Reading: Chap. 21, Sect.21.4-21.6
Final Exam: Wednesday, December 18; 4:30-6:30PM, ***Room 0117 MacKay***
Homework 10: Due in recitation Friday, next Monday
COURSE EVALUATIONS AVAILABLE ONLINE

Last time: **Formation of Planetary Systems**

- Observational Clues: from our current Solar System & the stars
- Collapse of interstellar cloud
  - collapse, fragmentation, spinup and disk formation
- The Solar Nebula (the SS 4.6 Gyr ago)
- Planet formation
  - differential condensation & the frost line
  - accretion - growth of planetessimals

Today: **Other Planetary Systems**

- Imaging of planets – difficult, but not impossible
- Detection by orbital motion ("radial velocity)
- The *Kepler* Mission - planets are everywhere!
- > 3000 exoplanetary systems now known
- Properties of exoplanets - are they representative?

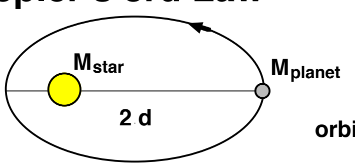
Searching for other planetary systems

this is a hard problem!

- Jupiter and the Sun
  - the Sun has a luminosity of 4 x10^{33} erg/s
  - Jupiter emits at most 8 x10^{24} erg/s
  - the Sun emits **500,000,000 times more light** than Jupiter
  - viewed from 10 pc, they are separated by 5 arc sec
- equivalent to
  - 1 candle,
  - 10 feet away from a stadium light bank,
  - viewed from 80 miles away!

Wobbles of stars from reflex motion:

- **Kepler's 3rd Law**



$$\frac{d^3}{P^2} = M_{star} + M_{planet}$$

orbital period [yrs]

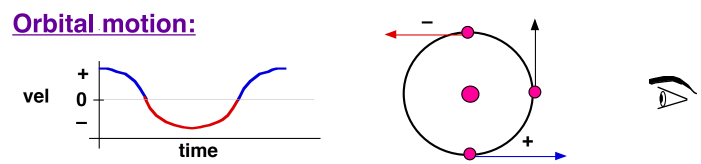
- **The "See-Saw" Law**

$$\frac{M_{planet}}{M_{star}} = \frac{d_{star}}{d_{planet}}$$

- $M_{planet} << M_{star}$
  - star moves in a small orbit
  - measure d_{star} and you know M_{planet}

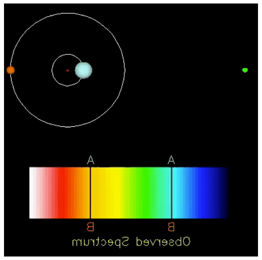
The "Radial Velocity" technique:

look for orbital *VELOCITY* of star around CM



$$V = \frac{2\pi d}{P} \quad \text{so}$$

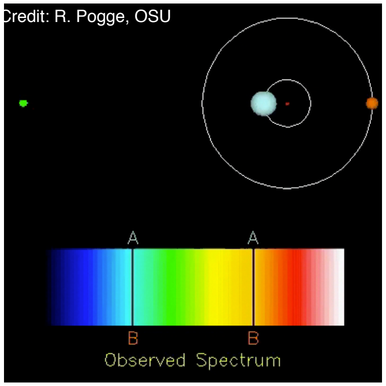
$$V_{star} = 30 \, m/s \times \frac{2\pi}{\sqrt{M_{star}}} \times \frac{1}{\sqrt{d}} \times \frac{M_{planet}}{M_{Jupiter}}$$



- Biggest effect if viewed EDGE ON
- Tilt of orbit to line-of-sight reduces observed velocity

Reflex Orbital Motion

- via reflex orbital motion: **precision spectroscopy**
- as of today: 786 planets in 581 systems



Credit: R. Pogge, OSU

Jupiter as an example:

- V_{Sun} around CM of Solar System = 13 m/s (= 30 mph)
- Doppler effect of 13 m/s is 1 part in 23,000,000 (!)
- varies cyclically over a 12 year cycle
- very difficult (but not impossible) to measure
- need stable spectroscope over long time
- **Earth? 9 cm/s!**

Improved chances for detection (V_{star} bigger):

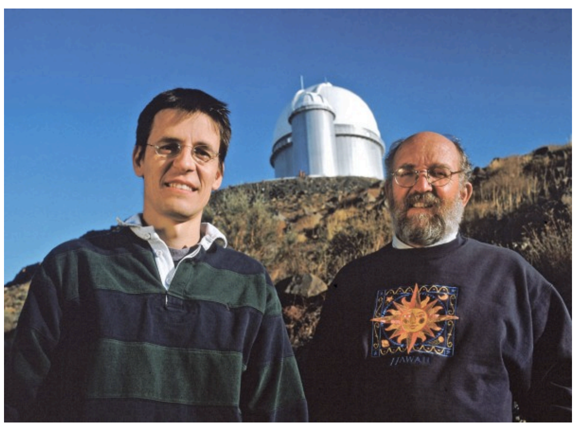
if planet is massive

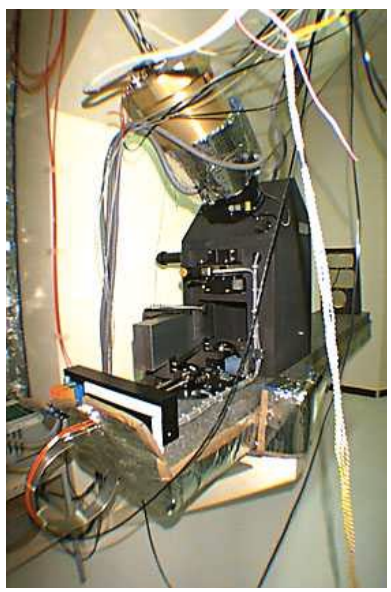
$$V_{star} = 30\,{}^{m}\!/\!{}_{s} \times \frac{2\pi}{\sqrt{M_{star}}} \times \frac{1}{\sqrt{d}} \times \frac{M_{planet}}{M_{Jupiter}}$$

if planet is close to star

also - shorter period = faster detection

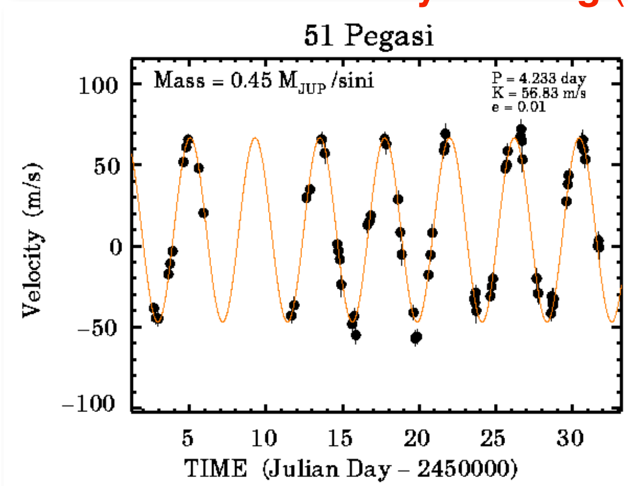
Didier Queloz Michel Mayor





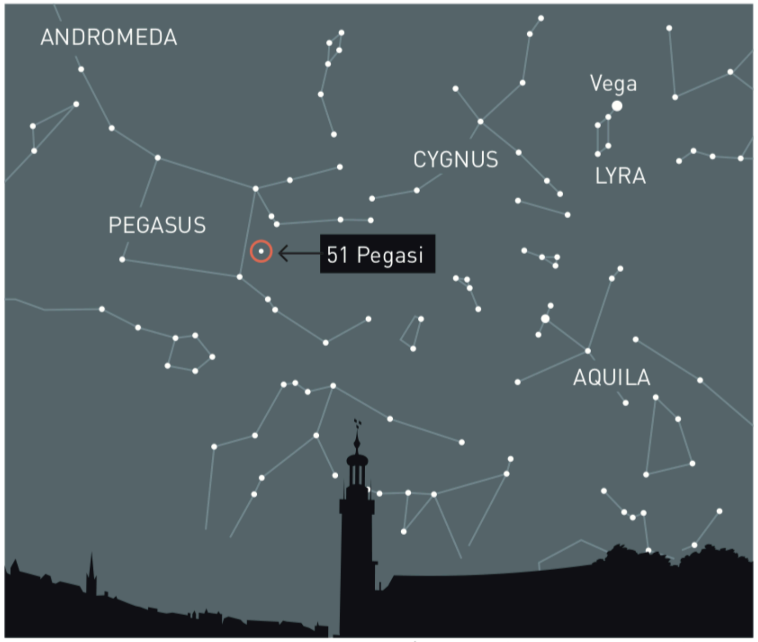
ELODIE

- pre-1995 - The Search is On
  - initial search for 'ordinary planets'
  - P_{orb} ~ months
- **1995 -first discovery - 51 Peg** (Mayor & Queloz)



P_{orb} = 4.233 days

M_{planet} = 0.45 $M_{Jupiter}$



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Discovery Paper

ARTICLES

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[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[6,7]. 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 the mass of the companion. Alternative explanations to the observed radial velocity variation (pulsation or spot rotation) are unlikely.

The very small distance between the companion and 51 Peg is certainly not predicted by current models of giant planet formation[8]. As the temperature of the companion is above 1,300 K, this object seems to be dangerously close to the Jeans thermal evaporation limit. Moreover, non-thermal evaporation effects are known to be dominant[9] over thermal ones. This jovian-mass companion may therefore be the result of the stripping of a very-low-mass brown dwarf.

The short-period orbital motion of 51 Peg also displays a long-period perturbation, which may be the signature of a second low-mass companion orbiting at larger distance.

Discovery of Jupiter-mass companion(s)

Our measurements are made with the new fibre-fed echelle spectrograph ELODIE of the Haute-Provence Observatory, France[10]. This instrument permits measurements of radial velocity with an accuracy of about 13 m s^{-1} of stars up to 9 mag in an exposure time of <30 min. The radial velocity is computed

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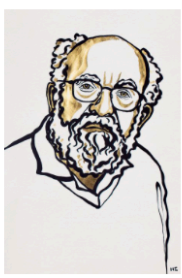
The Nobel Prize in Physics 2019

Ill. Niklas Elmedhed. © Nobel Media.

James Peebles

Prize share: 1/2



Ill. Niklas Elmedhed. © Nobel Media.

Michel Mayor

Prize share: 1/4

Ill. Niklas Elmedhed. © Nobel Media.

Didier Queloz

Prize share: 1/4

The Nobel Prize in Physics 2019 was awarded "for contributions to our understanding of the evolution of the universe and Earth's place in the cosmos" with one half to James Peebles "for theoretical discoveries in physical cosmology", the other half jointly to Michel Mayor and Didier Queloz "for the discovery of an exoplanet orbiting a solar-type star."

Discovery Paper

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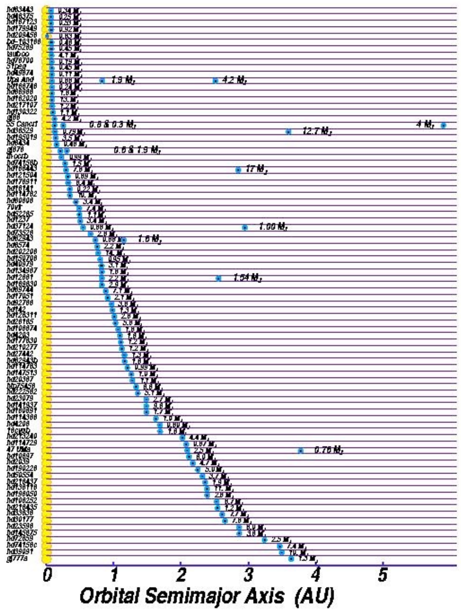
LETTERS TO NATURE

The search for extrasolar planets can be amazingly rich in surprises. From a complete planetary system detected around a pulsar[24,25], to the rather unexpected orbital parameters of 51 Peg b, searches begin to reveal the extraordinary diversity of possible planetary formation sites.

Note added in revision: After the announcement of this discovery at a meeting held in Florence, independent confirmations of the 4.2-day period radial-velocity variation were obtained in mid-October by a team at Lick Observatory, as well as by a joint team from the High Altitude Observatory and the Harvard–Smithsonian Center for Astrophysics. We are deeply grateful to G. Marcy, P. Butler, R. Noyes, T. Kennelly and T. Brown for having immediately communicated their results to us. □

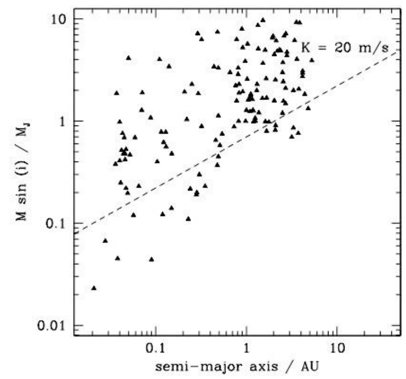
1995 - 2019 Huge strides

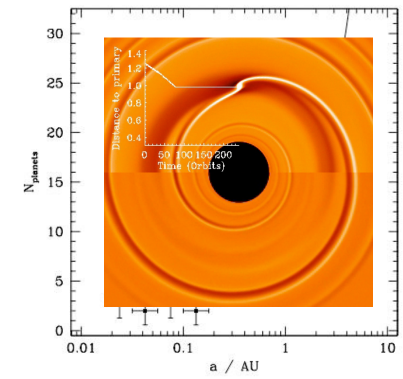


- now over 640 confirmed extrasolar planetary systems (860 planets) found via Radial Velocities
- Most are **massive planets**
- Most have **small orbits**
- Many are multiple-planet systems

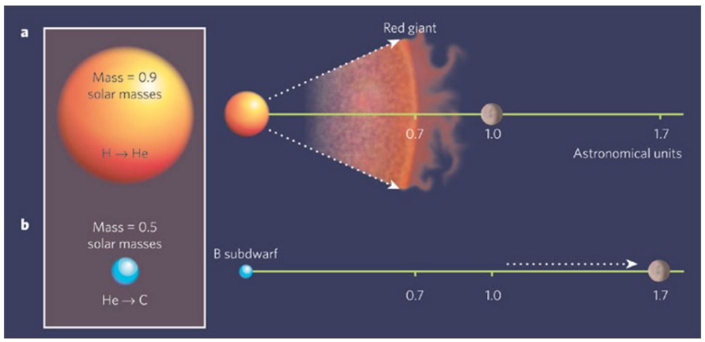
Planet 'Migration'

- Jupiter-mass planets can't form so close to parent stars.
- Can form farther out
- migrate inwards by losing angular momentum to gas within disk

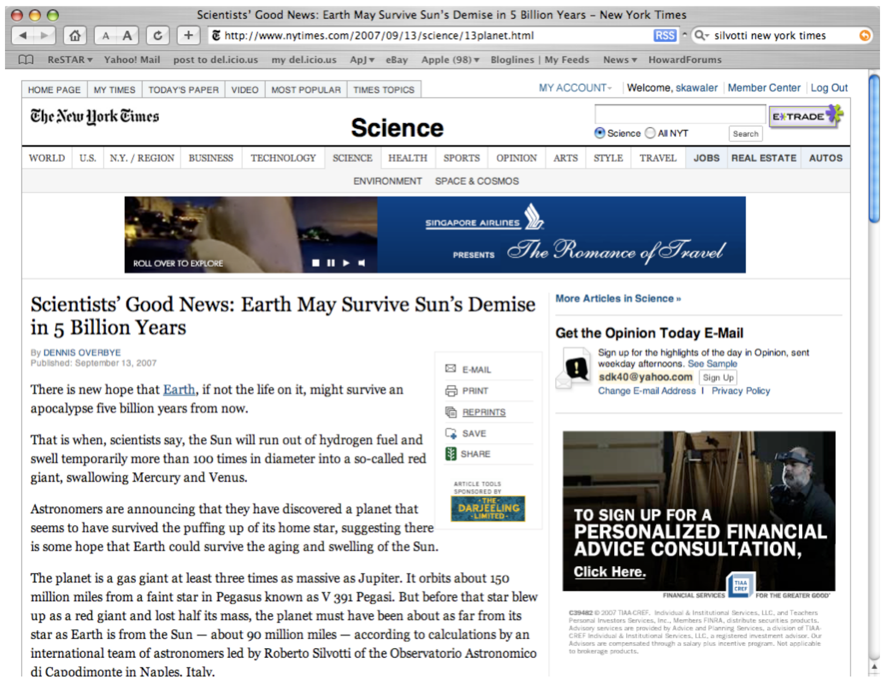




V391 Pegasi



- planetary system that has survived first death of the parent star
- discovered by pulsation phase drift in the remnant stellar core
- **work done (in part) at Iowa State**
- Roberto Silvotti (Naples) and a bunch of us!



Scientists' Good News: Earth May Survive Sun's Demise in 5 Billion Years – New York Times

Science

Scientists' Good News: Earth May Survive Sun's Demise in 5 Billion Years

By DENNIS OVERBYE
Published: September 13, 2007

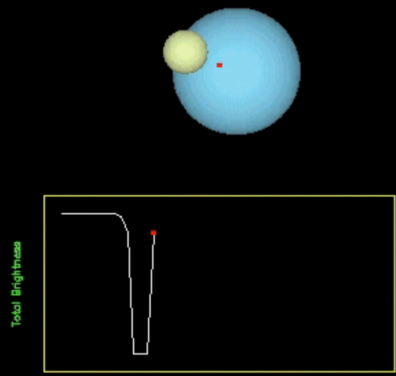
There is new hope that Earth, if not the life on it, might survive an apocalypse five billion years from now.

That is when, scientists say, the Sun will run out of hydrogen fuel and swell temporarily more than 100 times in diameter into a so-called red giant, swallowing Mercury and Venus.

Astronomers are announcing that they have discovered a planet that seems to have survived the puffing up of its home star, suggesting there is some hope that Earth could survive the aging and swelling of the Sun.

The planet is a gas giant at least three times as massive as Jupiter. It orbits about 150 million miles from a faint star in Pegasus known as V 391 Pegasi. But before that star blew up as a red giant and lost half its mass, the planet must have been about as far from its star as Earth is from the Sun — about 90 million miles — according to calculations by an international team of astronomers led by Roberto Silvotti of the Observatorio Astronomico di Capodimonte in Naples, Italy.

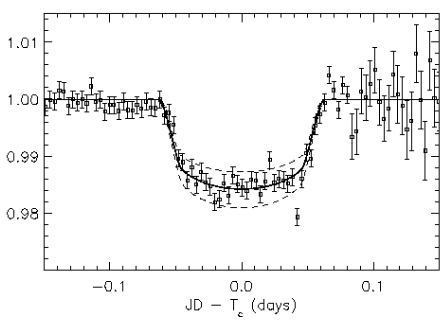
extrasolar planet detection via precision photometry



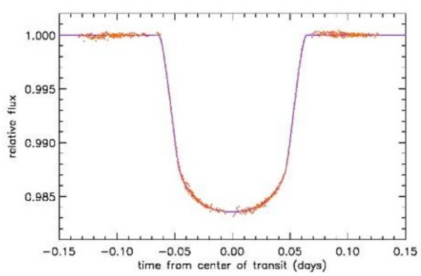
Credit: R. Pogge, OSU

- as of today, number of systems/planets discovered by transits:
  total: 2231 planetary systems, 2970 planets, 482 multiples
  from space: 1745 planetary systems, 2431 planets , 4247 candidates

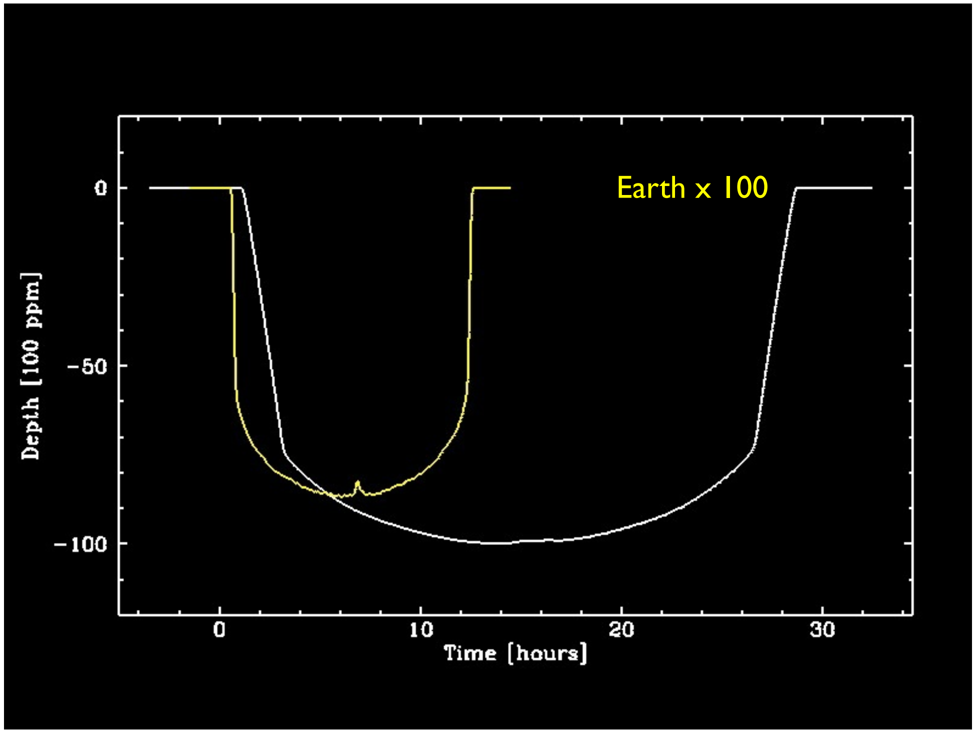
The first transiting extrasolar planet: HD209458



Discovery by Charbonneau et al. 1999



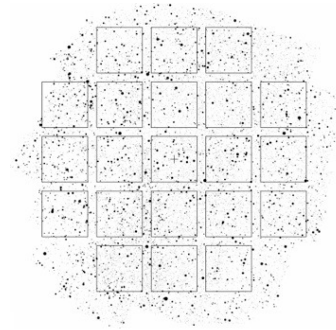
Hubble Space Telescope light curve



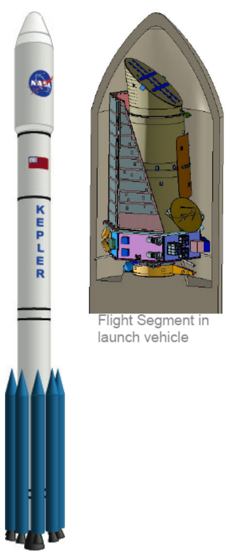
Kepler Mission Concept

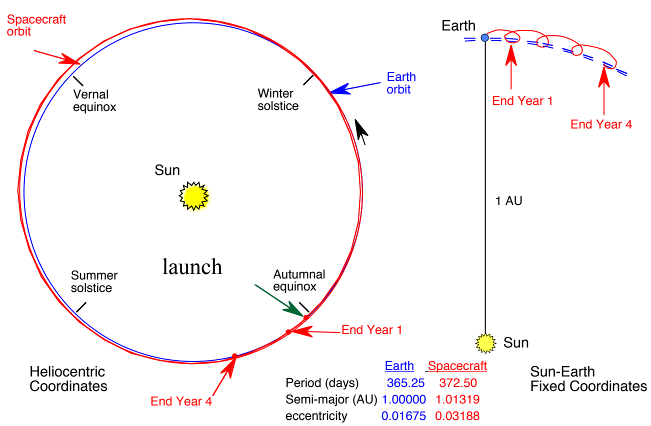
Kepler
A Search for Habitable Planets

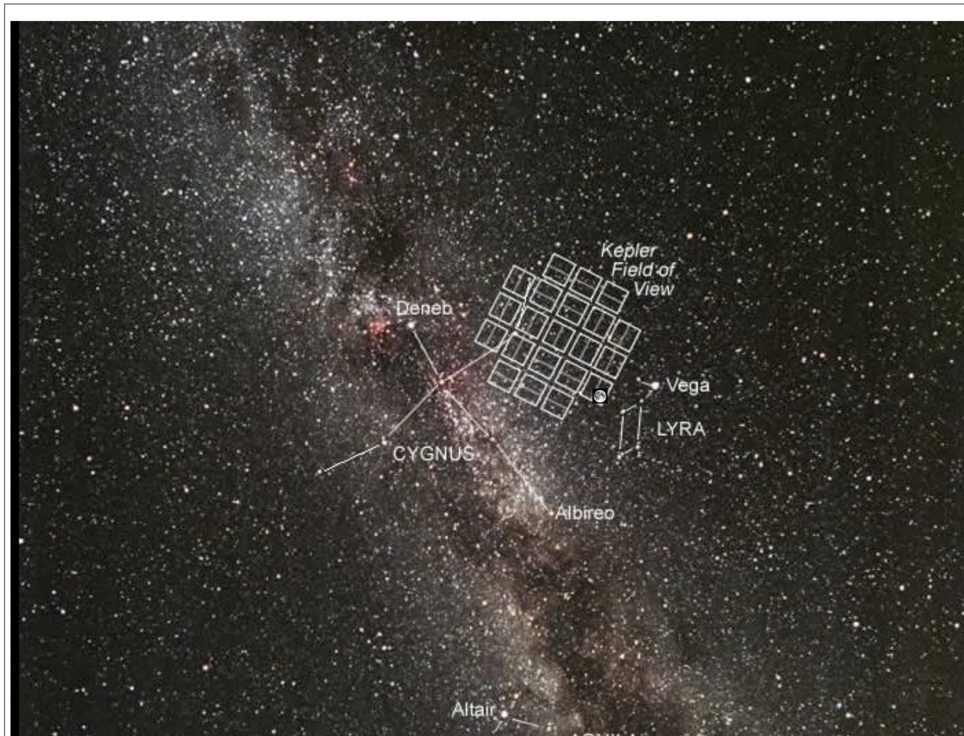
- Launched 6 March 2009
- 0.95m Schmidt telescope:
  FOV >100 deg² with an array of 42 CCD
- Optimized for finding habitable planets (0.5 to 10 $M_\oplus$) in the HZ (near 1 AU) of solar-like stars
- Continuously and simultaneously monitor 150,000 main-sequence stars
- Heliocentric orbit for continuous viewing
  4 year duration

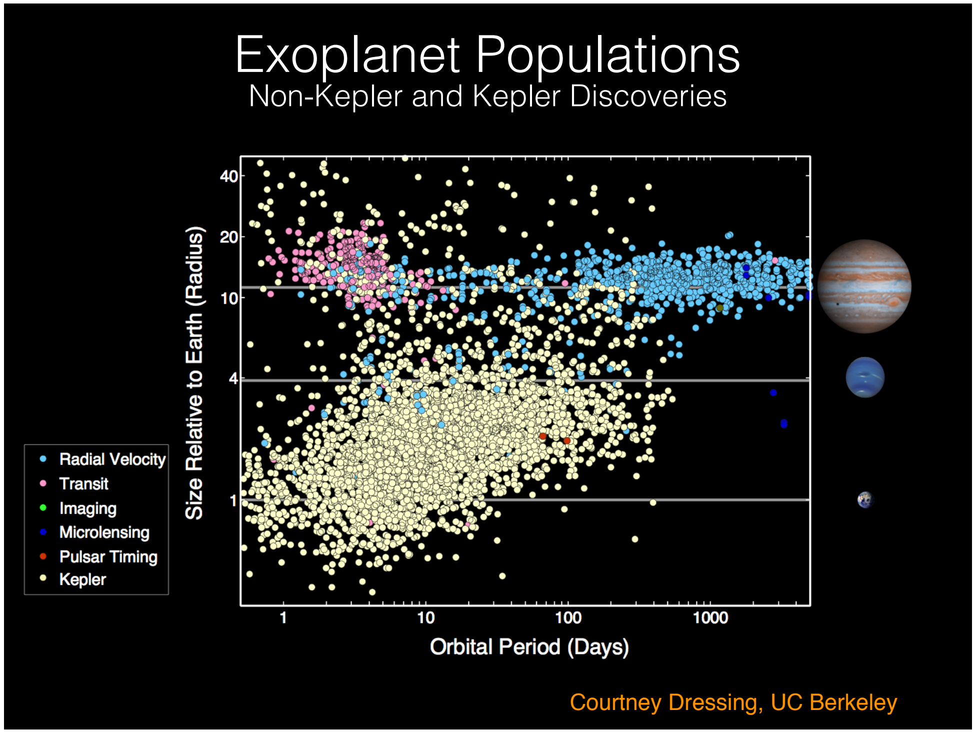


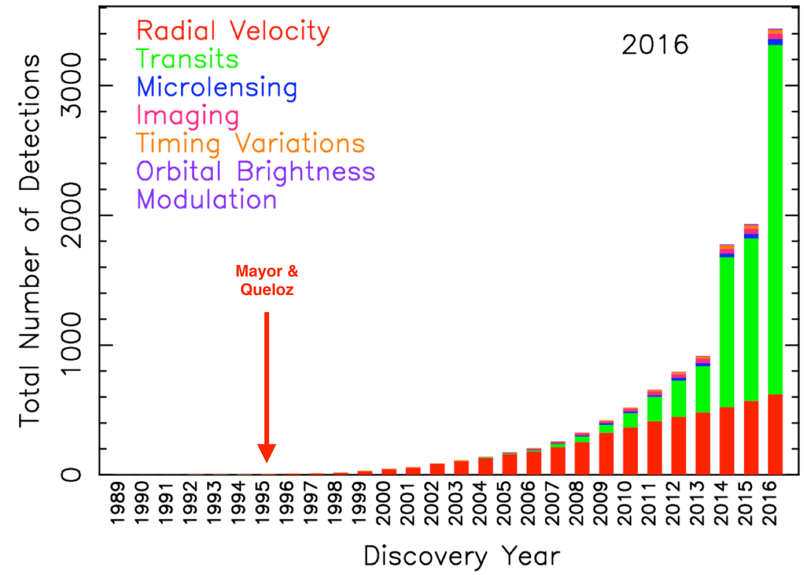
Earth-trailing Heliocentric Orbit








Exoplanet Populations
Non-Kepler and Kepler Discoveries
Size Relative to Earth (Radius)
40
20
10
4
1
Orbital Period (Days)
1
10
100
1000
Radial Velocity
Transit
Imaging
Microlensing
Pulsar Timing
Kepler
Courtney Dressing, UC Berkeley


Radial Velocity
Transits
Microlensing
Imaging
Timing Variations
Orbital Brightness
Modulation
2016
Mayor &
Queloz
Total Number of Detections
0
1000
2000
3000
1989
1990
1991
1992
1993
1994
1995
1996
1997
1998
1999
2000
2001
2002
2003
2004
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2006
2007
2008
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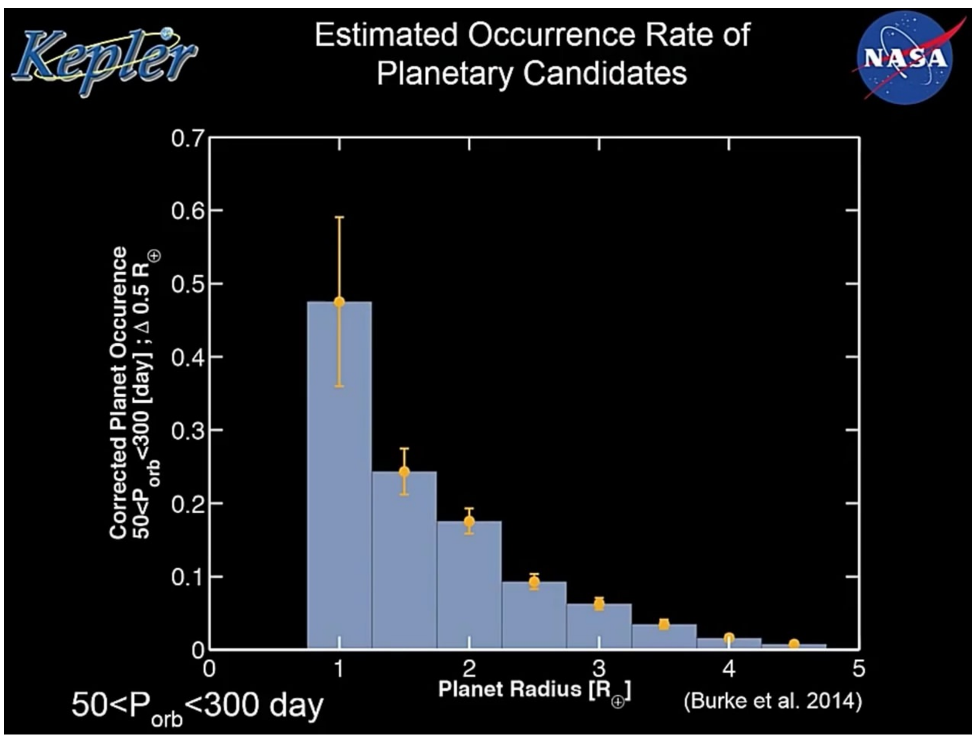
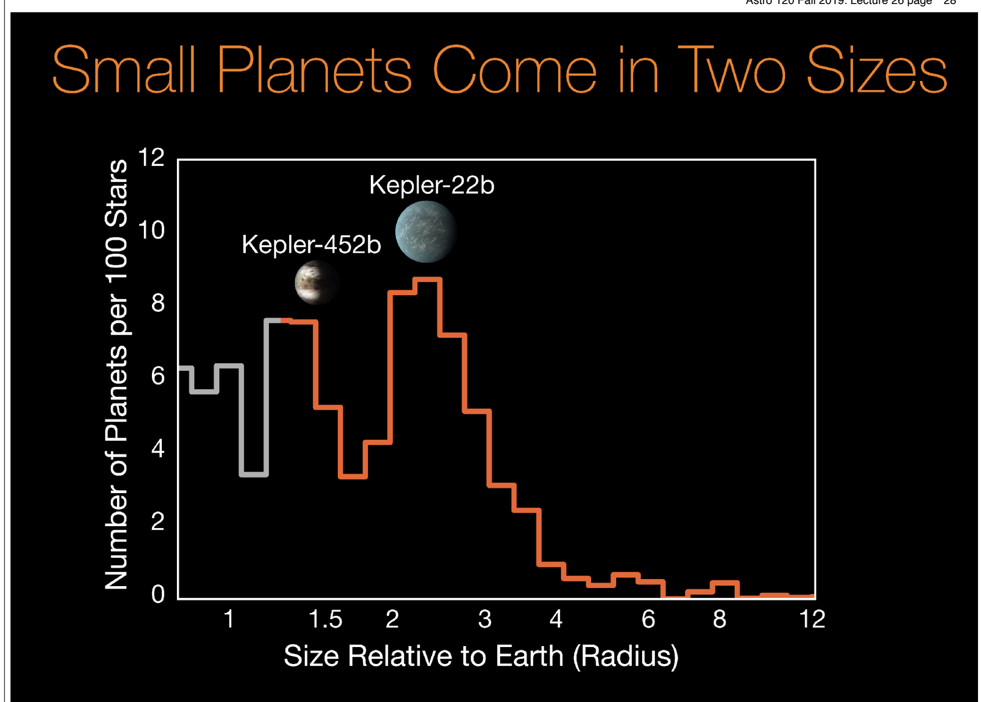
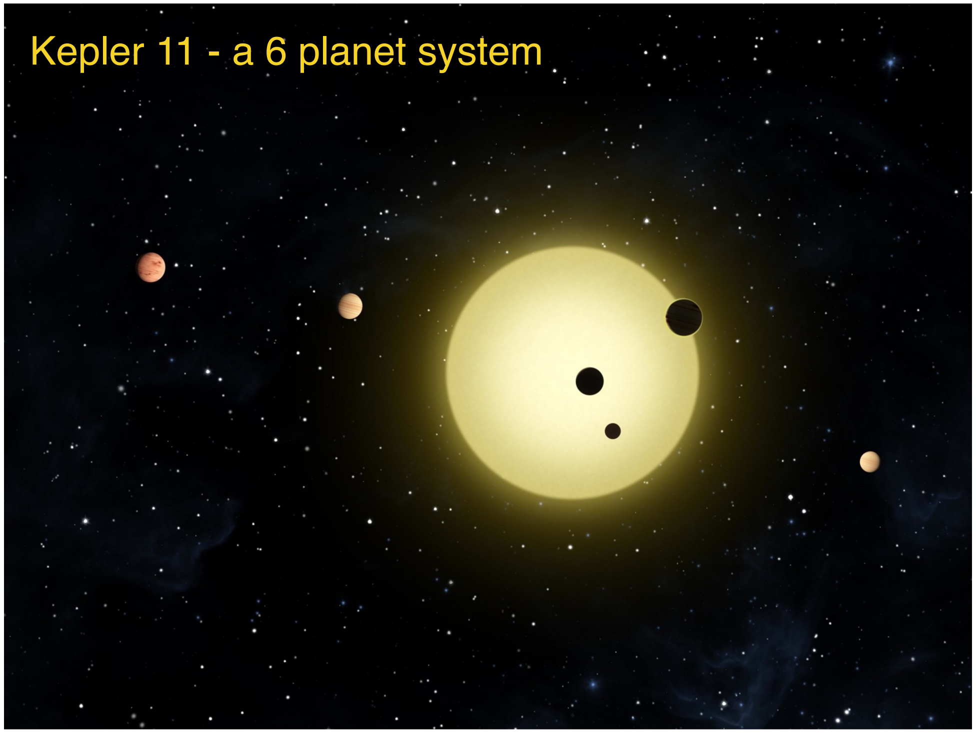
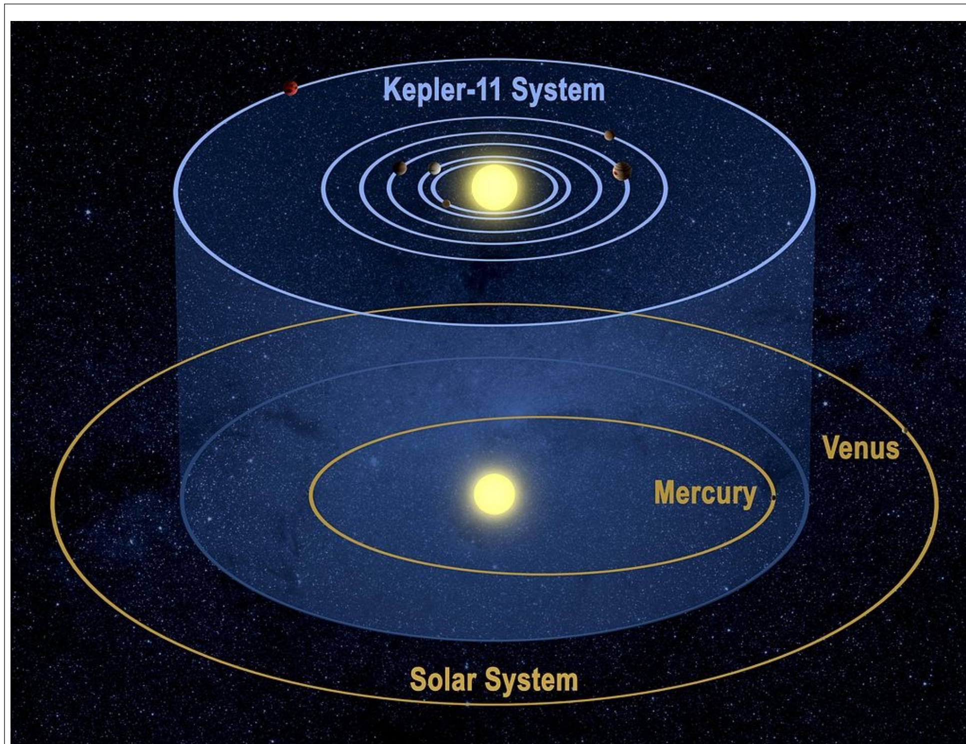
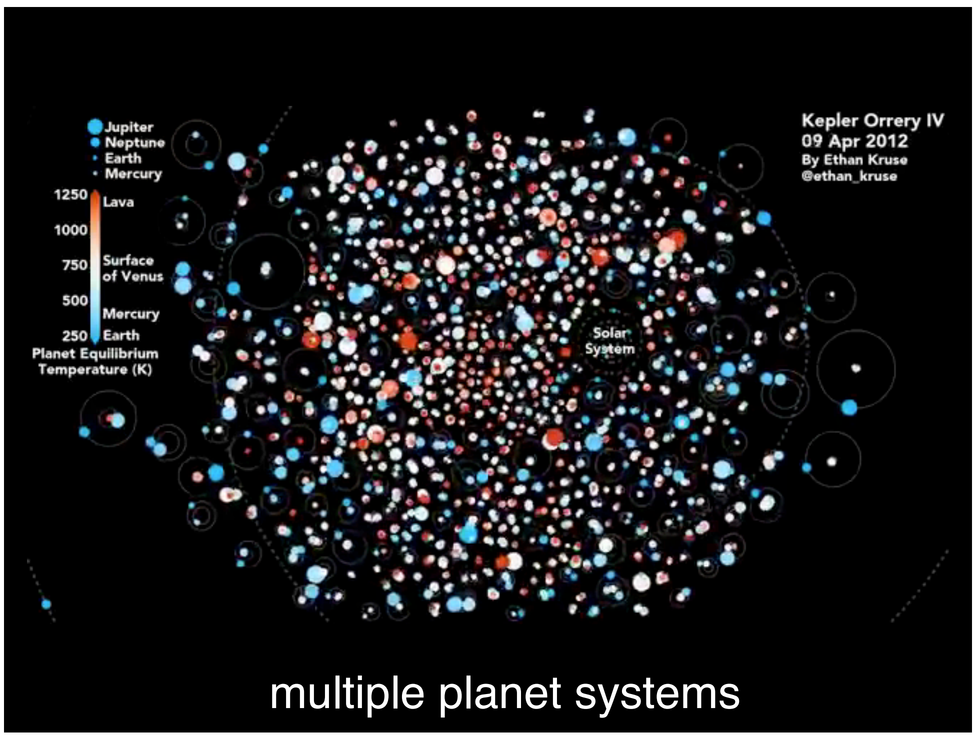
2010
2011
2012
2013
2014
2015
2016
Discovery Year

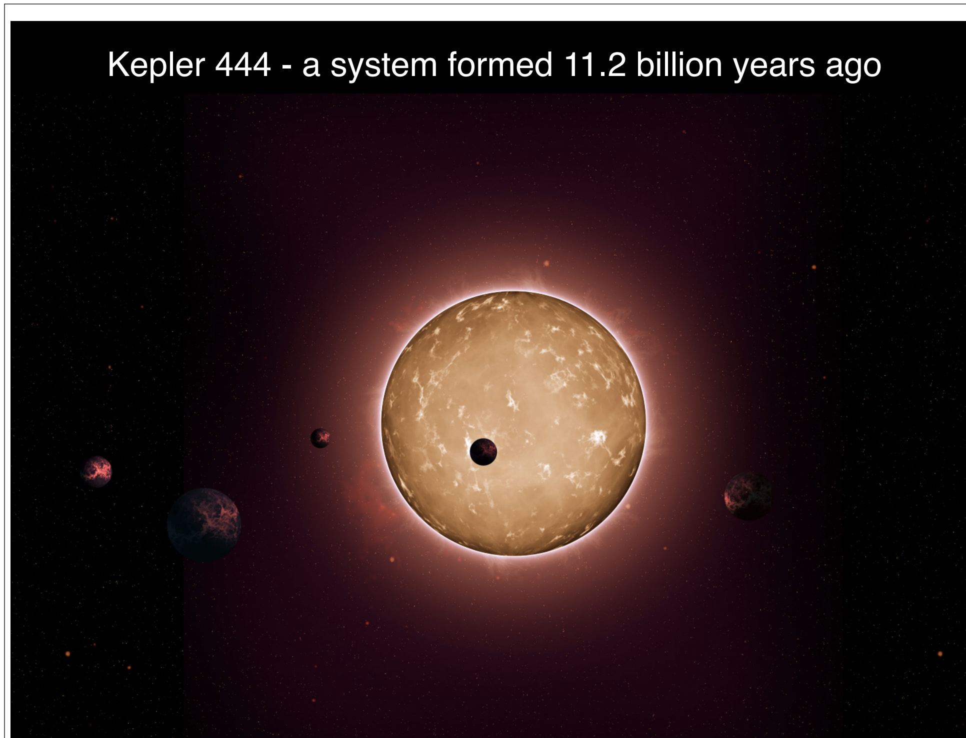

Kepler
Estimated Occurrence Rate of
Planetary Candidates
NASA
Corrected Planet Occurence
50<P_{orb}<300 [day] ; Δ 0.5 R⊕
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
1
2
3
4
5
Planet Radius [R⊕]
(Burke et al. 2014)
50<P_{orb}<300 day

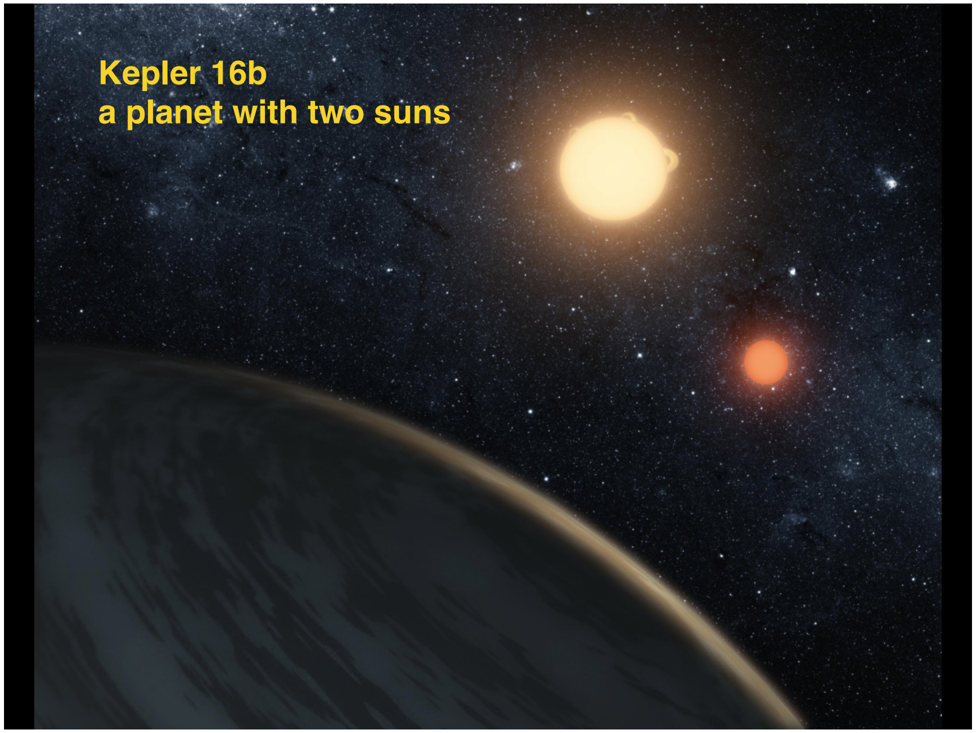

Small Planets Come in Two Sizes
Kepler-22b
Kepler-452b
Number of Planets per 100 Stars
12
10
8
6
4
2
0
1
1.5
2
3
4
6
8
12
Size Relative to Earth (Radius)


Kepler 11 - a 6 planet system


Kepler-11 System
Venus
Mercury
Solar System

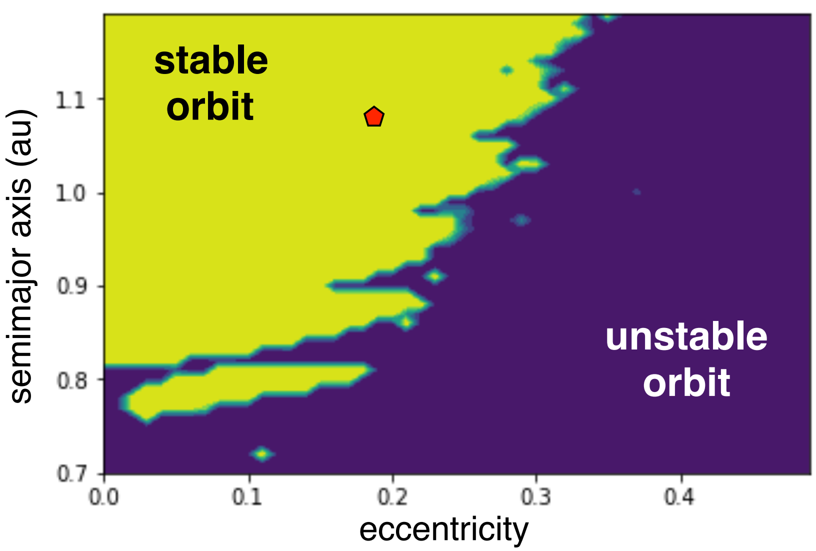

Jupiter
Neptune
Earth
Mercury
1250
1000
750
500
250
Lava
Surface of Venus
Mercury
Earth
Planet Equilibrium Temperature (K)
Kepler Orrery IV
09 Apr 2012
By Ethan Kruse
@ethan_kruse
Solar System
multiple planet systems


Kepler 444 - a system formed 11.2 billion years ago

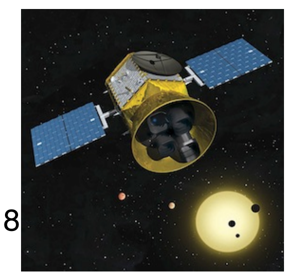


Kepler 34AB & Kepler 34 b

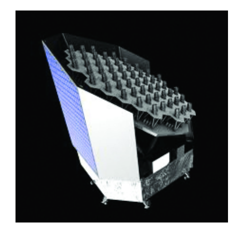
Drew Thomas (ISU sophomore research student)



What is next?

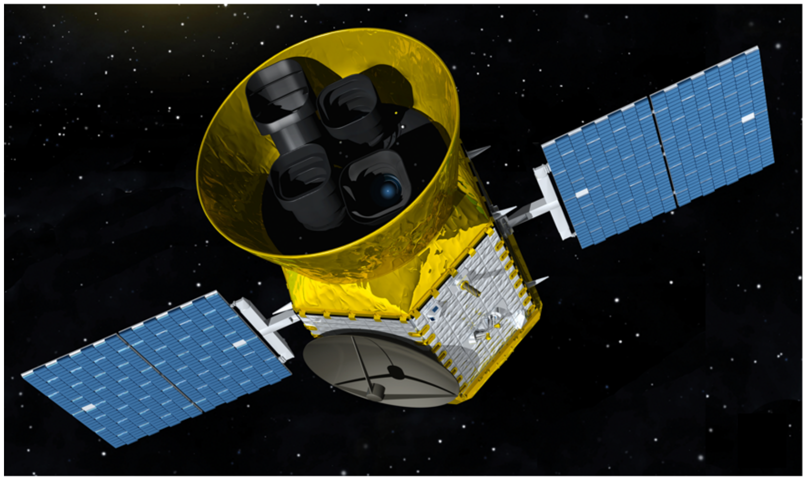


- ***TESS*** (MIT/GSFC lead)
  - 500,000 “bright” stars, over entire sky
  - strong asteroseismology component
  - launched April 2018, began science July 2018



- European Space Agency: ***PLATO***
  - multiple-telescope orbital platform
  - 9 x area of Kepler
  - 100,000 stars with capacity for 1,000,000
  - approved in February 2014; launch in **2024**
- Beyond 2024 - ?

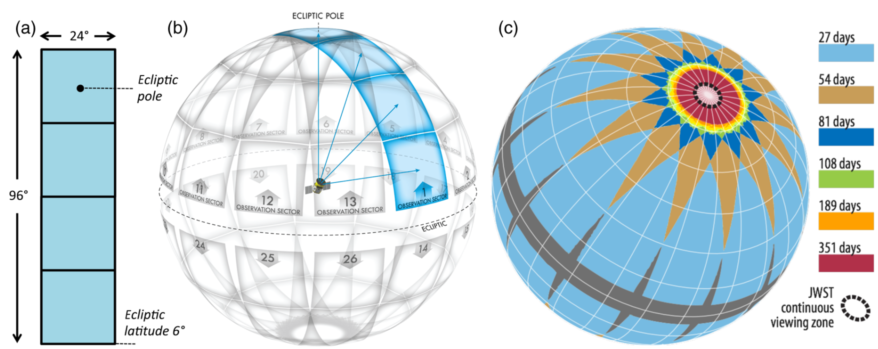
TESS - April 2018 launch



G. Ricker et al., SPIE J. Astron. Telesc. Instrum. Syst. 1(1), 014003 (2014)

TESS - April 2018 launch

TESS sky coverage



G. Ricker et al., SPIE J. Astron. Telesc. Instrum. Syst. 1(1), 014003 (2014)