The Prevalence of Earth-Size Planets Orbiting Sun-Like Stars

Erik Petigura – UC Berkeley Toward Other Earths II, Porto, Portugal September 15, 2014

Collaborators: Geoff Marcy, Andrew Howard, Lauren Weiss, Howard Isaacson, Rea Kolbl, Lea Hirsch and many more Thanks to: UC Berkeley, IfA, Keck Observatory, NASA

Kepler Planet Haul



Addison Wesley (2004)











Kepler Planet Haul



Kepler Planet Haul



40,000 bright GK stars

Brightest GK stars



Brightest GK stars



7

40,000 bright GK stars

Search for significant transits using TERRA photometric pipeline

2184 TCEs



Optimized for small planet detection

In house pipeline enables measurement of planet detectability (completeness) via injection and recovery experiments

TERRA – optimized for small planets

Time domain preprocessing

- Start with raw photometry
- Gaussian process detrending
- Calibration
- Petigura & Marcy 2012

Transit search

- Matched filter
- Similar to BLS algorithm
- Leverages Fast-Folding Al (Staelin+ 68; Petigura+ 1.

Data validation

- Significant peaks in perio inconsistent with exoplar

Photometric errors common to many stars





TERRA – optimized for small planets

Time domain preprocessing

- Start with raw photometry
- Gaussian process detrending
- Calibration
- Petigura & Marcy 2012

Transit search

- Matched filter
- Similar to BLS algorithm (Kovcas+ 02)
- Leverages Fast-Folding Algorithm (Staelin+ 68; Petigura+ 13, in prep)

Data validation

- Significant peaks in periodogram, but inconsistent with exoplanet transit

Detrended/calibrated photometry



40,000 bright GK stars

Search for significant transits using TERRA photometric pipeline

2184 TCEs



2184 TCEs

Search for significant transits using TERRA photometric pipeline Q1–Q15

Remove non-astrophysical false positives



836 eKOIs



Search for significant transits using TERRA photometric pipeline

Remove non-astrophysical false positives

Remove astrophysical false positives

- Transit shape
- Secondary eclipse



Identifying eclipsing binaries using secondary eclipses

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Primary 7% dimming

Identifying eclipsing binaries using secondary eclipses





Search for significant transits using TERRA photometric pipeline

Remove non-astrophysical false positives

Remove astrophysical false positives

- Transit shape
- Secondary eclipse





574 (95%) KOIs (Nov 2013)



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597 (99%) KOIs (Jun 2014)



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Keck HIRES spectra of 318 eKOIs



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Keck HIRES spectra of 318 eKOIs

Keck spectra of all 62 candidates with P > 100 days



Keck HIRES Spectra

Better stellar parameters

- R_{*} good to 10%
 (photometry: 30%)
- L★ good to 25%
 (photometry: 80%)

Find false positives

- Detect second set of lines
- Kolbl and Marcy (2014)













10 Earth-size Candidates in HZ



10 Earth-size Candidates in HZ

9/10 are KOIs



10 Earth-size Candidates in HZ

9/10 are KOIs

Keck spectra of all 10


























Completeness from Injection and Recovery



Planet occurrence size and orbital period



Planet occurrence size and orbital period



Planet size distribution



Planet size distribution



Planet size distribution



Orbital period distribution



Fraction of stars with planets of having different orbital periods

Planet occurrence size and incident flux









Summary

Independent search for planets in raw *Kepler* photometry (Q1-Q15) using TERRA pipeline

603 planet candidates found, 10 are Earth-size (1–2 R_E) and in HZ ($F_P = 0.25-4 F_E$)

Keck spectroscopy of all HZ candidates and all planet candidates with P > 100 days

Measured completeness using injection and recovery

22±8% of GK stars have 1–2 R_E planet in the HZ

Extra Slides

GK stars





The Keck Planet Search: Detectability and the Minimum Mass and Orbital Period Distribution of Extrasolar Planets

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Orbital period distribution



Multiplicity Correction







84% 98% 98% 97% 98% 97% 98% 97% 96% 94% 92% 63% 10 98% 99% 97% 98% 98% 99% 98% 96% 96% 91% 85% 62% Planet Size [Earth-radii] 83% 98% 97% 97% 97% 95% 98% 90% 63% 98% 97% 92% 5 98% 97% 96% 96% 96% 88% 83% 64%98% 98% 97% 92% 4 3 96% 98% 94% 89% 84% 96% 95% 94% 92% 90% 78% 59% 93% 88% 93% 93% 92% 85% 85% 83% 76% 69% 60% 40% 2 85% 75% 87% 75% 73% 73% 64%55% 53% 34% 25% 13% 66% 53% 47% 44%35% 30% 22% 18% 10% 5% 4% 3% 1 1% 1% 1% 21% 21% 12% 9% 5% 6% 4% 1% 0% 01% **२**% በ% 1% በ% በ% 0% 0% 0% 0% 0.5 10 20 40 50 30 100 200 300 400 5 Orbital Period [days]

Completeness
THE OCCURRENCE RATE OF SMALL PLANETS AROUND SMALL STARS

COURTNEY D. DRESSING^{1,2} AND DAVID CHARBONNEAU¹ (Dated: February 25, 2013) Accepted to ApJ

temperatures. Our sample includes 2 Earth-size planet candidates in the habitable zone, allowing us to estimate that the mean number of Earth-size planets in the habitable zone is $0.15^{+0.13}_{-0.06}$ planets per cool star. Our 95% confidence lower limit on the occurrence rate of Earth-size planets in the habitable zones of cool stars is 0.04 planets per star. With 95% confidence, the nearest transiting Earth-size

