... the ways by which men arrive at knowledge of the celestial things are hardly less wonderful than the nature of these things themselves.

— Johannes Kepler 1571-1630

Do there exist many worlds or is there but a single one? This is one of the most noble and exalted questions in the study of Nature

— Saint Albertus Magnus 1206-1280
Scholar, Patron Saint of Scientists
The Once and Future Kepler: Recent Results and News from the Sweet Hereafter

Jon M. Jenkins
SETI Institute

Monday May 20, 2013

Exoplanets in the Post-Kepler Era

Harvard CfA, Cambridge
Overview

- Recent Results
- The road to $\eta_\odot$
- Upcoming Features
- Characterizing the Kepler system
- What’s Next?
Recent Science Results
A Search for Earth-size Planets

Kepler-62 System

Habitable Zone

62f 62e 62d 62c 62b

Mercury Venus Earth Mars

Planets and orbits to scale

Solar System
A Search for Earth-size Planets

Kepler-69 System

69c  69b

Habitable Zone

Solar System

Planets and orbits to scale
A Search for Earth-size Planets

Exoplanet Detections, 2009-2013

- Velocimetry
- Transit: non-Kepler
- Transit: Kepler

Radius Relative to Earth vs. Orbital Period in days
A Search for Earth-size Planets

Habitable Zone Candidates

22 Months: May 2009 - Mar 2011

Kopparapu et al 2013
arXiV: 1301.2649

Stellar Surface Temperature

Empirical HZ
Narrow HZ
Rp < 2 Re & Fp < 2 Fe

Stellar Flux at Planetary Orbit, \( \log(F_p/F_e) \)
3 Small HZ Candidates Orbiting M-type Stars

6% host planets smaller than $2.5R_e$ in the HZ

Dressing et al. 2013
arXiv:1302.1647
This is no time to fall asleep!
Another Birthday for **Kepler**

Bill Borucki never dream small dreams!
Some Key Ingredients:
1. Planet candidates and confirmed/validated planets
2. Completeness of the *Kepler* planet discovery system
3. Reliability of the *Kepler* planet discovery system
4. Updated stellar properties
5. Knowledge of background eclipsing binary distribution
6. Relation of target sample to general galactic stellar population

* Natalie explains how it’s done.
A Search for Earth-size Planets

Putting It All Together

Threshold Crossing Event Review Team

Running Pipeline Generating KOIs

Transit Injection Studies At the Pixel Level

Auto-Vetting

Transit Timing Variations WG

Asteroseismology (KASC)

Statistical Validation

KFOP & CFOP

Stellar Props WG

False Positive WG

Eclipsing Binaries WG
Characterizing the *Kepler* System
A Search for Earth-size Planets

The *Kepler* Sausage Maker

We need to characterize the completeness and reliability of the entire system!
A Search for Earth-size Planets

The Details: The Present

CAL
Pixel level Calibration

PA
Photometric Analysis

PDC
Pre-search Data Conditioning

DV
Data Validation

TPS
Transiting Planet Search

TCERT
Threshold Crossing Event Review Team

Planet, or dud?

Raw Light Curves & Centroids

Calibrated Pixels

Threshold Crossing Events (TCEs)

Corrected Light Curves

Diagnostic Metrics & Reports

Raw Data

Calibrated Pixels

Raw Light Curves & Centroids

Transiting Planet Search
A Search for Earth-size Planets

Closing the Loop

- Artificial Transit & BEB Injection Machine
  - Raw Data
  - CAL Pixel level Calibration
    - Calibrated Pixels
  - Diagnostic Metrics & Reports
- Artificial Transits and Eclipses
  - Raw Light Curves & Centroids
  - Threshold Crossing Events (TCEs)
- Photometric Analysis
  - Calibrated Pixels
- Pre-search Data Conditioning
  - Corrected Light Curves
- Data Validation (DV)
- Transiting Planet Search (TPS)
  - Planet, or dud?
- Threshold Crossing Event Review Team (TCERT)

Did We Get the Right Answer?
Keeping Up With the Data Avalanche

A Search for Earth-size Planets

Artificial Transit & BEB Injection Machine

Raw Data → CAL (Pixel level Calibration) → Photometric Analysis → TPS (Transiting Planet Search) → Planet, or dud?

CAL (Pixel level Calibration)

PA (Photometric Analysis)

PDC (Pre-search Data Conditioning)

TPS (Transiting Planet Search)

DUD (Data Validation)

TCERT (Threshold Crossing Event Review Team)

TCERT (Threshold Crossing Event Review Team)

Auto-Vetting

Applying machine learning to candidate evaluation

Raw Light Curves & Centroids → Calibrated Pixels → Diagnostic Metrics & Reports → Threshold Crossing Events (TCEs) → Corrected Light Curves

Artificial Transits and Eclipses

Corrected Light Curves

Diagnostic Metrics & Reports

Keeping Up With the Data Avalanche
A Plague of Planet-like Signatures

Speed up the conveyer belt!

Welcome to the Extended Kepler Mission!
Random Forests for Autovetting

Leonid Kulik Expedition
A Search for Earth-size Planets

**Q1-Q12 Three Class Vetting**
Q1-Q12 Classifying the Knowns

A Search for Earth-size Planets
Auto-Triage Classifier Performance

Keplerian Classification Performance AUC = 0.9985
A Search for Earth-size Planets and (B)Ebs

Auto-Vetter Classifier Performance

PC vs. AFP Performance AUC = 0.9693
Classifying the Unknowns
The Road Ahead
A Search for Earth-size Planets

DV Report Summary
(for Q1-16 NExScI Export and Triage)

KIC: 5130369  Candidate: 1 of 2  Period: 19.979 d

Kp: 13.85  R*: 1.84 R\(_\odot\)  Teff: 9628.0 K  Logg: 4.23  Fe/H: -0.200

Sec Phase: 9.229 Days  Sec MES: 15.2

SNR: 109.9  \(\chi^2\)/DoF: 1.1  Depth: 1195.2 [12.0] ppm

DV Fit Results:
Period = 19.9761 [0.00005] d
Epoch = 137.1716 [0.0019] BJD
R\(_p/R_\odot\) = 0.0372 [0.0003]
\(a/R_\odot\) = 7.05 [0.17]
b = 0.93 [0.00]
T\(_q\) = 1339 K
R\(_p\) = 7.45 R\(_\odot\)
a = 0.1849 AU

DV Diagnostic Results:
Epoch–sig: 99.7% [0.0%]
ShortPeriod–sig: 0.1% [3.35%]
LongPeriod–sig: N/A
Bootstrap–ptf: N/A
Centroid–sig: 0.0%
Centroid–sc: 13.837 arcsec [126.34%]
OotOffset–rm: 5.804 arcsec [76.93%]
KicOffset–rm: 5.870 arcsec [82.06%]
OotOffset–bf: N/A
KicOffset–bf: N/A
KicOffset–at: N/A
DiffImageQuality–fjm: 1.00 [15/15 of 15]

Software Revision: svn+ssh://murzim/repo/social/repo/release/9.1@51443  Date Generated: 06–May–2013 17:23:08 Z
0.1% Amplitude of Median Flux Multiscale MAP

msMAP; Amplitude of Corrupted Signal at Injected Sine Wave Frequency

Normalized Amplitude Corruption to Injected Signal [relative to 100% amplitude]

Period [days]
Hardware Architecture

NAS/ Pleiades Supercomputer
1.09 Pflop/s
120,000 cores
191 of TB of RAM
6.6 PB of storage
84 hosts, 712 CPUs, 3.7 TB of RAM,
148 TB of raw disk storage

Run Q1-Q16 through TPS/DV; Auto-Vet Results; Prep Senior Review
Uncle Kepler wants you

To enlist in the η Army
Summary

- *Kepler* has initiated an explosion of exoplanet research, effectively tripling the number of known exoplanets.
- There are an astonishing number of multiple planet systems and these are remarkably coplanar – like the solar system.
- *Kepler* asteroseismology has led to major breakthroughs: (1) for dwarfs many precision applications and ensemble comparisons enabled, (2) the finding of, and outline of how to interpret g-, or mixed-modes in red giants.
- *Kepler* has pushed technology on all fronts.
- There is still much to glean from the data we already have: over one year of data has yet to be searched.
- The theme of the extended extended mission will be sensitivity and characterizing the completeness and reliability of the catalog.
- *Kepler’s* legacy will last for decades.
Raise a Cheer for Kepler