We thank the IRTF TAC & the Caltech TAC for enabling these follow-up observations and the K2 Guest Observer Office for supporting our numerous K2 proposals.

From Red Dwarfs to Pale Blue Dots: Searching for Potentially Habitable Planets in the Galaxy with Kepler, K2, TESS, & Beyond

Courtney Dressing

NASA Sagan Fellow at Caltech

LUVOIR Seminar

November 30, 2016

Collaborators: Elisabeth Newton, Josh Schlieder, Andrew Vanderburg, Ian Crossfield, Arturo Martinez, Heather Knutson, David Charbonneau, the K2 California Consortium, & the HARPS-N Consortium
The Big Question: *Are we alone?*
Questions Addressed Today

1. How common are planets orbiting low-mass stars?
2. How diverse are the compositions of small planets?
3. How can we identify potentially habitable planets?
Transit Observations Reveal Planet Sizes

Radial Velocity Observations Reveal Planet Masses

Image credit: NASA/SDO, Scientific American
How detectable are these signals?
The Sun

1 Solar Radius
1 Solar Mass
5777 Kelvin

Proxima Centauri

14% Solar Radius
12% Solar Mass
3042 Kelvin

Early M Dwarf
Most Stars are M Dwarfs
Most Stars are M Dwarfs
Most Stars are M Dwarfs

How many planets orbit these stars?
The *Kepler* Mission: 2009 - 2013

Credit: NASA/Kepler mission
Kepler Looked for Planets Orbiting These Stars

Credit: NASA/Kepler mission
Locations of Kepler Planet Candidates

By Catalog Release Date

Credit: NASA/Kepler mission
Locations of Kepler Planet Candidates
By Catalog Release Date

- June 2010 Catalog Release
- February 2011 Catalog Release
Locations of Kepler Planet Candidates
By Catalog Release Date

- June 2010 Catalog Release
- February 2011 Catalog Release
- February 2012 Catalog Release

Credit: NASA/Kepler mission
Locations of Kepler Planet Candidates

As of January 7, 2013

Total Today: 4696!
The number of planets is equal to the number of planet candidates minus the number of false positives.

\[ \text{Number of Planets} = \text{Number of Planet Candidates} - \text{Number of False Positives} \]

**Planet Occurrence Rate**

Transit detectability depends on stellar and planetary properties.
Smaller Planets Are More Prevalent

Planets Orbiting Low-Mass Stars are Common

TOTAL: 2.5 ± 0.2 Planets per M dwarf with P<200 days, $R_p = 1-4 \, R_{\text{Earth}}$

Are any of these planets habitable?

Rocky Surface

Liquid Water

How large can a rocky planet be?

Image credit: NASA/Apollo 17
Our Solar System has Two Types of Planets

Not to scale
Planets 2-4x Larger than Earth are Common

Howard 2013, Science, 340, 572
Planets 2-4x Larger than Earth are Common

Howard 2013, Science, 340, 572
RV Observations of Transiting Planets
Constrain the Densities of Small Worlds

HARPS-N at TNG

HIRES at Keck
Carter+ 2012, Barros+ 2014, Haywood+ 2014,


For cooler planets, see Weiss et al. 2013; Weiss & Marcy 2014; Rogers 2015; Wolfgang & Lopez 2015

Also see:
Weiss + Marcy 2014
Rogers 2015
Wolfgang + Lopez 2015
Chen + Kipping 2016
Dorn+ 2016a, b
Are any of these planets habitable?

Rocky Surface

Liquid Water

Is there an upper limit on the size of a rocky planet?

Look for planets with temperate climates

Look for planets smaller than 1.7 Earth Radii

Image credit: NASA/Apollo 17
Likely Locations of Habitable Worlds

One orbit = 365 days

0.24 Earth-size planets per broad M dwarf HZ

Dressing & Charbonneau 2015, 807, 45

HZ Figure: PHL @ UPR Arecibo
Nearest HZ Earth 2.6 pc
Transiting HZ Earth 11 pc
How did these estimates fare?

- Nearest HZ Earth: 2.6 pc
- Transiting HZ Earth: 11 pc
How did these estimates fare?

- Nearest HZ Earth: 2.6 pc
- TRAPPIST-1 System: 12 pc

Gillon et al. 2016, Nature
How did these estimates fare?

Proxima Centauri b  1.3 pc
TRAPPIST-1 System  12 pc

Gillon et al. 2016, Nature
Anglada-Escudé et al. 2016, Nature
Do our other neighbors host potentially habitable planets?
The Kepler Mission: 2009 - 2013

Credit: NASA/Kepler mission
The Kepler Mission: 2009-2013

Credit: NASA/Kepler mission
Each K2 Campaign Lasts Roughly 80 Days

http://www.nasa.gov/kepler/keplers-second-light-how-k2-will-work
Where is K2 Looking?

Image Credit: F. Mullally
K2 is Observing Many Small Stars

41% of selected K2 targets are K and M dwarfs

Near-Infrared Spectroscopy Enables Host Star Characterization

IRTF/SpeX

- **21** (mostly partial)
- **1** partial
- 0.7 – 2.55 microns (SXD mode)
- 2000 (SXD mode with 0.3x15” slit)
- 3.0 meters

Palomar 200”/TripleSpec

- **7** (5 clear, 2 bad weather)
- **2** full
- 1.0 – 2.4 microns
- 2500 – 2700 (1x30” slit)
- 200” = 5.1 meters

Wavelength Coverage
Spectral Resolution
Telescope Aperture
We Concentrate on Bright Targets

Dressing et al. 2016a, accepted to ApJ

Median KepMag = 13.5

Median Kmag = 10.9
Only 51% of our targets are actually Low-mass Dwarfs.
The Cool Dwarf Sample Extends from K3 – M4

How big are these stars?

Dressing et al. 2016a, accepted to ApJ
Stellar Models Underestimate the Radii of Low-Mass Stars

Estimate Stellar Effective Temperatures using Features in J, H, & K Bands

Estimate **Stellar Radii** from Effective Temperatures & Metallicities


![Graph showing the relationship between Stellar Effective Temperature (K) and Radius (Solar Radii). The graph includes data points for Interferometry Stars and Field Stars. The x-axis represents the Stellar Effective Temperature (K), ranging from 2800 to 4200 K, while the y-axis represents the Radius (Solar Radii), ranging from 0.2 to 0.7. The data points are color-coded and show a trend with increasing Fe/H values.](image-url)
*Alternate Approach:* Directly Estimate **Temperatures,** **Luminosities,** and **Radii** Using H-Band Features

[diagram showing absorption features in the H-band spectrum]
Our Typical Cool Dwarfs are Roughly $0.6 \ R_{\text{Sun}}$

Dressing et al. 2016a, accepted to ApJ
Most stars are larger than previously estimated ($\Delta R_* = +0.13R_{\text{Sun}} = 34\%$)

Dressing et al. 2016a, accepted to ApJ
Most stars are larger than previously estimated \((\Delta R_* = +0.13 R_{\text{Sun}} = 39\%)\)

Dressing et al. 2016a, accepted to ApJ
We Use the Revised Stellar Radii to Update the Radii of the Associated Planet Candidates

Most of our Planets are Small

- Super-Jupiters
- Jupiters
- Neptunes
- Mini-Neptune
- Super-Earths
- Earths
- Mini-Earths

Dressing et al. 2016b (in prep)
Our K2 Planet Sample Is Similar to the *Kepler* Planet Sample...

Kepler Candidates & Planets: NASA Exoplanet Archive

Dressing et al. 2016b (in prep)
...but the K2 planets generally orbit brighter stars
Our Smaller Planets Tend to Orbit Cooler Stars (consistent with expected detection bias)

Dressing et al. 2016b (in prep)
Spectra are Expensive!

How can we classify the full K2 M dwarf sample?

- Trained random forest using spectroscopically-classified stars
- Reported probabilities that individual targets are M dwarfs

Girish Duvvuri
Senior at Wesleyan Caltech SURF 2016
Girish Estimated K2’s Sensitivity to Planetary Systems Orbiting M Dwarfs
Typical K2 M dwarfs host 1.2 small planets with periods < 50 days

<table>
<thead>
<tr>
<th>Size Range:</th>
<th>Period &lt; 10 Days</th>
<th>Period 10 – 50 Days</th>
</tr>
</thead>
<tbody>
<tr>
<td>Smaller than Earth</td>
<td>0.21</td>
<td>0.07</td>
</tr>
<tr>
<td>Earth – Neptune</td>
<td>0.35</td>
<td>0.45</td>
</tr>
<tr>
<td>Neptune - Jupiter</td>
<td>0.07</td>
<td>0.07</td>
</tr>
</tbody>
</table>
Looking toward the future:
A Pathway for the Discovery & Characterization of Potentially Habitable Worlds
Pathway to Earth 2.0

1. Constrain planet frequencies
2. Figure out which sizes of planets are rocky
   (Work in progress for cool planets)
3. Find cool potentially habitable planets
4. Measure masses to identify rocky worlds
5. Determine atmospheric compositions
6. Search for biosignatures
7. Perform detailed characterization
Pathway to Earth 2.0

- Constrain planet frequencies ✔
- Figure out which sizes of planets are rocky (Work in progress for cool planets)
- Find cool potentially habitable planets
- Measure masses to identify rocky worlds
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- Search for biosignatures
- Perform detailed characterization

For hot planets ✔
TESS Explorer Mission launch in 2017, to find hundreds of nearby small exoplanets amenable to detailed characterization

Ricker et al., JATIS, (2014)
TESS Slides from Zach Berta-Thompson

GEORGE RICKER (P.I.)
ROLAND VANDERSPEK (DEPUTY P.I.)
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

SCIENCE CENTER SHARED BETWEEN
MIT + HARVARD/SMITHSONIAN CfA

COLLABORATION INCLUDING:
NASA GODDARD, NASA AMES, MIT
LINCOLN LAB, ORBITAL SCIENCES, STSCI,
SAO, MPIA-GERMANY, LAS CUMBRES
OBservatory, GENEVA ObservATORY, OHP-
FRANCE, UNIVERSITY OF FLORIDA, AARHAS
UNIVERSITY-DENMARK, HARVARD COLLEGE
Observatory, VANDERBILT University

RICKER ET AL., JATIS, (2014)
Where do we point JWST?
Where do we point JWST?

TESS is our finder scope!
10.5 cm diameter, 24°x24° field of view

Ricker et al. (2014), Sullivan et al. (2015)
one CCD: 12°
FOV from one TESS camera:

24°
FOV from one TESS camera:

24°

constellations by H. A. Rey

Slide by Zach Berta-Thompson
TESS Slides from Zach Berta-Thompson

Ricker et al. (2014), Sullivan et al. (2015)
TESS Slides from Zach Berta-Thompson

Observation of exoplanets

- 27 days
- 54 days
- 81 days
- 108 days
- 189 days
- 351 days

Observable by JWST for >200 days/year

Ricker et al. (2014), Sullivan et al. (2015)
Play TESS Movie
Perform detailed characterization

Search for biosignatures

Determine atmospheric compositions

Measure masses to identify rocky worlds

Figure out which sizes of planets are rocky

Constrain planet frequencies

Pathway to Earth 2.0

✔ for hot planets

(Work in progress for cool planets)

Find cool potentially habitable planets
**Pathway to Earth 2.0**

1. **Constrain planet frequencies**
   - ✔️
2. **Figure out which sizes of planets are rocky**
   - ✔️
   - (Work in progress for cool planets)
3. **Find cool potentially habitable planets**
4. **Measure masses to identify rocky worlds**
5. **Determine atmospheric compositions**
6. **Search for biosignatures**
7. **Perform detailed characterization**
Pathway to Earth 2.0

- Constrain planet frequencies
- Figure out which sizes of planets are rocky (Work in progress for cool planets)
- Find cool potentially habitable planets
- Measure masses to identify rocky worlds
- Determine atmospheric compositions
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- Constrain planet frequencies
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Pathway to Earth 2.0

✔ for hot planets
(Work in progress for cool planets)
Pathway to Earth 2.0

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(Work in progress for cool planets)
Transits, Eclipses, and Phase Curves of Exoplanets Reveal Atmospheric Properties

Cowan et al. 2015, PASP, 127, 311
LUVOIR will Assess Planetary Habitability

This is one possible architecture for LUVOIR
Pathway to Earth 2.0

Constrain planet frequencies

Figure out which sizes of planets are rocky

Find cool potentially habitable planets

Measure masses to identify rocky worlds

Determine atmospheric compositions

Search for biosignatures

Perform detailed characterization

☑️

☑️

(Work in progress for cool planets)
How common are planets orbiting low-mass stars?

How diverse are the compositions of small planets?

How can we identify potentially habitable planets?
Big Picture Summary

1. How can we identify potentially habitable planets?
   - 2.5 small planets per M dwarf
   - 0.25 Earth-like planets per M dwarf

2. How diverse are the compositions of small planets?

3. How can we identify potentially habitable planets?
Big Picture Summary

1. 2.5 small planets per M dwarf
2. 0.25 Earth-like planets per M dwarf
3. Highly-irradiated small planets have Earth-like compositions
4. Larger planets require volatiles

How can we identify potentially habitable planets?
Big Picture Summary

1. **Planet detection with K2 + TESS**
   - 2.5 small planets per M dwarf
   - 0.25 Earth-like planets per M dwarf

2. **Follow-up with JWST + ELTs**
   - Highly-irradiated small planets have Earth-like compositions
   - Larger planets require volatiles

3. **Biosignatures with LUVOIR?**
   - Planet detection with K2 + TESS
   - Follow-up with JWST + ELTs
   - Biosignatures with LUVOIR?
K2 Highlights

- We’ve acquired **NIR spectroscopy of 144 possible low-mass stars** hosting K2 planet candidates
- **51%** of our targets are actually **low-mass dwarfs**

- Classified stars using **empirical relations** based on interferometry (Newton+ 2015, Mann+ 2013)
- Our **revised stellar radii** are 6-39% larger

- **63 planets** are smaller than Neptune
- **3 planets** are in or near the **habitable zone**
- **Red dwarfs** have lots of **small planets**!

*K2 planets are great for follow-up studies!*
Acknowledgements

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**TESS Minjas:** Phil Muirhead, Andrew Mann, Barbara Rojas Ayala

Current funding provided by the NASA Sagan Fellowship Program
Ground-based telescope time from Caltech TAC & IRTF TAC. K2 funding & targets from NASA.
Big Picture Summary

1. Planet detection with K2 + TESS
2. Follow-up with JWST + ELTs
3. Biosignatures with LUVOIR?

- 2.5 small planets per M dwarf
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- We’ve acquired **NIR spectroscopy of 144 possible low-mass stars** hosting K2 planet candidates
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- **3 planets** are in or near the habitable zone
- **Red dwarfs** have lots of **small planets!**

*K2 planets are great for follow-up studies!***
ADDITIONAL SLIDES
Most TESS Planets will be Inside the IWA

Figure 2.1.1 from the Habitability Science Case
Simulated Planets from Sullivan et al. (2015)
Some M Dwarf HZs will be Accessible

Figure 2.1.2 from the Habitability Science Case
Stars from Dittmann et al. (2015)
Exoplanet science goals in Roadmap

- **Present**
  - Complete the statistical census of exoplanets

- **Near Term**
  - Characterize giant planet atmospheres
  - Measure the frequency of potentially habitable planets

- **Formative**
  - Study the atmospheres of a broad range of exoplanets
  - Search for signs of habitable environments

- **Visionary**
  - LUVOIR Surveyor

**Missions**
- Kepler
- TESS
- Hubble
- James Webb Space Telescope
- Spitzer
- WFIRST-AFTA
- ExoEarth Mapper
How do we detect life on an exoplanet?
Observations with Large Space Telescopes Could Generate Coarse Surface Maps

### The M Dwarf Advantage

#### Detectability of Earth-like planet

<table>
<thead>
<tr>
<th></th>
<th>Sun</th>
<th><strong>Kepler M dwarf</strong></th>
<th><strong>Typical M dwarf</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Orbital Period (days)</strong></td>
<td>365</td>
<td>80</td>
<td>17</td>
</tr>
<tr>
<td><strong>Transit Probability (%)</strong></td>
<td>0.46</td>
<td>0.89</td>
<td>1.41</td>
</tr>
<tr>
<td><strong>Transit Depth (ppm)</strong></td>
<td>84</td>
<td>250</td>
<td>1890</td>
</tr>
<tr>
<td><strong>Doppler Wobble (cm/s)</strong></td>
<td>9</td>
<td>21</td>
<td>85</td>
</tr>
</tbody>
</table>
Spectroscopic investigations could expose potentially habitable worlds