrounding disk gas gravitationally to form hydrogen-rich atmospheres. If this occurs well before disk dispersal, the disk gas accretion proceeds in a runaway fashion beyond some critical point. This results in the formation of massive hydrogen-rich envelopes of gas giants [4, 5]. The critical point is when the atmospheric mass is approximately 20-30% of the protoplanetary total mass [6], the fraction being similar to those of the atmospheres of interest. This means that the inferred masses of the atmospheres of the Kepler-11 planets are close to critical. In this sense, the origin of their predicted atmospheres interests us.

In this study, we examine how likely the Kepler-11 planets are to have gained such intermediate-mass atmospheres from a protoplanetary disk within the context of recent theories of planetary accretion and disk evolution.

Methods: We have simulated the accumulation of hydrogen-rich atmospheres on rocky protoplanets embedded in the ambient disk gas with temperatures appropriate to the Kepler-11 planets. We newly include the effects of the concurrent disk dispersal. Recent *N*-body simulations demonstrate that final collisions of protoplanets occur during disk gas dissipation [7]. After the final giant collisions, the protoplanets cool, losing the collision energy, which results in the contraction and accumulation of the atmospheres.

Results: Our simulations demonstrate that the atmospheric growth has two distinctly different outcomes, depending on planetary mass. Light proto-super-Earths undergo significant atmospheric erosion during disk dispersal. At relatively high disk temperatures appropriate to the Kepler-11planets, they gain atmospheres only with mass of, at most, a few % of the planetary masses. In contrast, heavy proto-super-Earths undergo runaway disk-gas accretion to gain massive atmospheres like gas giants' envelopes. Thus, there are few solutions where the atmosphere constitute 10-20% of the planetary mass.

Conclusions: This study demonstrates that proto-planets with mass of 1-10 Earth masses, namely, proto-super-Earths rarely gain intermediate-mass hydrogen-rich atmospheres from protoplanetary disks. If the Kepler-11 planets were rocky planets with the predicted intermediate-mass hydrogen-rich atmospheres, those atmospheres would be unlikely to be primordial.

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Core Erosion in Gas Giant Exoplanets Predicted from Ab Initio Simulations

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The observed mass-radius relationships of several transiting gas giant exoplanets have revealed that they are substantially heavier than a planet composed of just a mixture of hydrogen, helium, and heavier elements in stellar proportion. This is typically interpreted as evidence of a dense rocky core. Alternatively, models with a homogeneous enrichment of the gas envelope has also been considered. Here we employ ab initio Gibbs free energy calculations to investigate whether the materials in the core of gas giant exoplanets are thermodynamically stable when exposed to the layers of metallic hydrogen above at expected pressure-temperature conditions at the core-mantle boundaries. We focus on two typical core materials: water and magnesium oxide. We demonstrate that both materials are unstable and will insetad dissolve into metallic hydrogen. This implies that the core of all gas giant planets are, at least partially, eroded and, furthermore, that the observed mass-radius relationships are not sufficient to demonstrate the existence of a rocky core today.

304. EXOPLANET THEORY

THEORETICAL ISSUES FOR ROCKY PLANET INTERIORS NEAR 1.0 EARTH-MASS AND M-R RELATIONS. Dimitar D. Sasselov, Harvard-Smithsonian Center for Astrophysics, 60 Garden St. Cambridge, MA 02138, dsasselov@cfa.harvard.edu

Introduction: We review several aspects of Earth's geodynamics that are uncertain under extrapolation. Our goal is to map the theoretical mass-radius parameter space for rocky planets in the vicinity centered on 1.0 M_e, 1.0 R_e. We focus on diverse compositional models, corresponding atmospheres and surface evolution, with an eye on reducing the inherent degeneracy of the M-R diagram for small planets. We consider only the region up to 1.25 R_e, the so called Earth-size planets, and implications for Kepler.

PLANET FORMATION AND THE DIVERSITY OF PLANETARY SYSTEMS.

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Introduction: We present new simulation results of planets growing from a sea of planetesimals within a protoplanetary disk. We track the viscous evolution of the disk, coagulation and fragmentation of planetesimals, gravitational dynamics of protoplanets, and accretion of gas by icy or rocky cores. The key physical parameters for our code include the initial mass of the disk (M_{disk}), the gas viscosity (α), and the disk's photoevaporation rate. Our results demonstrate how each parameter impacts the properties of newly-formed planetary systems. High M_{disk} and low α favor Jupiters over Neptunes. High photoevaporation rates favor Neptunes over Jupiters. We compare predicted mass distributions of planets inside ~1 AU with results from Kepler.

306. EXOPLANET THEORY

THE FINAL STAGE OF TERRESTRIAL PLANET FORMATION. E. Kokubo[1] and H. Genda[2], [1]National Astronomical Observatory of Japan (2-21-1 Osawa Mitaka Tokyo 181-8588 Japan), [2]University of Tokyo

Introduction: The final stage of terrestrial planet formation is known as the giant impact stage where protoplanets collide with one another to form planets. So far this stage has been mainly investigated by N-body simulations with an assumption of perfect accretion in which all collisions lead to accretion. However, this assumption breaks for collisions with high velocity and/or a large impact parameter. In order to understand the final stage of terrestrial planet formation, we have to take into account the effects of imperfect accretion on orbital and accretionary dynamics.

Methods: We derive an accretion condition for protoplanet collisions in terms of impact velocity and angle and masses of colliding bodies, from the results of numerical collision experiments[1]. We adopt this realistic accretion condition in N-body simulations of terrestrial planet formation from protoplanets and compare the results with those with perfect accretion and show how the accretion condition affects terrestrial planet formation[2]. We also perform N-body simulations with collisional debris to investigate the orbital evolution of terrestrial planets due to the interaction with the debris.

Results: We find that in the realistic accretion model, about half of collisions do not lead to accretion. However, the final number, mass, orbital elements, and even growth timescale of planets are barely affected by the accretion condition. For the standard protoplanetary disk model, typically two Earth-sized planets form in the terrestrial planet region over about 100 Myears in both realistic and perfect accretion models.

We also find that typically 10-20% of the total protoplanet mass is released as collisional debris in this stage. We demonstrate that if the debris is distributed locally around a planet orbit, the orbital eccentricity of an Earth-sized planet can be damped to ~ 0.01 through dynamical friction from the debris in about 100 Myears (Fig.1).

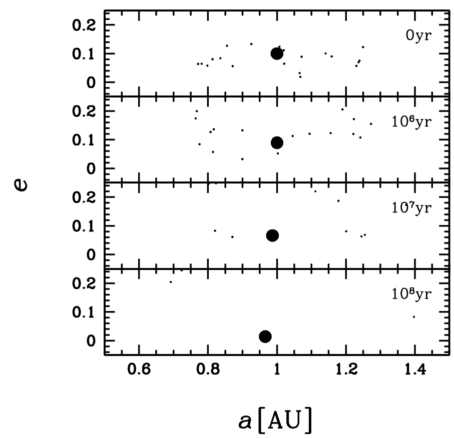

Figure 1: An example of the orbital evolution of a terrestrial planet with collisional debris on the semimajor axis-eccentricity plane. The initial planet mass is $0.9M_{\oplus}$ and the initial total mass of the debris is $0.1M_{\oplus}$. The initial planet semimajor axis and eccentricity are 1 AU and 0.1, respectively. The debris is initially represented by 20 particles with high eccentricity that are distributed between 0.75 AU and 1.25 AU. The planet eccentricity decreases from 0.1 to $\simeq 0.01$ due to the dynamical friction from the debris in 100 Myears.

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307. EXOPLANET THEORY

SNAGGING AN EARTH-CLASS EXOPLANETARY MOON. D. M. Williams[1] and A. I. Collins-Hed[2], [1]Penn State Erie, The Behrend College; 4205 College Drive, Erie PA, 16563; dmw145@psu.edu; [2]aic110@psu.edu

Introduction: Planets are now expected to migrate towards [1] and sometimes towards and away [2] from their host stars as they form. Such motion could destabilize the orbits of terrestrial planets that form in the same vicinity. This may result in close encounters between giant planets and terrestrial objects that produce a three-body "binary exchange" capture. In such an event, a binary terrestrial object – presumably formed through pairwise accretion - is tidally disrupted by a giant planet and one member of the binary is lost while the other member is retained as a moon [3]. Whether a moon is captured depends sensitively on the encounter distance and velocity, as well as the masses of the terrestrial binary, the planet, and the host star. Here we show that such encounters sometimes produce moons exceeding a Mars mass around Jupiter-class planets. Binary-exchange capture might then be the best way to form moons large enough to have atmospheres and to harbor water-dependent life [4].

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308. EXOPLANET THEORY

Are hot Neptunes partially evaporated hot Jupiters?

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Abstract

The detection of short period planets (hot Jupiters and their lower mass counterparts, hot Neptunes and super-Earths) still defies the models of planet formation and evolution. Several possibilities have been proposed to explain the nature and formation process of the lower mass population, including in situ formation, disk migration, planet-planet scattering and kozai evolution, and the evaporation of a higher mass hot Jupiter. Using dynamical models and the best estimates for evaporation velocities, we show that under reasonable (and observed) physical conditions, hot Jupiter evaporation may explain the observed population of hot Neptunes/super-Earths.

TRANSIT CONSTRAINTS FOR A GENERAL PLANET FORMATION THEORY PROVIDED BY CoRoT AND KEPLER. G. Wuchterl[1], [1] CoRoT (DLR), Thüringer Landessternwarte, Sternwarte 5, D-07778 Tautenburg, Germany.

Introduction: I present results on a probabilistic general theory of planet formation. It is general in the sense that

(1) it does not distinguish a-priori between planet-formation driven by a core and not driven by a core, and,

(2) makes no a-priori assumption about the planet forming nebulae, except they are gravitationally stable.

The goal of this approach is to understand the diversity of the exoplanet population as a consequence of the diversity of nebulae and with a minimum number of basic physical principles.

Methods: Planetary masses are determined by calculating all physically possible planetary equilibria – hydrostatic and thermal - in arbitrary gravitationally stable nebulae, cf. [1]. Planetary radii are determined by calculating the evolution of all planets found in the mass determination step. Frequencies of planets are obtained for given system age, host-star mass and planetary orbital period.

Results: We compare the theoretical planet frewuencies to detected transiting planets in a probabilistic mass-radius diagram (see Figure).

The theory is confronted to the discoveries of Kepler and CoRoT with the strength of the constraints for the theory estimated by the amount of volume of the "phase"-space of all physically possible planets that is excluded by the observed planetary properties.

Finally, in a less statistical approach we discuss how this approach helps to understand the extreme objects CoRoT-2b, CoRoT-18b, CoRoT-3b, CoRoT-15b, CoRoT-13b and CoRoT-20b.

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Acknowledgment: Supported by the *Deutsches Zentrum für Luft- und Raumfahrt* (DLR) under grant 50-OW0603.

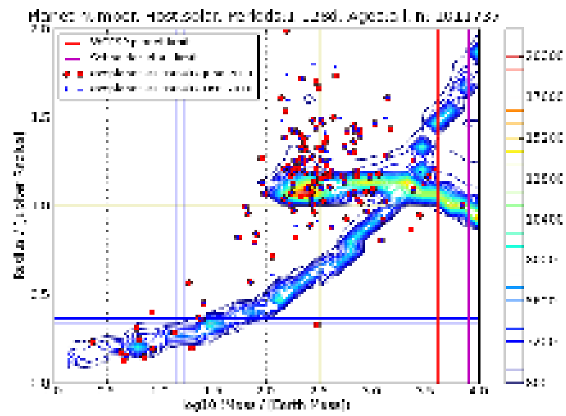

Figure: Probabilistic theoretical mass-radius diagram for planets in orbits of 1 to 128 days near a solar mass star for ages of 0.01 to 12 Ga. The number of planetary models is displayed with equidistant colour-enhanced contours. Exoplanets from the Extrasolar Planets Encyclopedia, [2] are plotted as of Oct. 2010 (blue dots) and Mai 2011 (red dots). The new proposed planet mass limit, [3] is plotted as a magenta vertical line, the WGESP-limit as a red vertical line. Yellow and blue straight lines mark masses and radii of Jupiter, Uranus and Neptune.

310. EXOPLANET THEORY

Formation and Diversity of Planetary Systems around M dwarfs : Toward the Next-Generation Observations

○**Yasunori Hori** [1], Eiichiro Kokubo [1], Shoichi Oshino [1] and Shigeru Ida [2]

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[2] Tokyo Institute of Technology

The existence of low-mass planets gives us a key milestone for our understanding of the pathway from planetesimals to planets. Recently, the CoRoT and the Kepler missions have enabled us to detect low-mass planets with typically several times Earth-mass. However, target stars of those missions are mainly F, G, and K dwarfs. Planets around low-mass stars such as M dwarfs still remain to be poorly known. This motivates us to unveil planets orbiting M dwarfs as a next step. Although the HARPS has employed planet surveys around faint M dwarfs via high-precision radial velocity measurements at optical wavelengths, the number of planets around M dwarfs is limited to about 30. Nowadays the projects of IR doppler surveys and IR transit photometry for M dwarfs harboring planets as an alternative methodology are ongoing. Thus, in order to predict the properties of planets around M dwarfs to be discovered by the next-generation observations, we have investigated planet formation around M dwarfs on the basis of the standard framework of planetary accretion. In this talk, we review orbital properties of discovered planets around M dwarfs and then demonstrate the expected diversity of planetary systems around M dwarfs through a semi-analytical approach and population synthesis. We also discuss impacts of planetary migration, disk dispersal, stellar metallicity, and initial masses of protoplanetary disks on final configurations of planetary systems around M dwarfs. Finally, taking into account both mass loss of planets and tidal evolution, we present the expected planetary mass-semimajor axis distribution for M dwarfs.

311. GIANT PLANETS AND PLANET ATMOSPHERES

Kepler Giant Planet Discoveries S. Seager[1,2], B. Demory[1], and the *Kepler* Team. [1]Department of Earth, Atmospheric, and Planetary Sciences, Massachusetts Institute of Technology, Cambridge MA, 02139, [1]Department of Physics, Massachusetts Institute of Technology, Cambridge MA, 02139. seager@mit.edu, demory@mit.edu.

Introduction: The *Kepler Space Telescope* has discovered nearly one dozen confirmed giant planets and has additionally identified more than one hundred giant planet candidates**.** Based on *Kepler* Q0-Q2 data (1235 planet total candidates; [1]), there are 165 giant planet candidates with $6\ R_\oplus < R_p < 15\ R_\oplus$ and 19 candidates with $15\ R_\oplus < R_p < 22\ R_\oplus$ for a total of 184 objects. *Kepler* is changing giant exoplanet science by providing enough planet candidates for statistical studies, while at the same time because of large pool of planet candidates is yielding interesting individual giant planets.

The Power of *Kepler* Giant Planet Statistics:

Giant planet radius vs. semi-major axis. A long-standing question in giant exoplanets is the origin of the inflated radii. In a detailed analysis of 116 giant planet candidate light curves from Q0-Q2 public data we find a lack of inflated radii for *Kepler* giant planet candidates receiving modest stellar irradiation [2]. Here "modest irradiation" is observationally derived as a stellar irradiation level of less than $\sim 2 \times 10^8$ erg s^{-1} cm^{-2}. At this or lower irradiation levels the giant planet radii appear to be independent of host star luminosity. We discuss the analysis and results and point out which radius inflation theories still stand.

Giant planet albedos. For a second example of the science from *Kepler*'s large number of giant planet candidate light curves, we investigate hot Jupiter albeos using using Q0-Q6 data (presented by Demory et al., this conference). We summarize a comparative study aiming to identify and interpret secondary eclipses of *Kepler* hot-Jupiters. The secondary eclipse in the *Kepler* bandpass has both reflected light and thermal emission contributions, depending on the estimated planet atmosphere temperature. Our results show that irradiated giant planets have both reflective and dark atmospheres.

Individual *Kepler* Giant Planet Highlights: For a comprehensive overview we list the *Kepler* giant planet discoveries and emphasize any new constraints on planet formation and migration theories. The giant planet discovery highlights include: the first circumbinary planet (Kepler-16 (AB)b, [3]); the first non-transiting planet detected via transit timing variations (Kepler-19c, [4]); a low density inflated hot Jupiter (Kepler-12b, [5]); a massive hot Jupiter orbiting an F-star which is a member of a binary system (Kepler-14b, [6]); a hot-Jupiter orbiting a metal rich star ([Fe/H]=0.36) (Kepler-15b, [7]); a short period hot Jupiter with the determination of obliquity using star-spots and a stroboscopic effect (Kepler-17b, [8]).

Giant Planet False Positives: As a byproduct of our statistical analysis described above, we find a giant planet false positive rate of 17% as compared to the planet candidates identified by the *Kepler* data pipeline [1]. Our false positive rate comes from identifying secondary eclipses and by determining if the secondary eclipse depth is too large for a planetary origin [2]. The motivation for a false positive analysis is that the *Kepler* giant planet candidates understandably receive a lower priority for radial velocity followup and for "blender analysis" than the sub-Neptune-size planet candidates.

Outlook: We will conclude with *Kepler*'s future outlook for giant exoplanet science.

Acknowledgements: We thank the *Kepler* Giant Planet Working Group for many useful discussions. Funding for the *Kepler* Mission is provided by the National Aeronautics and Space Administration (NASA) Science Mission Directorate. This work was in part funded by the Kepler Participating Science Program grant NNX08BA51G.

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312. GIANT PLANETS AND PLANET ATMOSPHERES

THE HEAVY-ELEMENT MASSES OF EXTRASOLAR GIANT PLANETS, REVEALED. J. J. Fortney[1] and N. Miller, [1]Department of Astronomy and Astrophysics, University of California, Santa Cruz, 1156 High St., Santa Cruz, CA, USA 95064

We investigate a population of transiting planets that receive relatively modest stellar insolation, indicating equilibrium temperatures <1000 K, and for which the heating mechanism that inflates hot Jupiters does not appear to be significantly active. We use structural evolution models to infer the amount of heavy elements within each of these planets. There is a correlation between the stellar metallicity and the mass of heavy elements in its transiting planet(s). It appears that all giant planets possess a minimum of ~10–15 Earth masses of heavy elements, with planets around metal-rich stars having larger heavy-element masses. There is also an inverse relationship between the mass of the planet and the metal enrichment (Zpl/Zstar), which appears to have little dependency on the metallicity of the star. Saturn- and Jupiter-like erichments above solar composition are a hallmark of all the gas giants in the sample, even planets of several Jupiter masses. These relationships provide an important constraint on planet formation and suggest large amounts of heavy elements within planetary H/He envelopes. We suggest that the observed correlation can soon also be applied to inflated planets, such that the interior heavy-element abundance of these planets could be estimated, yielding better constraints on their interior energy sources. We point to future directions for planetary population synthesis models and suggest future correlations. This appears to be the first evidence that extrasolar giant planets, as a class, are enhanced in heavy elements.[1]

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313. GIANT PLANETS AND PLANET ATMOSPHERES

Kepler's Dark And Reflective Worlds. B.-O. Demory[1], P. Nutzman[2], S. Seager[1] and J. Fortney[2] [1]MIT, 77 Mass. Ave, 02139, Cambridge, MA – demory@mit.edu, seager@mit.edu, [2]University of California, pnutzman@ucolick.org, jfortney@ucolick.org

Introduction: Only a handful of giant planets do have constraints on their emission at visible wavelengths. Therefore, little is known about the processes that make those objects bright or dark. Incident stellar flux, atmosphere composition and dynamics play a salient role in producing the planetary emission. The precise photometry obtained with the Kepler mission allows to probe the planetary emission at visible wavelengths for a large sample of giant planets exhibiting various orbital and physical properties.

We present a comparative study aiming at characterizing hot-Jupiters visible flux in the Kepler bandpass, using Q0-Q6 data. Our results show that irradiated giant planets do have both reflective and dark atmospheres. We discuss the influence of planetary density and incident flux on the observed patterns. The statistical significance of our sample allows to constrain the possible origins of this diversity and emphasizes how Kepler contributes to the growing field of comparative exoplanetology.

314. GIANT PLANETS AND PLANET ATMOSPHERES

ALBEDO SPECTRA OF EXTRASOLAR GIANT PLANETS.

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Introduction: The geometric albedo spectrum of a giant planet is controlled by a balance between absorption and scattering by gasses and condensates. Typically Rayleigh scattering and photochemical haze absorption dominate at UV and blue wavelengths while molecular and atomic absorption and cloud scattering are primary at red wavelengths. As a result the geometric albedo of any given planet can vary dramatically as a function of wavelength. Meanwhile the Bond albedo, which measures the overall energy balance of a planet, depends both on the geometric albedo and the spectrum of incident light. The same planet with a fixed geometric albedo spectrum can have very different Bond albedos under the light of an A star and an M star [1] for example. Thus any constraint on a planet's geometric albedo spectrum can provide greater insight into atmospheric structure and chemistry than the Bond albedo.

Observational Constraints: Berdyugina and colleagues [2] recently employed polarimetry to constrain the geometric albedo of the non-transiting planet Upsilon Andromedae b in U, B, and V bands. They also combined their constraints with measurements of geometric albedo for various other hot Jupiters from the literature to construct a generic hot Jupiter albedo spectrum. They found that the geometric albedo of hot Jupiters varies from 0.5 at 365 nm to 0.3 at 500 nm to less than 0.1 at 800 nm. This very blue spectra--somewhat reminiscent of Neptune--matches well the expectations from planetary atmosphere models.

Modeling: In [3] we combined self-consistent radiative-convective equilibrium models of exoplanet atmospheres with a code that computes the geometric albedo spectrum and phase curves of arbitrary planets. In that paper we focused on planets which might be directly imaged, for example by space-based coronagraphs. The role of clouds in controlling the reflectance spectra of such planets is clearly seen here in Figure 1. Planets with clouds typically have a fairly neutral overall spectrum with deep absorption bands in the red. Cloud-free planets in contrast show a strong blue slope such as seen in the composite exoplanet spectrum constructed by Berdyugina et al. [2].

While the spectrum shown in Figure 1 is for a cloudless Jupiter, it is nevertheless a planet at 0.8 AU and thus not a “hot Jupiter”. We are now computing similar geometric albedo spectra for true hot Jupiter cases, employing the atmospheric models of Fortney and collaborators. In our presentation we will discuss the geometric albedo spectra of such models and compare them both to the available exoplanet data and solar system observations. As albedo spectra are measured for more planets it may be possible to detect the transition from clear to cloudy atmospheres and thus place new constraints on the atmospheric physics of these exotic worlds.

References: [1] Marley M. S. et al. (1999) *ApJ., 513,* 879. [2] Berdyugina S. V. et al. (2011) *arxiv:1109.3116v1* [3] Cahoy K. L. et al. (2010) *ApJ., 724*, 189.

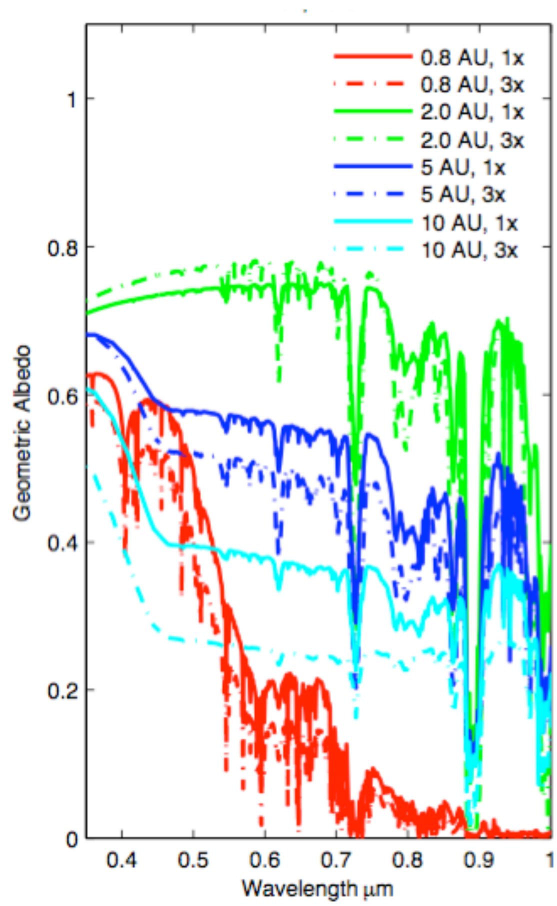


Figure 1: Geometric albedo spectra of various model Jupiter-mass planets (from [3]). Solar composition models are shown as solid lines, models with three times solar abundance of heavy elements are shown as dash-dotted lines. Note that Jupiters lacking atmospheric clouds (here the red curves) have a very blue spectrum while cloudy models have a much flatter reflection spectrum.

Title: Search for Secondary Eclipses of Hot Jupiters in Kepler Q2 Light Curves

Authors: Mercedes López-Morales (CSIC-IEEC, Spain) & Jeffrey L. Coughlin (NMSU, USA)

Abstract:

We present the results of searching the Kepler Q2 public dataset for the secondary eclipses of 76 hot Jupiter planet candidates from the list of 1,235 candidates published by Borucki et al. (2011). The search has been performed by modeling both the original Kepler PDC light curves and new light curves produced via our own photometric pipeline. We derive new stellar and planetary parameters for each system, while calculating robust errors for both. We find 16 systems with 1-2σ, 14 systems with 2-3σ, and 6 systems with >3σ confidence level secondary eclipse detections in at least one light curve, however, results can vary depending on the light curve modeled and whether eccentricity is allowed to vary or not. We estimate false alarm probabilities of 31%, 10%, and 6% for the 1-2σ, 2-3σ, and >3σ confidence intervals respectively. Comparing each secondary eclipse result to theoretical expectations, we find that many of the detected planet candidates emit more light than expected, indicating either high albedos, strong non-LTE processes, or mis-identification of brown dwarfs or stellar blends. Based on these results we estimate an 11% false positive rate in the current Kepler planet candidate sample of hot Jupiters. We also establish robust upper limits on the eclipse depth for the remaining systems, and find that the emission of most of those systems is consistent with the planets having very low albedos, i.e., at least 30% of all systems have $A_g < 0.3$ at 1σ confidence levels. This result augments the current number of constrained exoplanetary albedos and extends the sample of low albedo determinations to planets with temperatures as low as 1200 K. Finally, we note that continued observations with the Kepler spacecraft, are needed to better characterize these systems.

316. GIANT PLANETS AND PLANET ATMOSPHERES

Asymmetric transit curves as indication of orbital obliquity: stars and companion in KOI-13 Gy. M. Szabó[1], R. Szabó[1], J. M. Benkő[1], H. Lehmann[2], Gy. Mező[1], A. E. Simon[1], Zs. Kővári[1], G. Hodosán[1], Zs. Regály[1], B. Sipőcz[3], L. L. Kiss[1,4], [1]Konkoly Observatory of the Hungarian Academy of Sciences, PO. Box 67, H-1525 Budapest, szgy@konkoly.hu, [2]Thüringer Landessternwarte, 07778 Tautenburg, Germany,[3]Centre for Astrophysics Research, University of Hertfordshire, Hatfield AL10 9AB, [4]Sydney Institute for Astronomy, School of Physics A28, University of Sydney, NSW 2006, Australia

Introduction: Exoplanets orbiting rapidly rotating stars may have unusual light curve shapes. These objects transit across an oblate disk with non-isotropic surface brightness, caused by the gravitational darkening[1]. If such asymmetries are measured, one can infer on the orbital obliquity of the exoplanet and the gravity darkened star, even without the analysis of the Rossiter-McLaughlin effect or interferometry.

KOI-13.01, a planet-sized companion in an A-type optical double star, was announced as one of the 1235 Kepler planet candidates in 2011 February[2]. On 23 September, new data (Q3 SC) become available, and now the whole dataset covers ~220 days.

Results: KOI-13 is a common proper motion binary, with two rapidly rotating components (vsin i~65-70 km/s) at 1.18 arcsec separation. The transit curves show significant distortion that is stable in shape. and the transit curve asymmetry is consistent with a companion orbiting a rapidly rotating star on an oblique orbit [3]. In August, 2011, new time-resolved high-resolution spectroscopy of a transit was performed with the Nordic Optical Telescope (NOT) in DDT, and 3 weeks later, an out-of-transit spectum was taken with high S/N. Preliminary results confirm the oblique orbit.

With pixel-level photometry of Kepler data, and additional, complementary fast photometry of a transit we identified the host star of KOI-13.01 which is the brighter component, KOI-13 A. The transit depth, corrected to the second light (containing 45% of the total flux) is 8400 ppm. This implies a relative radius of 0.0884, setting the size of KOI-13.01 at around 2 R_J.

KOI-13.01 can also be detected in secondary eclipse (Figure 1, bottom panel), with an eclipse depth of 0.00012 ± 0.00001 and eclipse duration (t1 to t4) of 3.0 ± 0.2 hr, while its mid-time occurs at 0.5004 ± 0.0004 phase. There is no hint for an eccentric orbit of KOI-13.01. The variation of the reflected light is observed in the out-of-transit phases, and it is also asymmetric in shape. The temperature of KOI-13.01 is about 3150 K from the eclipse depth, which is 17% more than the equilibrium temperature on the companion's orbit. This difference is not unprecedented for exoplanets, and there is no hint for excessive internal heat production of the companion [3].

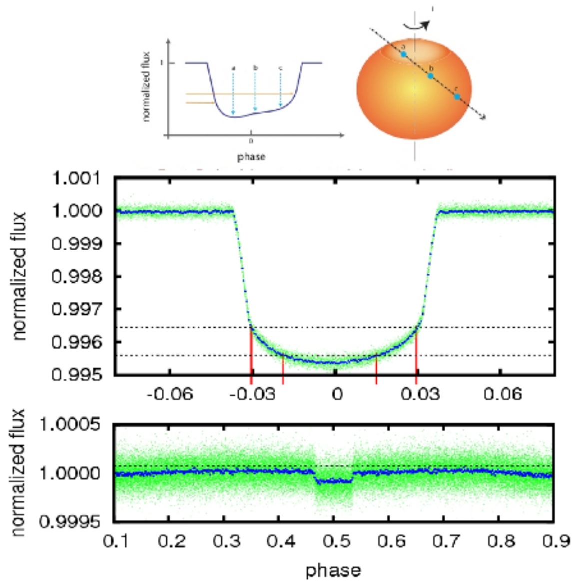


Fig. 1. Top: Stellar temperature gradient due to gravity darkening causes light curve distortions (based on the Barnes 2009 models). Middle: folded Kepler light curve of KOI-13 Bottom: the out-of-transit phase and the eclipse. Note the grid lines which emphasize the distortions.

There are indicative signs of non-axisymmetric flux distribution in our NOT spectroscopy. A variation of the line profile in a few week's timescale is suggested. Also, the out-of-transit light variation (Q2-Q3, Kepler SC) shows a complex structure of frequencies, which is probably related to stellar rotation. The scatter of the folded light curve is significantly larger than what is expected from photometric errors, also suggesting a slight variation of the transit light curve shape, and hence, structures on the stellar surface.

KOI-13 is a spectacular astrophysical laboratory of close-in companions in an oblique orbit. Two blue giants orbit each other, one of them hosts and an overheated close-in companion that glows in red light.

Acknowledgements. This project has been supported by the Hungarian OTKA Grants K76816, K81421, K83790 and MB08C 81013, and the "Lendület" Young Researchers' Program of the Hungarian Academy of Sciences.

317. GIANT PLANETS AND PLANET ATMOSPHERES

Interpreting Geometric Albedos, Phase Curves, and Polarization of Reflected Light from Exoplanets. N. Madhusudhan[1] and A. Burrows[1], [1]Princeton University (4 Ivy Lane, Peyton Hall, Princeton, NJ 08544; Email: nmadhu@astro.princeton.edu, burrows@astro.princeton.edu.)

Abstract: New observational facilities are becoming increasingly capable of observing reflected light from extrasolar planets. Kepler observations of occultations and phase curves have been reported for several hot-Jupiters [1-3]. In this study, we provide an analytic framework to interpret such observations of phase curves, geometric albedos, and polarization of giant exoplanetary atmospheres. We compute these observables for non-conservative Rayleigh scattering in homogeneous semi-infinite atmospheres using both scalar and vector formalisms [4,5]. We compare phase curves and albedos obtained for Rayleigh scattering with those obtained for Lambertian, isotropic, and asymmetric scattering phase functions [6], and discuss observable diagnostics to differentiate between the different scattering sources. We provide analytic expressions for geometric and spherical albedos as functions of the scattering albedo for semi-infinite Rayleigh scattering. Given an observed geometric albedo, our prescriptions can be used to estimate the underlying scattering albedo which is indicative of the scattering and absorptive properties of the atmosphere [7]. Using a combination of analytic and numerical approaches, we demonstrate how Kepler observations of occultations and phase curves of transiting exoplanets can be used to constrain their atmospheric properties: their scattering mechanisms, geometric albedos, presence of stratospheric absorbers, chemistry, and photospheric temperatures. We also study the dependence of polarization [8,9] of reflected light from Rayleigh scattering atmospheres on the orbital parameters of the system, particularly on the orbital inclination.

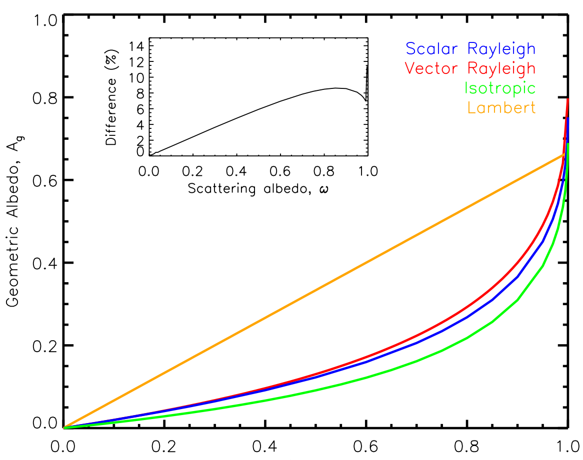


Fig. 1: Geometric albedos as a function of scattering albedo for different single-scattering phase functions. The red and blue curves in the main panel in Fig.1 show geometric albedos for Rayleigh scattering using the full phase matrix and using only the scalar phase function, respectively. The inset shows the percent difference between the two curves. The green and orange curves in the main panel correspond to isotropic and Lambert scattering, respectively. The scattering albedo (ω) is given by $\omega = \sigma_{scat}/(\sigma_{abs} + \sigma_{scat})$, where σ_{scat} is the single-scattering cross section and σ_{abs} is the absorption cross section.

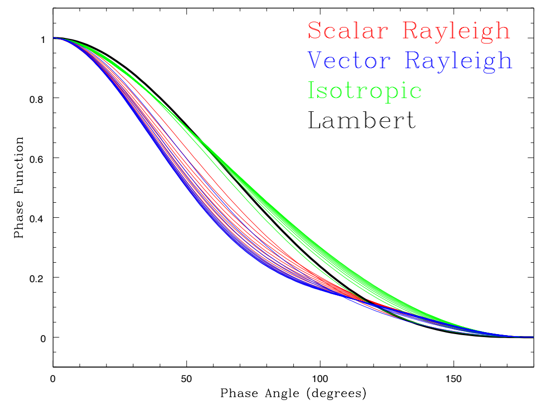


Fig. 2.— Comparison of phase curves for different single-scattering phase functions. The phase curves for Rayleigh scattering (both scalar and vector) and isotropic scattering are shown for several scattering albedos between 0 and 1; higher phase curves correspond to larger scattering albedos. For Lambert scattering, the phase curve is independent of the scattering albedo.

References: [1] Christiansen, J. L. et al. (2010), *ApJ*, 710, 97. [2] Desert, J.-M., et al. (2011), *arXiv*:1102.0555. [3] Demory, B-O. et al. (2011), *ApJ*, 735, L12. [4] Abhyankar, K.D., Fymat, A.L. (1970), *A&A* 4, 101. [5] Horak, H.G. & Chandrasekhar, S. (1961), *ApJ*, 134, 45. [6] Horak, H. G. (1950), *ApJ*, 112, 445. [7] Sudarsky, D., Burrows, A., & Pinto, P. (2000), *ApJ*, 538, 885. [8] Seager, S., Whitney, B.A., & Sasselov, D.D. (2000), *ApJ*, 540, 504 [9] Stam, D. M., Hovenier, J. W., & Waters, L. B. F. M. (2004), *A&A*, 428, 663.

Acknowledgements: The authors acknowledge support from NASA ATP grant NNX07AG80G, HST grants and JPL/Spitzer Agreements.

318. GIANT PLANETS AND PLANET ATMOSPHERES

Constraints on the True Obliquity of the Orbit of HAT-P-7b. J. A. Carter[1], J. A. Johnson, J. N. Winn, G. W. Marcy, A. W. Howard, M. J. Holman, D. Fischer, R. Sanchis-Ojeda, [1]Harvard-Smithsonian Center for Astrophysics, Cambridge, MA; jacarter@cfa.harvard.edu

Abstract: The orbit of the exoplanet HAT-P-7b is known to be significantly inclined relative to the spin-directed equatorial plane of its host, based upon analyses of the Rossiter-McLaughlin anomaly (e.g., Winn et al. 2009). These previous observations were only sensitive to sky projections of the stellar-rotational and orbital angular momentum vectors but favored two different, but equally extraordinary orbital configurations: polar or retrograde.

We present the light curve of HAT-P-7, observed over many quarters with Kepler, and describe a number of analyses of this data that may help resolve the true spin-orbital configuration. We focus on photometric indications of spin-orbit obliquity including but not limited to transit light curve anomalies resulting from stellar rotational brightening (e.g., Barnes 2009) and/or those due to coherent starspot crossings during transit (e.g., Sanchis-Ojeda et al. 2011).

We describe how we combine the Kepler data with new radial velocity data (including new observations of the Rossiter-McLaughlin effect) to address the true spin-orbit obliquity and better constrain the bulk properties of the planet and star.

References:

[1] Winn J. N. et al. (2009) *ApJL, 730,* L99. [2] Barnes J. W. (2009) *ApJ*, *705,* 683. [3] Sanchis-Ojeda R. et al. (2011) *ApJ*, *733*, 127.

319. GIANT PLANETS AND PLANET ATMOSPHERES

Measuring the Spin-Orbit Misalignment of KOI-13.01 from Kepler Transit Photometry Using Gravity Darkening Jason W. Barnes[1], Ethan Linscott[2], and Avi Shporer[3] [1]University of Idaho, Department of Physics, Campus Box 440903, Moscow, ID 83844-0903 (jwbarnes@uidaho.edu), [2]Oklahoma Baptist University, Department of Physics, Shawnee, OK 74804, [3]University of California Santa Barbara, Department of Physics, Santa Barbara, CA 93106 [4]Los Cumbres Observatory Global Telescope Network, Santa Barbara, CA 83117.

Abstract: Barnes (2009) showed that gravity darkening in rapidly-rotating stars can lead to unusual and asymmetric transit lightcurves for objects orbiting such stars. Gravity darkening can be used to identify the relative angle between the angular momentum vectors of the star's rotation and the planet's orbit – the spin-orbit angle. Building from the discovery of an asymmetric transit lightcurve for Kepler Object of Interest (KOI) 13.01 by Szabo et al. (2011), we use a gravity-darkened stellar model to fit the KOI-13.01 lightcurve. We find that a model with plausible parameters can fit the KOI-13.01 lightcurve much better than a non-rotating stellar model (Figure 1). The fit tightly constrains the spin-orbit angle. We measure the full spin orbit angle for KOI-13.01 to be 56°+/-4°, composed of a stellar obliquity of 48°+/-4° and a projected orbital angle of 23°+/-4°. This represents the first instance where gravity darkening has been used to determine the spin-orbit angle of a planetary system. As such gravity darkening is the third demonstrated technique to measure spin-orbit angles (after the Rossiter-McLaughlin Effect and transits of starspots). This purely photometric technique presently leaves a degeneracy between prograde and retrograde planetary orbit solutions (Figure 2). Future Kepler data should improve the photometric precision of the lightcurve for this system. Those future, higher precision data may be able to break the prograde-retrograde degeneracy using the photometric Rossiter-McLaughlin Effect.

The origin of such a high obliquity for KOI-13.01 is difficult to explain when considered in conjunction with the orbit's circularity as evidenced by secondary eclipse timing. Influence from KOI-13's companion star via the Kozai mechanism should have left KOI-13.01 in a highly eccentric orbit, like that of HD80606b, that should not have been able to tidally circularize in the star's 1 Gyr lifetime. Hence planet-planet scattering would seem to be the most plausible origin for KOI-13.01's spin-orbit misalignment. The KOI-13 system bears resemblance to WASP-33, which is also a short-period, spin-orbit-misaligned giant planet orbiting an A-type star.

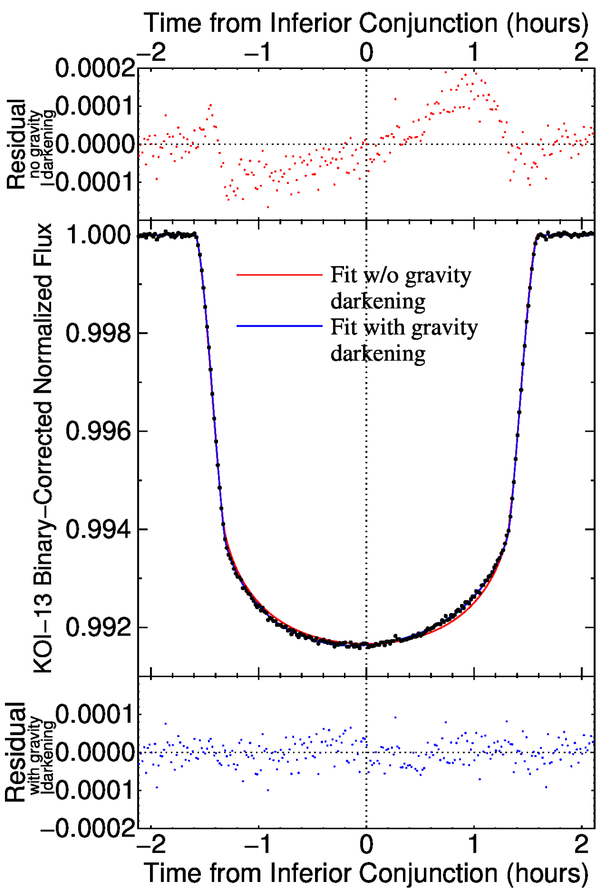


Figure 1: Kepler lightcurve for KOI-13.01, along with best-fit models and residuals both with (blue) and without (red) gravity darkening.

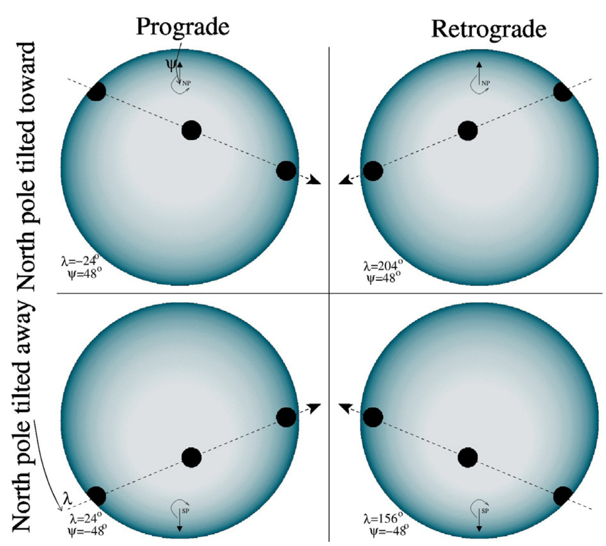


Figure 2: Allowed geometries for the orbit of KOI-13.01.

320. GIANT PLANETS AND PLANET ATMOSPHERES

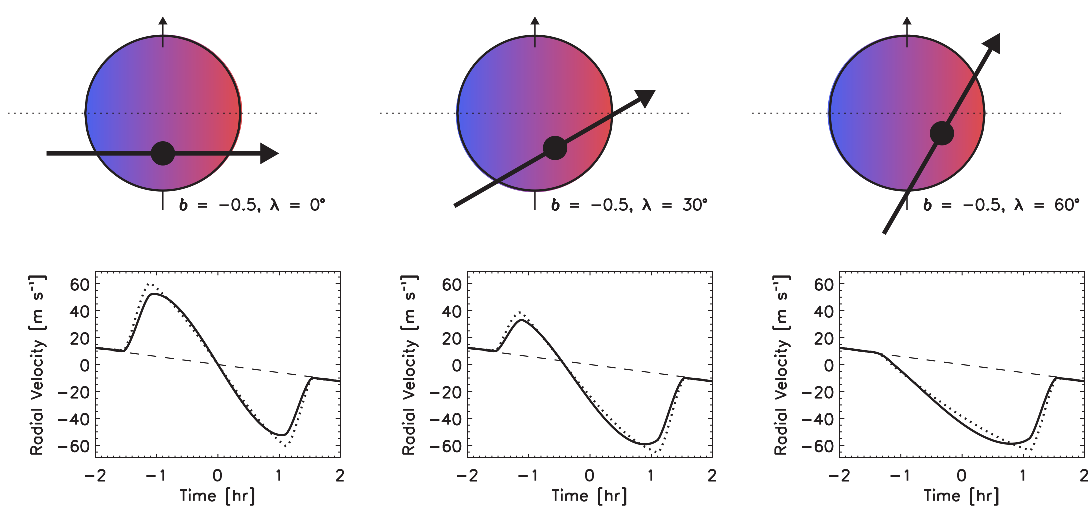
CLUES ON THE ORIGINS OF HOT JUPITERS. Amaury H.M.J. Triaud amaury.triaud@unige.ch
Observatoire Astronomique de l'Université de Genève, Chemin des Maillettes 51, CH-1290 Sauverny, Switzerland

We now know that hot Jupiters are around only one in 200 solar type star. Volume limited surveys using radial velocities discovered those unexpected objects and demonstrated the potential of the transit method. While they found only a handful of hot Jupiters, the transit method allowed the discovery of dozens of those worlds, in addition with providing many observables otherwise unreachable via the Doppler method. These strange planets, unknown to our Solar System, are outliers to the general planet population and as such deserve our attention as they can strongly constraint the theoretical framework aiming to understand planetary systems, which in turns helps in refining our position in the Universe. We are now studying these worlds using various methods.

One such characterization method is to observe the transit spectroscopically. Thanks to the Rossiter-McLaughlin effect is possible to measure the sky projection of the angle between the stellar spin and the planet's orbital spin.

I will present the state of the on-going effort to survey the spin/orbit angle distribution of hot Jupiters, and, combining it with other observables, I will comfront current theories of planetary orbital migration and orbital reorganization.

Then I will show how the Kepler mission can help refining our current image on the origins of hot Jupiters.



The Rossiter-McLaughlin effect in various situations, for an aligned orbit and two inclined orbits
Graphics from Gaudi & Winn 2007, coloured.

Kepler Harvest of Eclipsing Binary Stars

A. Prša & the Kepler Team

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Abstract

The eclipsing binary field witnessed its scientific rebirth with the ultra-high precision Kepler data. The practically uninterrupted data acquisition and photometry of unprecedented quality revealed physical phenomena at a level of detail that challenges even the most sophisticated of models. We discovered and characterized over 2400 eclipsing binaries in the first three quarters of data. Here we summarize the approach and tools to process eclipsing binary data. We present statistical results of the observed sample, show some of the most interesting light curves with significant eclipse timing variations, tertiary events due to circumbinary objects, eccentric close binaries exhibiting "heartbeat" patterns, and identify future goals to keep the sample as complete as possible. A survey program is underway at Kitt Peak's 4-m telescope to acquire high-resolution spectroscopy of the scientifically most interesting targets. These observations complement Kepler photometry and allow us to determine the fundamental parameters of binary components (masses, radii and luminosities) in absolute units. Recent and ongoing modeling advancements targeted for the Kepler level of accuracy in the PHOEBE modeling code are also discussed, notably the Doppler beaming effect, axial misalignment, pulsating components in binaries, and error estimates based on Bayesian inference. Finally, we touch on the likelihood of background eclipsing binaries contaminating foreground stars and thus being potentially confused with planet candidates.

1

402. ECLIPSING AND INTERACTING BINARIES

KOI-54: A Remarkable Periastron-Pumped Pulsating Binary Star

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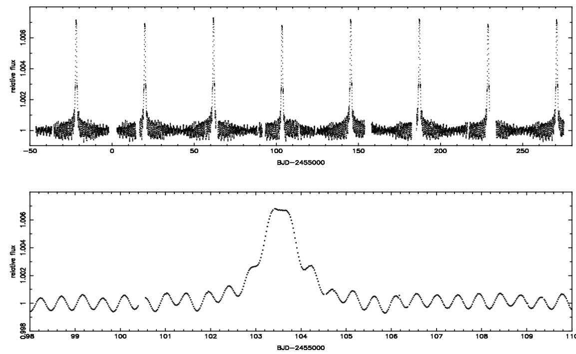
Kepler observations of a previously-known bright but unremarkable A star revealed a fascinating light curve: KOI-54 exhibits sharp periodic brightening events every 41.8 days with a superimposed set of oscillations forming a beat pattern in phase with the brightenings. Spectroscopy revealed that this is a highly eccentric (e=0.83) binary star. We are able to match the *Kepler* light curve and radial velocities with a nearly face-on binary star model in which the brightening events are caused by tidal distortion and irradiation of nearly identical A stars during their close periastron passage [1]. There are two dominant oscillations in the light curve that are responsible for the beat pattern and have frequencies that are the 91st and 90th harmonic of the orbital frequency. The power spectrum of the light curve reveals at least 30 significant pulsations, nearly all of which have frequencies that are either integer multiples of the orbital frequency or are tidally-split multiples of the orbital frequency. This pattern unambiguously establishes the pulsations as resonances between the dynamic tides at periastron and the free oscillation modes of one (or both) of the stars.

Yet despite our detailed understanding of this system, some intriguing puzzles remain. In this talk, I will show updated *Kepler* observations, present the details of the modeling, and discuss the puzzles and potential discoveries that may be possible from this rich system.



References:
[1] Welsh, W.F. et al. (2011) ApJ (in press); arXiv:1102.1730v2

Heartbeat Stars: A Class of Tidally Excited Eccentric Binaries

S. E. Thompson[1], T. Barclay[2], F. Mullally[3], M. Everett[4], S. B. Howell[5], M. Still[6], J. L. Christiansen[7], and J. Rowe[8]
[1]SETI Institute/NASA Ames M/S 244-30, Moffett Field, CA 94035, USA, susan.e.thompson@nasa.gov, [2]Bay Area Environmental Research Institute, thomas.barclay@nasa.gov, [3]SETI/NASA Ames, fergal.mullally@nasa.gov, [4]NOAO, everett@noao.edu, [5]NASA Ames, steve.b.howell@nasa.gov, [6]Bay Area Environmental Research Institute, martin.still@nasa.gov, [7]SETI/NASA Ames, jessie.l.christiansen@nasa.gov, [8]SETI/NASA Ames, jason-frowe@gmail.com

Introduction: We have discovered a class of eccentric binary systems undergoing dynamic tidal distortions and tidally induced pulsations in the Kepler data. Each has a uniquely shaped light curve that is characterized by periodic brightening or variability at time scales of 4-20 days which is frequently accompanied by shorter period oscillations (Figure 1). We can explain the dominant features of the entire class with changing tidal forces that occur in close, eccentric binary systems. In this case the large variety of light curve shapes arises from viewing systems at different angles. A hypothesis that is confirmed with radial velocity measurements that show an eccentric orbit (Figure 2).

Prior to the discovery of these 17 new systems, KOI-54 [1] was the only system with direct detection of these dynamic tides and tidally induced oscillations. While significant work remains to include all the physics required to accurately model these systems and begin to understand how tidal effects influence the system, in this presentation we present preliminary fits to the light curves (Figure 3) and describe the properties of this class of stars as a whole.

References:

[1] Welsh et al. (2011) ApJ, *accepted*
[2] Kumar et al. (1995) ApJ, *449: 294*

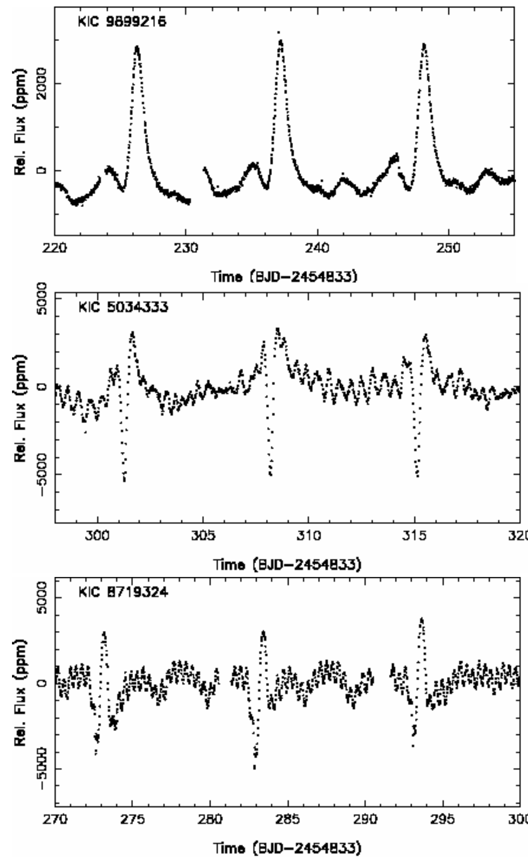


Figure 1. Example light curves.

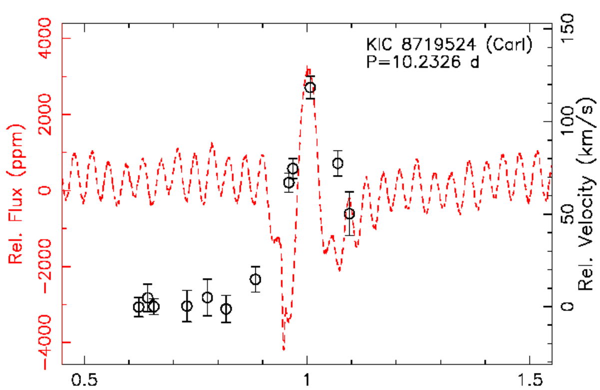


Figure 2. Folded light curve (red) and phased radial velocity measurements (black) of one eccentric binary system.

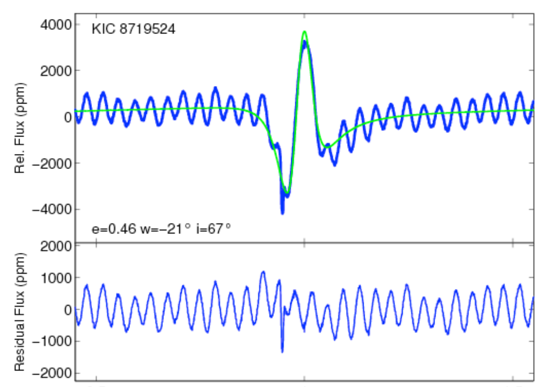


Figure 3. Folded light curve (blue) and preliminary fit (green). The bottom panel contains the residuals of the fit. The fit was performed using only the dynamic tidal distortions that occur as the star passes through periastron [2].

404. ECLIPSING AND INTERACTING BINARIES

Tests of Age, Mass, and Radius from Binary Stars in Open Clusters. E. L. Sandquist[1], K. Brogaard[2], et al.[3] [1]San Diego State University (Department of Astronomy, 5500 Campanile Drive, San Diego, CA USA 92182; erics@sciences.sdsu.edu), [2]University of Victoria (Department of Physics and Astronomy, P.O. Box 3055, Victoria, BC, CANADA V8W 3P6; kfb@phys.au.dk), [3] for GO Program 20044.

Abstract:
The unprecedented observations of open star clusters in the Kepler field provides the opportunity to develop a more complete catalog of their eclipsing binary populations. Here we present a current tally of currently identified eclipsing binaries and probability of cluster membership, focusing on the rich old (~2.5 Gyr) open cluster NGC 6819. NGC 6819 has been the subject of a long-term radial velocity monitoring program by Robert Mathieu and collaborators[1], making precise mass measurements possible for many of the systems.

The masses and radii for stars at or brighter than the turnoff will be used to derive a statistical age constraint for the cluster, and to constrain the physics of convective overshoot in the stellar cores. A precise turnoff mass measurement for the cluster also removes one of the larger uncertainties in determining points on the white dwarf initial-final mass relationship. Observations of fainter stars within detached binaries will also provide a scaffolding of precise stellar masses for testing main sequence models for other uses, and in particular, helping to identify the helium abundance for cluster stars.

Interesting discoveries among cluster members include a near-contact binary with period 0.349 d and a light curve that modulates from a continuously varying W UMa-type to a detached eclipsing binary every 1.89 d, and (we believe) the longest period totally-eclipsing binary containing two main sequence stars detected to date.

References:

[1] Hole, K. T.. et al. (2009) *AJ, 138,* 159.

AN ECLIPSING WHITE DWARF - M DWARF SYSTEM OBSERVED WITH KEPLER

R. Alonso[1], J. M. Almenara[2], J. A. Belmonte[3,4], H. J. Deeg[3,4], and M. Rabus[5]

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[2]Laboratoire d'Astrophysique de Marseille, France (josemanuel.almenara@oamp.fr),
[3]Instituto de Astrofísica de Canarias, Spain (jba@iac.es, hdeeg@iac.es)
[4]Departamento de Astrofísica de la Universidad de La Laguna, Spain,
[5]Universidad Católica de Chile (mrabus@astro.puc.cl)

The system KIC 10544976 is one of the few in the Kepler FOV that contains an eclipsing white dwarf [1]. It is composed of a ~20500 K DA white dwarf and an active M4V star in a close 0.35 d orbit, and it is thought to have formed after a binary system evolved through a common envelope phase. There are only a handful of such systems known in the sky, and none has been observed photometrically with the good coverage provided by Kepler.

We have observed in 1-min cadence the system as part of a Guest Observer program since the beginning of this program. We will present the results of the Cycle 1 and Cycle 2 (Q2-Q8) observations of the system. The target is faint (Kepmag=18.679), and contaminated by at least three fainter stars that provide a significant amount of extra flux to the aperture mask. We used the measurement of the motion of the sky across the center of the CCD channel (the POS_CORR1 and POS_CORR2 vectors), the astrometry of the Full Frame Images, and the knowledge of the relative positions between the contaminants to try to deduce the relative contribution of the contaminants to the aperture mask. In this case, the optimal aperture mask was only one or two pixels, depending on the position of the target in the detector.

The final light curve, containing more than 1500 complete orbits of the system in a span of two years, is used to investigate the stellar activity and its dependence on the orbital phase. There are many flares recorded in the Kepler curve; we will describe their properties and their evolution since the beginning of the Kepler observations. We searched for pulsations in the system, and we will give upper limits to their amplitudes.

The out of eclipse portion of the orbit is dominated by the "reflection" effect, but ellipsoidal modulation and relativistic doppler boosting (or beaming effect) are also detected in the data. The precise shape of the short ingress and egress phases (when the white dwarf dissappears and reappears from behind the M dwarf) are used to attempt a detection of features in the surface of the white dwarf. The centers of the eclipses are measured to a precision of about 5 s, and used to investigate the presence or absence of departures from a linear ephemeris. There are several systems in the literature where departures have been reported (e.g. [2],[3],[4]), while their interpretation is controversial in some cases. The KIC 10544976 is thus a valuable system for this type of studies, as the eclipses are being observed continuosly for several years.

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406. ECLIPSING AND INTERACTING BINARIES

CIRCUMBINARY COMPANIONS OF INTERMEDIATE-MASS ECLIPSING BINARY STARS

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Kepler Survey: Binaries are commonplace among stars, and the binary frequency increases from low mass to high mass stars (≈100%). This suggests that the formation of binary stars is intrinsic to the formation process of more massive stars [1] and that the angular momentum of the natal cloud is transformed into orbital angular momentum of binary stars. Many close binaries (often eclipsing) have distant third companions. These companions may have drained angular momentum from the inner region during the star formation process, leading to a close, central binary [2].

We are conducting a Kepler program to search for such companions by recording the time shifts in the eclipses of the central binary due to the light travel time across the span of the reflex orbit. We use the orbital eclipses as a basic clock whose “pulse” arrival times vary as the central binary orbits the center of mass with the distant third star. Measurements of the eclipse times then provide the displacement of the binary along the line of sight as a function of time. In addition, the gravitational pull of the third star will impose changes on the inner orbit that lead to osculating orbital elements that cause additional variations in the eclipse timings [3].

We are involved in a 3 cycle program of Kepler observations of 41 eclipsing binaries that are detached systems with components of similar brightness, masses greater than the Sun’s, and that display deep eclipses. These are the gems of the Kepler field of view, because we can obtain very accurate eclipse timings (within a few seconds in long cadence observations) and we can determine a double-lined spectroscopic orbit for the central binary from spectroscopy.

From the eclipse timings of this accuracy we should be able to detect companions as small as a few Jupiter masses [4] and from the spectroscopy and light curve we can find the masses of the central stars, a key component in the analysis of the eclipse timing variations. Here we present a summary of the eclipse timing results to date and the associated spectroscopy.

Spectroscopy: Our goal is to determine the mass of each eclipsing binary through a combined spectroscopic and photometric study. We have now collected moderate resolution spectra of most of the targets in observing runs with the KPNO 4 m, Lowell Observatory 2 m, and DAO/HIA 2 m telescopes. We aim to collect at least six spectra per target at the important quadrature phases. We employ cross-correlation methods to measure radial velocities, and use the program ELC [5] to make a joint light and velocity solution of the orbital elements. In addition to the critical mass data, this data set will also provide accurate stellar temperature, radius, and metallicity for the components of each binary system. We show an example for KIC 5513861 of the radial velocity curve and individual spectra reconstructed using a Doppler tomography algorithm [6] in Figures 1 and 2.

Our survey of intermediate mass eclipsing binaries will determine the frequency and masses of these low mass companions (detecting all stellar companions with orbits of three years or less). These properties will offer important insight about the star formation process for intermediate mass stars.

We gratefully acknowledge support from NASA awards NNX10AC39G and NNX11AB70G.

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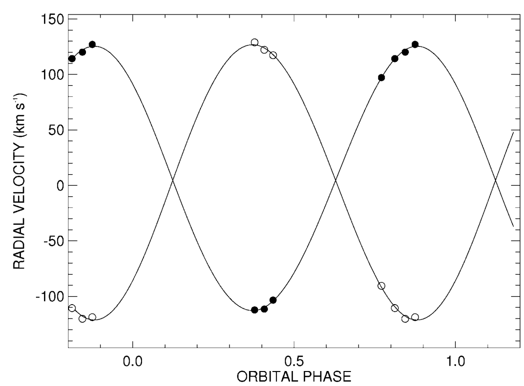

FIG. 1- The radial velocity curves of KIC5513861.

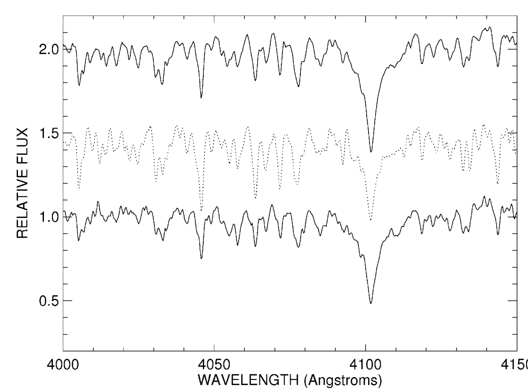

FIG. 2 - Reconstructed spectra of KIC5513861 (top = primary, middle = model, bottom = secondary).

PHOTOMETRIC DETECTION OF NON-TRANSITING SHORT-PERIOD BINARIES THROUGH THE BEAMING, ELLIPSOIDAL AND REFLECTION EFFECTS IN THE *KEPLER* LIGHT CURVES

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We present a simple algorithm, BEER, to find non-transiting short-period binaries by using precise light curves. The algorithm is based on the beaming (aka Doppler boosting) effect, which causes an increase (decrease) of the brightness of a light source approaching (receding from) the observer [1,2]. Because the beaming effect is very small, on the order of *4V/c*, where *V* is the stellar velocity and *c* is the speed of light, the effect has become relevant only recently, when CoRoT and *Kepler* are producing hundreds of thousands of uninterrupted light curves with high precision.

The BEER algorithm searches for a combination of the BEaming effect together with two other well-known modulations – the Ellipsoidal and the Reflection/heating periodic effects, induced by non-transiting companions [3].

We present seven newly discovered non-eclipsing short-period binary systems with low-mass companions, identified by the BEER algorithm, applied to the Q0, Q1 and Q2 *Kepler* data. The seven detections were confirmed by spectroscopic radial-velocity follow-up observations performed with the TRES spectrograph, indicating secondary masses in the range 0.07-0.4 Solar masses [4].

The discovered binaries establish for the first time the feasibility of the BEER algorithm as a new detection method for short-period non-eclipsing binaries, with the potential to detect in the near future non-transiting brown-dwarf secondaries, or even massive planets. The BEER project has the potential of substantially changing our knowledge of the short-period binary population, as it is equivalent to a radial-velocity survey of a quarter of a million stars, which are being observed by the *Kepler* and CoRoT satellites.

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408. ECLIPSING AND INTERACTING BINARIES

Dynamical Tides in Eccentric Binaries and Tidally-Excited Stellar Pulsations in KEPLER KOI-54

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Recent observation of the tidally-excited stellar oscillations in the main-sequence binary KOI-54 by the KEPLER satellite provides a unique opportunity for studying dynamical tides in eccentric binary systems. We develop a general theory of tidal excitation of oscillation modes of rotating binary stars, and apply our theory to tidally excited gravity modes (g-modes) in KOI-54. The strongest observed oscillations, which occur at 90 and 91 times the orbital frequency, are likely due to prograde m=2 modes (relative to the stellar spin axis) locked in resonance with the orbit. The remaining flux oscillations with frequencies that are integer multiples of the orbital frequency are likely due to nearly resonant m=0 g-modes; such axisymmetric modes generate larger flux variations compared to the m=2 modes, assuming that the spin inclination angle of the star is comparable to the orbital inclination angle. We examine the process of resonance mode locking under the combined effects of dynamical tides on the stellar spin and orbit and the intrinsic stellar spin-down. We show that KOI-54 can naturally evolve into a state in which at least one m=2 mode is locked in resonance with the orbital frequency. Our analysis provides an explanation for the fact that only oscillations with frequencies less than 90-100 times the orbital frequency are observed. We have also found evidence from the published KEPLER result that three-mode nonlinear coupling occurs in the KOI-54 system. We suggest that such nonlinear mode coupling may explain the observed oscillations that are not harmonics of the orbital frequency.

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KOI-54 Tidally Excited Oscillations: Jim Fuller & Dong Lai

Kepler observations of rapid optical variability in active galactic nuclei

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Abstract: Over three quarters in 2010-2011, Kepler monitored optical emission from four active galactic nuclei (AGN) with ~30 min sampling, >90% duty cycle and ≲0.1% repeatability. These data were used in the first direct determination of AGN optical fluctuation power spectral density functions (PSDs) over a wide range in temporal frequency. Fits to these PSDs yielded power-law slopes of -2.6 to -3.3, much steeper than typically seen in the x-rays. We find evidence that individual AGN exhibit intrinsically different PSD slopes. The steep PSD fits are a challenge to recent AGN variability models but seem consistent with first order MRI theoretical calculations of accretion disk fluctuations.

410. STELLAR ACTIVITY AND ROTATION

Early Results from Kepler on Stellar Activity

Gibor Basri, UC Berkeley

I review current science that results from the unprecedented ability of the Kepler mission to study the precision photometric variability of stars. The data are of a precision, longevity, and continuity that brings stellar science into a realm that has been previously restricted to only our Sun. I begin by discussing the data characteristics, especially some challenges that must be overcome to fully realize the promise of the data. I next discuss characteristics of the main sequence stars in bulk, particularly their levels of variability on different timescales. One interesting result has been that the Sun may be typical in some respects, but atypical in others. Next I touch on the kinds of analysis that are beginning to bear fruit, such as determination of stellar rotation periods, differential rotation, starspot modeling, starspot evolution and lifetimes, flaring rates and energetics, cluster studies, and stellar cycles. In a few cases, exoplanets transit across starspots and provide an opportunity for more detailed information on spot sizes and stellar orientation. One broad scientific goal is better characterization of rotation-activity-age relations on convective stars of different masses.

411. STELLAR ACTIVITY AND ROTATION

The flaring behavior of G stars observed by *Kepler*. David R. Soderblom[1], Ron Ballouz[1], Rachel Osten[1], and Jeff Valenti[1], [1]Space Telescope Science Institute, 3700 San Martin Drive, Baltimore MD 21218 USA; drs@stsci.edu

Kepler's capabilities (precision, cadence, persistence, and sample size) make it possible to study stellar phenomena at a previously-impossible level. As a dramatic example, the Sun is the only G star that previously exhibited flares in integrated broad-band light (and just barely), yet a significant number (~1%) of Kepler's G targets show white-light flares.

The Kepler photometry makes it possible to determine properties of the flares themselves:

- Their total energies can exceed 10^{36} ergs, at least 4 orders of magnitude greater than the largest solar flares ever seen.
- Flare shapes are classic FREDs (fast rise with exponential decay), with secondary events often seen during the decay phase.
- Decay times are 1-4 hours (this is partly because most of the data have 30-minute cadence).
- The distribution of flare energies follows a power law for one especially well-studied star.

In a few cases there exists one-minute data for flaring G stars, and in those instances more complete information can be measured.

The Kepler photometry by itself, however, is not sufficient for determining the nature of the flaring stars. Their nominal (KIC) radii imply that G stars over a broad range of evolutionary states (ZAMS to subgiants and giants) are capable of flaring. The Kepler light curves reveal rotation periods, but there is no obvious connection between, say, rapid rotation and flaring behavior.

Spectra of the flaring stars are needed to elucidate the nature of the stars. This is probably not just an age-related phenomenon, both because of the range of apparent radii seen and because the Kepler field is well out of the Galactic plane.

The phenomenology of the flaring behavior in these G stars and what information is known on the stars themselves will be summarized.

412. STELLAR ACTIVITY AND ROTATION

Starspotting: Looking at Kepler Data for Insight into Stellar Magnetic Activity L. M. Walkowicz[1] and G. Basri[2], [1]Princeton University, Peyton Hall, 4 Ivy Lane, Princeton NJ 08544-1001, lucianne@astro.princeton.edu, [2]University of California at Berkeley, basri@berkeley.edu

Introduction: Stellar magnetic activity leads to observable phenomena on a range of timescales, from spots that cause variation at the stellar rotation rate, to flares that result in rapid emission from subseconds to hours. Now in its third year of operations, NASA's Kepler Mission is providing a new view into stellar activity through its precision photometry and continuous time coverage.

Starspots in Kepler data: Kepler's photometry allows us to measure stellar variation due to starspots on a unprecedently large sample of stars, both like the sun and quite different from it. These spots modulate the lightcurve as the star rotates, and are themselves manifestations of the magnetic field generated by the star's rotation. Because of the intimate link between stellar rotation and the generation of the magnetic field, measuring the rotation periods, differential rotation and spot parameters for a large sample of stars provides feedback to our understanding of magnetic activity.

In this talk, I will discuss how modeling starspots can provide insight into stellar activity, as well as our ongoing work to measure stellar rotation in the Kepler data and to develop a simple yet reliable starspot modeling code that may be applied to a large sample of stars.

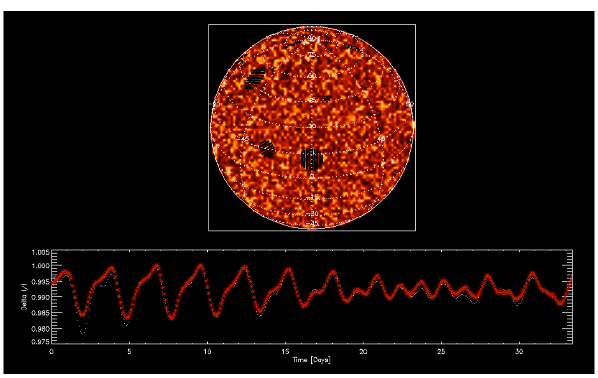

Figure 1. Example fit to a Kepler lightcurve wfith diferential rotation for KIC11296561, using the starspot modeling code Cheetah (Walkowicz et al. 2011).

SPOT EVOLUTION AND DIFFERENTIAL ROTATION ON SUN-LIKE STARS.

S. V. Berdyugina[1], H. Korhonen[2], A. Brown[3], S. Hawley[4], A. Kowalski[4], G. Harper[5], L. Walkowicz[6], T. Ayres[3], [1]Kiepenheuer Instut fuer Sonnenphysik, Schoeneckstr 6, D-79104 Freiburg, Germany, svetlana.berdyugina@kis.uni-freiburg.de; [2]Niels-Bohr Institute, University of Copenhagen, Denmark, heidi.korhonen@nbi.ku.dk; [3]University of Colorado, USA, alexander.brown@colorado.edu, thomas.ayres@colorado.edu; [4]University of Washington, USA, slh@astro.washington.edu, kowalski@astro.washington.edu, [5]Trinity College Dublin, Ireland, graham.harper@tcd.ie; [6]Princeton University, USA, lucianne@astro.princeton.edu.

Starspots: Stellar activity is expressed in various, frequently eruptive phenomena, such as starspots, flares, prominences, and coronal mass ejections, which are driven by magnetic fields generated in differentially rotating convective envelopes. Spots on sun-like stars harbour the strongest magnetic field and the coldest plasma on the stellar surface. Therefore, they are readily detected from periodic dimming of the star's brightness as it rotates dark starspots into view. *Kepler* mission provides continuous photometric light-curves of unprecedented accuracy, allowing for detecting a multitude of starspots, investigating their properies and evolution, and constraining global magnetic dynamo mechanisms.

Novel Light Curve Inversions: We present a new light-curve inversion technique which fully exploits the benefits of continuous monitoring of stellar variability by *Kepler*. In contrast to earlier inversions, we are able to constrain the differential rotation of the star and reconstruct spots at a genuine 2D stellar surface, i.e., obtain both longitudes and latitudes of spots, which can also evolve in time. This results in a comprehensive picture of stellar rotation and spot evolution. In particular, we can investigate stellar butterfly diagrams and spot migration.

Sun-like Active Stars: We apply our new technique to *Kepler* Q1-Q7 data for a sample of active solar-type stars (GALEX-selected) with typical rotation periods of a few days, that we have observed as part of our 200 target *Kepler* Cycle 1/2 Guest Observer programs. We obtain synoptic maps of stellar activity, determine stellar rotation and differential rotation rates, and evaluate starspot properties. One example is presented in Fig. 1.

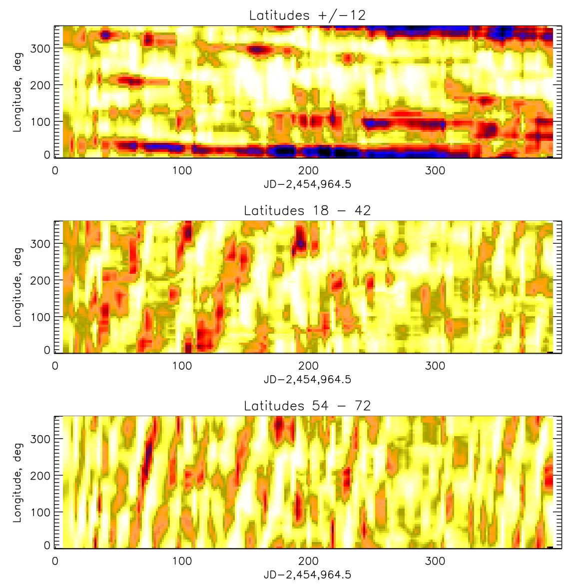

Figure 1: Synoptic maps of one of our targets for three latitude ranges revealing the differential rotation and evolution of starspots.

414. STELLAR ACTIVITY AND ROTATION

NEW METHODS TO MODEL ACTIVITY-INDUCED SIGNALS IN PHOTOMETRY AND RADIAL VELOCITY. S. Aigrain[1] , F. Pont[2], S. Zucker[3] and S. Roberts[4]
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Introduction: Transit surveys such as Kepler are a treasure trove of information about relatively poorly understood process in stellar physics, in particular rotation and magnetic activity. Unverstanding this signal is also a necessary step to maximize the exoplanet detection and characterization performance of this kind of mission. In this contribution I will discuss new tools I have developed in the past year to model activity-induced signals in stellar light curves, and to predict and mitigate the corresponding activity-induced radial velocity variations.

Quasi-periodic Gaussian process models: I will first present a class of quasi-periodic models [1,2] which can be used to measure rotation periods in long-baseline light curves, allowing for the evolution of active regions and the overall activity level. The use of a Gaussian process framework [3] enables complex variations to be modeled using only a handful of parameters, which are directly related to physical quantities of interest. Using simulations, I will show that they can be used to recover accurate periods in cases where standard periodogram methods fail. They also be used to gather information on the statistics of active regions, including their lifetime, and to test for evidence of activity cycles. I will then apply them to Kepler public datasets, and in particular the light curves of Kepler transit candidate host stars.

Predicting activity-induced RV variations: I will then present a new, simple method to predict activity-induced radial velocity variations using high-precision time-series photometry [4]. It is based on insights from a simple spot model, has only two free parameters (one of which can be estimated from the light curve) and does not require knowledge of the stellar rotation period. I will illustrate its performance using tests on simulated data, simultaneous MOST/SOPHIE observations of the planet host-star HD 189733, and the Sun, where I will demonstrate that it can reproduce variations well below the m/s level. We have also applied it to Quarter 1 data for Kepler transit candidate host stars, where it can be used to estimate RV variations down to the 2–3 m/s level, and show that RV amplitudes above that level may be expected for approximately two thirds of the candidates we examined. By coupling this method with the aforementioned quasi-periodic Gaussian process models, it is possible to apply it also to stars monitored only from the ground, with much sparser time-coverage, and to compute RV variability estimates with robust error bars.

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STARSPOTS AND SPIN-ORBIT ALIGNMENT FOR KEPLER EXOPLANETARY SYSTEMS. R. Sanchis-Ojeda[1] and J. N. Winn[1], [1]Massachusetts Institute of Technology (first author address: 77 Massachusetts Avenue, Office 37-602, 02139, MA), (emails, RSO: rsanchis@mit.edu, JNW: jwinn@mit.edu).

Introduction:

When a transiting planet passes in front of a star-spot on the photosphere of its host star, an anomaly is observed in the light curve. We have been developing a new method that exploits these spot-crossing anomalies to measure the obliquity of the star with respect to the orbital plane of a transiting planet. Traditionally, obliquities have been measured through the Rossiter-McLaughlin effect, and have provided interesting information about exoplanetary systems. Obliquities are important because they are fundamental geometric parameters, and because they bear clues about the formation, migration, and tidal evolution of close-in planets [1-8].

If the spot-crossing anomalies are observed to recur with a progressively increasing phase during consecutive transits, we may conclude the trajectory of the spots is parallel to the orbital motion of the planet, and the host star has a low obliquity. This phenomenon has been observed in the WASP-4b [9], CoRoT-2b [10] and Kepler-17b [11] systems.

Knowledge of the stellar rotation period can help us predict the position of spots on the surface of the star for different values of the obliquity, and hence test whether the star is aligned or misaligned in a simple way. For Kepler stars, this test is often available due to the rotation induced variations of the flux of the star, which permit a measurement of the rotation period of the star, and could be potentially implemented for hundreds of exoplanetary systems.

In this contribution we will also explain how, thanks to the continuous monitoring of its planetary candidates, Kepler is also allowing us to measure the obliquity for misaligned systems. In particular, the appearance of active latitudes on the host star has allowed us to measure the obliquity of HAT-P-11b with high precision [12]. Knowledge of the orientation of the star allowed us to measure the latitude of the spots transited by the planet, information that can be used to construct an analog of the solar butterfly diagram. This method of obtaining the butterfly diagram could be potentially used for any misaligned system, so long as the star is active enough to show spot anomalies.

Many more systems show these spot-anomalies among the released 1235 Kepler candidates. We will show our current effort to develop techniques to measure the obliquity of many of these systems, and particular examples that show the strength of our methods.

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416. STELLAR ACTIVITY AND ROTATION

THE KEPLER CLUSTER STUDY AND STELLAR ROTATION IN CLUSTERS.

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Today, ground- and space-based time-domain observations are revolutionizing the study of stellar rotation with photometric measurements of unprecedented precision, cadence, and duration. Open clusters - young and old - are targeted and the data promise a leap in our empirical knowledge of the dependencies of stellar rotation on the most fundamental stellar properties - age and mass. Observations in young clusters probe the early rotational evolution and have revealed well-defined and age-dependent relations between surface rotation period and mass. However, because of the challenge of measuring - from the ground - the spot-induced photometric fluctuations for old and slowly rotating stars, the Hyades has long been the oldest cluster with measured rotation periods. Kepler offers a special opportunity to overcome this difficulty. The Kepler Cluster Study is targeting 3 clusters older than the Hyades with the goal of deriving rotation periods for late-type main-sequence members!

I will present results from the Kepler Cluster Study, and discuss the implications for understanding the rotational evolution of late-type stars and for the prospect of determining their ages from measurements of their rotation periods and colors alone (Gyrochronology).

ASTEROSEISMOLOGY: NEW INSIGHTS IN VARIABLE STARS IN THE CLASSICAL INSTABILITY STRIP. D. W. Kurtz, Jeremiah Horrocks Institute, University of Central Lancashire, Preston PR1 2HE, UK; kurtzdw@gmail.com

In 1926 in the opening paragraph of his now-classic book, *The Internal Constitution of the Stars*, Sir Arthur Eddington lamented, “What appliance can pierce through the outer layers of a star and test the conditions within?” While he considered theory to be the proper answer to that question, there is now an observational answer: asteroseismology. This talk will introduce the concepts of asteroseismology, then look at a selection of discoveries made with the micromagnitude precision the Kepler Mission data that have revolutionised the study of classical pulsating stars. Here are but three examples from an abundance of new results:

The discovery of solar-like oscillations in a δ Scuti star: Solar-like oscillators are the prime targets of Kepler asteroseismology, since they yield stellar masses and radii that are needed for full characterisation of discovered planets. Theory has long predicted the existence of hotter solar-like pulsators in the instability strip, but there has been no success in finding them with the world’s largest telescopes and the most precise ground-based data. Now solar-like oscillations have been found for the first time in a δ Scuti star in the Kepler field. Convection transports energy through the outer 30% of the Sun, yet only through a shallow layer in delta Scuti stars. The Kepler discovery shows that convection in hotter stars in much more efficient than in the Sun, hence illuminates our understanding of this important physical process. [1]

The century-old mystery of the Blazhko Effect: The “Blazhko Effect” is an amplitude and phase modulation of the light curves of RR Lyrae stars that has been known since 1907. Understanding the physics of these 12-hour period pulsators is important, since they are a “standard candle” for determining distances within the Milky Way and in nearby galaxies, thus are a foundation of galactic structure. Kepler data now show that as many as 50% of all RR Lyrae stars are Blazhko stars. They also show that three competing models to understand this are not viable. After a century of work we now know from Kepler data for RR Lyrae itself that the physics of the Blazhko Effect is an unsolved mystery and that the Blazhko cycles are not fully repetitive. We have also discovered a new phenomenon, period doubling, that is caused by a resonance for which we have good models; this phenomenon was predicted, but never observed before Kepler precision brought it to light. The long-term observing of RR Lyrae may finally solved the problem of the Blazhko Effect and improve the galactic and nearby extragalactic distance relationship for these important stars. [2]

The discovery of the first bi-axial pulsating star: It has been a useful simplification in stellar astrophysics to characterise stars as spheres. But real stars rotate, and they have magnetic fields, both of which distort the spherical symmetry. Now Kepler data are so precise that we can begin to probe the effects of these distortions. An extreme example is the strongly magnetic peculiar star KIC10195926. Kepler data show that this star pulsates with two separate pulsation axes which are neither the rotation axis nor the magnetic axis, confirming a previously untested theoretical prediction. The star also shows the first evidence of torsional modes in a classical pulsator. But for spots on the star these would normally be invisible. Only with Kepler precision can this new physical phenomenon be seen. Observations over years are needed to explore this in detail. [3]

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502. ASTEROSEISMOLOGY

THE PHYSICS OF STOCHASTIC EXCITATION. P. Goldreich[1] and J. A. Johnson[2], [1]Division of Physics, Mathematics and Astronomy, Caltech 350-17, Pasadena CA. 91125, pmg@ias.edu, [2] Caltech, johnasherjohnson@gmail.com

Introduction:

A stellar mode achieves energy equipartition with the kinetic energy of convective eddies whose correlation times are comparable to its period. The energies of the most visible modes are similar to those of individual granules, or equivalently to the stellar flux that passes through a granule during its lifetime.

Interactions that excite and damp an acoustic mode take place above the mode's acoustic cavity; they merely tickle the mode's evanescent tail. As a consequence, the mode's linewidth is much smaller than its frequency and the modal peak rises above the level of the convective noise in velocity and intensity power spectra.

Scaling observational properties of stochastically excited modes from helioseismology to asteroseismology implicity assumes that the maximum convective Mach number, **M**, is the same in all stars with convective envelopes. For some properties, such as the frequency of maximum visibility, this works pretty well; **M** is expected to be of order a few tenths and only enters to the first power. Other observational quantities depend more sensitively on **M**. Peaks of low degree modes rise by of order $\mathbf{M}^{-4}$ above the convective noise in velocity and intensity power spectra formed from observations of an unresolved star, and the ratio of linewidth to mode frequency depends on even higher powers of **M**. Scaling of velocity is more direct than that of intensity since the latter is sensitive to the opacity.

503. ASTEROSEISMOLOGY

ASTEROSEISMOLOGY OF THE SOLAR ANALOGS 16 CYG A & B FROM KEPLER OBSERVATIONS.

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Abstract: The evolved solar-type stars 16 Cyg A & B have long been studied as solar analogs, yielding a glimpse into the future of our own Sun. The orbital period of the binary system is too long to provide meaningful astrometric constraints on the stellar properties, but asteroseismology can help because the stars are among the brightest in the *Kepler* field. We present an analysis of three months of nearly uninterrupted photometry of 16 Cyg A & B from the *Kepler* satellite. We extract a total of 46 and 41 oscillation frequencies for the two components respectively, including a clear detection of l=3 modes in both stars. We derive the properties of both stars using the Asteroseismic Modeling Portal (AMP), fitting the individual oscillation frequencies and other observational constraints simultaneously. We evaluate the systematic uncertainties from an ensemble of results generated by a variety of stellar evolution codes and fitting methods. The longer data sets that will ultimately become available will allow future studies of differential rotation, convection zone depths, and long-term changes due to stellar activity.

504. ASTEROSEISMOLOGY

Observational Constraints, Stellar Models, and *Kepler* Data for θ Cyg, the Brightest Star Observable in the *Kepler* Field of View

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θ Cyg (13 Cyg) is an F4 main sequence star that, at visual magnitude V=4.48, is the brightest star observable by the Kepler spacecraft. Short-cadence photometric data using a custom aperture were obtained for this star during Quarter 6 (June-Sept 2010) and Quarter 8 (Jan-March 2011).

We will present analyses of the solar-like oscillations first discovered in the Q6 data [1, 2]. We use observational constraints from the literature and recent ground-based observations including angular diameters from optical interferometry to construct stellar evolution and pulsation models of this star. We discuss the expectations for solar-like oscillations, and the prospects for detecting longer-period gravity-mode pulsations as seen in gamma Doradus variable stars of spectral type A-F, given these constraints.

With an effective temperature near 6500 K and near 'solar' element abundances, θ Cyg is near the edge of the gamma Doradus instability strip, where high-order gravity-mode pulsations with periods of ~1 day may be present. If the envelope convection zone of the star is not too deep, these gravity-mode pulsations may be driven by the convective blocking mechanism. The calculated envelope convection zone depth depends on the element abundance mixtures adopted for the stellar models [2]. Asteroseismic studies of θ Cyg therefore have potential to shed light on the solar abundance problem [3, 4], as well as to put constraints on the presence and detectability of g-mode pulsations for main-sequence solar-like stars.

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505. ASTEROSEISMOLOGY

Seismic age calibration and heavy-element abundance in solar-type stars. G. Houdek[1], [1]Institute of Astronomy, University of Vienna, 1180 Vienna, Austria (guenter.houdek@univie.ac.at).

Introduction: We introduce a new method for estimating the seismic age and heavy-element abundance in the Sun and solar-type stars. The method uses an asteroseismic calibration of theoretical stellar models using only low-degree acoustic modes. It can therefore be applied to solar-type stars, such as those observed by the NASA satellite Kepler and the planned ground-based Danish-led SONG network.

For the Sun, using this new seismic method and BiSON data, we obtain the age, 4.60 ± 0.04 Gy, which is similar to, although somewhat greater than, today's commonly adopted values, and the surface heavy-element abundance by mass, $Z_S = 0.0142 \pm 0.0005$, lies between the values quoted recently by Asplund et al. (2009) and by Caffau et al. (2009).

References:

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506. ENSEMBLE ASTEROSEISMOLOGY OF SOLAR-TYPE STARS

ENSEMBLE ASTEROSEISMOLOGY OF SOLAR-TYPE STARS.

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Our ability to constrain the fundamental properties and to "see" the interiors of other solar-type stars has taken a major step forward thanks to the NASA Kepler Mission, which, in addition to its search for potentially habitable exoplanets, is providing exquisite data for asteroseismology, the study of the natural oscillations of stars.

During the first ten months of science operations the Kepler Asteroseismic Science Consortium (KASC) undertook an asteroseismic survey of solar-type stars that met with unprecedented success, yielding detections of solar-like oscillations in more than 500 stars [1]. Around 100 of these stars are now being monitored continuously for asteroseismology. In this talk I shall review the science that these unprecedented asteroseismic data are making possible, including results from ensemble and statistical studies. I shall also discuss exciting science opportunities that will be made possible by the analysis of multi-year Kepler datasets.

There are strong synergies between asteroseismology and exoplanet science. Asteroseismology can provide key input to characterize exoplanet systems, e.g., through measurement of accurate and precise stellar radii (for placing tight constraints on planetary radii), stellar ages, and stellar dynamics (including stellar angles of inclination). I shall discuss the work of the Kepler Asteroseismic Science Operations Centre (KASOC), which is providing asteroseismic input on exoplanet candidate host stars to Kepler Science Team.

[1] Chaplin, W. J., et al.. (2011) *Science, 332,* 213 – 216.

507. ENSEMBLE ASTEROSEISMOLOGY OF SOLAR-TYPE STARS

ASTEROSEISMIC MODELLING OF KEPLER STARS Sarbani Basu[1]
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The Kepler mission is providing us exquisitely precise data on stellar oscillations. These oscillations allow us to study stellar properties with amazing detail. In this talk I shall review how we use asteroseismic data to study the properties of stars. I shall start with the basics of how we asteroseismic data can constrain stellar masses and radii and go on to detailed modelling of a stars interior structure and physics of stars. Some the methods that I shall describe are also being applied to data obtained from exoplanet host stars to provide inputs that can characterize the exoplanet systems.

508. ENSEMBLE ASTEROSEISMOLOGY OF SOLAR-TYPE STARS

LONG-BASELINE INTERFEROMETRY FOLLOW-UP OF KEPLER STARS USING THE CHARA ARRAY. D. Huber[1], M. J. Ireland[2], T. R. Bedding[1], O. Benomar[1], I. Brandao[3], H. Bruntt[4], W. J. Chaplin[5], M. Cunha[3], J. De Ridder[6], C. Farrington[7], S. Frandsen[4], P. J. Goldfinger[7], V. Maestro[1], H. A. McAlister[7], T. S. Metcalfe[8], A. Miglio[5], J. Molenda-Zakowicz[9], M. J. P. F. G. Monteiro[3], L. Piau[10], G. Schaefer[7], D. Stello[1], J. Sturmann[7], L. Sturmann[7], T. ten Brummelaar[7], M. Thompson[8], N. Turner[7], P. G. Tuthill[1], K. Uytterhoeven[11], and T. R. White[1]. [1]Sydney Institute for Astronomy (SIfA), School of Physics, University of Sydney, NSW 2006, Australia; dhuber@physics.usyd.edu.au, [2]Department of Physics and Astronomy, Macquarie University, NSW 2109, Australia, [3]Centro de Astrofisica and Faculdade de Ciencias, Universidade do Porto, Rua das Estrelas, 4150-762 Porto, Portugal, [4]Danish AsteroSeismology Centre (DASC), Department of Physics and Astronomy, Aarhus University, DK-8000 Aarhus C, Denmark, [5]School of Physics and Astronomy, University of Birmingham, Birmingham B15 2TT, UK, [6]Instituut voor Sterrenkunde, K.U.Leuven, Belgium, [7]Center for High Angular Resolution Astronomy, Georgia State University, P.O. Box 3969, Atlanta, GA 30302-3969, USA, [8]High Altitude Observatory, NCAR, P.O. Box 3000, Boulder, CO 80307, USA, [9]Astronomical Institute of the University of Wroclaw, ul. Kopernika 11, 51-622 Wroclaw, Poland, [10]Laboratoire AIM, CEA/DSM-CNRS, Universite Paris 7 Diderot, IRFU/SAp, Centre de Saclay, 91191, Gif-sur-Yvette, France, [11]Instituto de Astrofisica de Canarias, Calle Via Lactea s/n, E - 38205 La Laguna, Spain

Introduction: The direct determination of stellar radii and effective temperatures is essential for improving our understanding of stellar structure and evolution and our ability to predict fundamental parameters of faint stars. We present results of a campaign using the PAVO beam combiner at the CHARA Array to measure the angular sizes for a sample of main-sequence, subgiant and red-giant stars for which solar-like oscillations have been detected by the Kepler mission and the CoRoT space telescope (see Figure 1). By combining angular diameters with parallaxes we measure linear radii and compare these to radii determined using asteroseismology. By combining bolometric fluxes with angular diameters we measure effective temperatures and compare these to determinations using spectroscopy, as well as comment on the possibility of using independent constraints from asteroseismology, interferometry and spectroscopy to improve model physics of low-mass stars such as the calibration of convection formalisms. Finally, we comment on the possibility of using CHARA observations to help confirm exoplanet candidates around the brightest Kepler Objects of Interest by constraining or eliminating stellar companions at small angular separations.

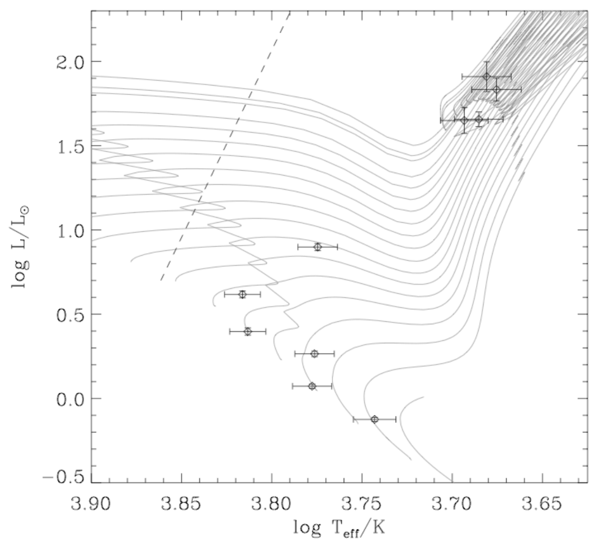

Figure 1: H-R diagram with the position of all Kepler and CoRoT stars included in the follow-up campaign using the CHARA Array. Grey lines show 0.8-2.6$M_\odot$ model tracks in steps of 0.1$M_\odot$. The dashed line marks the cool edge of the instability strip.

ASTEROSEISMIC ANALYSIS OF TWO SUN-LIKE *KEPLER* SUBGIANTS: KIC11395018 AND KIC10920273

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We performed asteroseismic modeling of two G-type subgiant stars using 8 months of Kepler data. The extraction of individual oscillation frequencies was carried out by the Kepler Asteroseismic Science Consortium (KASC) -- Working Group1, and the atmospheric constraints ([Fe/H], T_{eff} and log$g$) were determined through spectroscopic observations at Nordic Optical Telescope, La Palma, Spain. From a classical point of view, these two stars have very similar properties (almost the same T_{eff} and log$g$), however, thanks to asteroseismology we can determine their own global parameters and compare their predicted internal structures.

510. RED GIANT OSCILLATIONS

ASTEROSEISMOLOGY OF RED GIANTS. T. R. Bedding, School of Physics, University of Sydney 2006, Australia, t.bedding@physics.usyd.edu.au

The *Kepler* Mission has produced some spectacular results for red giant stars. It was already known from ground-based spectroscopy and CoRoT photometry that red giants oscillate in a similar way to the Sun, but with longer periods and higher amplitudes. Now, thanks to the long time series from *Kepler*, we are able to carry out asteroseismology on hundreds of stars. I will review some of the key results, which include the detection of gravity-dominated mixed modes that allow us to distinguish between stars that have begun core helium burning and those still burning only hydrogen.

Red giants unveiled

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The *Kepler* mission provides us with thousands of red-giant light curves that allow a very precise asteroseismic study of these objects. Before CoRoT and *Kepler*, the red-giant oscillation patterns remained obscure. Now, these spectra are much more clear and unveil many crucial interior structure properties. For thousands of red giants, we can derive from the seismic data: precise estimates of the stellar mass and radius, the evolutionary status of the giants (with a clear difference between clump and RGB stars), the internal differential rotation, the mass loss, the distance of the stars... Analyzing this mass of information is made easy by the identification of the largely homologous red-giant oscillation patterns. For the first time, both pressure and mixed mode oscillation patterns can be precisely depicted. The mixed-mode analysis allows us, for instance, to probe directly the helium core and the thin region around the stellar core where hydrogen is burning. Fine details completing the red-giant oscillation pattern then provide further information for a more detailed view on the interior structure, including differential rotation.

512. RED GIANT OSCILLATIONS

The Intersection of Asteroseismology and Abundances. C. R. Epstein[1], M. Pinsonneault[1], and J. A. Johnson[1], [1]The Ohio State University, Department of Astronomy, McPherson Laboratory, 140 W 18th Ave.,Columbus, Ohio 43210; epstein,pinsono,jaj@astronomy.ohio-state.edu

Introduction: Stellar ages provide fundamental information on the dynamical and chemical evolution of the Milky Way, but they are one of the most difficult parameters to measure. Asteroseismology presents a new technique capable of determining stellar ages to 18%, if supplemented by accurate chemical abundance information.

Current Work: As part of SDSS-III, the Apache Point Observatory Galactic Evolution Experiment (APOGEE) is obtaining high-resolution (R~20,000), high signal-to-noise (S/N~100) H-band spectra of 100,000 red giant stars spanning the Galactic bulge, halo, and thin and thick disks. In recognition of the wide variety of opportunities made possible by combining Kepler asteroseismic information with abundance measurements, APOGEE will observe 12,000 stars in the Kepler field. This cross-survey collaboration between the APOGEE and Kepler teams will produce a large sample of stars, mostly giants, identified with an evolutionary state and precise measurements of mass, radii, age, and chemical abundances.

In addition, we have obtained high-resolution optical spectra of ~100 Kepler dwarfs and giants. Preliminary results, the current status of the collaboration with APOGEE, and scientific possibilities stemming from this work will be discussed.

PROBING THE INNER ROTATION PROFILE OF THE SUBGIANT KIC7341231. S. Deheuvels[1] and KASC, [1]Department of Astronomy, Yale University, P.O. Box 208101, New Haven, CT 06520-8101, USA, sebastien.deheuvels@yale.edu

Rotation is suspected to have an important influence on the structure and the evolution of stars. However, the transport processes induced by rotation are still uncertain and taking them into account in stellar models is very complex. To achieve a better understanding of these processes, we desperately need to obtain observational constraints on the rotation profiles of stars. To date, this has only been possible for the Sun.

We here present the case of the subgiant KIC7341231, which was observed with the Kepler satellite over a 9-month period. In its oscillation spectrum, we have detected mixed modes, i.e. modes that behave as p modes near the surface and as g modes in the core. Very interestingly, non-radial modes are clearly rotationally split in this star. This provides the exciting opportunity to probe the rotation profile in the star, including in the most central layers, where the rotation is uncertain even in the Sun. We first search for a stellar model reproducing both the seismic and spectroscopic constraints available for KIC7341231. We then perform inversions of the observed rotational splittings of the modes to obtain estimates of the rotation profile in the star. We show that to reproduce the observations, the core has to spin about 6 times faster than the surface. This result sheds new light on the evolution of rotation in solar-like stars because the mass of KIC7341231 happens to be close to 1 $M_{\odot}$.

514. EXTRAGALACTIC AND OTHER ASTROPHYSICS, AND EPO

EXOPLANETS AND ASTROBIOLOGY. C. B. Pilcher, NASA Astrobiology Institute, NASA Ames Research Center, MS247-6, Moffett Field, CA 94035 carl.b.pilcher@nasa.gov

The first discoveries of extrasolar planets in the mid-1990's contributed to the scientific foundation and programmatic motivation for establishing NASA's Astrobiology Program and the NASA Astrobiology Institute (NAI). The Kepler Mission is now making a pivotal contribution to that foundation, further strengthening the field of astrobiology and advancing our understanding of the potential of the universe to harbor life beyond Earth. Since its inception in 1998, the NAI has supported a rich portfolio of extrasolar planet research, including the Virtual Planetary Laboratory's modeling of potential exoplanetary biospheres [1, 2] and the extension of precision radial velocity measurement capability into the near-infrared to improve our ability to detect planets around M-stars, the most common stellar type in the galaxy [3, 4]. In this talk I will summarize the exoplanet research supported by the NAI and look toward the future of the field.

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