Review of Kepler Science & Prospects for the Future

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Exoplanet Exploration Program Analysis Group
in association with the 44th AAS DPS Meeting
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Outline

• Review of *Kepler* Exoplanet Results
• Future *Kepler* Exoplanet Science
• Needs to Extract *Kepler* Science
• Lessons Learned
NASA’s Kepler Mission

- Photometry of >190,000 stars
- Looking for Earth-like planets in transit
- 50μmag in 6 hours; 30 minute cadence
- All data public as of Oct 28, 2012
Sizes of Planet Candidates
As of February 27, 2012

- 1,118 - Neptune-size (2 - 6 \( R_\oplus \))
- 676 - Super Earth-size (1.25 - 2 \( R_\oplus \))
- 246 - Earth-size (< 1.25 \( R_\oplus \))
- 210 - Jupiter-size, (6 - 15 \( R_\oplus \))
- 71 - Larger, (> 15 \( R_\oplus \))

Batalha et al. 2012
Possible False Positives

For expected rates see:
Borcuki et al. 2011b
Morton & Johnson 2011
Howard et al. 2011
Follow-Up Observation Program

- Imaging (Standard, AO, Speckle, HST)
  - Removes confusion due to crowding
- Spectroscopy
  - Low-Res removes some false positives (e.g., binaries)
  - High-Res can measure mass of some planets
  - Upper limit to RV for small planets
- Transit Observations
  - Test for triples
- Combining FOP & Kepler data
  - Light curves
  - Centroid motion
  - Occultations
  - Transit Timing
Highlights from 2 Years Ago
Kepler-9 b-d  Kepler-10b  Kepler-11 b-g
The Kepler Orrery

credit: D. Fabrycky

$\text{t[BJD]} = 2454965$
Systems w/ Multiple Transiting Planets

Transit durations are greatly exaggerated

Brightness

Time (days)

Image credit: NASA Ames/Kepler
Hot Jupiters are Lonely

- 63 Hot Jupiters
- No other transiting planets
- No TTV signals
- Consistent with eccentricity excitation followed by tidal circularization

(Steffen et al. 2012 PNAS; but see Szabo et al. arxiv)
Kepler’s Near Resonant Systems

(a) Histogram showing the distribution of near resonant systems with different periods.

(b) Scatter plot showing the relationship between the ratio of outer to inner periods and the planet radius in units of Earth radius.

(c) Scatter plot showing another perspective of the same relationship.

Fabrycky et al. 2012
Kepler’s Multiple Planet Systems

Holman+ 2011; Batalha+ 2010; Torres+ 2010; Lissauer+ 2011; Cochran+ 2011; Ford+ 2012; Steffen+ 2012ab; Fabrycky+ 2012; Fressin+ 2012; Muirhead+ 2012; Nesvorny+ 2012; Xie 2012; Orosz+ 2012
Non-Transiting Planets

- Kepler-19c
- Kepler-46c
- Probably dozens more in TTV catalogs
- Important for disentangling distributions for inclination & multiplicity

Ballard et al. 2011
Nesvory et al. 2012
Ford et al. 2012
Systems of Tightly-packed Inner Planets (STIPs)
TTVs Characterize Planet Masses for Rapidly Interacting Systems

Kepler-36b&c: Chaotic due to 29:34 and 6:7 MMRs!

Exoplanet Mass-Radius Relation

Weiss et al. (2012)
Super-Earths or Mini-Neptunes?
Circumbinary Planets

$M_p = 0.333 \pm 0.016 M_{\text{Jup}}$

Doyle et al. 2011
Transiting Circumbinary Planets

Kepler-34
Kepler-16
Kepler-47
Kepler-35
Kepler-38

Doyle et al. 2011
Winn et al. 2011
Welsh et al. 2012
Orosz et al. 2012ab
Transiting Planets in the HZ

Kepler-47 System
- Kepler-47 c
- Kepler-47 b

Kepler-22 System
- Kepler-22b

Solar System
- Mercury
- Venus
- Earth
- Mars

Habitable Zone

Image Credits: NASA

Orosz et al. 2012

Borucki et al. 2012
Future Kepler Science

NASA Senior Review recommended extending *Kepler* data collection from 3.5 years to 7.5 years
Purpose of Extended *Kepler* Mission

- Extend the Exoplanet Survey
  - Produce vetted catalogs of planet candidates
  - Including a sample of Earth-size candidates in/near HZ

- Enable the determination of $\eta_{\text{Earth}}$, the frequency of rocky planets in the habitable zone

- Support a limited Follow-up Program
  - Focus on planets with $R_p < 2.5 \, R_{\text{Earth}}$
  - Improve planet radii (by improving stellar parameters)
  - Improve catalog reliability (e.g., high-resolution imaging)

- Build, maintain & support a legacy archive
- Support community observations & archival analysis
- Continue a robust EPO Program
Science in the Extended Mission

• Primary focus of extended mission: Measure $\eta_{\text{Earth}}$, the frequency of rocky planets in the HZ

• Kepler data will enable much more great science:
  Exoplanets
  – Larger Planets
  – Short-period small planets
  – Mass-Radius Relation
  – RV Follow-up observations
  – Transit Timing Variations
  – Planetary Architectures
  – Circumbinary Planets
  – Correlations w/ Stellar properties

  Astrophysics
  – Eclipsing Binaries
  – Astroseismology
  – Variable Stars
  – Stellar activity cycles
  – Your idea here
Small Transiting Planets

Mars  KOI-961.03  KOI-961.02  KOI-961.01  Kepler-20e  Earth  Kepler-20f

NASA

Fressin+ 2012; Gautier+ 2012; Muirhead+ 2012
Future Prospects for TTVs

TTVs can confirm planets around:
• Faint stars
• Stars w/o RVs

Expect to confirm & characterize many more planets via TTVs

Since typical TTV timescales ~ years, extending time baseline TTVs offers:
• Masses for short-period planets
• Confirmation of closely spaced systems in HZ (w/ sensitivity increasing as ~t^{5/2})

KOI 500

Observations (short-term) Nominal Model (long-term)

Ford et al. 2011
Future Prospects

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Ford et al. 2012; Xie 2012; Ragozzine et al. in prep
Future Prospects for Measuring Masses via TTVs

1 Earth-mass, 3:2 MMR, Kp=13

2 Earth-mass, 3:2 MMR, Kp=13
Kepler-30: Coplanarity via Spot Crossings

Sanchis-Ojeda+ 2012
Small Planets don’t need Metal-Rich Stars

Buchave et al. 2011
What do we need to extract the best science from *Kepler*?

- More Kepler Data *(on the way)*,
- More High-Value Planetary Systems *(optimistic)*,
- More Time/Brain Power *(i.e., $$$)*,
- More Follow-Up Observations *(start planning now)*
More *Kepler* Data

- Mission will continue observing stars:
  - With planet candidates &
  - Best targets for finding Earth-size planets in HZ
- Starting to consider whether some targets will be dropped during extended mission
- Increasing targets available to Guest Observer Program
  - 7,000 Long Cadence Targets
  - 96 Short Cadence Targets
  - Cycle 5 due Jan 18, 2013 (see [http://keplerscience.arc.nasa.gov](http://keplerscience.arc.nasa.gov))
Improve Analysis of *Kepler* Data

- **Good news:** The *Kepler* pipeline keeps improving!
- **Challenge:** Specific science goals often benefit from specialized algorithms, e.g.
  - Photometry of saturated/faint/crowded target stars
  - Searching for circumbinary planets
  - Searching for planets with large TTVs
  - Measuring transit times of small planets
- **Needs:**
  - Funding for algorithm development & data analysis (e.g., ADAP)
  - Collaborate with Statisticians & Computer Scientists, e.g., “Modern Statistical and Computational for Analysis of Kepler Data” at SAMSI, June 10-28, 2013
  - Share tools via working groups and/or keplerscience.arc.nasa.gov
More Time & Brain Power

• NASA Funding Mechanisms
  – Origins of Solar Systems
  – Astrophysical Data Analysis Program (ADAP)
  – Participating Scientist Program (PSP)
  – Guest Observer Program
  – Others (e.g., Sagan fellowship programs)

• Work Efficiently: Join or take a leadership role in a working group
  – Benefit from experience of others
  – Coordinate research plans
  – Facilitate collaborations
  – Excellent opportunities for students/postdocs
Increasing Community Involvement

• Light curves will go public available as soon as processed via MAST (http://archive.stsci.edu/kepler/)

• More data products will become available via NASA Exoplanet Archive (http://exoplanetarchive.ipac.caltech.edu)
  – Transit search results, Transit diagnostics, Planet candidate catalogs

• Facilitating coordination & data sharing via Kepler Community Follow-Up Observing Program website (http://cfop.ipac.caltech.edu)

• Facilitating working groups (Contact: Natalie Batalha natalie.m.batalha@nasa.gov), including:
  – Star Properties
  – Transit Timing & Multi-body Systems
  – Eclipsing Binaries
  – Planet Populations?
Increasing Community Involvement

• Funding Opportunities
  – Origins of Solar Systems
  – Astrophysical Data Analysis Program (ADAP)
  – Participating Scientist Program (PSP)
  – Guest Observer Program

• Increasing targets for Guest Observer Program
  – 7,000 Long Cadence Targets
  – 96 Short Cadence Targets
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• Presence at DPS & other meetings
  – Science Talks & Posters (Mon & Tues, plenary & Tahoe room)
  – Joint Kepler & NExSci Booth
More Follow-Up Observations

- So many planet candidates, so little telescope time
  - Spectroscopy for stellar characterization
  - Low & High-precision RVs
  - High-resolution imaging
  - Complimentary transit observations
- Should observe stars w/o transiting planets to understand how planet host stars compare to full Kepler target list
- Encouraging community to use CFOP website:
  - Find data already available for targets you’re studying
  - Share your data (or at least advertise it)
  - Coordinate your observations with others
  - Solicit observations of favorite object from the community
- Need community to “buy-in” to sharing data
SDSS 2.5-meter telescope
at the Apache Point Observatory, NM
Image Credit: Sloan Digital Sky Survey

- High-S/N, high-resolution (R~22,500) spectroscopic survey
  H-band (1.5-1.7 micron)
- 100,000 stars in disk, bulge, halo
- ~10,000 targets in Kepler field, incl.
  ~2,000 dwarfs & subgiants V<11
- Chemical abundances to 0.1 dex precision
  - Molecular bands (OH, CN, CO)
  - α-elements (O,Mg, Si, S, Ca, Ti)
  - Iron-peak (Cr, V, Mn, Fe, Co, Ni)
  - “Odd-Z” (Na, K, Al)
  - possibly even neutron capture
APOGEE for Follow-Up of Kepler Planet Candidates

- RV precision of ~100m/s can recognize most false positives

- For 100m/s precision, APOGEE is ~2x as efficient as other facilities

- Frees Keck, HARPS-N, SOPHIE, HET to focus on high-precision for best planet candidates

- SDSS Field of View well matched with Kepler modules (95% of planet candidates using 1 APOGEE field/Kepler module)

- Also measures 15 abundances & binarity for stars, both with and without transiting planets
Steps to Measuring $\eta_{\text{Earth}}$

- Identify small planet candidates in/near HZ
  - Observe more transits, improve data analysis algorithms
  - Understand pipeline completeness
- Characterize star properties (hosts & non-hosts)
  - Coordinated spectroscopic observing campaigns
- Confirm planets (or at least validate them)
- Establish that planets orbit target star & maximum dilution
  - Spectroscopy, high-contrast imaging, additional transit photometry
  - Detailed analysis of Kepler & FOP data
- Characterize planet masses & densities
  - For most cases will need to infer based on mass-radius relationship
- Characterize mass-radius relationship at small periods
  - RV observations (favorable stars, short-period planets)
  - Transit Timing Variations (favorable architectures)
- Understand selection effects/observational biases
Testing Planet Formation Theory

Orbital eccentricities, inclinations & multiplicity are three key probes of planet formation:

- **Eccentricity distribution** (+ stellar densities) → Transit duration distribution
- **Inclination distribution** + Frequency of multiple planet systems (+ Period distribution) → Frequency of multiply transiting systems
- Frequency of multiple planet systems + **Eccentricity Distribution** (+ Period distribution) → Distribution of TTV signatures

One complex inverse problem!

(observables, desired distributions, both)
Lessons Learned

Teamwork is Key!
Plan for Surprises
Lessons Learned

• Measuring $\eta_{\text{Earth}}$ is a marathon, not a sprint
  – Too complex for a single analysis
  – Don’t try to do everything yourself
  – Report results in a way that can be combined with other observations/analyses

• Robust science requires
  – Understanding details of Kepler & follow-up data
  – Being on the lookout for rare objects

• Even a single planet confirmation has too many parts for one person to do it all.
  – Collaborate (hopefully via a working group)
  – People focus on papers that are likely to finish soon
  – Organize big projects into small papers
Lessons Learned

• Coordinate observations/analysis to avoid duplication & allocate resources wisely
• Lots of new possibilities thanks to Kepler’s exquisite photometry & clever people
• Grad students or postdocs can pioneer a new sub-field of exoplanet science
• Plan for surprises & new ideas
• Learn to work probabilistically
  – Non-transiting planets
  – Some false positives (false positive rate is not 1 number)
  – Degenerate parameters