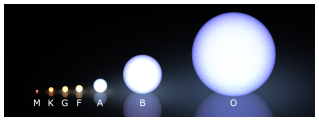
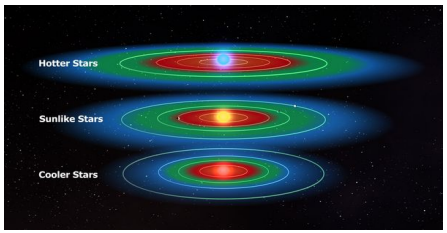
Questions?

Summary

- Stars are very far away
- Stars come in a variation of colors, sizes and brightnesses



- "Earth-like" means a rocky planet in the habitable zone

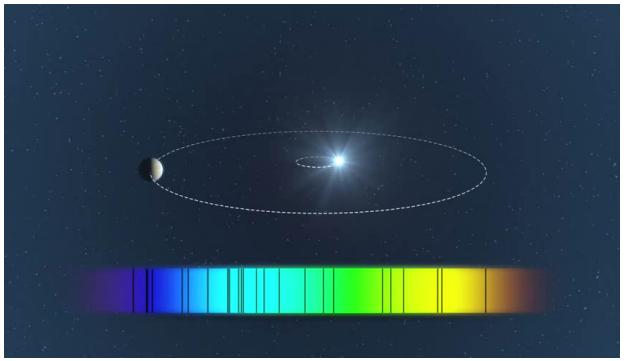


Summary

- We can't see planets directly
- We look for planet's effects on stars by Examining the starlight
- We're looking for a planet that is
  - The right size (Rocky and large enough to have an atmosphere)
  - In the right place (habitable zone)

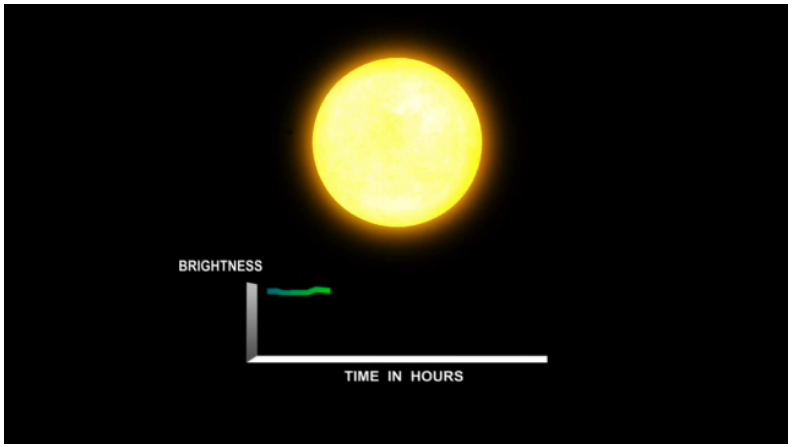
Doppler Method

- Measures planet mass
- Found 527 planets
  - Mostly large, a small number of rocky planets

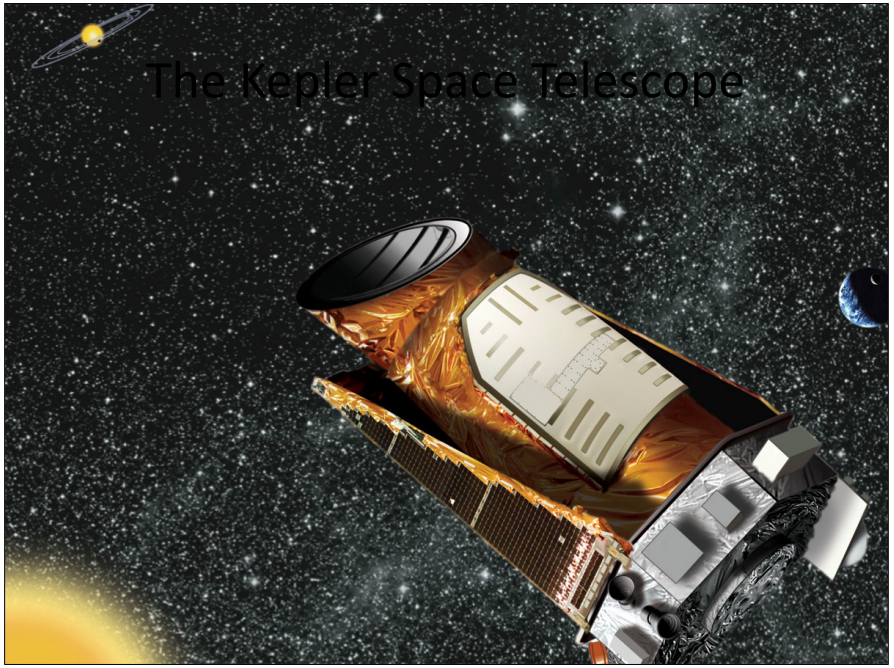


Transit Method

- Measures the planet's size



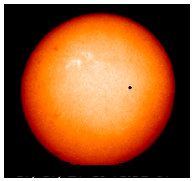
The Kepler Space Telescope



Where Kepler Searched for Planets

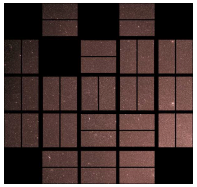
Basic Strategy: Stare for a Long Time

- Original funding: observe the same stars for 3.5 years
  - Long enough to easily see Earth analogs, so long as all stars are as quiet as the Sun
  - But it turned out the Sun is quieter than average, so Kepler needed more time
  - Applied for a 4-year extension, so the same stars would be observed for 8 years
    - Plenty for finding Earth analogs
    - Extension granted in Fall, 2012



But Kepler Broke

- Lost the ability to control pointing in 3 dimensions
  - Can control two directions, such as pitch and yaw
  - Kepler can no long resist the push of photon pressure from the Sun
- Almost 4 years after launch
  - Just after getting a 4-year mission extension to 8 years
- We also lost almost 10% of the pixels
- But otherwise a wonderful telescope
  - On a wobbly mount



Rebranded and Now Operating as K2

- By being Very Clever, Kepler can point at one spot for as long as 90 days, so long as it points in the direction of its orbit
  - Along the ecliptic
  - 80-90 days in one direction, then turn to another direction
- Entirely proposal driven: any astrophysics is fair game
- Details in the last class

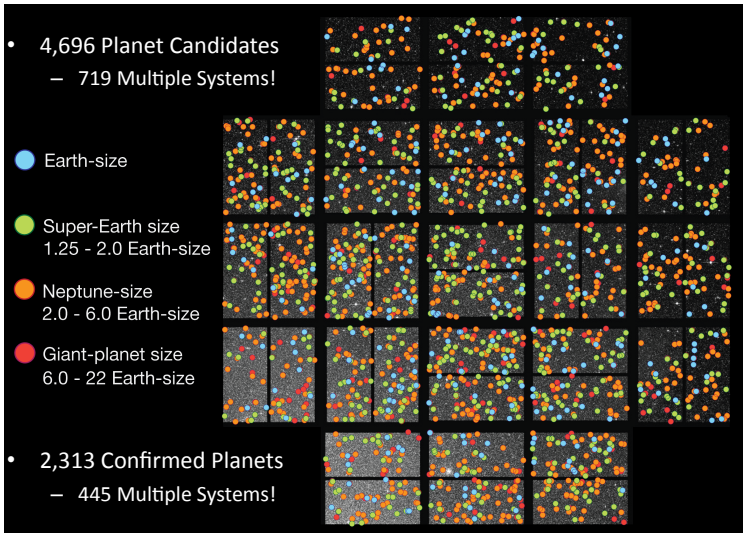
How Kepler Planets Were Found Before 2015

- Computer-based transit detections are identified and called *Threshold Crossing Events* (TCEs)
- Inspection of the TCEs select signals that look like real transits, called *Kepler Objects of Interest* (KOIs)
- KOIs are carefully inspected and are divided into Planet Candidates and False Positives
  - False positive only when it's obviously not a planet

Automating the Identification of Planet Candidates

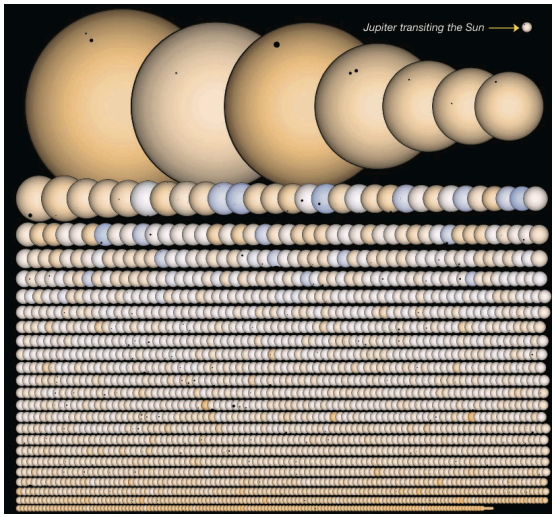
- By 2015 the transit detection system was sensitive enough to detect more than 24,000 TCEs
- 7000 TCEs were turned into KOIs
- Manually examining that many KOIs takes far too long
  - Can't be finished before the end of the mission
    - When the money runs out
- But by then the manual examination taught us many techniques that could be turned into computer programs
- So the last two planet candidate catalogs were produced by (carefully supervised) computer programs
  - Big advantage: all planet candidates are selected by the same criterion
    - Instead of the mood/fatigue of a human
    - Very important for statistical analysis

Announced Planet Candidates

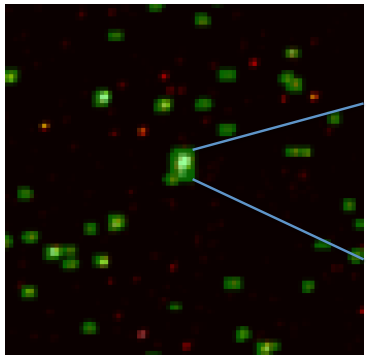


The Transiting Stars

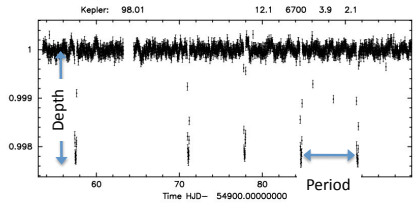
- Shown with their real colors



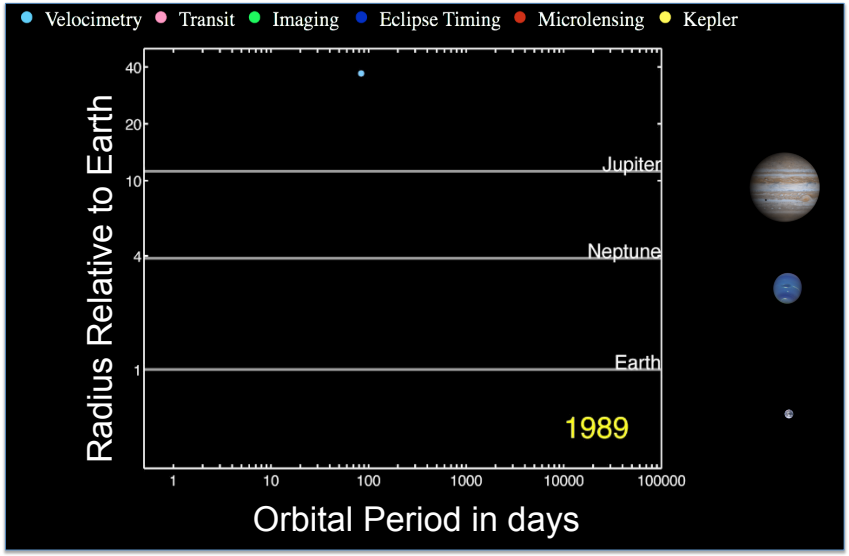
Transits Measure Planet Radius and Orbital Period



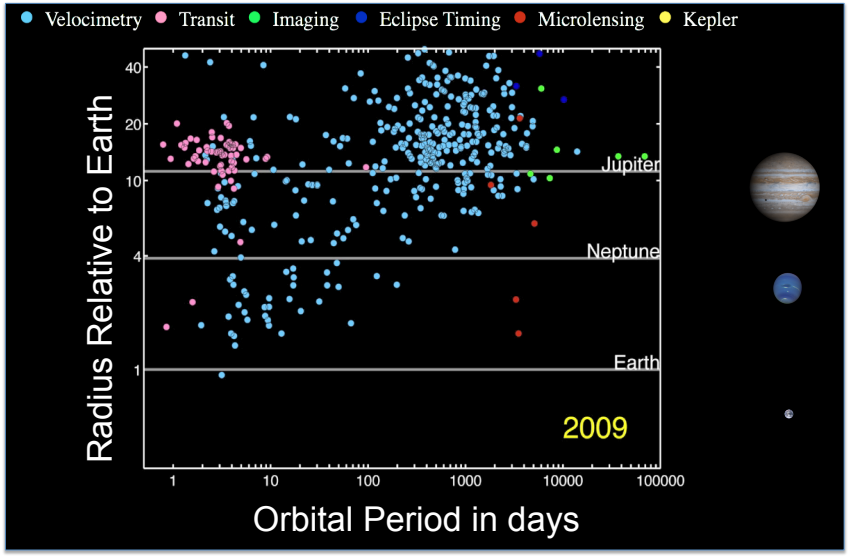
- The Depth tells you the fraction of the star covered by the planet
  - Tells you the size of the planet
- The time between transits is the period of one orbit of the planet around its star



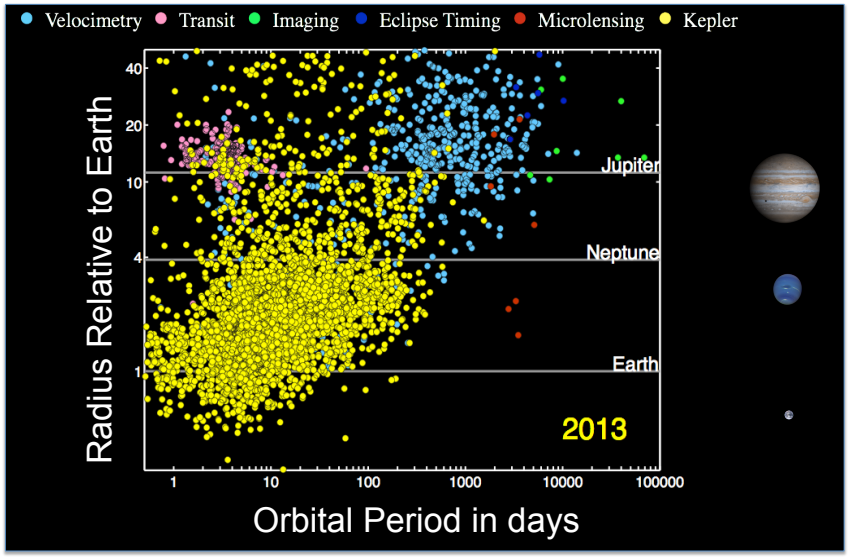
The First Detected Exoplanet (Dave Latham)



At Kepler Launch

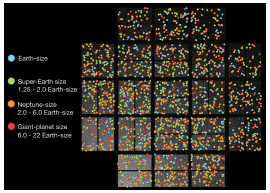


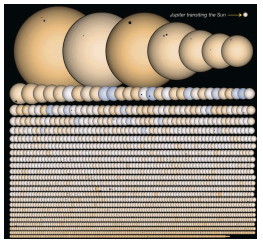
At the End of 2013



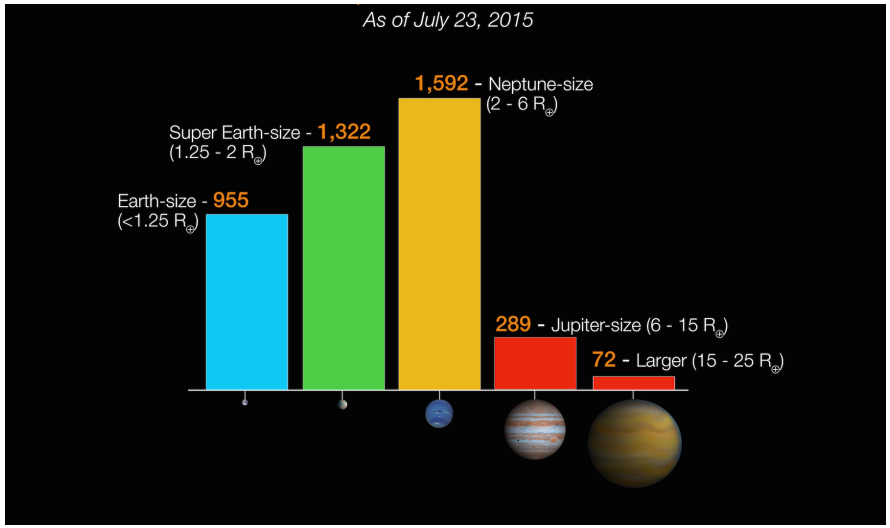
So Many Planets

- What can we learn from the all these planets as a group?
  - How common are different planet sizes?
  - How common are different planet temperatures?
- This allows us to answer the question:
  - How unusual is the Earth?

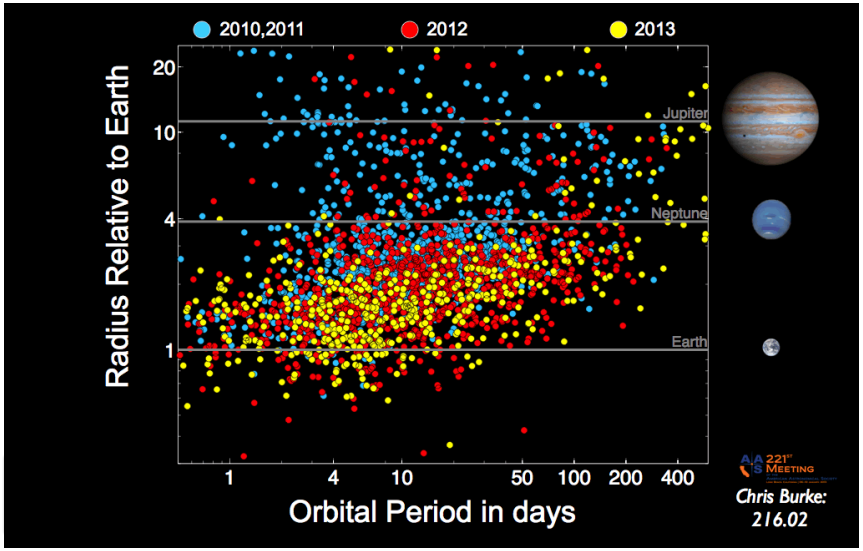




Kepler Candidate Planet Sizes

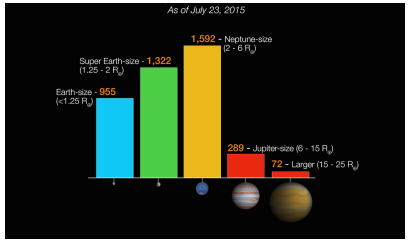


Kepler Planet Size and Orbital Period



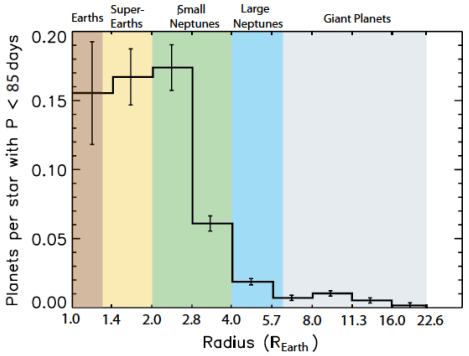
Most Exoplanets are Neptune Size

- Or are they?
  - Smaller planets are harder to find
  - Kepler data analysis probably misses many Earth-size planets
    - Test by inserting fake transits in the data and see how many we find



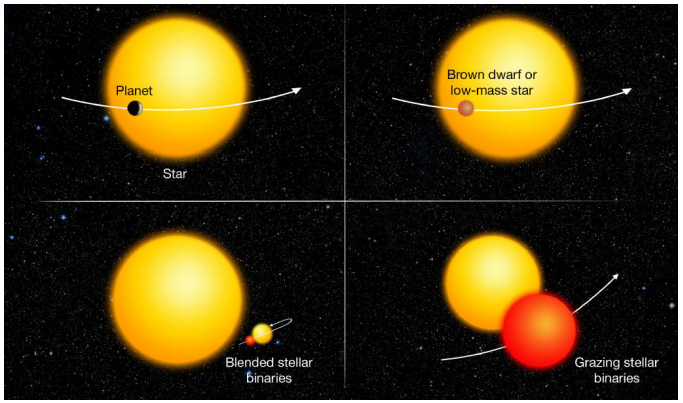
After Correcting for Missing Planets

- It seems that Earth-size through Neptune-size are equally common, with Jupiter-size less common



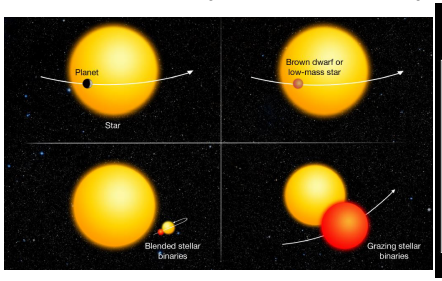
How Reliable Are Planet Candidates?

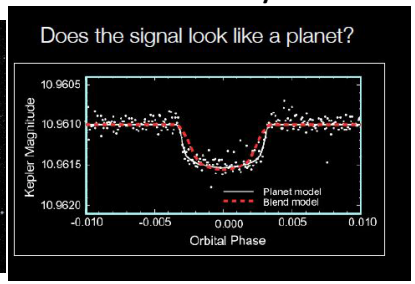
- Binary stars can resemble a planet transit signal



How Reliable Are Planet Candidates?

- Obvious false positives have already been removed
- But sometimes a binary star won't be obvious
- Careful analysis of the transit shape can tell us how likely it is to be a planet vs. a binary



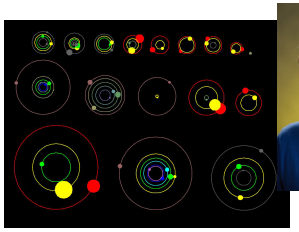


Confirmation/Validation

- Confirmation: Detect the planet using other methods (about 150 planets)
  - Doppler Method
  - Look for the gravitational pull of one planet on another
  - Not possible with small planets in long orbits (like the Earth)
- Validation: Determine that it is very likely that the signal is due to a planet
  - Require probability to be a planet be > 99%
  - Detailed study of the transit shape (20-30 planets as of last week)
    - Very time consuming and labor intensive

Validation Via Multiple-Planet Systems

- Kepler has observed many multi-planet systems
- Analysis of the orbital periods can rule out multiple star systems
- This leaves the possibility of background binaries, but the probability of three or more lining up with the star observed by Kepler is very very small
- Leads to the validation of 851 planets in 2014




Jason Rowe


Jack Lissauer


Geoff Marcy


Steve Bryson

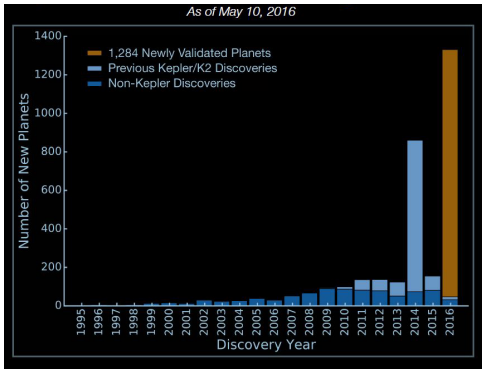
Tuesday's Announcement

- Validation of 1,284 planets via Automated Shape Analysis

FALSE POSITIVE PROBABILITIES FOR ALL KEPLER OBJECTS OF INTEREST:
1284 NEWLY VALIDATED PLANETS AND 428 LIKELY FALSE POSITIVES

TIMOTHY D. MORTON[1], STEPHEN T. BRYSON[2], JEFFREY L. COUGHLIN[2,3], JASON F. ROWE[4], GANESH RAVICHANDRAN[5], ERIK A. PETIGURA[6,7], MICHAEL R. HAAS[2], AND NATALIE M. BATALHA[2]

Tim Morton



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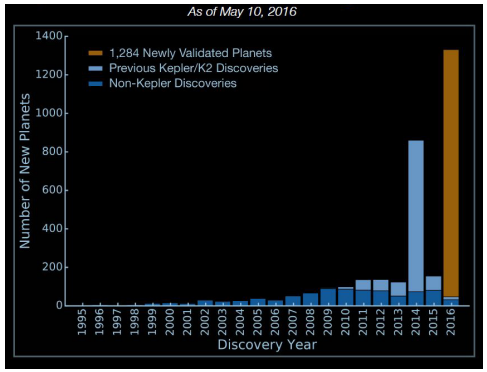
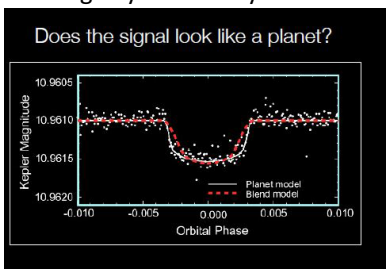
Tim Morton playing my harpsichord

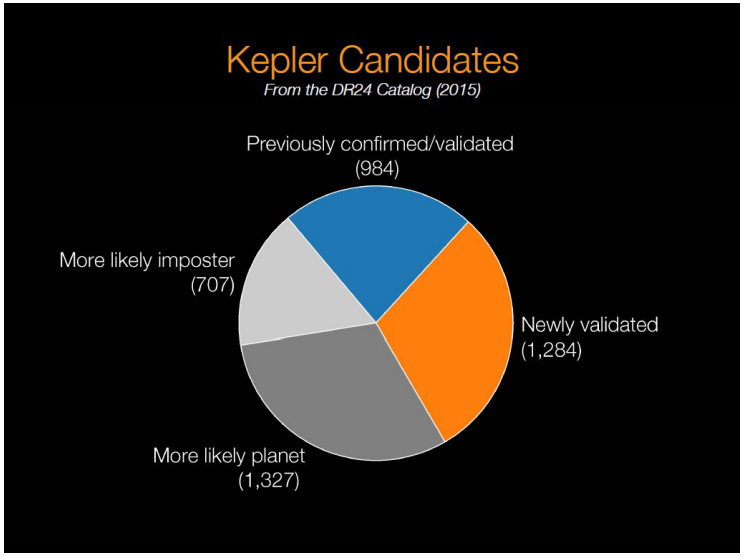


Transit Shape Analysis

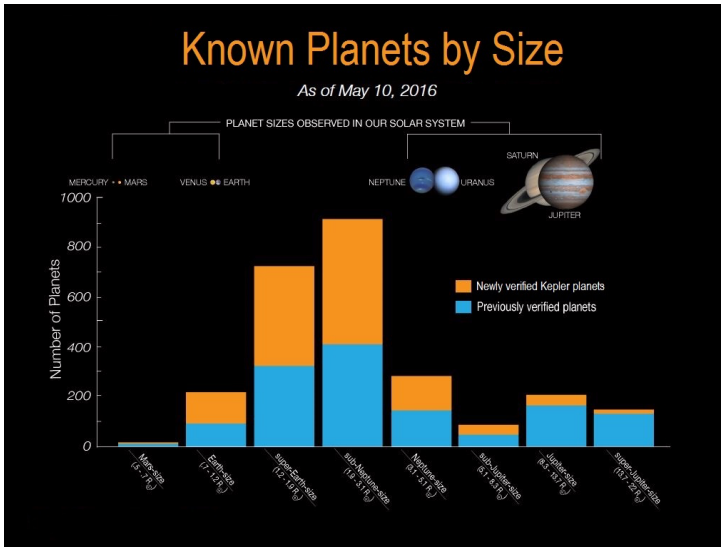
- Simulate transits of various scenarios
  - Binary/multiple star system
  - Background (blended) binary stars
  - Planet
- Compare the simulated transit shape to the observed transit
  - Quantify the similarity between the simulated scenarios and observations using Bayesian analysis



Shape-Based Validation Results

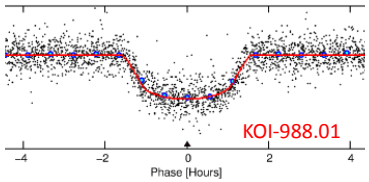


Confirmed/Validated Planet Sizes

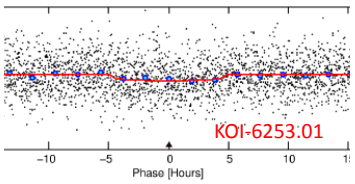


Confirmation/Validation is Limited

- When the signal is weak validation does not work as well



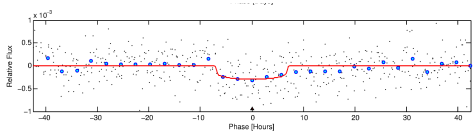
Easy to validate
(Validated as part of a multi system)



Not easy to validate
(Still only a planet candidate)

How Reliable Are Planet Candidates?

- But the Kepler telescope can also create signals that look like planet transits
- Example: KOI-6981.01
  - Shallow planet candidate at 593 days, 1.9 R_e
    - Passed all tests!

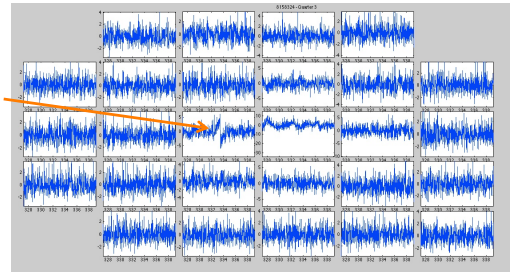


    - Super-Earth in the habitable zone?
    - Observed 3 transits

But KOI-6981.01 is Not a Planet

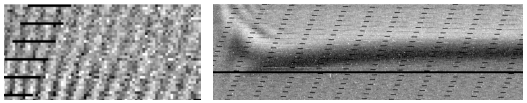
- Examination of how the light changed in each pixel shows something very different:

Sudden Pixel Sensitivity Dropout (SPSD):
A discontinuous loss of sensitivity in a pixel, usually due to a cosmic ray hit.
This is one of three transits; the other two did not look like transits at all

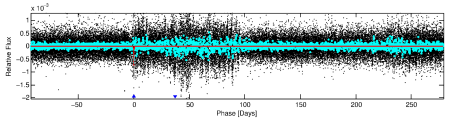


Many TCEs Match the Orbital Period of Kepler (372 days)

- Kepler's temperature changes as it orbits the Sun
- Leads to orbit-coupled periodic spurious signals

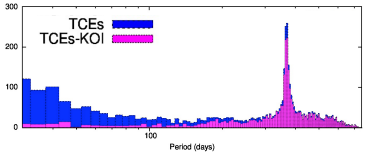


Images of pixels during tests with no light



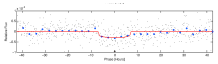
KOI 5302.01
Period 372 days
Marked FP on archive

- Leads to many many detections near 372 days



How Reliable Are Planet Candidates

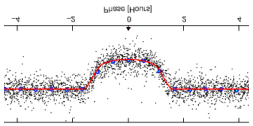
- About half the planet candidates are now confirmed/ validated
- But very few of the Earth-analog candidates are confirmed/ validated
  - Signal is too small for good analysis
  - Many of the detections with period about 365 days are instrumental problems with the telescope
    - So many of the ones thrown out may be real
- It can be very difficult to tell by looking at individual planet candidates



- But if we knew the fraction of planet candidates that were bad, then we can do statistics!

Measuring Reliability

- We want realistic data that contains no transits
  - Very accurate simulation is very difficult
    - Will miss causes of false positives that we don't know about
  - But actual data has transits from real planets
- Solution: turn the data upside down
  - Very few things left that look like transits
    - Real transits look like things getting brighter, so they won't be detected
- Currently ongoing activity



How Many Stars Have Planets?

- "Occurrence Rate": Need to completely and carefully understand the data
  - Weed out false positives, account for missed planets
- Several estimates in the literature
  - Somewhat different results
  - Different assumptions about reliability
- On average, there is at least one planet per star