The Kepler Exoplanet Survey: Instrumentation, Performance and Results

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Basic Kepler Science Goal

- Determine frequency and orbital properties of terrestrial & larger planets in/near the habitable zones of a wide variety of stars.

Kepler is designed to discover the frequency of potentially habitable worlds outside the Solar System: terrestrial planets in the habitable zones of their stars.

Concentrate on solar-like stars: F, G, K and early M dwarfs
The Habitable Zone

The region around a star where liquid water might exist on a planet’s surface

The Goldilocks Zone

**Hotter Stars**
- F0
- 2 to 10 year orbits

**Sunlike Stars**
- G2
- 9 months to 3.5 years

**Cooler Stars**
- K5
- 3 to 13 months

Too hot
Too cold
Just right
Radial Velocity Detection Won’t Do

• Classic discovery method is spectroscopic detection of the reflex motion of the host star due to an orbiting planet is the.
  — RV detection gives the planet mass

• Long habitable zone orbits and low terrestrial planet masses make RV unsuitable for Kepler’s goal
  — Best RV sensitivity of 0.5 m/s insufficient to see low mass planets in HZs

• Need to use the transit detection method.

Max reflex velocity for dwarf stars and 1 $M_{\text{Earth}}$ planet in HZ

<table>
<thead>
<tr>
<th>Star Type</th>
<th>Reflex Velocity</th>
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<tbody>
<tr>
<td>F5</td>
<td>0.06 m/s</td>
</tr>
<tr>
<td>G0</td>
<td>0.09</td>
</tr>
<tr>
<td>K0</td>
<td>0.13</td>
</tr>
<tr>
<td>M0</td>
<td>0.26</td>
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</tbody>
</table>
Discovering Planets with Transits

- When an extrasolar planet’s orbit takes it directly between its star and the Earth the star will dim slightly
  - Relative change in brightness ($\Delta L/L$) is the ratio of areas ($A_{\text{planet}}/A_{\text{star}}$)

  ![Image of Jupiter and Earth or Venus]

  - Jupiter: 1% area of the Sun (1/100)
  - Earth or Venus: 0.008% area of the Sun (1/12,000)

  - 0.008% is SMALL. Must get above the Earth’s atmosphere to measure.
  - You must be patient. Transits last only a few hours out of the orbital period
  - Need at least 3 transits to be sure a planet is detected
    - May need more for sufficient reliability
Can’t See Every Planet

- Not all orbits are aligned to make a transit
- Geometry for transit probability

1) Range of Pole Positions = \( \frac{d^*}{D/2} \)

2) Solid angle of \( 4\pi d^*/D \) for all possible pole positions for any given LOS

3) Geometric Transit Probability = \( d^*/D \)

- Diameter of Sun: \( \sim 0.01 \text{ AU} \)  Diameter of Earth’s orbit: \( 2 \text{ AU} \)
- Probability of seeing a distant Earth-Sun analog transit: 0.5%
- Must look at a lot of stars to get statistical sample of planets.
Kepler Mission Requirements

- Monitor >100,000 solar-like stars for 4 years
- Don’t blink! Continuous observation is needed.
  - Must catch transits only 6 – 16 hours long
- Sufficient sensitivity to see an earth-size planet transiting a solar-size star
  - Need 7σ detection of planet with 1 year orbit period
    - Controls false detections due to random noise
  - Requires ~4σ detection of single 80 ppm transit: 20 ppm 1σ
  - Noise budget for our fiducial 12th magnitude star
    - 14 ppm photon noise in 6.5 hr transit with 1 meter aperture
    - 10 ppm stellar variability (noise level of the Sun)
    - 10 ppm instrument noise (read noise, dark current, pointing stability, etc.)
Kepler Mission Design

- Continuously and simultaneously monitor >150,000 stars cool dwarf stars (F-M)
- 95 centimeter Schmidt telescope
  - >115 deg$^2$ field-of-view
  - 42 CCDs, 96M pixels, 4 arcsec/pixel
  - Sample every 30 minutes
    - 1000 targets with 1 sec samples.
- Photometric precision of < 20 ppm in 6.5 hours on $V_{mag}$ = 12 solar-like star
  → 4σ detection of 1 Earth-sized transit

- Heliocentric orbit for continuous visibility of target field
- 3.5 year lifetime with capability of >10 years (budget requirement)
- Break data collection monthly for down-link and quarterly to roll 90° for Sun attitude
Focal Plane Array

- 21 science CCD modules
  - Two 1044 x 2200 back illuminated CCDs from e2v
  - 27µm pixels
  - Sapphire field flattener lens.

- >115 deg² field of view
  - 4 arcsec pixels

- 430 – 890 nm passband
- Shutterless operation

FPA under assembly at Ball Aerospace

Single CCD module
Kepler Implementers

- Proposed by Bill Brouck at NASA Ames Research Center
  – Selected as the 10th Discovery mission.
- Overall management by Jet Propulsion Laboratory, CalTech
- Ball Aerospace Corporation built and integrated the hardware
- Mission Operations at LASP (University of Colorado) and Ball Aerospace
- Science operations and flight phase management at NASA Ames Research Center
Kepler Launched March 6, 2009
EARTH-TRAILING HELIOCENTRIC ORBIT

Launch 3/6/2009

Season 1
Season 2
Season 3
Season 4

Year 1
Year 4

Vernal Equinox

Winter Solstice

Summer Solstice

Kepler's orbit

Earth's orbit

Ecliptic Reference
Period (days) 365.24 371.54
Semi-major Axis (AU) 1.00 1.01
Eccentricity 0.02 0.01
Inclination (deg) 0.00 0.49
Arg. of Periapse (deg) 102.96 -42.30
Long. of Node (deg) 0.00 27.46
Kepler Full Field Image

Kepler records and sends back about 5% of this image

Small “postage stamps” around each of ~150,000 target stars
Milky Way Galaxy

Kepler Search Space
3,000 light years

Sagittarius Arm
Orion Spur
Perseus Arm

Searches the Extended Solar Neighborhood
Representative target distribution
Targets vary somewhat by season as stars fall on and off the detectors.
Mission status and performance

- On orbit 40 months, collecting survey data for 38 months
- H/W functioning well
  - But lost one detector module early in mission due to electrical short
    - 4.8% of focal plane
    - Effects data completeness in 19% of FOV due to rolls
- Just started 14th quarter of data collection
Instrument Health

No significant changes since launch

**Dark Current:** increasing by $0.33e^-/s/year \Rightarrow$ additional 0.2 ppm noise in 6.5 hours at $Kp=12$

**Charge Transfer Inefficiency:** linear increase from Q4 to Q12 from about 60 to 140 PPM, ~40 PPM per year. Might amount to 400 PPM increase after 8 years. Will need to reassess our photometric aperture selection towards the end of an extended mission.

**Throughput:** flux from bright stars dropping 1%/year \Rightarrow 8*0.5% increase in shot noise after 8 years (optical ghost signals increasing ~0.2%/year)

Noise performance nearly constant from Q3-Q11 once pipeline improvements have been taken into account.

Doug Caldwell, SETI Institute

7/3/12
Kepler Saw Some Excess Noise

- Noise levels seen on-orbit for 12th magnitude dwarfs show a median of ~30 ppm instead of the design requirement of 20 ppm for 6.5 hr transits
- Investigation shows most “sunlike” stars are noisier than the sun on transit time scales
- Instrument performance is close to design value

<table>
<thead>
<tr>
<th>Component</th>
<th>Variance (ppm²)</th>
<th>Noise (ppm)</th>
<th>Baseline Noise (ppm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intrinsic stellar</td>
<td>380.5</td>
<td>19.5</td>
<td>10.0</td>
</tr>
<tr>
<td>Poisson + readout</td>
<td>283.0</td>
<td>16.8</td>
<td>14.1</td>
</tr>
<tr>
<td>Intrinsic detector</td>
<td>116.2</td>
<td>10.8</td>
<td>10.0</td>
</tr>
<tr>
<td>Quarter dependent</td>
<td>60.1</td>
<td>7.8</td>
<td>—</td>
</tr>
<tr>
<td>Total</td>
<td>839.8</td>
<td>29.0</td>
<td>20.0</td>
</tr>
</tbody>
</table>

Global roll-up of Kepler noise sources for 12th magnitude star. “Baseline Noise” are the noise levels assumed for photometer design.
Candidates as of Feb 2012
2321 total

Orbital Period in days
Size Relative to Earth

Jun 2010
Feb 2011
Feb 2012

Jupiter-size
Neptune-size
Earth-size
Numbers of Planet Candidates
As of February 27, 2012

1,118 - Neptune-size (2 - 6 R_⊕)
2321 total

676 - Super Earth-size (1.25 - 2 R_⊕)

246 - Earth-size (< 1.25 R_⊕)

210 - Jupiter-size, (6 - 15 R_⊕)

71 - Larger, (> 15 R_⊕)
HZ Candidates

48 with $T_{eq}$ between 185 and 303 K

Equilibrium Temperature (K) vs. Size Relative to Earth (Radius)

- Jun 2010
- Feb 2011
- Feb 2012

Planets:
- Jupiter
- Neptune
- Earth
74 confirmed planets

63 from the Kepler Team
11 from other astronomers
3 known before Kepler
Many habitable zone planets.
Lots of Earth-size planets.
No confirmed Earth-size HZ planet yet. But soon!

Potential Habitable Exoplanets
(4 confirmed and 27 unconfirmed NASA Kepler Candidates)

Credit: Planetary Habitability Laboratory, UPR Arecibo (phil.upr.edu) April 2012
Multiple Planet Systems

Unexpected find
Tells us about planet systems, not just planets
Self confirming because multiple occurrence of false positives on a single star is very unlikely
Multi-planet systems

• Feb 2012 candidate catalog
  – 2321 candidates around 1791 unique stars
  – 365/1791 stars host multiple candidates
  – 898/2321 candidates are part of multiple systems
  – Fraction of stars with multiple systems: 20%

• Expect to soon publish paper confirming ~800 of these candidates based on their presence in multiple planet systems.
Kepler’s Confirmed Multiple Planet Systems

Total 19 systems with 52 planets and 8 candidates
Sizes from > Jupiter to ~1/2 Earth
Many different configurations

(2 systems post date this chart)
Hot Jupiters are Lonely

Dearth of short period (hot) giant planets in multi-planet systems persists

Giant Planets Need Metals

Results - Astrophysics

• Kepler’s 20 ppm precision provides unprecedented sensitivity for studying stellar variability
  — Kepler is a watershed for many aspects of stellar physics
• Lots of interesting new objects, hierarchical multiple systems, eccentricity driven ringing, many more ...
• Big deal is asteroseismology
  — Acoustic oscillations in stars can be seen as small brightness variations on time scales of minutes to hours
    • Analysis gives stellar parameters: mass, $T_{\text{eff}}$, age
    • Probes internal structure of stars
  — Thousands of stars being observed at 30 minute cadence
  — More thousands are rotated monthly into the 1000 targets that Kepler can sample at 1 sec cadence
Core Helium vs. Hydrogen Shell Burning Stars

Red giant stars burning helium in their cores are nearly indistinguishable photometrically from those burning only hydrogen in a shell during part of their evolution.

Plotting pressure mode spacings (X axis) from the envelope vs gravity mode spacings (Y axis) from the core clearly separate H shell burning stars (blue points) from He core burning stars (red and orange points).

What’s Next

• Now have well over 3000 planet candidates
  – Search of 10 quarters of observations
  – Publication of a new candidate list to occur this fall
    • Small radii, longer orbits

• Radial velocity work to measure masses of some smaller planets
  – Get densities to find the transition from gassy and icy planets to rocky planets in the 2.5 \(-\) 1 $R_{\text{earth}}$ region.

• Extended mission
  – 3.5 year prime mission will end in November with Q15
  – Extended mission will then start to provide a total of 7.5 years of data which should make up for higher than predicted stellar noise level
  – Fill in the area of the plot to see HZ earths around G type dwarfs

• Continue with marvelous astrophysics
Kepler Extended Mission Target:
Habitable Zone Earths

Size Relative to Earth

Orbital Period in days

Jun 2010
Feb 2011
Jan 2012

Jupiter-size
Neptune-size
Earth-size

Extended mission target
Earth analogs

7/3/12