Transit Surveys

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Sagan Exoplanet Summer Workshop
July 29, 2015
Our Mission: *Find a transiting Earth-like planet*

- Designing transit surveys
- Constraining planetary parameters
- Accounting for selection effects
- Estimating planet occurrence rates
If 1\% of FGK stars harbor hot Jupiters (Marcy et al. 2005), then how many stars will we need to survey in order to find a single transiting hot Jupiter?
Transit Geometry

\[ d = \text{Star}-\text{planet separation during transit} \]
$f = \text{true anomaly}$

$\omega = \text{longitude of periapse}$

$\theta = f + \omega$

$\theta = 0$ towards arbitrary reference direction

d = a (1 + e)

d = a (1 - e)
Transit Geometry

\[ \theta = f + \varpi \]

- \( f = \text{true anomaly} \)
- \( \varpi = \text{longitude of periapse} \)

\[ d = a (1+e) \]

\[ d = a (1-e) \]

\[ d = \frac{a (1-e^2)}{1+ e \cos f} \]
Transit Probability = \( \frac{(R_\star \pm R_p)}{a} \left( \frac{1 + e \sin \varpi}{1 - e^2} \right) \)

**Easier formula for circular orbits with** \( a \gg R_\star \)

Transit Probability = \( \frac{\text{Stellar Radius}}{\text{Semimajor Axis}} \)

<table>
<thead>
<tr>
<th>Transit Probability</th>
<th>Sun</th>
<th>Kepler M dwarf</th>
<th>Typical M dwarf</th>
</tr>
</thead>
<tbody>
<tr>
<td>Orbital period = 3.5 days</td>
<td>10%</td>
<td>7%</td>
<td>4%</td>
</tr>
<tr>
<td>Insolation = 1 ( F_{\text{Earth}} )</td>
<td>0.5%</td>
<td>0.9%</td>
<td>1.4%</td>
</tr>
</tbody>
</table>
If 1% of FGK stars harbor **hot Jupiters** and 10% of those planets transit then

\[
N = \frac{1}{0.01} \times \frac{1}{0.1} = 1000 \text{ stars}
\]

to find a single *transiting* hot Jupiter.
What precision do we require?

Transit Depth $\approx \left( \frac{\text{Planet Radius}}{\text{Stellar Radius}} \right)^2$
Transit Depth $\delta \approx \left( \frac{\text{Planet Radius}}{\text{Stellar Radius}} \right)^2$

- **Sun**
  - 1 solar radius
  - 5777K

- **Jupiter**
  - $\delta = 1\%$

- **Neptune**
  - $\delta = 0.1\%$

- **Earth**
  - $\delta = 84$ ppm
Transit Depth $\delta \approx \left( \frac{\text{Planet Radius}}{\text{Stellar Radius}} \right)^2$

- **Sun**
  - 1 solar radius
  - 5777K
  - Neptuine: $\delta = 0.1\%$
  - Earth: $\delta = 0.1\%$
  - Jupiter: $\delta = 1\%$

- **“Large” M dwarf**
  - Jupiter: $\delta = 3\%$
  - 0.6 solar radii
  - 3900K

- **F star**
  - Jupiter: $\delta = 0.6\%$
  - 1.3 solar radius
  - 6500K
Estimating the Signal-to-Noise Ratio

\[
S/N = \frac{C_\star \times t}{\left[ (C_\star \times t) + (C_{\text{sky}} \times t \times n_{\text{pix}}) + (\text{RN}^2 + (G/2)^2 \times n_{\text{pix}}) + (D \times n_{\text{pix}} \times t) \right]^{0.5}}
\]

- e\textsuperscript{-} per second from target star
- integration time (seconds)
- number of pixels in aperture
- read noise (e\textsuperscript{-})
- Inverse Gain (e\textsuperscript{-}/DN)
- Dark Current (e\textsuperscript{-}/pixel/second)
- e\textsuperscript{-} per second per pixel from sky background
Bright Star Approximation

\[ S/N = \sqrt{\left[ (C_\star \times t) + (C_{\text{sky}} \times t \times n_{\text{pix}}) + (RN^2 + (G/2)^2 \times n_{\text{pix}}) + (D \times n_{\text{pix}} \times t) \right]^0.5} \]

- \( S/N \): Signal-to-Noise Ratio
- \( C_\star \): e\(^{-}\) per second from target star
- \( t \): Integration time (seconds)
- \( C_{\text{sky}} \): e\(^{-}\) per second per pixel from sky background
- \( n_{\text{pix}} \): Number of pixels in aperture
- \( RN \): Read noise (e\(^{-}\))
- \( G \): Inverse Gain (e\(^{-}\)/DN)
- \( D \): Dark Current (e\(^{-}\)/pixel/second)
Bright Star Approximation

$S/N \approx (C \times t)^{0.5}$

$e^{-}$ per second from target star

Integration time (seconds)

<table>
<thead>
<tr>
<th>Precision for V=10 Star (ppm)</th>
<th>5 sec</th>
<th>60 sec</th>
<th>600 sec</th>
</tr>
</thead>
<tbody>
<tr>
<td>10-cm telescope</td>
<td>2690</td>
<td>780</td>
<td>250</td>
</tr>
<tr>
<td>1-meter telescope</td>
<td>270</td>
<td>78</td>
<td>25</td>
</tr>
<tr>
<td>5-meter telescope</td>
<td>54</td>
<td>16</td>
<td>5</td>
</tr>
</tbody>
</table>
Advantages of Long-Term Monitoring

Number of Transits Observed ≈ Time Coverage Orbital Period

\[ \frac{S}{N}_{\text{multiple}} \approx \frac{S}{N}_{\text{single}} \times (N_{\text{transits}})^{0.5} \]

\[ \frac{S}{N}_{\text{multiple}} \approx \frac{\delta}{\sigma} \left( \frac{T}{P} \right)^{0.5} \]
What are the relevant timescales?
Total duration

\[
\frac{P}{\pi} \sin^{-1}\left(\frac{R_*}{a} \frac{((1+k)^2 - b^2)^{0.5}}{\sin i}\right)
\]
Characteristic Timescale:

\[ T_0 = \frac{R_★ P}{\pi a} \approx 13 \text{ hr} \left(\frac{P}{1 \text{ yr}} \frac{\rho_★}{\rho_☆}\right)^{1/3} \]

Transit Duration \( \approx T_0 (1-b^2)^{0.5} \)

Ingress Duration \( \approx T_0 k(1-b^2)^{-0.5} \)

for small planets in circular orbits with \( a \gg R_★ \) and \( b \ll 1-k \)

---

**Event Duration for a Jupiter with \( P = 3.5 \text{ days} \)**

<table>
<thead>
<tr>
<th></th>
<th>Late F star</th>
<th>Sun</th>
<th>Early M dwarf</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Transit (hr)</td>
<td>3</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>Transit Ingress (min)</td>
<td>16</td>
<td>17</td>
<td>20</td>
</tr>
</tbody>
</table>
Plot made with filtergraph
TESS Dwarf Catalog

(plot made with filtergraph)
TESS Dwarf Catalog

FOV = 5° x 360°
Ideal Survey Design Depends on Stellar Sample

MEarth-South telescopes in action (February 2014)
Surveys with smaller FOV are often deeper.
Two Possible Approaches to Calibration

Employing designated reference stars

Using the ensemble of science targets

Petigura et al. 2013
What have we found?
HD 209458
$T_{\text{eff}} = 6065$ K
Mass = 1.1 $M_\odot$

HD 209458 b
$P = 3.5$ days
Mass = 0.69 $M_J$
Radius = 1.4 $R_J$
<table>
<thead>
<tr>
<th>Planet</th>
<th>Radius (Earth Radii)</th>
<th>Orbital Period (days)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HD 209458 b</td>
<td></td>
<td></td>
</tr>
<tr>
<td>HD 80606 b</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Orbital Period (days)

Planet Radius (Earth Radii)
Orbital Period (days)

Planet Radius (Earth Radii)

2014
Orbital Period (days)

Planet Radius (Earth Radii)
Back to the opening question:
How many stars do we need to survey to obtain a 4σ detection of an Earth-like planet transiting a Sun-like star?
Case Study: The *Kepler* Mission

Earth – Sun transit depth: **84 ppm**

**Required Precision** for 4σ detection

\[
\frac{84 \text{ ppm}}{4} = 20 \text{ ppm}
\]

**Noise model**

\[
20 \text{ ppm} > \sigma = \left[ (\sigma_{\text{shot}})^2 + (\sigma_{\text{star}})^2 + (\sigma_{\text{meas}})^2 \right]^{0.5}
\]

If \( \sigma_{\text{star}} = 10 \text{ ppm} \) and \( \sigma_{\text{meas}} = 10 \text{ ppm} \) then

\[
\sigma_{\text{shot}} < (20^2 - (10^2 + 10^2))^{0.5} = 14 \text{ ppm}
\]
Case Study: The *Kepler* Mission

Earth – Sun transit duration: **13 hr**

**Mission Requirement:** Detect **84 ppm transit in 6.5 hr**


Required Number of Photons in 6.5 hr

\[
\left( \frac{1}{14 \text{ ppm}} \right)^2 = 5 \times 10^9
\]

*Suggests we should target stars with \( V \leq 12 \)
Earth-sized planet + Sun-like star
Transit Probabilities for Potentially Habitable Worlds

One orbit = 365 days

transit probability = 0.5%

80 days 0.9%

17 days 1.4%

CREDIT: PHL @ UPR Arecibo
If 5% of Sun-like V=12 stars harbor Earth-like planets and 0.5% of those planets transit then

\[ N = \frac{1}{0.5} \times \frac{1}{0.005} = 4000 \text{ stars} \]

to find a single transiting Earth-like planet.
How might we estimate planet occurrence?

Completeness Case Study: the Kepler M Dwarfs
Most Stars are M Dwarfs
Most Stars are M Dwarfs
Planet Occurrence

Equally Valid Alternative Choice:
Planet occurrence = Fraction of Stars with Planetary Systems
Planet Occurrence Rate = \frac{\text{Number of Planets}}{\text{Number of Stars “Searched”}}

\# of Planets = \# of Planet Candidates - \# of False Positives
Planet Occurrence Rate = Number of Planets / Number of Stars “Searched”

# of Planets = # of Planet Candidates – # of False Positives

Transit detectability depends on stellar and planetary properties
Which astrophysical phenomena can produce transit-like brightness dips?

1. Transiting planet

Figure credit: Sarah Ballard
High-Contrast Imaging

One of several ways to identify astrophysical false positives

<table>
<thead>
<tr>
<th>K01677</th>
<th>K02754</th>
<th>K02754</th>
<th>K02790</th>
</tr>
</thead>
<tbody>
<tr>
<td>ARIES Ks</td>
<td>ARIES J</td>
<td>ARIES Ks</td>
<td>ARIES Ks</td>
</tr>
<tr>
<td>K02879</td>
<td>K02879</td>
<td>K02904</td>
<td>K02904</td>
</tr>
<tr>
<td>ARIES J</td>
<td>ARIES Ks</td>
<td>ARIES J</td>
<td>ARIES Ks</td>
</tr>
</tbody>
</table>

Kepler targets with companions within 1"

Why High-Resolution Imaging Matters:
Thwarting the Aspirations of Potentially Habitable M Dwarf Planets

Keck NIRC2-AO
K band
Ciardi

KOI 2626

KOI 1422

HST WFC3
F775W
Cartier+ 2014

CFOP
Kepler Community Follow-up Observing Program
Searching for Planets Orbiting *Kepler* M Dwarfs

Normalize to remove quarterly offsets
Searching for Planets Orbiting *Kepler* M Dwarfs

Use median filtering and sigma clipping to remove spots and lingering pointing offsets.
Searching for Planets Orbiting *Kepler* M Dwarfs

Ready for planet search!
Planet Search Results:

**Planet Search Results:**
We Detect Most Previously Known Planets

![Graph showing the relationship between planet radius and period (days). The graph is labeled with points indicating detected planets.]

**Planet Search Results:**

We Miss a Few Tricky Planets *(Some may be false positives)*

Planet Search Results:

We Found One New Planet Candidate

Planet Occurrence Rate = \frac{\text{Number of Planets}}{\text{Number of Stars “Searched”}}
Planet Occurrence Rate = \[
\frac{\text{156 Planets}}{\text{Number of Stars “Searched”}}
\]

How many stars did we search at each planet radius & orbital period?
Estimating Pipeline Sensitivity

KID1162635

Habitable?

Estimating Pipeline Sensitivity

KID1162635

Planet Radius ($R_{\text{Earth}}$)

Period (Days)

Not detectable at all

Estimating Pipeline Sensitivity

KID1162635

Failed “Realistic” Test

Estimating Pipeline Sensitivity

KID1162635

Planet Radius ($R_{\text{Earth}}$) vs. Period (Days)

Ran Full Pipeline

Estimating Pipeline Sensitivity

KID1162635

- Planet Radius ($R_{\text{Earth}}$) vs. Period (Days)
- Not Detected vs. Detected

We Produced Star-by-Star Sensitivity Maps

Sensitivity to Earth-size Planets Depends Strongly on Orbital Period

How does our search completeness compare to theoretical predictions?
Improvement 3: Measured Pipeline Completeness

Difference (DC15 - Ramp)

Planet Radius ($R_{Earth}$)

Detection Fraction

-0.37
-0.30
-0.22
-0.14
-0.06

Period (Days)
Kepler Pipeline Completeness for GK Dwarfs

Burke et al. 2015
Another view of Completeness for Kepler’s FGK Target Stars

Results from $10^4$ Injection and Recovery Experiments

TERRA Completeness for Best12k Sample

How common are planetary systems orbiting M dwarfs?
Smoothed Population of Planet Candidates

MCMC Results

Planet Radius ($R_{\text{Earth}}$) vs. Period (Days)

Full Search Completeness
(Includes Sensitivity & Transit Probability)
Smaller Planets Are More Prevalent

Small, Long-Period Planets are Common

**Total:** 2.5 ± 0.2 Planets per M dwarf with P<200 days, $R_p = 1-4$ REarth

Further Evidence for the Commonality of M Dwarf Planetary Systems


2.01 ± 0.36 planets per star
(with orbital period < 180 days)
Further Evidence for the Commonality of M Dwarf Planetary Systems

2.00 ± 0.45 planets per star (with orbital period < 150 days)

How flat are exoplanetary systems?
Evidence for Two Populations of M Dwarf Planetary Systems

45% of systems
- roughly 5 planets with coplanar orbits

55% of systems
- only 1 planet
- or
- multiple planets with high mutual inclinations

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
### Planet Occurrence (%)

<table>
<thead>
<tr>
<th>Planet Radius ($R_{\text{Earth}}$)</th>
<th>Insolation ($F_{\text{Earth}}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.0</td>
<td></td>
</tr>
<tr>
<td>3.5</td>
<td></td>
</tr>
<tr>
<td>3.0</td>
<td></td>
</tr>
<tr>
<td>2.5</td>
<td></td>
</tr>
<tr>
<td>2.0</td>
<td></td>
</tr>
<tr>
<td>1.5</td>
<td></td>
</tr>
<tr>
<td>1.0</td>
<td></td>
</tr>
<tr>
<td>0.5</td>
<td></td>
</tr>
</tbody>
</table>

**Log$_{10}$ Occurrence**

-5.00 -4.00 -3.00 -2.00 -1.00

**Recovery < 15%**

Smaller, Cooler Planets Are More Common

**Narrow Habitable Zone**

**Total:** 0.24 Earth-size planets per broad M dwarf HZ

---

Nearest HZ Earth: 2.6 pc
Transiting HZ Earth: 11 pc
M Dwarf Planetary Systems are Common

- **Per star:**
  - 0.56 \((+0.06/-0.05)\) Earth-size planets with \(P<50\) days
  - 0.46 \((+0.07/-0.05)\) super-Earths with \(P<50\) days
  - 2.5 \((\pm 0.2)\) small \((1-4 \, R_E)\) planets with \(P<200\) days

- **Empirical Venus/Mars Habitable Zone:**
  - 0.24 \((+0.18/-0.08)\) Earth-size planets
  - 0.21 \((+0.11/-0.06)\) super-Earths
  - 11 pc to nearest transiting Earth-like planet
Current & Future Missions
Targeting Planets
Orbiting Small Stars
Kepler Stared at One Field
K2 Will Look at Multiple Fields
The Transiting Exoplanet Survey Satellite

- Launch in 2017
- Two-year survey
- 90% of sky

Hundreds of Earth-size planets & super Earths!
K2 & TESS Have Complementary Sky Coverage

Ricker et al. 2014
Simulation of TESS Planet Detections

TESS Will Find Dozens of Earth-size Planets and Hundreds of Super-Earths

TESS Will Find Some Potentially Habitable Planets Orbiting Cool Stars

PUTTING EVERYTHING TOGETHER
Confirmed Transiting Planets

<table>
<thead>
<tr>
<th>Planet</th>
<th>Radius (Earth Radii)</th>
<th>Orbital Period (days)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Confirmed Transiting Planets & Kepler Candidates

- **Planet Radii (Earth Radii):**
  - Confirmed Transiting Planets
  - Kepler Candidates

- **Orbital Period (days):**
  - Hot Jupiters
  - Cool Giants
  - Hot Small Planets
  - Habitable?
What we’ve learned so far

- Exoplanetary systems are diverse
- Many stars harbor close-in planets with high transit probabilities
- Transiting planets offer unique laboratories to investigate atmospheric compositions and bulk densities

The future is bright.
Additional Slides
TESS Detections will be Well-Suited for Mass Measurement

Potential for Studying the Atmospheres of TESS Planets

Transit Anatomy

Slide from Josh Winn’s Presentation at the 2012 Sagan Exoplanet Workshop
<table>
<thead>
<tr>
<th>Component</th>
<th>Value</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Optics</td>
<td>Brashear &amp; Tinsley</td>
<td>Manufacturers</td>
</tr>
<tr>
<td>Schmidt corrector</td>
<td>0.99 m dia./0.95 m dia. stop</td>
<td>Corning Fused silica</td>
</tr>
<tr>
<td>Primary mirror</td>
<td>F1 1.40 m dia., silver coated</td>
<td>Corning ULE®</td>
</tr>
<tr>
<td>Central obscuration</td>
<td>23.03%</td>
<td>Due to focal plane and spider</td>
</tr>
<tr>
<td>FFIs</td>
<td>2:5 square</td>
<td>Sapphire</td>
</tr>
<tr>
<td>PRF</td>
<td>3.14–7.54 pixels, 95% encircled energy diameter</td>
<td>Depends on FOV location</td>
</tr>
<tr>
<td>Sunshade</td>
<td>55° sun avoidance</td>
<td>From center of FOV</td>
</tr>
<tr>
<td>CCDs</td>
<td>e2v Technologies</td>
<td>Two outputs per CCD</td>
</tr>
<tr>
<td>Format</td>
<td>1024 rows x 2200 columns</td>
<td>Four phases</td>
</tr>
<tr>
<td>Pixel size</td>
<td>27 μm square</td>
<td>Set by parallel clock voltage</td>
</tr>
<tr>
<td>Plate scale</td>
<td>3.98 arcsec pixel⁻¹</td>
<td>Meets photometric precision</td>
</tr>
<tr>
<td>Full well</td>
<td>1.05 × 10⁶ electrons, typical</td>
<td>10 mK stability</td>
</tr>
<tr>
<td>Dynamic range</td>
<td>7 ≤ Kp ≤ 17</td>
<td>Design and manufacturer</td>
</tr>
<tr>
<td>Operating temperature</td>
<td>−85 °C</td>
<td>Multiplexed into 20 ADCs on five electronic board pairs</td>
</tr>
<tr>
<td>Controller</td>
<td>Ball Aerospace</td>
<td>Selectable 2.5–8 s</td>
</tr>
<tr>
<td>Channels</td>
<td>84</td>
<td>Fixed</td>
</tr>
<tr>
<td>CCD integration time</td>
<td>6.02 s</td>
<td>270 integrations + reads</td>
</tr>
<tr>
<td>CCD readout time</td>
<td>0.52 s</td>
<td>9 integrations + reads</td>
</tr>
<tr>
<td>LC period</td>
<td>1765.80 s</td>
<td>Average 32 pixels/target</td>
</tr>
<tr>
<td>SC period</td>
<td>58.86 s</td>
<td>Average 85 pixels/target</td>
</tr>
<tr>
<td>Maximum LC targets</td>
<td>170,000</td>
<td>For asteroseismology and transit timing</td>
</tr>
<tr>
<td>Maximum SC targets</td>
<td>512</td>
<td>Design, integration, and test</td>
</tr>
<tr>
<td>Timing accuracy</td>
<td>50 ms</td>
<td>5% points</td>
</tr>
<tr>
<td>System</td>
<td>Ball Aerospace</td>
<td>115 deg² of non-contiguous active silicon</td>
</tr>
<tr>
<td>Spectral response</td>
<td>423–897 nm</td>
<td>1σ per axis</td>
</tr>
<tr>
<td>FOV</td>
<td>105 deg² &lt;10% vignetted</td>
<td>V = 12 solar-like star including 10 ppm for stellar variability</td>
</tr>
<tr>
<td>Pointing jitter</td>
<td>3 mas per 15 minutes</td>
<td>&lt;1 day observing gap</td>
</tr>
<tr>
<td>CDPP (total noise)</td>
<td>20 ppm in 6.5 hr for &gt;90% of FOV</td>
<td>Baseline. May be extended</td>
</tr>
<tr>
<td>Data downlink period</td>
<td>31-day average</td>
<td>Earth-trailing heliocentric</td>
</tr>
<tr>
<td>Mission length</td>
<td>3.5 years</td>
<td></td>
</tr>
<tr>
<td>Orbital period</td>
<td>372 days by year 3.5</td>
<td></td>
</tr>
</tbody>
</table>
Table 1
Detector Properties Summary

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Where Measured</th>
<th>Minimum</th>
<th>Maximum</th>
<th>Median</th>
</tr>
</thead>
<tbody>
<tr>
<td>Read noise ($e^- \text{read}^{-1}$)</td>
<td>Flight</td>
<td>81</td>
<td>307 [140]$^a$</td>
<td>95</td>
</tr>
<tr>
<td>Gain ($e^- \text{DN}^{-1}$)</td>
<td>Ground</td>
<td>94</td>
<td>120</td>
<td>112</td>
</tr>
<tr>
<td>Saturation (Kepler Mag)$^b$</td>
<td>Flight</td>
<td>11.6</td>
<td>10.3</td>
<td>11.3</td>
</tr>
<tr>
<td>PRNU$^c$ (%)</td>
<td>Ground</td>
<td>0.82</td>
<td>1.20</td>
<td>0.96</td>
</tr>
<tr>
<td>LDE undershoot (%)</td>
<td>Flight</td>
<td>0.08</td>
<td>1.92</td>
<td>0.34</td>
</tr>
</tbody>
</table>

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Yale Bright Star Catalog
Yale Bright Star Catalog
TrES-2b

**the Star**

- \( V = 11.4 \)
- Mass = 0.98 \( R_\odot \)
- Radius = 1.0 \( M_\odot \)
- \( \text{Teff} = 5850 \text{ K} \)

**the Planet**

- Radius = 1.2 \( R_\oplus \)
- Mass = 1.2 \( M_\oplus \)
- \( P = 2.5 \text{ days} \)
TrES-2b

Kepler Light Curve (Short Cadence Data)

A Patch of Sky: All Stars with Kepmag < 15

dec vs. ra (point size: kepmag)
A Patch of Sky: Dwarf Stars with Keplmag < 15

Declination (deg) vs. Right Ascension (deg) (point size: keplmag)

Fainter

Brighter
Revised Properties After Imaging

**KOI 2626.01**

- Planet Radius: 1.37 \( R_{\text{Earth}} \)
- Insolation: 0.66 \( F_{\text{Earth}} \)
- Mini-Earth: 0%
- Earth-sized: 2%
- Super-Earth: 24%
- Neptune-sized: 72%
-太热: 54%
-适居: 40%
-太冷: 5%

**KOI 1422.02**

- Planet Radius: 0.92 \( R_{\text{Earth}} \)
- Insolation: 0.82 \( F_{\text{Earth}} \)
- Mini-Earth: 0%
- Earth-sized: 0%
- Super-Earth: 0%
- Neptune-sized: 75%
-太热: 97%
-适居: 2%
-太冷: 0%
Revised Properties After Imaging
Most TESS Planets will have Short Periods