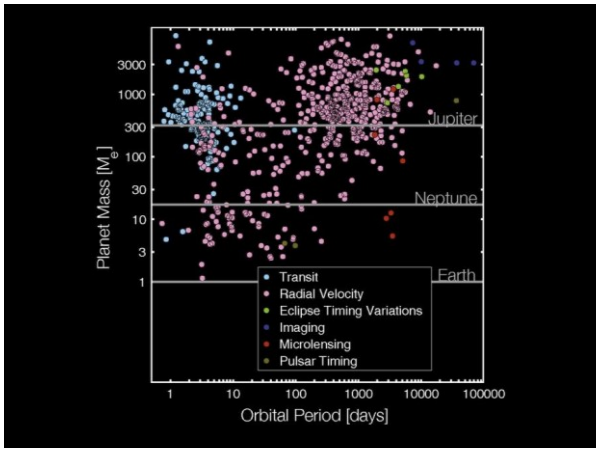
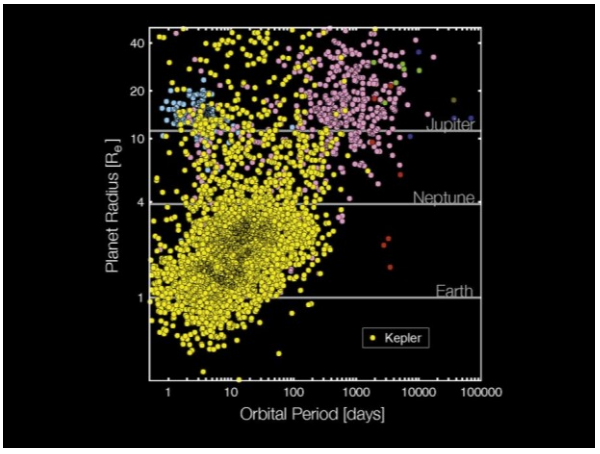
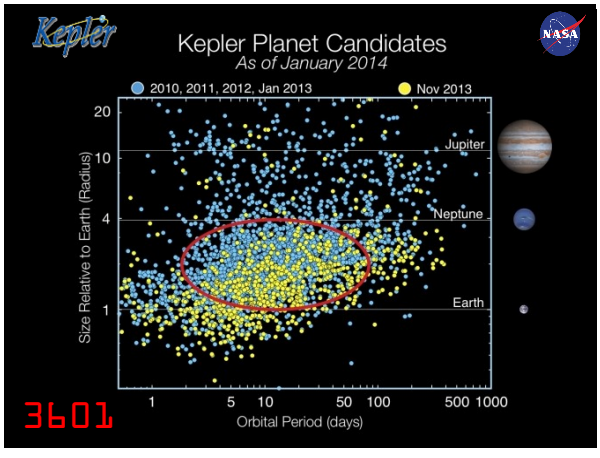
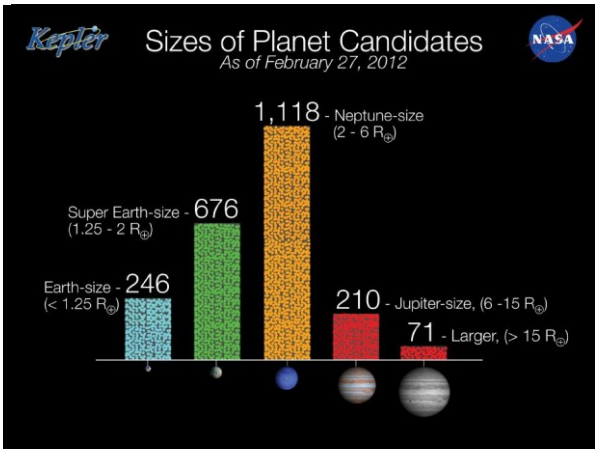
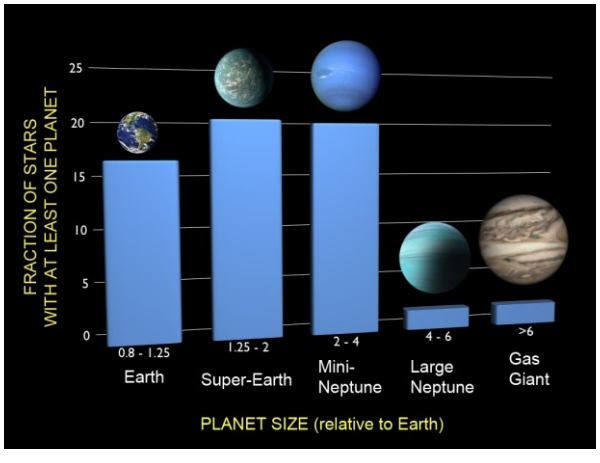
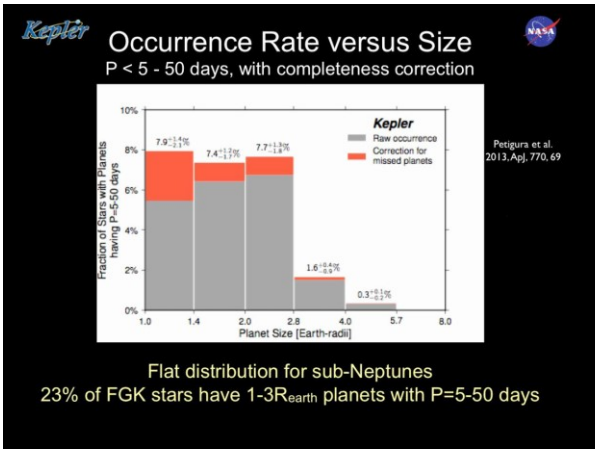

Planet Mass [$M_\oplus$]
3000
1000
300
100
30
10
3
1
Jupiter
Neptune
Earth
Transit
Radial Velocity
Eclipse Timing Variations
Imaging
Microlensing
Pulsar Timing
1
10
100
1000
10000
100000
Orbital Period [days]


Planet Radius [$R_\oplus$]
40
20
10
4
1
Jupiter
Neptune
Earth
Kepler
1
10
100
1000
10000
100000
Orbital Period [days]


Kepler
Kepler Planet Candidates
As of January 2014
2010, 2011, 2012, Jan 2013
Nov 2013
Size Relative to Earth (Radius)
20
10
4
1
Jupiter
Neptune
Earth
1
5
10
50
100
500
1000
Orbital Period (days)
3601

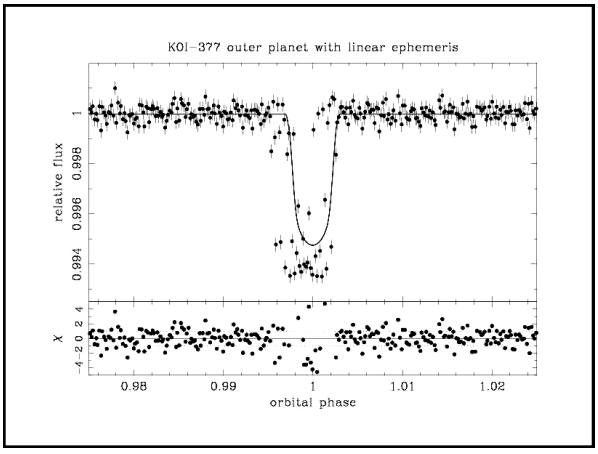

Kepler
Sizes of Planet Candidates
As of February 27, 2012
1,118 - Neptune-size (2 - 6 $R_\oplus$)
Super Earth-size - 676 (1.25 - 2 $R_\oplus$)
Earth-size - 246 (< 1.25 $R_\oplus$)
210 - Jupiter-size, (6 -15 $R_\oplus$)
71 - Larger, (> 15 $R_\oplus$)

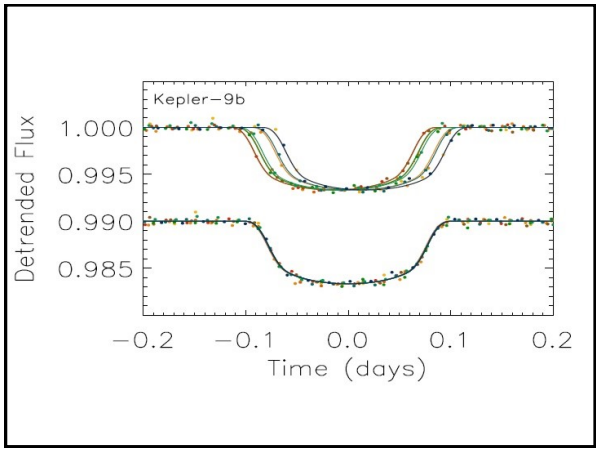

FRACTION OF STARS WITH AT LEAST ONE PLANET
25
20
15
10
5
0
0.8 - 1.25
Earth
1.25 - 2
Super-Earth
2 - 4
Mini-Neptune
4 - 6
Large Neptune
>6
Gas Giant
PLANET SIZE (relative to Earth)

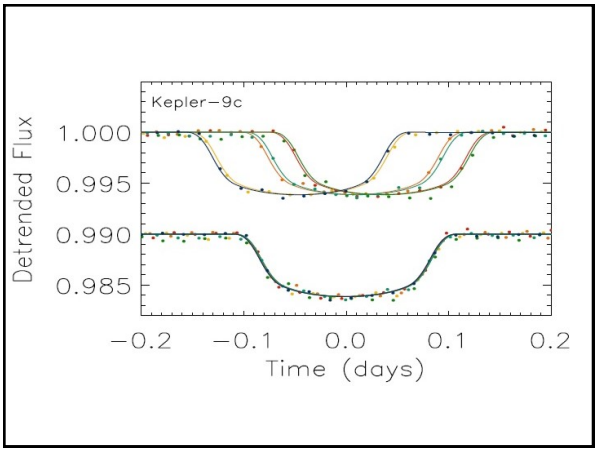

Kepler
Occurrence Rate versus Size
P < 5 - 50 days, with completeness correction
Fraction of Stars with Planets having P=5-50 days
10%
8%
6%
4%
2%
0%
Kepler
Raw occurrence
Correction for missed planets
1.0
1.4
2.0
2.8
4.0
5.7
8.0
Planet Size [Earth-radii]
Petigura et al. 2013, ApJ, 770, 69
Flat distribution for sub-Neptunes
23% of FGK stars have 1-3R_{earth} planets with P=5-50 days

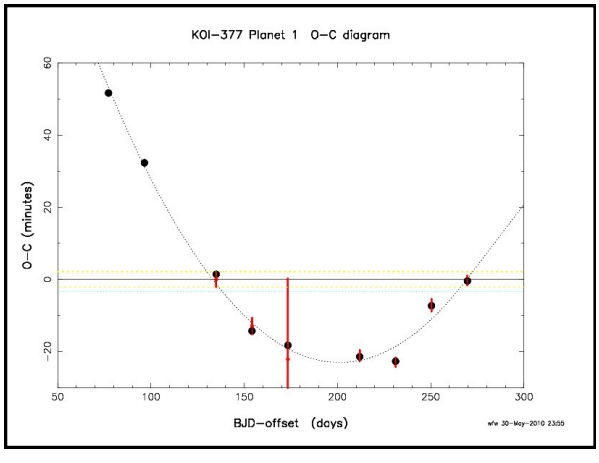

Science
AAAS

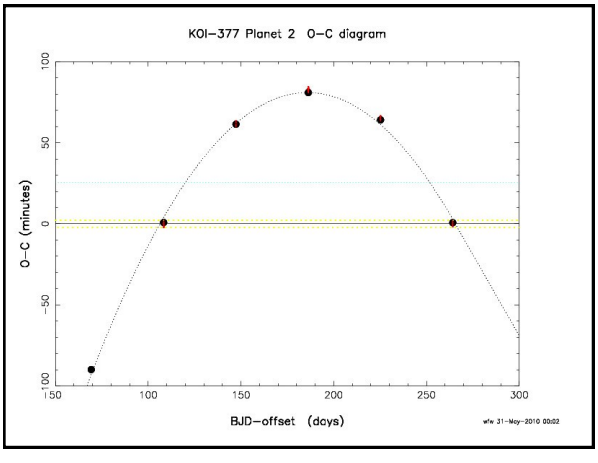
Kepler 9


KOI-377 outer planet with linear ephemeris
relative flux
0.994
0.996
0.998
1
χ
−4
−2
0
2
4
0.98
0.99
1
1.01
1.02
orbital phase


Kepler−9b
Detrended Flux
1.000
0.995
0.990
0.985
−0.2
−0.1
0.0
0.1
0.2
Time (days)


Kepler−9c
Detrended Flux
1.000
0.995
0.990
0.985
−0.2
−0.1
0.0
0.1
0.2
Time (days)


KOI−377 Planet 1 O−C diagram
O−C (minutes)
60
40
20
0
−20
50
100
150
200
250
300
BJD−offset (days)
w/e 30−May−2010 23:55


KOI−377 Planet 2 O−C diagram
O−C (minutes)
100
50
0
−50
−100
150
100
150
200
250
300
BJD−offset (days)
w/e 31−May−2010 00:02

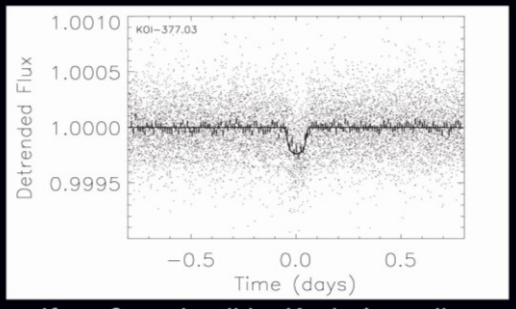
Kepler-9b&c: The First Multiple Transiting Planet System

slide courtesy of N. Batalha

Kepler-9

- First multiple-transiting planet system
- First planets confirmed by gravitational interaction as measured via transit timing variations
- Planets are in a 2:1 resonance
- Planet b is 20% more massive than planet c; both are less massive than Saturn
- Mutual inclination < 10°
- and more….

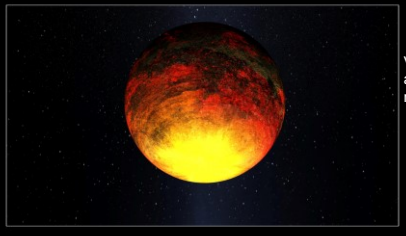
… and another?



If confirmed, will be Kepler's smallest planet at ~ 1.5 times radius of Earth.

slide courtesy of N. Batalha

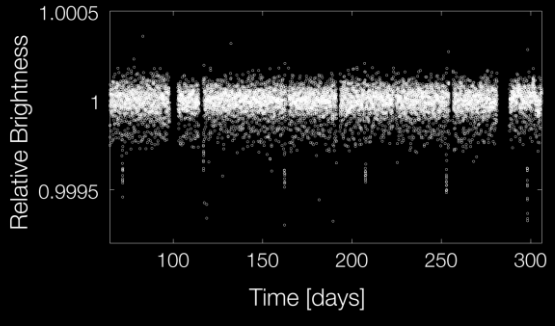
Kepler's First Rocky Planet: Kepler-10b



VERY MUCH an artist's rendition!

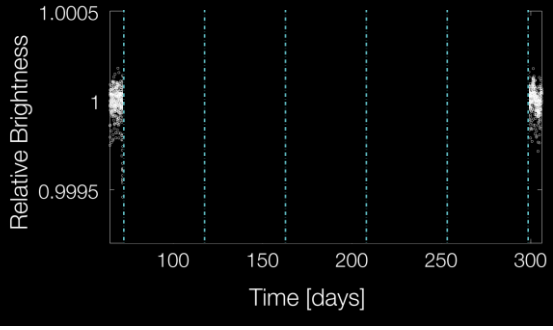
At the time of discovery, Kepler-10b was the smallest known exoplanet: only 42% larger than Earth – but way too hot!

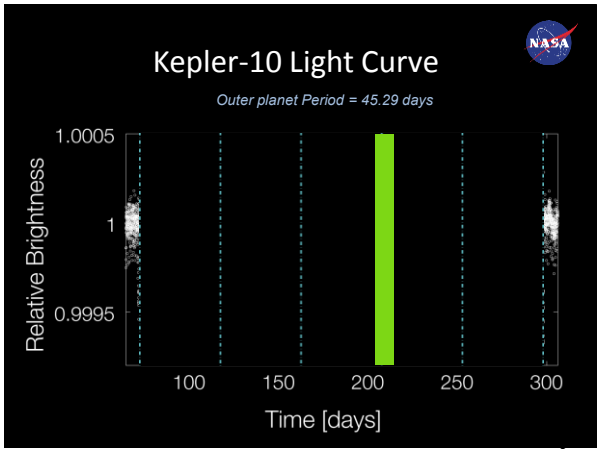
Kepler-10 Light Curve

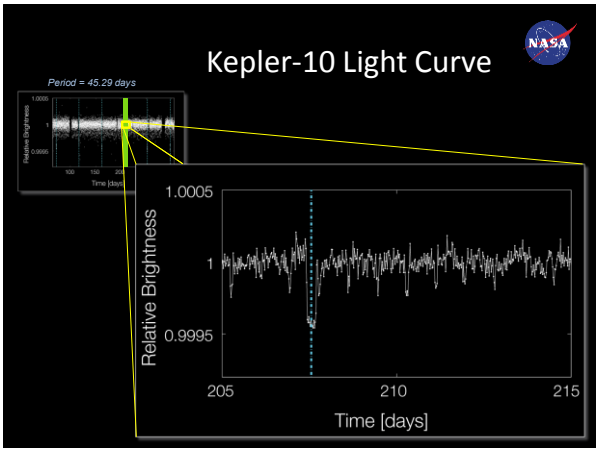


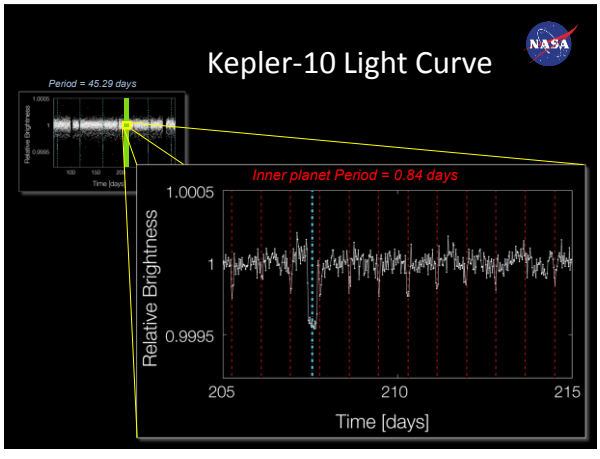
Kepler-10 Light Curve

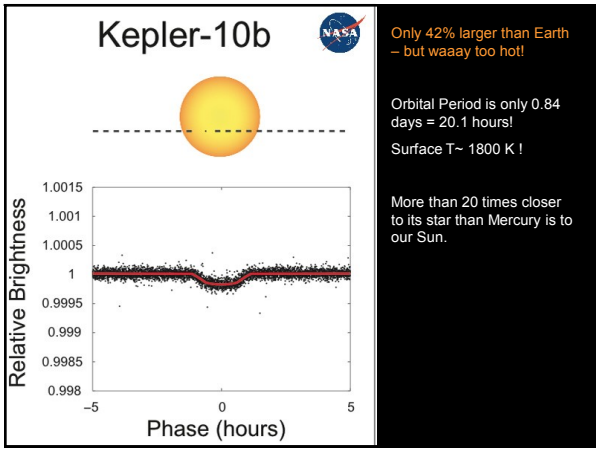
Outer planet Period = 45.29 days



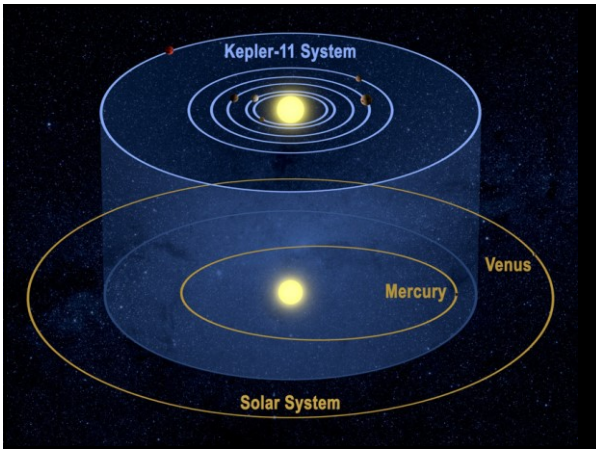

Kepler-10 Light Curve
Outer planet Period = 45.29 days
Relative Brightness
1.0005
1
0.9995
100
150
200
250
300
Time [days]

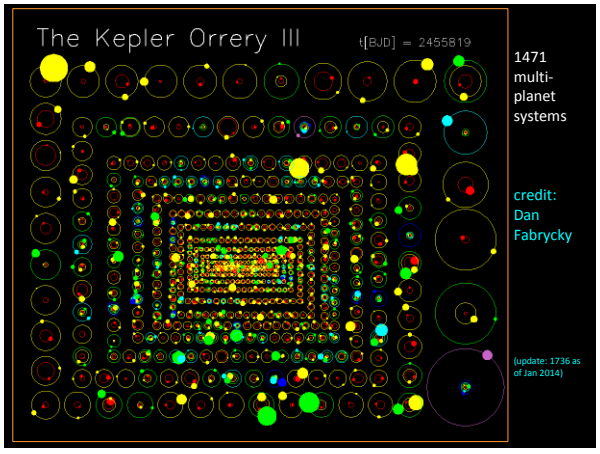

Kepler-10 Light Curve
Period = 45.29 days
Relative Brightness
1.0005
1
0.9995
205
210
215
Time [days]

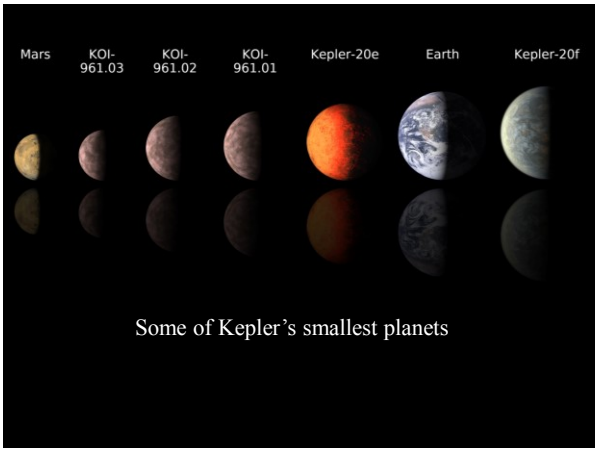

Kepler-10 Light Curve
Period = 45.29 days
Inner planet Period = 0.84 days
Relative Brightness
1.0005
1
0.9995
205
210
215
Time [days]


Kepler-10b
Relative Brightness
1.0015
1.001
1.0005
1
0.9995
0.999
0.9985
0.998
−5
0
5
Phase (hours)
Only 42% larger than Earth – but waaay too hot!
Orbital Period is only 0.84 days = 20.1 hours!
Surface T~ 1800 K !
More than 20 times closer to its star than Mercury is to our Sun.

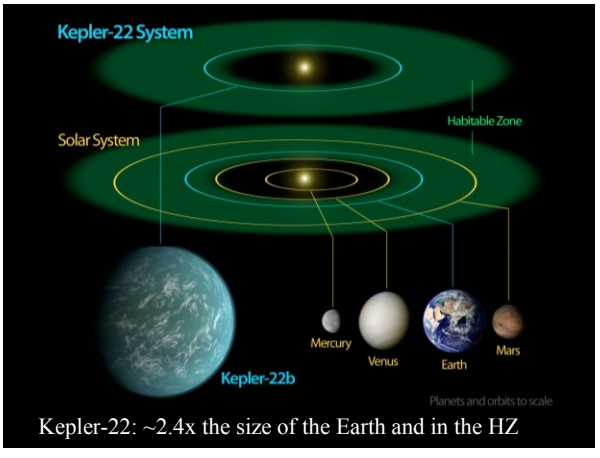

nature
THE INTERNATIONAL WEEKLY JOURNAL OF SCIENCE
SIX NEW WORLDS
NEAR-COPLANAR PLANETARY SYSTEM ORBITING SUN-LIKE STAR KEPLER-11 PAGE 53

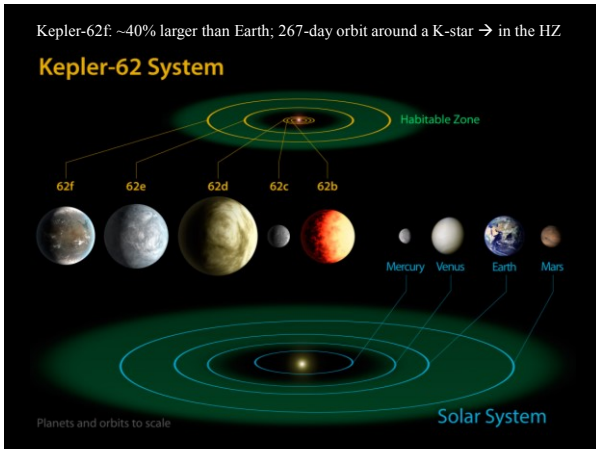

Kepler-11 System
Venus
Mercury
Solar System

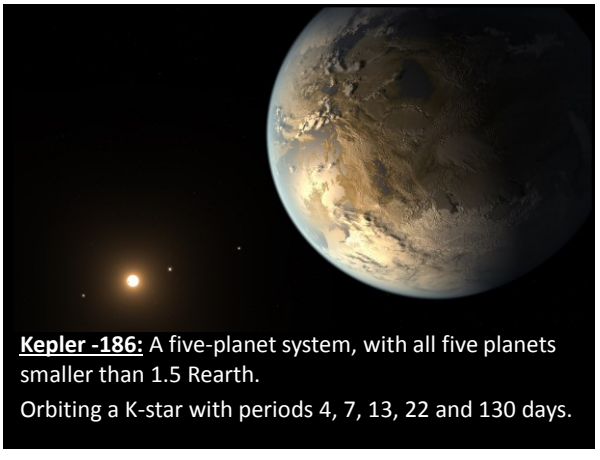

The Kepler Orrery III
t[BJD] = 2455819
1471 multi-planet systems
credit: Dan Fabrycky
(update: 1736 as of Jan 2014)

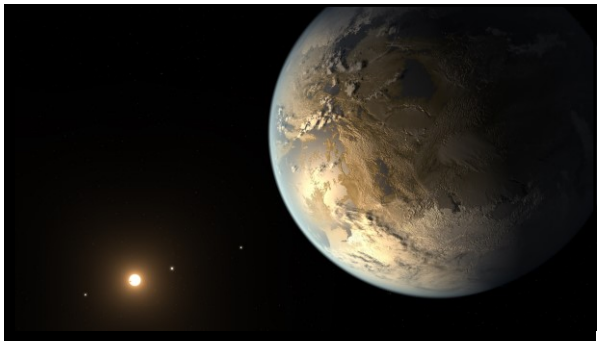

Mars
KOI-961.03
KOI-961.02
KOI-961.01
Kepler-20e
Earth
Kepler-20f
Some of Kepler's smallest planets


Moon
Kepler-37b
Mercury
Mars
Kepler-37c
Earth
Kepler-37b:
radius=0.30 R⊕ → the smallest known planet...so far.
P=13.4 days R_star=0.77 R_sun (Barclay et al. 2013)

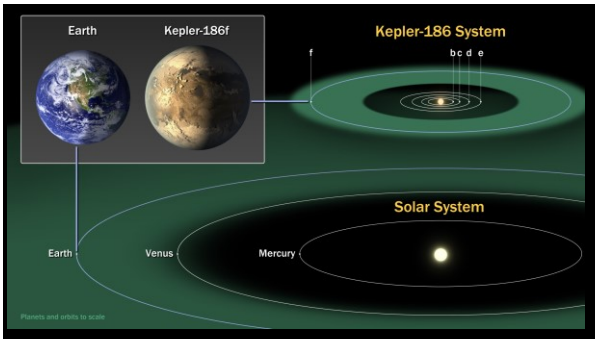

Kepler-22 System
Solar System
Habitable Zone
Mercury
Venus
Earth
Mars
Kepler-22b
Planets and orbits to scale
Kepler-22: ~2.4x the size of the Earth and in the HZ


Kepler-62f: ~40% larger than Earth; 267-day orbit around a K-star → in the HZ
Kepler-62 System
Habitable Zone
62f
62e
62d
62c
62b
Mercury
Venus
Earth
Mars
Planets and orbits to scale
Solar System

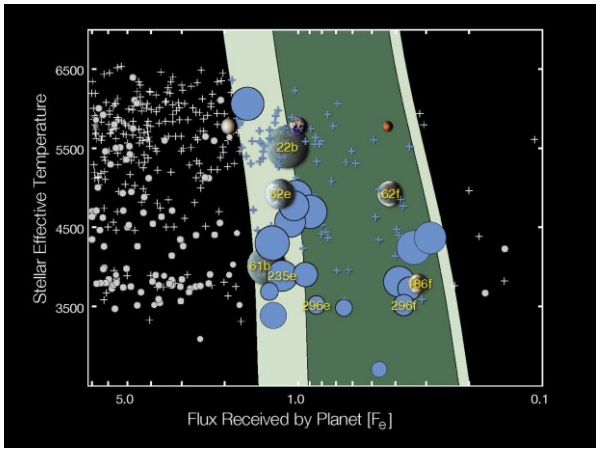

Kepler -186: A five-planet system, with all five planets smaller than 1.5 Rearth.
Orbiting a K-star with periods 4, 7, 13, 22 and 130 days.

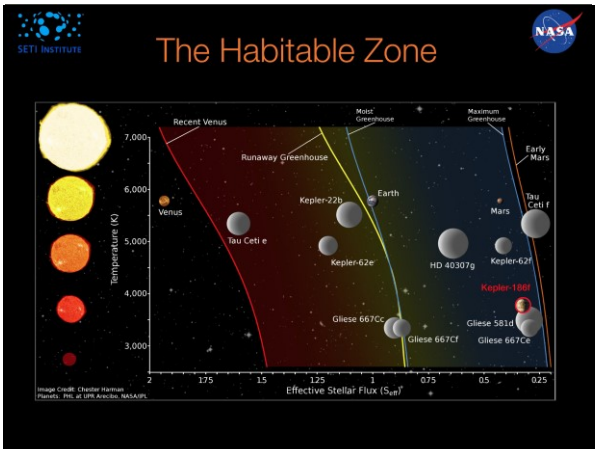


Kepler-186f: The most Earth-like planet currently known.
R=1.11 +/- 0.14 R_{Earth}, P=130 d; Mass = unknown



Kepler-186f: The most Earth-like planet currently known.
R=1.11 +/- 0.14 R_{Earth}, P=130 d; Mass = unknown





Kepler Discoveries as of 2015 May 1:

~5 years into its ~~3~~ 4 year mission:

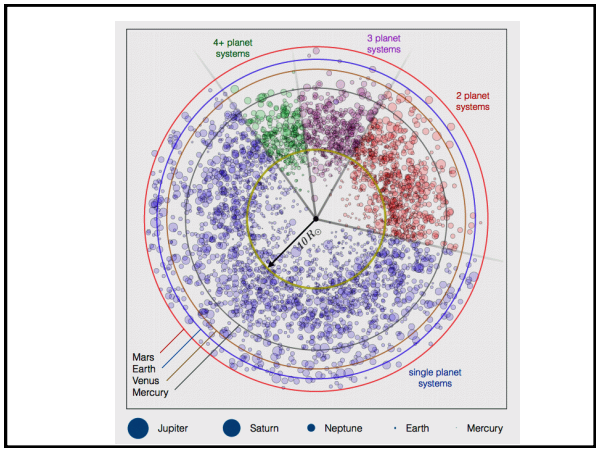
- 1020 confirmed planets
- 4604 planet *candidates*
- Most common planet is a "super Earth":
  1.25-2.0 R_{Earth} – nothing comparable in our Solar System
- 297 candidate planets in the HZ
  14 are <1.25 R_{Earth}
- Estimate that *at least* 70% of Sun-like stars have planets; *at least* 17% are Earth-size

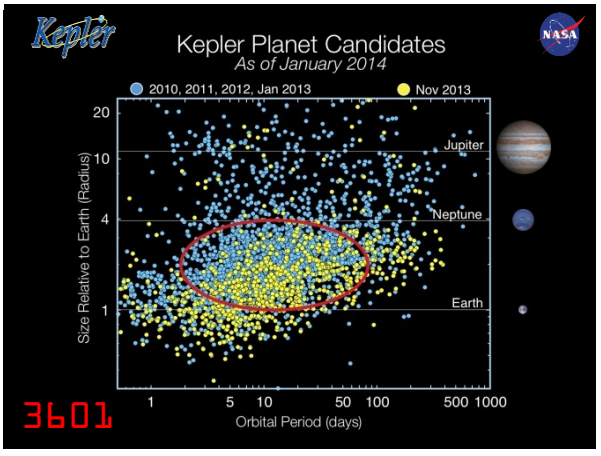
Extrapolation of the Kepler results puts the occurrence rate of Earth-size planets (0.5-1.4 R_e) in the HZ at

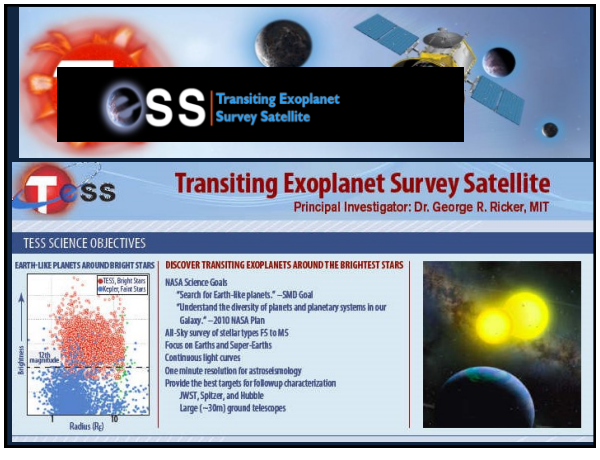
~ 22% for G & K-stars

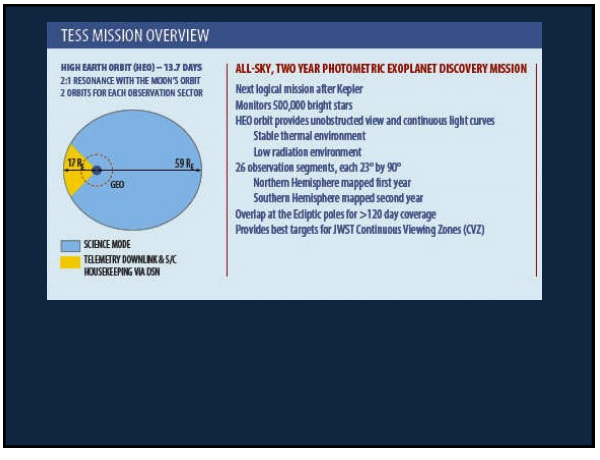
and

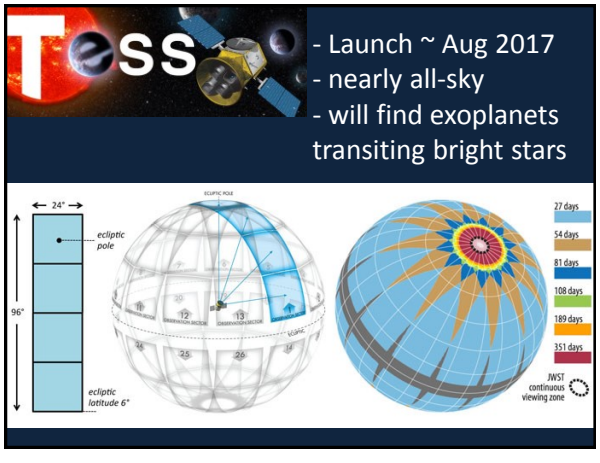
~50% for M stars!


4+ planet systems
3 planet systems
2 planet systems
single planet systems
Mars
Earth
Venus
Mercury
Jupiter
Saturn
Neptune
Earth
Mercury


Kepler
Kepler Planet Candidates
As of January 2014
2010, 2011, 2012, Jan 2013
Nov 2013
Size Relative to Earth (Radius)
Jupiter
Neptune
Earth
Orbital Period (days)
3601


Transiting Exoplanet Survey Satellite
Transiting Exoplanet Survey Satellite
Principal Investigator: Dr. George R. Ricker, MIT
TESS SCIENCE OBJECTIVES
EARTH-LIKE PLANETS AROUND BRIGHT STARS
DISCOVER TRANSITING EXOPLANETS AROUND THE BRIGHTEST STARS
NASA Science Goals
"Search for Earth-like planets." – SMD Goal
"Understand the diversity of planets and planetary systems in our Galaxy." – 2010 NASA Plan
All-Sky survey of stellar types F5 to M5
Focus on Earths and Super-Earths
Continuous light curves
One minute resolution for astroseismology
Provide the best targets for followup characterization
JWST, Spitzer, and Hubble
Large (~30m) ground telescopes


TESS MISSION OVERVIEW
HIGH EARTH ORBIT (HEO) – 13.7 DAYS
2:1 RESONANCE WITH THE MOON'S ORBIT
2 ORBITS FOR EACH OBSERVATION SECTOR
17 R_E
59 R_E
GEO
SCIENCE MODE
TELEMETRY DOWNLINK & S/C HOUSEKEEPING VIA DSN
ALL-SKY, TWO YEAR PHOTOMETRIC EXOPLANET DISCOVERY MISSION
Next logical mission after Kepler
Monitors 500,000 bright stars
HEO orbit provides unobstructed view and continuous light curves
Stable thermal environment
Low radiation environment
26 observation segments, each 23° by 90°
Northern Hemisphere mapped first year
Southern Hemisphere mapped second year
Overlap at the Ecliptic poles for >120 day coverage
Provides best targets for JWST Continuous Viewing Zones (CVZ)


- Launch ~ Aug 2017
- nearly all-sky
- will find exoplanets transiting bright stars
24°
96°
ecliptic pole
ecliptic latitude 6°
27 days
54 days
81 days
108 days
189 days
351 days
JWST continuous viewing zone