A1199
Are We Alone?
The Search for Life in the Universe
Summer 2019

Instructor: Shami Chatterjee


Presentations and Final Paper – please work on them.

Now: Exoplanets
Gravitational Microlensing

The Earth, a close star, and a brighter, more distant star, happen to come into alignment for a few weeks or months. Gravity from the closer star acts as a lens and magnifies the distant star over the course of the transit.

The change in brightness can be plotted on a graph.

If there is a planet orbiting the closer star, and it happens to align with the Einstein ring, its mass will enhance the lens effect and increase the magnification for a short time.

The planet causes a small blip on the graph.
Direct imaging

- Use coronograph to directly image planets – dream for Terrestrial Planet Finder, JWST.
- Can be done from the ground too. Difficult…

Kuchner & Traub (2002):

Planets around HR8799 with coronograph at Palomar Hale telescope.
Measured motion of Fomalhaut b

Dust ring is eccentric and is sculpted by Fomalhaut b.

→ Fomalhaut b orbit is eccentric too.

Current position? Planet was probably deflected by a larger planet closer in to the star, not yet seen.
Beta Pictoris b

Imaging in spectral lines of CO and H$_2$O reveals planet.

(No detection of CH$_4$ or NH$_3$.)
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

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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\(^1\).\(^5\). 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\(^6\).\(^9\). 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
e: 0.075 +/- 0.053
P: 4.231 +/- 0.001 d
α: 132.54 +/- 7.98
T: -1.936 +/- 0.070 (HJD - 50000.0)

RMS[residuals]: 8.15 m/s 38 pts fitted
reduced χ²: 0.85

Orbital Phase
Triple system in Gliese 581.

**Fig. 4.** Temporal display of the 3-planet Keplerian model of Gl 581, on time intervals with dense observational sampling.
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.
Discovering Extrasolar Planets I

• **Pulsar timing:**
  – Measuring the change in path length from pulsar to Earth caused by recoil of the neutron star from planetary motion.
    • Can measure position of neutron star to ~ one light microsecond or better.

• **Radial velocity measurements of starlight:**
  – Doppler recoil of star from planetary orbits.
  – “Radial” means motion along the line of sight.
    • Measurement accuracy ~10 m/s (not as good as pulsar timing).

• **Transits:** passing of planet across stellar disk.
  – < 1% dips in the star’s brightness.
  – Orbit needs to be nearly “edge on” unless planet is large and close to the star.
  – Secondary transit as planet passes behind star.
Discovering Extrasolar Planets II

• **Gravitational microlensing:**
  – Gravitational bending of light (focusing).
  – Predicted by Einstein in 1912.
  – Background star is lensed by foreground star + planet.

• **Direct detection:** imaging a planet’s light directly.
  – Difficult because of host star’s brightness (10^5 to 10^6 times brighter).
  – Planet’s light is reflected starlight.
Discovering Extrasolar Planets III

- **Astrometry**: measuring the wobble of a star’s position on the sky from recoil motion.

- **Planetary radiation**:
  - Analogous to the Jupiter-Io effect (non-thermal radiation from particles from Io in Jupiter’s magnetic field).

- **SETI**: search for transmissions from technological civilizations.
  - Low likelihood, tremendous payoff.
  - The ETs can tell us all about their planet (and presumably many others).
DETECTING EXOPLANETS WITH PLANETARY TRANSITS
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 $R_p$
The probability of a star showing a transit from a single planet depends on the line of sight (LOS) being in the transit 'cone'.

Line of sight needs to be in this range to see transit:

\[ 2 R_* \leq a_p \leq 2 R_p \]

Small angle approximation:
\[ \alpha \sim \frac{R_* + r_p}{a_p} \sim \frac{R_*}{a_p} \]

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:
\[ p \sim \frac{\Omega}{4\pi} \sim \alpha \]

Earth:
\[ P \sim \frac{R_\odot}{1 \text{ AU}} \]
\[ \sim 0.005 \Rightarrow 0.5\% \]
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.
Transit Duration

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:
\[ T_{\text{trans}} \sim 2 \times 7 \times 10^5 \text{ km} / 30 \text{ km/s} \]
\[ \sim 46,000 \text{ s} \]
\[ \sim 13 \text{ hr in every year.} \]
## 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
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*
Transit Light Curves

<table>
<thead>
<tr>
<th></th>
<th>Flux</th>
<th>Phase (hours)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kepler 4b</td>
<td>1.000</td>
<td>-6 to 6</td>
</tr>
<tr>
<td></td>
<td>0.995</td>
<td>-6 to 6</td>
</tr>
<tr>
<td></td>
<td>0.990</td>
<td>-6 to 6</td>
</tr>
<tr>
<td>Kepler 5b</td>
<td></td>
<td>-6 to 6</td>
</tr>
<tr>
<td></td>
<td></td>
<td>-6 to 6</td>
</tr>
<tr>
<td></td>
<td></td>
<td>-6 to 6</td>
</tr>
<tr>
<td>Kepler 6b</td>
<td></td>
<td>-6 to 6</td>
</tr>
<tr>
<td></td>
<td></td>
<td>-6 to 6</td>
</tr>
<tr>
<td></td>
<td></td>
<td>-6 to 6</td>
</tr>
<tr>
<td>Kepler 7b</td>
<td></td>
<td>-6 to 6</td>
</tr>
<tr>
<td></td>
<td></td>
<td>-6 to 6</td>
</tr>
<tr>
<td></td>
<td></td>
<td>-6 to 6</td>
</tr>
<tr>
<td>Kepler 8b</td>
<td></td>
<td>-6 to 6</td>
</tr>
<tr>
<td></td>
<td></td>
<td>-6 to 6</td>
</tr>
<tr>
<td></td>
<td></td>
<td>-6 to 6</td>
</tr>
</tbody>
</table>

Orbital Period (days)

- Kepler 4b: 3.2 days
- Kepler 5b: 3.5 days
- Kepler 6b: 3.2 days
- Kepler 7b: 4.9 days
- Kepler 8b: 3.5 days
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)

- Kepler 38-b
- PH-1
- Kepler 47-b
- Kepler 16-b
- Kepler 34-b

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."

<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 452b

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)

- [12 ly] tau Cet e*
- [13 ly] Kapteyn b
- [16 ly] GJ 832 c
- [17 ly] GJ 682 c*
- [24 ly] GJ 667 c
- [24 ly] GJ 667 c f*
- [24 ly] GJ 667 c e*
- [38 ly] GJ 180 c*
- [38 ly] GJ 180 b*
- [41 ly] GJ 422 b*
- [42 ly] HD 40307 g
- [49 ly] GJ 163 c
- [59 ly] GJ 3293 c*
- [111 ly] EPIC 201912552 b
- [117 ly] EPIC 201367065 d
- [473 ly] Kepler-438 b
- [561 ly] Kepler-186 f
- [620 ly] Kepler-22 b
- [783 ly] KOI-4427 b*
- [851 ly] Kepler-440 b
- [1063 ly] Kepler-61 b
- [1115 ly] Kepler-442 b
- [1174 ly] Kepler-174 d
- [1200 ly] Kepler-62 f
- [1200 ly] Kepler-62 e
- [1566 ly] Kepler-298 d
- [1693 ly] Kepler-296 e
- [1693 ly] Kepler-296 f
- [1742 ly] Kepler-283 c
- [2941 ly] Kepler-443 b

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

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Planet Hunters: the first two planet candidates identified by the public using the Kepler public archive data

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13Planet Hunter

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 ± 0.00039 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
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⊕. 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 ~0.5 arcsec and ΔMv < 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 positive candidates, which provide a lower bound on the false positive rate.
The End of the Story: Problems with Kepler

- Reaction wheels – used for orienting the spacecraft
  - 3 needed, 1 spare
  - 1 failed in 2012, a 2\textsuperscript{nd} 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-like 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. Look carefully: some 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
ALL 786 KNOWN PLANETS TO SCALE

(JUNE 2012)

THIS IS OUR SOLAR SYSTEM.

THE REST OF THESE GREAT OTHER STARS AND WE'RE ONLY DISCOVERED RECENTLY. MOST OF THEM ARE HUGE BECAUSE THOSE ARE THE KIND WE LEARNED TO DETECT FIRST, BUT NOW WE'RE FINDING THAT SMALL ONES ARE ACTUALLY MORE COMMON. WE KNOW NOTHING ABOUT WHAT'S ON ANY OF THEM WITH BETTER TELESCOPES, THAT WOULD CHANGE.

THIS IS AN EXCITING TIME.
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’.
A home away from home

EXTRASOLAR HABITABILITY: EARTH-LIKE PLANETS?
Exoplanet Habitability

Sara Seager

The search for exoplanets includes the promise to eventually find and identify habitable worlds. The thousands of known exoplanets and planet candidates are extremely diverse in terms of their masses or sizes, orbits, and host star type. The diversity extends to new kinds of planets, which are very common yet have no solar system counterparts. Even with the requirement that a planet’s surface temperature must be compatible with liquid water (because all life on Earth requires liquid water), a new emerging view is that planets very different from Earth may have the right conditions for life. The broadened possibilities will increase the future chances of discovering an inhabited world.

Main point: the HZ (H₂O) for life may be much larger than typically estimated because the diversity of potential atmospheres (temperatures, pressures) may provide extreme greenhouse effects.
Known exoplanets as of March 2011: Exoplanets are found at a nearly continuous range of masses and semimajor axes. Many different techniques are successful at discovering exoplanets, as indicated by the different symbols. The solar system planets are denoted by the first one or two letters of their name. The horizontal line is the conventional upper limit to a planet mass, 13 Jupiter masses. The sloped, lower boundary to the collection of gray squares is due to a selection effect in the radial velocity technique. Small planets are beneath the threshold for the current state of almost all exoplanet detection techniques. Data are from http://exoplanet.eu/.
**Fig. 2. The habitable zone.** The light blue region depicts the "conventional" habitable zone for planets with N$_2$-CO$_2$-H$_2$O atmospheres (9, 10). The yellow region shows the habitable zone as extended inward for dry planets (36, 37), as dry as 1% relative humidity (37). The outer darker blue region shows the outer extension of the habitable zone for hydrogen-rich atmospheres (34) and can extend even out to free-floating planets with no host star (35). The solar system planets are shown with images. Known exoplanets are shown with symbols [here, planets with a mass or minimum mass less than 10 Earth masses or a radius less than 2.5 Earth radii taken from (66)].
Searching for Habitable Worlds

KEPLER-20e
DECEMBER 2011

KEPLER-22b
DECEMBER 2011

KEPLER-452b
JULY 2015

KEPLER-186f
APRIL 2014

ARTISTIC CONCEPT
KOI 4036
K-star with Habitable Zone Planet
Kepler 452b

Kepler 452:
G2 star, 6 Gyr old,
1400 light yr away.

Kepler 452b:
385 day orbit.
60% larger than Earth.
In habitable zone.
A Window Into Time

Energy Received by Planet vs. Age, Billions of Years

- Optimistic Habitable Zone
- Conservative Habitable Zone

Current Age of Earth: 4 Billion Years
Current Age of 452b: 6 Billion Years

Sun
Kepler-452
Kepler’s Small Habitable Zone Planets
As of July 2015

Planets enlarged 25x compared to stars

G Stars
- Kepler-452b (Earth)

K Stars
- Kepler-442b
- 155c
- 235e
- 62f
- 62e
- 283c
- 440b

M Stars
- Kepler-438b
- 186f
- 296e
- 296f
Twelve New Small Kepler Candidates in the Habitable Zone

Kepler-452b / KOI-7016.01

- NEW
- OLD
- CONFIRMED PLANETS

Surface Temperature of Star

Energy Received by Planet
New Kepler Planet Candidates
As of July 23, 2015

Total = 4,696
Twenty Years of Progress

KEPLER-452b
July 23, 2015

51 PEG b
Oct. 6, 1995

ARTISTIC CONCEPT

Credit: Fahad Sulehria