Recently: Life, its origin, early Earth, habitability.
Today: Exoplanets

Reading: As posted.
Homework #4 posted, due Thursday 3rd May.
Final paper: draft or outline+refs, due Thursday 26th April.
Detecting Extrasolar Planets

Basic tools for detecting exoplanets:

• Image them directly (seeing is believing).

• Other direct radiation (natural IR, radio emission).

• Measure gravitational perturbations:
  - Doppler shift of spectral lines from the host star.
    The planet orbits the center of mass of its star + planetary system.
    So does the star, but with smaller and slower orbit.
  - Wobble of star on the plane of the sky (astrometry).
  - Time of arrival of pulses from a pulsar with orbiting planet.
  - Gravitational microlensing of background stars by foreground stars
    and planets (bending of light).

• Photometry of host star with orbiting planets: measure change
  in light when planet transits the star or star eclipses the planet.

• Perhaps: measure signals from exo-civilizations.
DETECTING EXOPLANETS
WITH RADIAL VELOCITY MEASUREMENTS
Doppler Shift due to Stellar Wobble
If ETs were measuring the radial velocity of the Sun ...

Solar velocity and position along the [1,0,0] direction

All planets in the solar system contribute to the Sun’s motion.

This is the distance of the Sun from the solar system’s barycenter in units of the Sun’s radius.
A Jupiter-mass companion to a solar-type star

Michel Mayor & Didier Queloz

Geneva Observatory, 51 Chemin des Maillettes, CH-1290 Sauverny, Switzerland

The presence of a Jupiter-mass companion to the star 51 Pegasi is inferred from observations of periodic variations in the star's radial velocity. The companion lies only about eight million kilometres from the star, which would be well inside the orbit of Mercury in our Solar System. This object might be a gas-giant planet that has migrated to this location through orbital evolution, or from the radiative stripping of a brown dwarf.

For more than ten years, several groups have been examining the radial velocities of dozens of stars, in an attempt to identify orbital motions induced by the presence of heavy planetary companions. The precision of spectrographs optimized for Doppler studies and currently in use is limited to about 15 m s\(^{-1}\). As the reflex motion of the Sun due to Jupiter is 13 m s\(^{-1}\), all current searches are limited to the detection of objects with at least the mass of Jupiter (\(M_J\)). So far, all precise Doppler surveys have failed to detect any jovian planets or brown dwarfs.

Since April 1994 we have monitored the radial velocity of 142 G and K dwarf stars with a precision of 13 m s\(^{-1}\). The stars in our survey are selected for their apparent constant radial velocity (at lower precision) from a larger sample of stars monitored for 15 years\(^6\). After 18 months of measurements, a small number of stars show significant velocity variations. Although most candidates require additional measurements, we report here the discovery of a companion with a minimum mass of 0.5 \(M_J\), orbiting at 0.05 AU around the solar-type star 51 Peg. Constraints originating from the observed rotational velocity of 51 Peg and from its low chromospheric emission give an upper limit of 2 \(M_J\) for
51 Pegasi observations

AFOE observations of 51Peg

K: 57.496 +/- 2.871 m/s
P: 4.231 +/- 0.001 d
To: -1.936 +/- 0.070 (HJD = 50000.0)

RMS(residuals): 8.15 m/s 38 pts fitted
reduced x^2: 0.85
Planets around Neutron Stars

• Method: pulsar timing.
• Pulsars are effectively clocks that can be used to measure their motions and the influence of gravity (from companions and from gravitational waves).
• Measure the arrival time of a set of pulses at an observatory over a span of years.
• If the pulsar has orbital companion(s), the arrival times will be affected by the reflex motion of the pulsar.
  • Same reflex effect as for radial velocities except time of arrival measures path length, not velocity.
  • Arrival times are also affected by the observatory’s motion around the geocenter and the barycenter of the solar system.
• Best TOAs have a precision of about 30 ns! But are more typically ~1 μs to 1 ms.
• The best timed pulsars are those that are spinning > 200 times per second (>12,000 RPM).
Pulsars as Clocks

The spinning NS = the clock
~ 10 km radius

Single pulses

Crab pulsar
shot pulses (ns)

Relativistic emission regions
magnetosphere ~ 100 – 10^4 km

Hankins & Eilek 2007
Topocentric arrival times → solar system barycenter (SSBC)

Pulse phase model is evaluated at the SSBC

\[ \hat{n} \text{ is a function of time if pulsar moves and if it is at finite distance.} \]
\[ \text{proper motion: milliseconds} \]
\[ \text{parallax: } \mu s \text{ or less} \]

\[ t_{\text{barycenter}} = t_{\text{observatory}} - c^{-1} \hat{n} \cdot \vec{r} \]

Roemer delay 500 s

Solar system barycenter is near the sun’s photosphere
The spin period of the pulsar is 6.22 ms.

160 rotations of the neutron star per second.

Variations in period are due to the Doppler effect from the NS’s reflect motion from two planets.

Detailed studies show that the planets interact gravitationally and thus affect the arrival times.

FIG. 3 Period variations of PSR1257 +12. Each period measurement is based on observations made on at least two consecutive days. The solid line denotes changes in period predicted by a two-planet model of the 1257 +12 system.

Wolszczan & Frail (1992)
Giant planets around solar-type stars

Earth-mass planets around a neutron star
# Pulsar Planets

## Confirmed planets

<table>
<thead>
<tr>
<th>Pulsar</th>
<th>Planetary object</th>
<th>Mass</th>
<th>Semimajor axis (AU)</th>
<th>Orbital period</th>
<th>Discovered</th>
</tr>
</thead>
<tbody>
<tr>
<td>PSR B1620-26</td>
<td>PSR B1620-26 b</td>
<td>2.5 $M_J$</td>
<td>23</td>
<td>100 years</td>
<td>2003</td>
</tr>
<tr>
<td>PSR B1257+12</td>
<td>PSR B1257+12 A</td>
<td>0.020 $M_\oplus$</td>
<td>0.19</td>
<td>25.262±0.003 days</td>
<td>1994</td>
</tr>
<tr>
<td>PSR B1257+12</td>
<td>PSR B1257+12 B</td>
<td>4.3 $M_\oplus$</td>
<td>0.36</td>
<td>66.5419±0.0001 days</td>
<td>1992</td>
</tr>
<tr>
<td>PSR B1257+12</td>
<td>PSR B1257+12 C</td>
<td>3.90 $M_\oplus$</td>
<td>0.46</td>
<td>98.2114±0.0002 days</td>
<td>1992</td>
</tr>
</tbody>
</table>

## Candidate planets

<table>
<thead>
<tr>
<th>Pulsar</th>
<th>Planetary object</th>
<th>Mass</th>
<th>Semimajor axis (AU)</th>
<th>Orbital period</th>
<th>Announced</th>
</tr>
</thead>
<tbody>
<tr>
<td>PSR J1719-1438</td>
<td>PSR J1719-1438 b</td>
<td>~1 $M_J$</td>
<td>0.004</td>
<td>2.176951032 hours</td>
<td>25 August 2011</td>
</tr>
</tbody>
</table>

Planet claimed to be essentially pure carbon and in diamond form
DETECTING EXOPLANETS WITH PLANETARY TRANSITS

The Kepler mission
Planetary Transits

Exoplanet Orbit Orientations

These planets transit

These planets do not transit
Transit of Venus
June 5, 2012
Lasted 6h 40m

Transits come in pairs, separated by 8 years. Next: 2117 and 2125.
Probability of seeing a transit

Line of sight

LOS needs to be in this range to see transit

Angle \sim R_*/a

Prob \sim 0.5\% for Earth at 1 AU

2 R_* 

2 R_p
Probability of a star showing a transit from a single planet

Line of sight

2 $R_*$

Line of sight

No transits

$2 R_p$

$2 \alpha$

$\alpha \sim (R_* + r_p) / a_p \sim R_* / a_p$

Solid angle in which transits are seen: $\Omega \sim 2\pi \times 2\alpha$
(View as a cone revolved around $2\pi$ radians of the orbit)

The probability of the line of sight being in the transit ‘cone’ is $p \sim \Omega / 4\pi \sim \alpha$

Earth:
$P \sim (R_{\odot} / 1 \text{ AU})$
$\sim 0.005 \Rightarrow 0.5\%$
Probability that a transit will be observed if the geometry is right

- Transits: depth and breadth.
- Probability of seeing a transit depends on:
  1. How long one looks compared to the transit duration, as well as
  2. The transit depth compared to photometric sensitivity.
- Also: repeatability by observing through multiple orbital passes.
- Favors short orbit periods if a mission has finite lifetime.
The duration of the transit is given by:

\[ T_{\text{trans}} \approx \frac{\text{angular size of star}}{\text{angular rate of line of sight}} \]

\[ \approx \frac{R_* / d}{v_p / d} = \frac{R_*}{v_p} \]

Earth and Sun:

\[ T_{\text{trans}} \approx 2 \times 7 \times 10^5 \text{ km} / 30 \text{ km/s} \]

\[ \approx 46,000 \text{ s} \]

\[ \approx 13 \text{ hr in every year.} \]
## Transit Properties of Solar System Objects

<table>
<thead>
<tr>
<th>Planet</th>
<th>Orbital Period P (years)</th>
<th>Semi-Major Axis a (A.U.)</th>
<th>Transit Duration (hours)</th>
<th>Transit Depth (%)</th>
<th>Geometric Probability (%)</th>
<th>Inclination Invariant Plane (deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mercury</td>
<td>0.241</td>
<td>0.39</td>
<td>8.1</td>
<td>0.0012</td>
<td>1.19</td>
<td>6.33</td>
</tr>
<tr>
<td>Venus</td>
<td>0.615</td>
<td>0.72</td>
<td>11.0</td>
<td>0.0076</td>
<td>0.65</td>
<td>2.16</td>
</tr>
<tr>
<td>Earth</td>
<td>1.000</td>
<td>1.00</td>
<td>13.0</td>
<td>0.0084</td>
<td>0.47</td>
<td>1.65</td>
</tr>
<tr>
<td>Mars</td>
<td>1.880</td>
<td>1.52</td>
<td>16.0</td>
<td>0.0024</td>
<td>0.31</td>
<td>1.71</td>
</tr>
<tr>
<td>Jupiter</td>
<td>11.86</td>
<td>5.20</td>
<td>29.6</td>
<td>1.01</td>
<td>0.089</td>
<td>0.39</td>
</tr>
<tr>
<td>Saturn</td>
<td>29.5</td>
<td>9.5</td>
<td>40.1</td>
<td>0.75</td>
<td>0.049</td>
<td>0.87</td>
</tr>
<tr>
<td>Uranus</td>
<td>84.0</td>
<td>19.2</td>
<td>57.0</td>
<td>0.135</td>
<td>0.024</td>
<td>1.09</td>
</tr>
<tr>
<td>Neptune</td>
<td>164.8</td>
<td>30.1</td>
<td>71.3</td>
<td>0.127</td>
<td>0.015</td>
<td>0.72</td>
</tr>
</tbody>
</table>

\[ P^2 M^* = a^3 \]
\[ M^* = \text{star mass (Sun} = 1) \]
\[ 13 \sqrt{a} \]
\[ \% = \left( \frac{d_p}{d^*} \right)^2 \]
\[ d^* = \text{dia. of star} \]
\[ \varphi \]
The Kepler Mission

Milky Way Galaxy

Kepler Search Space

Sagittarius Arm

Orion Spur

Perseus Arm

Portrait of the Milky Way © Jon Lomberg  www.jonlomberg.com
The Kepler Mission
http://kepler.nasa.gov/Mission/discoveries/

- 0.95 m telescope, 95 Megapixel camera.
- Earth-trailing heliocentric orbit.
- Continuously pointed at a single star field in Cygnus-Lyra region (except during downlink).
  - ~12 deg diameter field of view (115 deg²), equivalent to ~ 0.3% of the whole sky.
  - Monitored ~ 150k stars to an average distance ~ 1 kpc.
  - How representative?
- Primary mission lifetime of 4 years. (March 2009 – March 2013).
- Planet detection requires identification of three transits so longer period orbits can be detected as the mission extends.
  ➔ Candidate planets vs. confirmed planets.
The Kepler focal plane is approximately one foot square. It's composed of 25 individually mounted modules. The 4 corner modules are used for fine guiding and the other 21 modules are used for science observing. Note that the fine guidance modules in the corners of the focal plane are very much smaller CCDs than the science modules. On the left, a single science module with two CCDs and a single field flattening lens mounted onto an Invar carrier. On the right, a focal plane assembly with all 21 science modules and four fine-guidance sensors, one in each corner, installed. Under normal operations, each module and its electronics convert light into digital numbers. For the darkest parts of the image between stars, we expect these numbers to be very small (but not zero). Correspondingly, for the brightest stars in the image, much larger numbers are expected creating an image of each observed star and its background neighborhood.

Credit: NASA/Kepler mission
Iron melts: 3500°F, 2000°C
Gold melts: 3000°F, 1500°C
Molten lava: 2500°F, 1000°C
Lead melts: 2000°F, 500°C
Water boils: 212°F, 100°C
Water freezes: 32°F, 0°C
Mercury: 500°F, 273°C
Venus: 1500°F, 780°C
Earth: 2000°F, 1000°C
Kepler 4b: 1500°F, 780°C
Kepler 6b: 2000°F, 1000°C
Kepler 7b: 2500°F, 1200°C
Kepler 5b: 3000°F, 1500°C
Kepler 8b: 3500°F, 2000°C
Neptune: 32°F, 273°C
Jupiter: 212°F, 100°C
Locations of Kepler Planet Candidates

- Earth-size
- Super-Earth size
  1.25 - 2.0 Earth-size
- Neptune-size
  2.0 - 6.0 Earth-size
- Giant-planet size
  6.0 - 22 Earth-size
Kepler-11 is a G dwarf star about 2,000 light-years from Earth. Variations in the brightness of Kepler-11 have been monitored with an effective duty cycle of 91%. Shown are Kepler photometric data, raw from the spacecraft with each quarter normalized to its median (a) and after detrending with a polynomial filter (b). The six sets of periodic transits are indicated with dots of differing colours.
The Kepler Orrery
credit: D. Fabrycky
\[ t[\text{BJD}] = 2454965 \]
Planet around a double-star
Observed circumbinary planets
(orbits normalized to the instability region)
Circumbinary planets: Eclipses + Transits

Kepler 34(AB)b, Kepler 35(AB)b

Primary and secondary transits

Kepler 35b: low-density gas-giant planet on an orbit closely aligned with that of its parent stars.

(b-e) Red points denote primary transits, green points denote a secondary transit. Note the differences in transit duration.
(f) Close-up views of the primary eclipses and secondary eclipses.
The timing residuals from a constant period for KOI-1081.01 (Upper) and Kepler-23b (Lower).

The intervals between transits for a given planet may not be equally spaced if the planet interacts with other planets.

TTV = transit time variation
Earth-like planet found in distant sun's habitable zone

Harwood, Dec 2011

• "Today I have the privilege of announcing the discovery of Kepler's first planet in the habitable zone of a sun-like star, Kepler-22b," Bill Borucki, the Kepler principal investigator at NASA's Ames Research Center, told reporters. "It's 2.4 times the size of the Earth, it's in an orbital period (or year) of 290 days, a little bit shorter than the Earth's, it's a little bit closer to its star than Earth is to the sun, 15 percent closer.

• "But the star is a little bit dimmer, it's a little bit lower in temperature, a little bit smaller. That means that planet, Kepler-22b, has a rather similar temperature to that of the Earth...If the greenhouse warming were similar on this planet, its surface temperature would be something like 72 Fahrenheit, a very pleasant temperature here on Earth."

• It is not yet known whether Kepler-22b is predominantly rocky, liquid, or gaseous in composition, but the finding confirms for the first time the long-held expectation that Earth-size planets do, in fact, orbit other suns in the habitable zones of their host stars.

• That, in turn, greatly improves the odds for the existence of life, as it is commonly defined, beyond Earth's solar system.”

No Place Like Home … Yet (2014).

<table>
<thead>
<tr>
<th>Planet</th>
<th>Near Earth size?</th>
<th>Sunlike star?</th>
<th>In habitable zone?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kepler-20e</td>
<td>✔️ (0.8 Earth radius)</td>
<td>✔️</td>
<td>No (too hot)</td>
</tr>
<tr>
<td>Kepler-22b</td>
<td>No (2.4 Earth radii)</td>
<td>✔️</td>
<td>✔️</td>
</tr>
<tr>
<td>Kepler-186f</td>
<td>✔️ (1.1 Earth radii)</td>
<td>No (red dwarf)</td>
<td>✔️</td>
</tr>
<tr>
<td>Not yet found</td>
<td>&quot;Earth 2.0&quot;</td>
<td>Yes</td>
<td>Yes</td>
</tr>
</tbody>
</table>

... only a matter of time.
Kepler 452:
G2 star, 6 Gyr old,
1400 light yr away.

Kepler 452b:
385 day orbit.
60% larger than Earth.
In habitable zone.
Potentially Habitable Exoplanets

Ranked by Distance from Earth (light years)

Artistic representations. Earth, Mars, Jupiter, and Neptune for scale. Distance is between brackets. Planet candidates indicated with asterisks.

CREDIT: PHL @ UPR Arecibo (phl.upr.edu) April 2, 2015
Planet Hunters: the first two planet candidates identified by the public using the Kepler public archive data*

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13Planet Hunter

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ABSTRACT
Planet Hunters is a new citizen science project designed to engage the public in an exoplanet search using NASA Kepler public release data. In the first month after launch, users identified two new planet candidates which survived our checks for false positives. The follow-up effort included analysis of Keck HIRES spectra of the host stars, analysis of pixel centroid offsets in the Kepler data and adaptive optics imaging at Keck using NIRC2. Spectral synthesis modelling coupled with stellar evolutionary models yields a stellar density distribution, which is used to model the transit orbit. The orbital periods of the planet candidates are 9.8844 ± 0.0087 d (KIC 10905746) and 49.7696 ± 0.000 39 d (KIC 6185331), and the modelled planet radii are 2.65 and 8.05 R⊕. The involvement of citizen scientists as part of Planet Hunters is therefore shown to be a valuable and reliable tool in exoplanet detection.

Key words: stars: individual: KIC 10905746 – stars: individual: KIC 6185331 – planetary systems.

1 INTRODUCTION
The past decade has witnessed an explosion in the number of known planets beyond our Solar system. From the ground, planet searches using techniques that include Doppler observations, transit photometry, microlensing and direct imaging have identified more than 500 exoplanets (Schneider 2011; Wright et al. 2011). These observations have provided a wealth of information, including constraints on dynamical interactions in multiplanet systems, non-coplanar orbits of hot Jupiters and atmospheric properties of transiting gas giant

*This publication has been made possible by the participation of more than 40000 volunteers in the Planet Hunters project. Their contributions are individually acknowledged at http://www.planethunters.org/authors.
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‡NSF Fellow.
§Einstein Fellow.
Figure 6. The time series data for KIC 8242434 (top) include photometry for Q1–Q7, provided by the Kepler team. Planet Hunters flagged a single transit in the Q1 data and two additional transits were found in the Q2 data. The bottom panel shows the data folded at the prospective orbital period, 44.9634 d. Unfortunately, the pixel centroid check shows that this is likely a background EB system.

computer algorithms. However, we expected that citizen scientists might discover unexpected patterns in the data or unusual types of transits, which could then be used as feedback to further improve the Kepler transit search algorithms. Citizen scientists identified some unusual objects in the Galaxy Zoo programme, and we expected that some unpredictable and unanticipated discoveries and correlations might also emerge from Planet Hunters. Automated algorithms and citizen science are complementary techniques and both are important to make the best use of the Kepler data.

An initial assessment was made of the performance and efficiency of the Planet Hunters participants by counting the number of transit events detected among the 306 candidates announced for Q1 data by Borucki et al. (2010a). We found that Planet Hunters flagged about two-thirds of those transit events. The deeper transits were found more often than the shallow transits.

In the first month after the launch of the Planet Hunters website, more than 40 stars were flagged as possible planet transits that were not known false positives (grazing binaries or blended BGEBs) or published Kepler candidates. Because we felt it was important to preserve the integrity of the Kepler planet candidates, we contacted members of the Kepler team who provided important data verification for our top 10 candidates. More than half of these were found to be false positives.

We present the first two planet candidates, discovered by Planet Hunters using Q1 data: KIC 10905746 and KIC 6315331, with orbital periods that range from 9.88 to 49.96 d and radii ranging from 2.32 to 8.0 R$_\oplus$. We have carried out a Monte Carlo analysis for a self-consistent set of stellar parameters and analysed the pixel centroid’s to check for astrometric motion. We also obtained AO observations to eliminate BGEBs with separations wider than $\sim$0.5 arcsec and $\Delta M_V < 5$ in the infrared $K$-band data. However, the pixel centroid analysis and AO observations cannot exclude eclipsing binaries that are closer than 0.5 arcsec or those with wider separations that are more than about 5 mag fainter than the tentative planet host stars. Because such systems could still produce the observed light curves, these two candidates are not confirmed planets.

We estimate false positive probabilities (FPP) for the two candidates presented here following the framework presented in Morton & Johnson (2011), which relies on Galactic structure and stellar population synthesis models. We consider two possible false
Over 40% of Sun-like stars are bound in binary or multistar systems. Stellar remnants in edge-on binary systems can gravitationally magnify their companions, as predicted 40 years ago. By using data from the Kepler spacecraft, we report the detection of such a “self-lensing” system, in which a 5-hour pulse of 0.1% amplitude occurs every orbital period. The white dwarf stellar remnant and its Sun-like companion orbit one another every 88.18 days, a long period for a white dwarf-eclipsing binary. By modeling the pulse as gravitational magnification (microlensing) along with Kepler’s laws and stellar models, we constrain the mass of the white dwarf to be \( \sim 63\% \) of the mass of our Sun. Further study of this system, and any others discovered like it, will help to constrain the physics of white dwarfs and binary star evolution.
Fig. 3. Illustration of lensing magnification. (Center) The false-color disk of a G dwarf (using an actual image of the Sun from NASA/SDO HMI), in which the green line shows the trajectory of the white dwarf, with the dotted portion indicating where it passes behind the G dwarf. (Left and right) Close-ups of areas boxed in center show the lensed image of the G dwarf at two different times during the microlensing pulse; the white dwarf is the blue sphere. The white dashed line shows the Einstein ring of the white dwarf. The model that we fit to the data does not contain spots; however, the spots and granulation make the lensing distortion more apparent.
Fig. 2. Model fit to the data. Detrended and folded Kepler photometry of KOI-3278 presented as black points (all pulses and occultations have been aligned), overplotted with the best-fit model (gray line) for the microlensing pulse (left) and occultation (right). Red error bars show the mean of the folded data over a 45-min time scale. Bottom graphs show the residuals of the data with the best-fit model subtracted. BJD, barycentric Julian date.

Fig. 1. Detrended flux versus time for all 16 microlensing pulses and 16 occultations in KOI-3278. Each row depicts the relative fluxes in 29.3-min Kepler cadences around an event. The rows are separated by the orbital period, $P = 88.18$ days. White represents brighter flux and black dimmer, whereas gray represents missing data or outliers that have been removed. ppm, parts per million.
Table 1: Parameters of the KOI-3278 binary star system. More information can be found in the supplementary text. The median and 68.3% bounds are given for each parameter. $g_1$, surface gravity in cm/s$^2$. $L_{WD}$, luminosity of the white dwarf. $e$, eccentricity. $\omega$, argument of periastron. $a$, semi-major axis. $i$, inclination. $F_2/F_1$, flux ratio between the white dwarf and G dwarf in the Kepler band. $D$, distance. $\sigma_{sys}$, systematic errors in the multiband photometry.

<table>
<thead>
<tr>
<th></th>
<th>$G$ dwarf:</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M_1 (M_\odot)$</td>
<td>$1.042_{-0.058}^{+0.028}$</td>
</tr>
<tr>
<td>$R_1 (R_\odot)$</td>
<td>$0.964_{-0.054}^{+0.034}$</td>
</tr>
<tr>
<td>$[Fe/H]_1$</td>
<td>$0.39_{-0.22}^{+0.22}$</td>
</tr>
<tr>
<td>$t_1$ (Gyr)</td>
<td>$1.62_{-0.55}^{+0.93}$</td>
</tr>
<tr>
<td>$T_{eff,1}$ (K)</td>
<td>$5568_{-38}^{+40}$</td>
</tr>
<tr>
<td>$\log(g_1)$</td>
<td>$4.485_{-0.026}^{+0.020}$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>$White$ dwarf:</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M_{2,init} (M_\odot)$</td>
<td>$2.40_{-0.53}^{+0.70}$</td>
</tr>
<tr>
<td>$M_2 (M_\odot)$</td>
<td>$0.634_{-0.055}^{+0.047}$</td>
</tr>
<tr>
<td>$T_{eff,2}$ (K)</td>
<td>$9960_{-760}^{+700}$</td>
</tr>
<tr>
<td>$R_2 (R_\odot)$</td>
<td>$0.01166_{-0.00056}^{+0.00099}$</td>
</tr>
<tr>
<td>$R_E (R_\odot)$</td>
<td>$0.02305_{-0.00107}^{+0.00093}$</td>
</tr>
<tr>
<td>$t_2$ (Gyr)</td>
<td>$0.96_{-0.53}^{+0.90}$</td>
</tr>
<tr>
<td>$t_{cool}$ (Gyr)</td>
<td>$0.663_{-0.057}^{+0.065}$</td>
</tr>
<tr>
<td>$L_{WD} (L_\odot)$</td>
<td>$0.00120_{-0.00024}^{+0.00024}$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>$Binary$ system:</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P$ (d)</td>
<td>$88.18052_{-0.00029}^{+0.00025}$</td>
</tr>
<tr>
<td>$t_0$ (-2,455,000 BJD)</td>
<td>$85.4190_{-0.00023}^{+0.00023}$</td>
</tr>
<tr>
<td>$e \cos \omega$</td>
<td>$0.014713_{-0.000061}^{+0.000047}$</td>
</tr>
<tr>
<td>$e \sin \omega$</td>
<td>$0.000_{-0.054}^{+0.049}$</td>
</tr>
<tr>
<td>$a$ (AU)</td>
<td>$0.4605_{-0.0103}^{+0.0064}$</td>
</tr>
<tr>
<td>$a/R_1$</td>
<td>$102.8_{-2.4}^{+3.7}$</td>
</tr>
<tr>
<td>$b_0$</td>
<td>$0.706_{-0.025}^{+0.020}$</td>
</tr>
<tr>
<td>$i$ (deg)</td>
<td>$89.607_{-0.020}^{+0.026}$</td>
</tr>
<tr>
<td>$F_2/F_1$</td>
<td>$0.001127_{-0.000039}^{+0.000039}$</td>
</tr>
<tr>
<td>$D$ (pc)</td>
<td>$808_{-49}^{+36}$</td>
</tr>
<tr>
<td>$\sigma_{sys}$</td>
<td>$0.0246_{-0.0078}^{+0.0127}$</td>
</tr>
<tr>
<td>$K_1$ (km/s)</td>
<td>$21.53_{-0.98}^{+0.96}$</td>
</tr>
<tr>
<td>$\pi$ (milli-arc sec)</td>
<td>$1.237_{-0.053}^{+0.079}$</td>
</tr>
<tr>
<td>$\alpha_1$ (milli-arc sec)</td>
<td>$0.2169_{-0.0072}^{+0.0076}$</td>
</tr>
<tr>
<td>$A_V$ (mags)</td>
<td>$0.206_{-0.016}^{+0.017}$</td>
</tr>
</tbody>
</table>
The End of the Story: Problems with Kepler

- Reaction wheels – used for orienting the spacecraft
  - 3 needed, 1 spare
  - 1 failed in 2012, a 2nd in 2013 May

- Moving parts in space are costly and do not last!

A reaction wheel (RW) is a type of flywheel used primarily by spacecraft for attitude control without using fuel for rockets or other reaction devices. They are particularly useful when the spacecraft must be rotated by very small amounts, such as keeping a telescope pointed at a star. They may also reduce the mass fraction needed for fuel. This is accomplished by equipping the spacecraft with an electric motor attached to a flywheel which, when its rotation speed is changed, causes the spacecraft to begin to counter-rotate proportionately through conservation of angular momentum. Reaction wheels can only rotate a spacecraft around its center of mass (see torque); they are not capable of moving the spacecraft from one place to another (see translational force). Reaction wheels work around a nominal zero rotation speed. However, external torques on the spacecraft may require a gradual buildup of reaction wheel rotation speed to maintain the spacecraft in a fixed orientation. (Wikipedia)
Using NASA's planet-hunting Kepler spacecraft, astronomers have discovered 2,326 candidate planets orbiting other stars in a search for Earth-size worlds that began in 2009. Kepler monitors a rich star field for planetary transits, which cause a slight dimming of starlight when a planet crosses the face of its star. In "Kepler's Planet Candidates," the systems are ordered by star diameter. The star's color represents its temperature as shown in the lower scale, and the letters (A, F, G, K, M) are how astronomers classify star types. The simulated stellar disks and the planet silhouettes are shown at the same scale, with saturated star colors. Leaked planetary systems have multiple planets. For reference, Jupiter is shown transiting the Sun. Higher resolutions of this graphic are available at http://kepler.nasa.gov/images/graphics
1235 confirmed planets as of March 2011
Kepler Highlights

1. Many planets, tremendous diversity: if nature could do it, it seems to actually have done so. Lonely hot Jupiters are easiest to understand if they migrated to their current locations.
   - No companion planets.
   - Difficult to form close to the star (tidal effects).
   - They probably wiped out all other planets as they migrated.

2. The implied number of Earth like planets is large: about 1 in 5 solar-type stars is estimated to have an ‘Earth’.