First Results from BOKS: Searching for extra-solar planets in the *Kepler* Field

John Feldmeier
Youngstown State University

The BOKS TEAM

PIs: John Feldmeier (YSU), Steve Howell (NOAO/WIYN)

Co-Is: Mandy Proctor (LPL), Kaspar von Braun (MSC), Mark Everett (PSI), Paul Harding (CWRU), Chris Mihos (CWRU), Craig Rudick (CWRU), Charles Knox (CWRU), William Sherry (NSO), Ting Hui-Lee (NOAO), David Ciardi (MSC), Gerard van Belle (MSC), Zachary Brown (YSU), Rebecca Kutsko (YSU)
We are living in the era of extra-solar planet detection

As of 9/19/07 – there are:
- 239 extra-solar planets detected via radial velocity
- 24 planets detected via transits
- 4 planets detected via microlensing
- 4 planets detected via direct imaging
- 5 planets detected via timing

(data via exoplanets.eu)

Transit Surveys – A method of extra-solar planet detection first discussed by Struve (1952)

Like most planet detections thus far, the transit method is most sensitive to Jupiter-sized planets in short orbits around their parent stars. These “Hot Jupiters” are most easily detected.

HD 209458b – Brown et al. (2001) $\sigma = 0.12$ mmag
What are the advantages of transit surveys?

- Relative size, not mass is the physical driver
- Less sensitive to properties of stellar photospheres than radial velocity surveys
- **Transits can determine inclination**, leading to evaluating the planet mass directly. The **radius** of the planet can also be determined, leading to the **surface gravity** of the planet.
- Transit surveys can be undertaken with small telescopes – in fact bright stars are **favored**, for radial velocity follow-up observations.

How many transits should we be able to observe?

From von Braun et al. (2005):

- assume Hot Jupiter (HJ) frequency around isolated stars of ~0.7% (Marcy et al. 2004) with a semi-major axis, \( a \sim 0.05 \) AU
- assume 10-20% of these have the favorable alignments (related to \( R* / a \)) needed for a transit
- assume we can only detect planets around single stars, and assume a binary fraction of 50%

About 1 star in 3000 should have an observable transit
Gilliland et al. (2000) – 8.3 days of transit observations of 47 Tuc – 30 transiting planets were predicted – none were found
“…Transit searches set out for a picnic in the field but it now starts looking more like a long trek in the jungle…”

- Frederic Pont, discussing the relatively few transit detections up until 2005

---

**Why so few transit detections?**

- Given the large number of astronomers, survey strategies, and telescopes, it is unlikely that any one cause is the culprit.

- Furthermore, transiting planets are being detected – just at much lower efficiency rate than originally predicted.

- So, what is going on?
Short telescope runs are not productive – especially if one requires two transits for a confirmed detection, unless you are lucky.

“Red Noise” – systematic errors in relative photometry (Pont, Zucker, & Queloz 2006)

Noise here is “white” – data points are perfectly uncorrelated with each other.

Noise here is “red” – data points are strongly correlated with each other on moderate timescales.

Noise here is “pink” – data points are weakly correlated with each other on timescales similar to that of a planetary transit.
Image crowding

Gillon and Magain (2007) find this to be a small effect (10%), but also say: “...Nevertheless, one has to keep in mind that part of the red noise could be due to the crowding...”

Lack of planet detections - astrophysics

- Transit detection depends on the relative size of the star/planet – many stars will be upper-main sequence stars or giants, and will not have observable transits (Gould & Morgan 2003; Brown 2003)

- Radial velocity surveys are biased towards metal-rich stars, implying that the HJ frequency may be overestimated (Gould et al. 2006)

- Low metallicity and a dense local environment are likely to suppress planet formation (Davies & Sigurdsson 2001; Weldrake et al. 2005; Soker & Hershenhorn 2007)
Goals of BOKS

1. Gather variability data on stars in the *Kepler* field for later comparison to space-based light curves – a critical verification.
2. Search for “Hot Jupiter” extra-solar planets in the Kepler field.
3. Determine stellar variability properties for stars in the BOKS field, taking advantage of the data gathered for *Kepler* (KIC; g,r,i,z,2MASS, Mgb)

Strengths of BOKS:
(or why do you think you can do as well or better than other surveys?)

- Longer duration
- Better control of systematic errors
- Telescope in a “sweet” spot of transit surveys
- *Kepler* follow-up
Duration is critical – reduce aliasing and reduce the effects of red noise

Smith et al. (2006) – number of extra-solar planets that should be discovered with SuperWASP, considering the effects of red noise

Burrell Schmidt Upgrade: good for surface photometry (and transit searches)

The Newtonian secondary was moved 14” up the tube. This allows for a unvignetted field of 5 degrees. This allows for better flats (intrinsically flat to 1%), and more stable flats. To accommodate this, in March 2002, we cut a hole in the 66-year old telescope (very carefully)
Scattered light is a factor of ~20 than most telescopes, and flat-fielding is good to one part in 1000.

Comparison of PSF between Burrell and KPNO 2.1m
(same star, same analysis techniques)

BOKS is a moderate-field (1.65 x 0.825 degrees), moderate aperture (61cm) transit survey, deeper than the wide-field, small aperture (~10 cm) transit surveys, but much shallower than large aperture transit surveys. BOKS has a larger angular area than most of these surveys (1.36 sq deg, versus ~0.3 sq. deg), but with slightly larger pixel scale (1.45" versus ~0.4").
BOKS “Field 0” results  
(Feldmeier et al. 2007)

Close to **worst case possible** – 5 nights of observations, all non-photometric, with no field-flattener in the CCD window, bad seeing, significant wind shake

We still got to milli-mag relative photometry on the brightest stars, and recovered many of the variables discovered by Everett et al. (2002)

---

Observing:

- Observations began Sep 1, 2006 and continued for the next **38 nights**.
- We obtained scientifically useful data on 27 nights, including one stretch of 22 days straight
- Cadence = once every 4 minutes (180s exposures + readout time)
- A total of 1896 r’ images, and 20 V-band images were taken, along with 358 bias images and 95 twilight flat images
- We also had coordinated AAVSO observations of brighter stars in the field (Henden et al. 2007)
1.36 square degrees, 67,194 stellar sources between r=14 and 20

One small region of the BOKS data (200 x 200 pixels)
Data Reduction and Analysis

- To better control false-positives due to data reduction, and to test for systematic errors, the BOKS data is being reduced and searched for planets independently.

- Group A: Proctor, von Braun, Everett
- Group B: Feldmeier, Brown, Everett
Differential Photometry (Everett & Howell 2001)

1. Create a local region or “zone”
2. Perform aperture photometry on all stars in a zone
3. Designate stars as constant photometrically – “ensemble” stars
4. Iterate the ensemble until only true “constant” stars remain
5. Use the ensemble stars to correct the effects of extinction and seeing effects
Searching for variables

- The light curves are then searched numerically, using a large number of tests (chi-squared test, Lomb-Scargle periodgrams, matched-filter, etc.)
- We dub a star “variable” if the reduced chi-square versus a constant flux model is greater than 3, and we dub an object an interesting planet candidate if the matched filter comes back with a false positive rate of less than $10^{-16}$
Variable stars – of all different types…

Variable stars – of all different types…
Some “near misses” – eclipsing binaries

So, have you found planets, or not…?

• Maybe…
• We have a number of candidates that pass all of our statistical test, show no signs of secondary eclipses, and cannot yet be ruled out as contaminants
• On August 18-19, the best of these candidates were observed with the WIYN telescope to look for large-scale radial velocity variations. If such variations are found, the object is not a transiting planet, but a more common eclipsing binary
Further Work

- Continue the tests on the candidates we have to date, with the goal of verification by the end of this year
- Compare carefully the results from both groups, with an attention on red noise
- Perform Monte-Carlo simulations of our detection efficiency (over all stars, transit parameters)
- BOKS II?