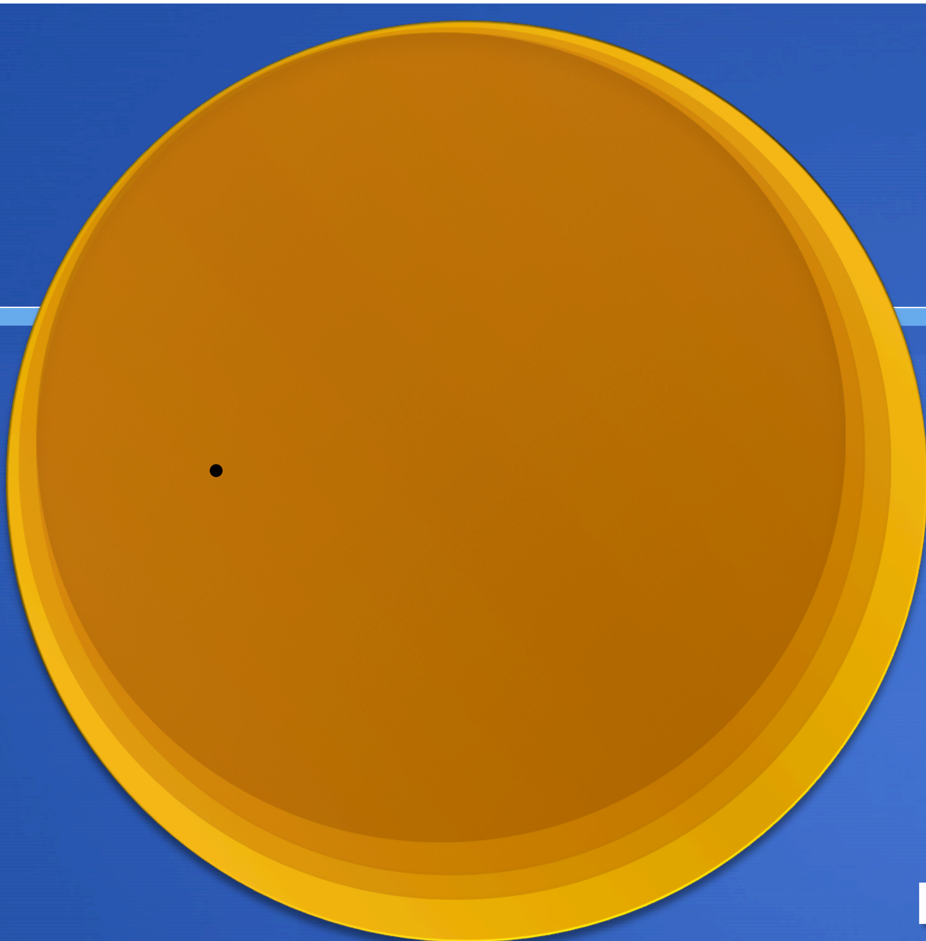


Space-Based Search for Exoplanets

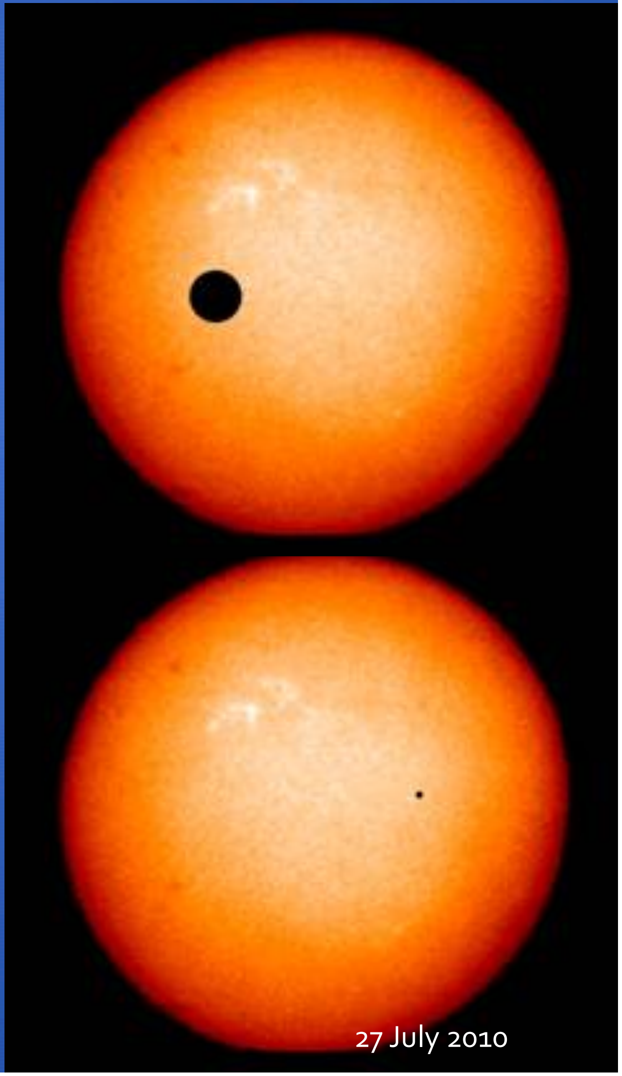
David R. Ciardi
NASA Exoplanet Science Institute

Outline of Talk

- Why go to space?
- CoRoT
- Kepler
- Where do we go next?

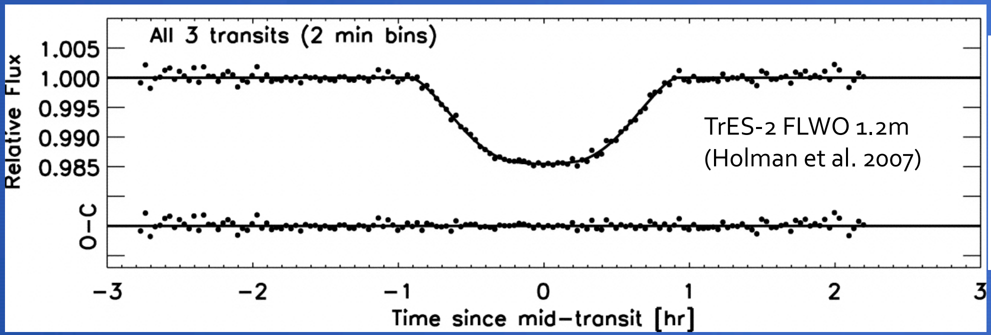
Why Go to Space

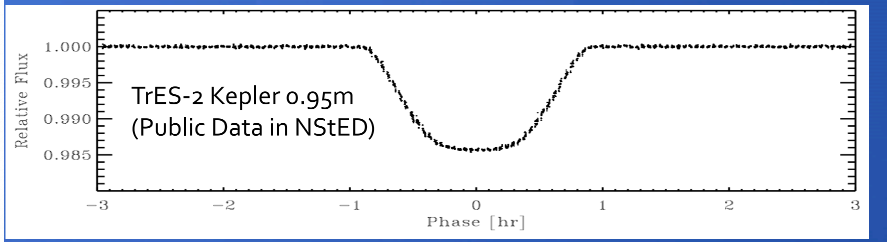
- Earth-like transit around a Sun-like star
  - 0.01% (0.1 mmag) transit depth
  - 1 transit every 12 months lasting 12 hrs
  - Probability of transit: ~0.5%
    - 1/200 × the fraction of stars with earths
- Space missions provide access to
  - Extremely high precision photometry
  - Long and uninterrupted baselines
  - Extremely large number of stars



Why Go To Space

- Nothing special about a telescope in space vs on the ground
  - Collect the same number photons in the same time frame
  - Statistical (white) noise properties are very similar

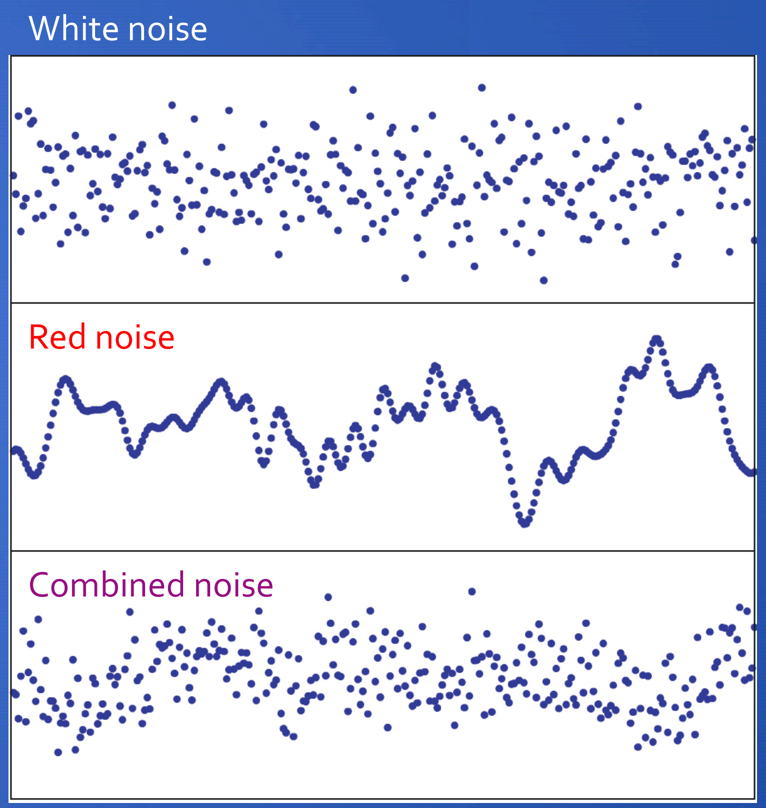




- So Why Space …
  - Minimize the ground-based (correlated) noise
  - Long baseline coverage to find the long period planets

Why Go To Space - Precision

- Uncorrelated (white) noise governed by normal statistics
  - Decreases with number of photons collected (star brightness, telescope size, integration time, binning)
  - Photon noise is primary source
- Minimize the correlated (red) noise
  - Independent of target brightness or number of measurements
  - Noise correlated from point to point – limits ability of smoothing/binning
  - Sources
    - Weather ✔
    - Comparison star noise ✔
    - Seeing changes ✔
    - Air mass (chromatic) effects ✔
    - Tracking/guiding errors ✔
    - Flat-fielding errors (✔)

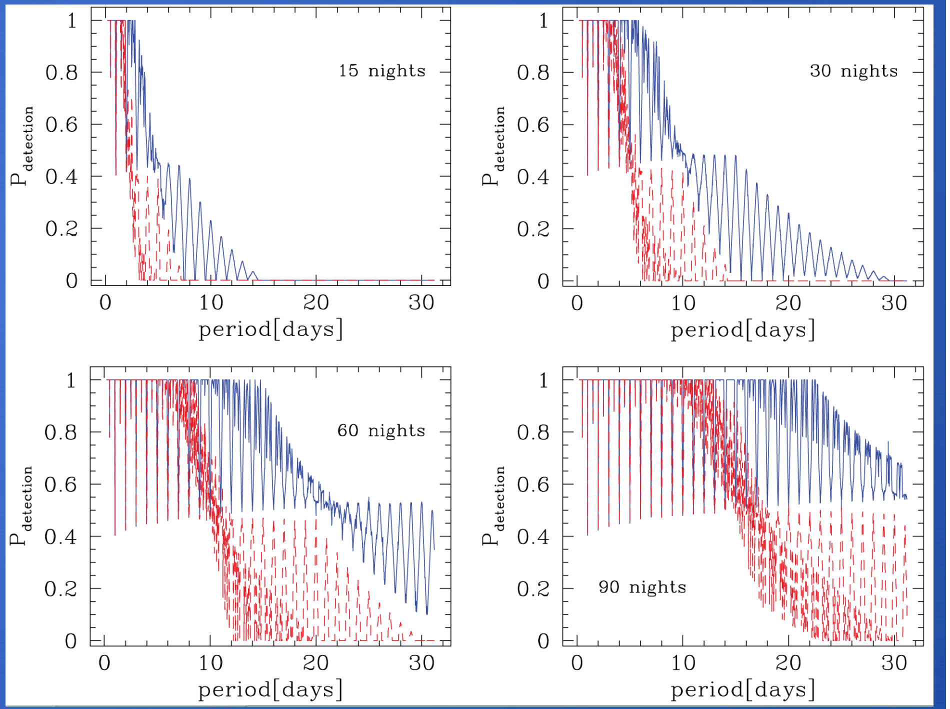


Pont 2006

Why Go To Space - Coverage

- Sensitivity to orbits of various periods is dependent upon the observing cadence and length of observing run
- The longer the orbital period the longer the observing time baseline that is needed
- Observing from the ground is limited by
  - Diurnal Cycle
  - Weather interruptions
  - Annual Cycle
- Mitigate some of this by having a network of telescopes at various longitudes (Gaspar's talk)

Ground Window Function

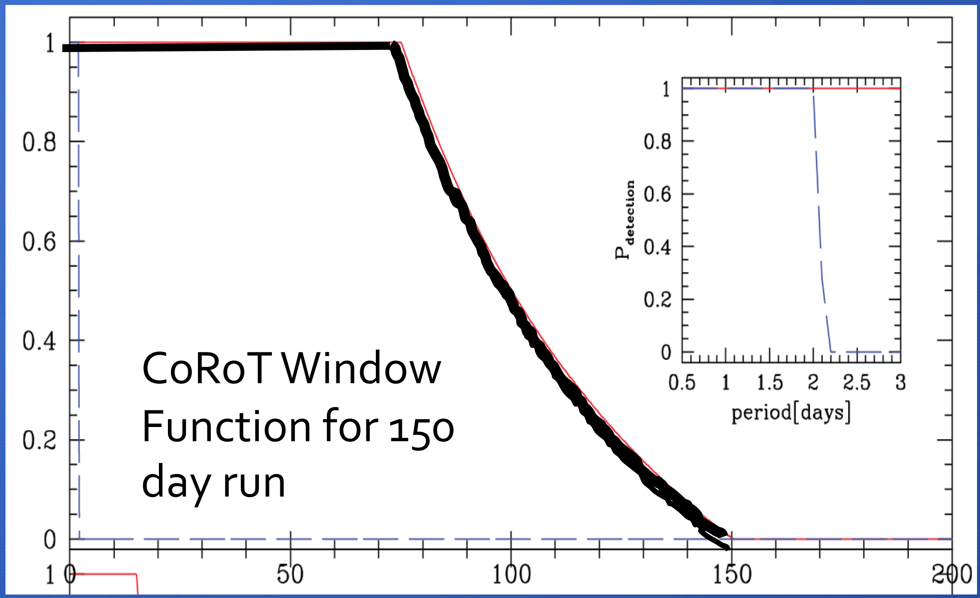


von Braun, Kane, & Ciardi 2009

Why Go To Space - Coverage

- Moving to space eliminates all three of these and enables uninterrupted and long observing cycles – in particular, the weather interruptions and the annual cycle

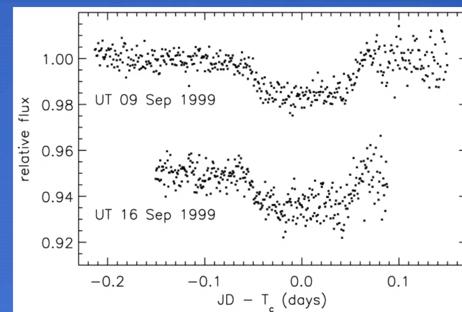
- To detect a 1-year orbit with a minimum of 3 transits → need 3+ years of interrupted observations



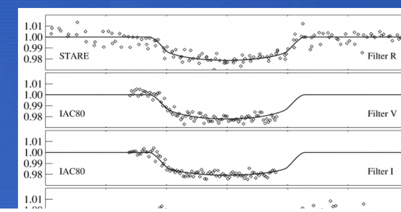
von Braun, Kane, & Ciardi 2009

Surveying from Space …

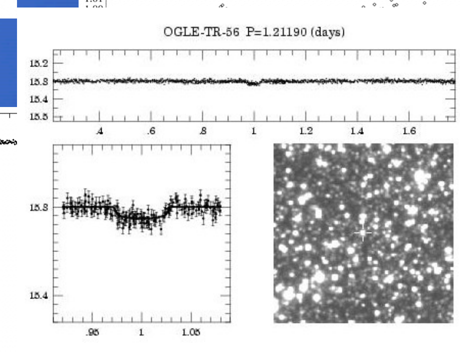
- Has been made possible by the success of the
  - Ground-transit surveys (e.g., TrES, XO, OGLE, SuperWASP, HATNet)
  - Demonstrated high-precision photometry from spacecraft (e.g., MOST, HST)
- Followed by the explosion of follow-up characterization work (see Giovanna's talk)
- CoRoT approved 2000
- Kepler approved 2001



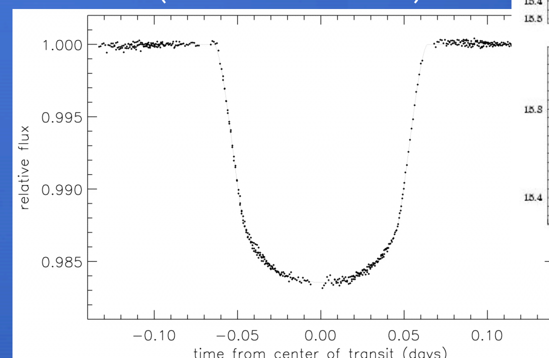
HD209458 Transit Discovery (Charbonneau 2000)

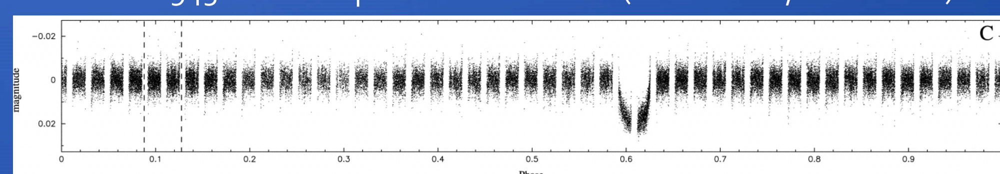


TrES-1 Discovery (Alonso 2004)



OGLE-TR-56 Discovery (Konacki 2003)



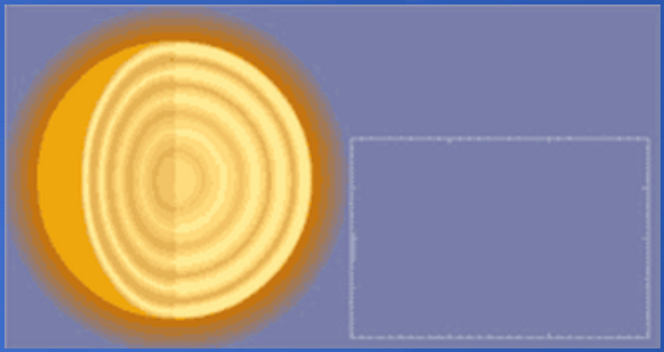


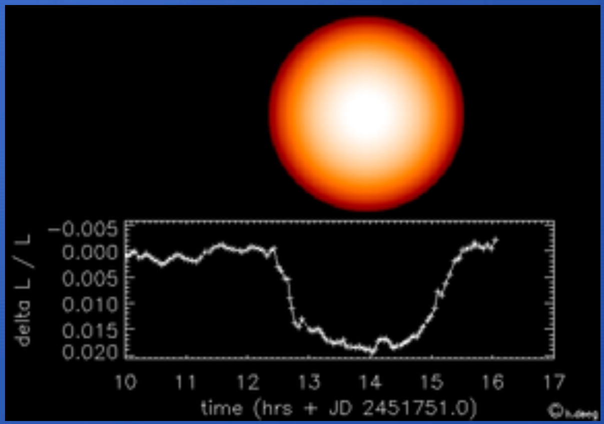
HD209458 Follow-up with HST & MOST (Brown 2001; Rowe 2006)

- Convection, Rotation and Transits Mission
- The first space mission with science dedicated to the discovery of exo-planets
- Launched: 27 December 2006
- Primarily CNES (France) with support from ESA, Austria, Belgium, Germany, & Spain

CoRoT: Mission Goals

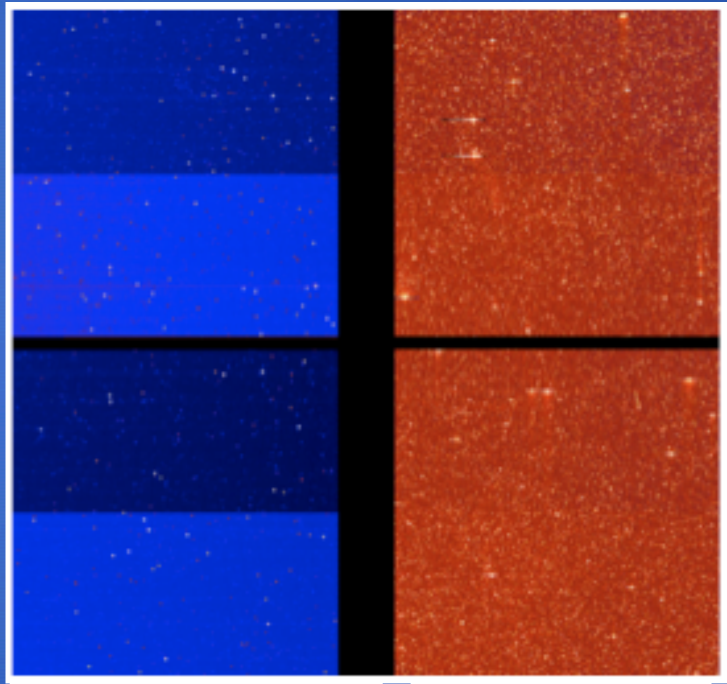
- CoRoT has 2 major scientific programs
  - Stellar seismology
  - Exoplanetary Transits
- Have similar requirements
  - High precision photometry
  - High duty cycle
  - Long duration observations





CoRoT: Differing Requirements

- Stellar seismology
  - 10-100 stars
  - Precisions of 10^{-6}
  - Very bright stars (V < 10 mag)
  - Shorter duration runs (20 days)
- Exoplanetary Transits
  - 10,000 – 100,000 stars
  - Precisions of 10^{-4}
  - Relatively faint stars (V 10 – 16 mag)
  - Long duration observations (150 days)
- Resulted in
  - Two separate channels
  - Interlaced long and short duration runs
  - Low-dispersion prism in exo-channel (3-color)

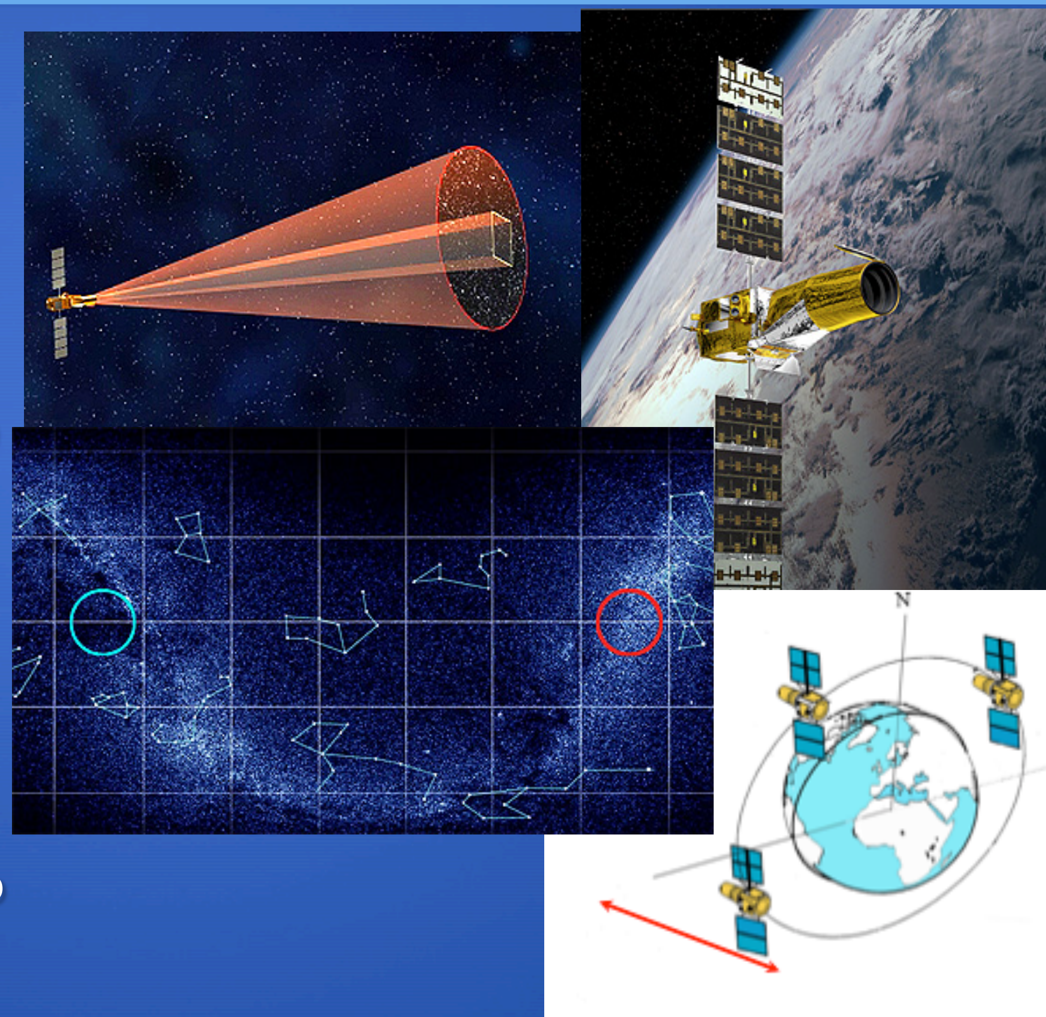


Seismo Channel: 32 s readout

Exo Channel: 32 s or 512 s readout

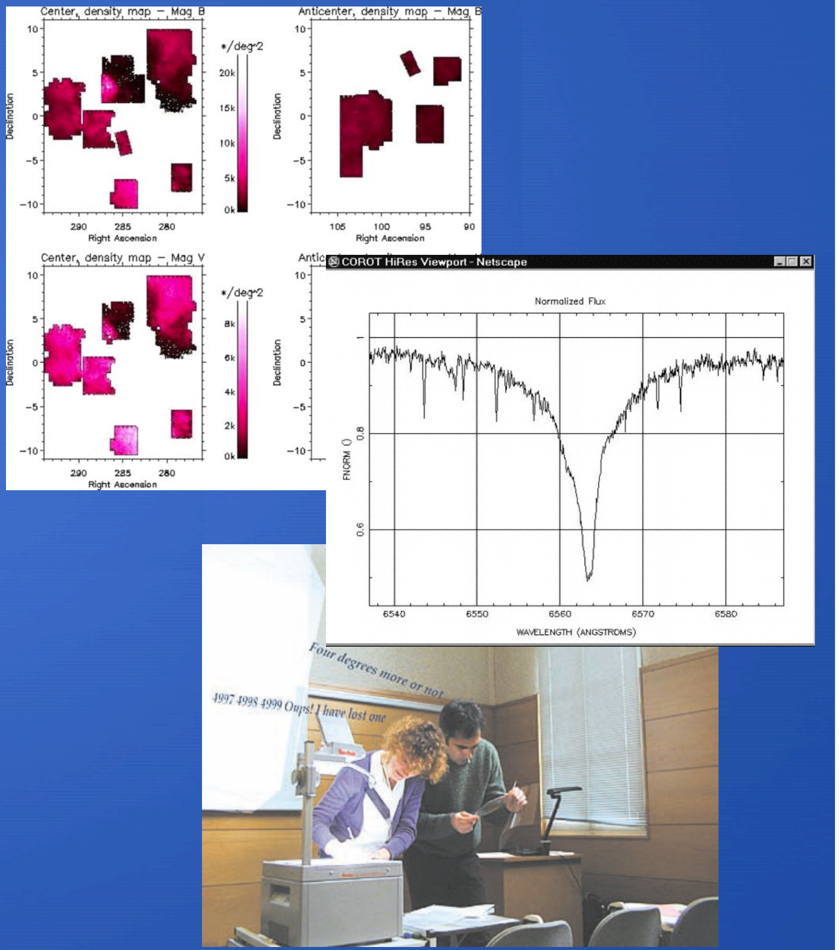
CoRoT: Telescope & Orbit

- 0.3-m telescope
- Four 2048 × 2048 CCDs
  - 2.3″ per pixel
- Earth polar orbit (864 km)
- Field of Regard: 10^{o}
  - $3^{o} \times 3^{o}$ Field of View
- CoRoT "Eyes"
  - α~6h & 18h; δ~0^{o}
  - Spacecraft flips every 150 days



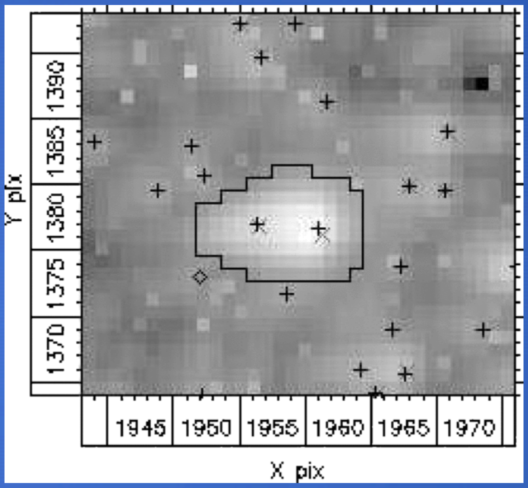
CoRoT: Preparatory Program

- Intensive pre-launch preparation and target selection program
- Had to balance seismology and exoplanet program desires
- Pre-launch archives of data collected from literature and newly collected data on thousands of candidate stars
  - Used for Final Field & Star Selections

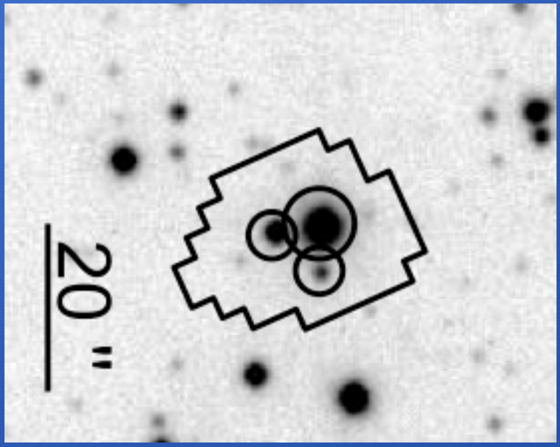


CoRoT: Survey Strategy

- 150 day long runs
  - 20 day runs are also searched but there is less information on those fields and sensitivity to longer orbital periods is limited
  - 2 runs per year (6 full runs completed)
- Coadd flux in aperture on-board and download lightcurve
  - 32 s reads – coadded to 512 seconds
  - Small subset can have 32 s sampling
    - These stars identified in "Alarm" mode from the daily downloads and quick look processing
  - Small subset: postage stamps (imagettes) are downloaded
- 10000 targets per run
  - Typically 300 candidates events
  - 50 stars selected for follow-up
  - Typically 2 – 4 planets/run



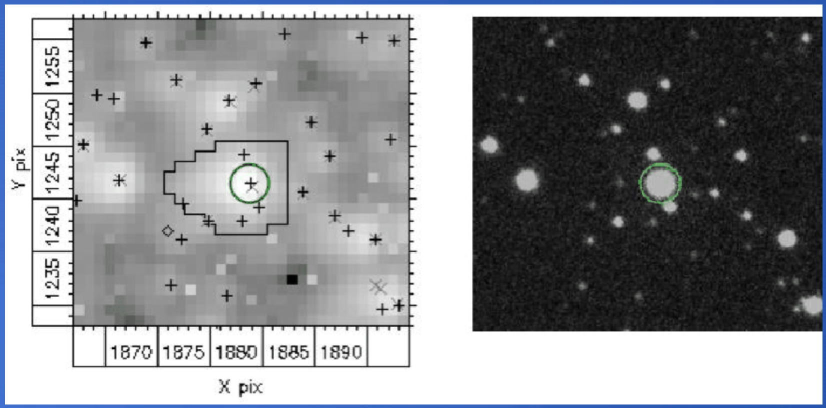
Aperture definition for a CoRoT target showing positions of all stars detected in ground program (Deleuil 2009)

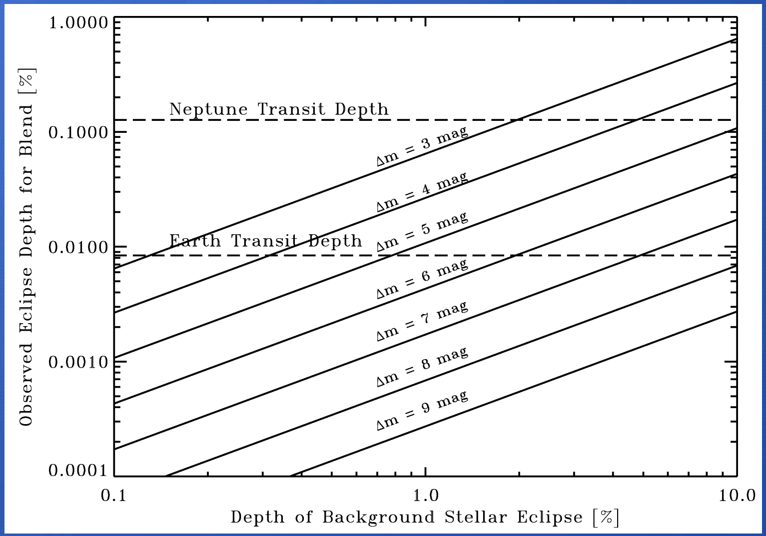


High resolution image and aperture definition for CoRoT-3 (Deleuil 2008)

CoRoT: Follow-Up Work

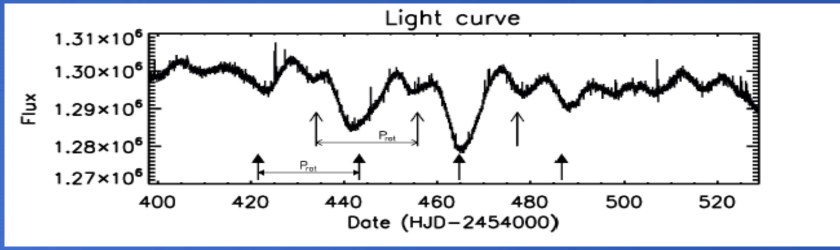
- Modeling of candidate light curves – only self-consistent good candidates are passed to follow-up
- Blended eclipsing binaries are main source of false positives
  - Background system
  - Hierarchical triples
- Photometric Follow-Up
  - In/out transit searching for EBs at time of transit
  - Easy to detect 10-50% EB
- Candidates that pass photometric follow-up are sent for RV confirmation

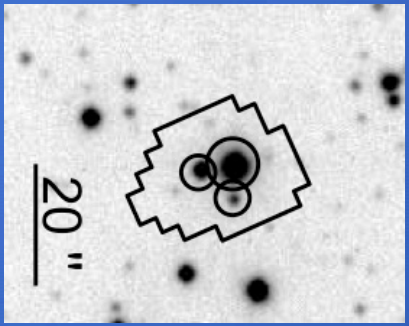


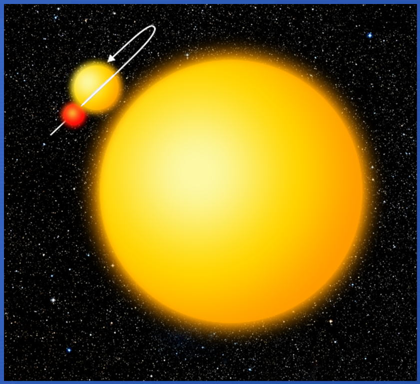


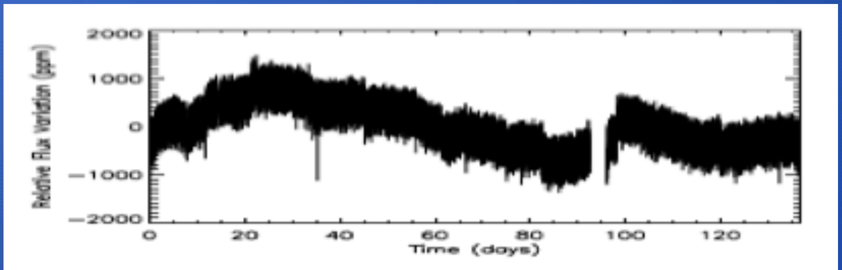
CoRoT: Challenges

- Active stars
  - Hides the transits
  - Makes follow-up difficult
- Background contamination
  - All surveys have this problem
  - CoRoT center field is crowded
- Earth-orbit
  - SAA, jumps, and discontinuities
- Half focal plane inactive as of March 2009
- Manpower
  - All projects have this problem



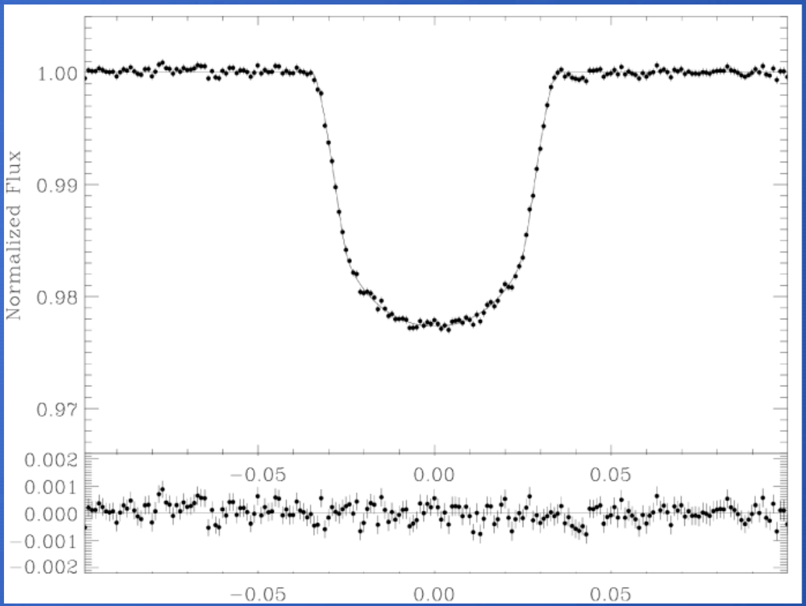






CoRoT: Results

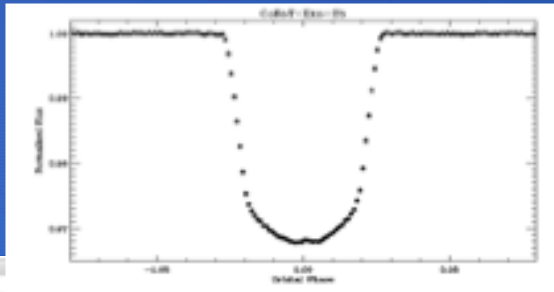
- 14 exoplanets (with more coming)
  - 7 in anti-center field
  - 7 in center field
- Mostly Jupiter mass planets
  - Mass ~ 0.02 – 22 M_{Jup}
  - Orbital Period ~ 0.85 – 95 days
- CoRoT-1b first announced 2007
  - M = 1.03 M_{Jup} ; R = 1.43 R_{jup}
  - P = 1.51 days ; a = 0.03 au

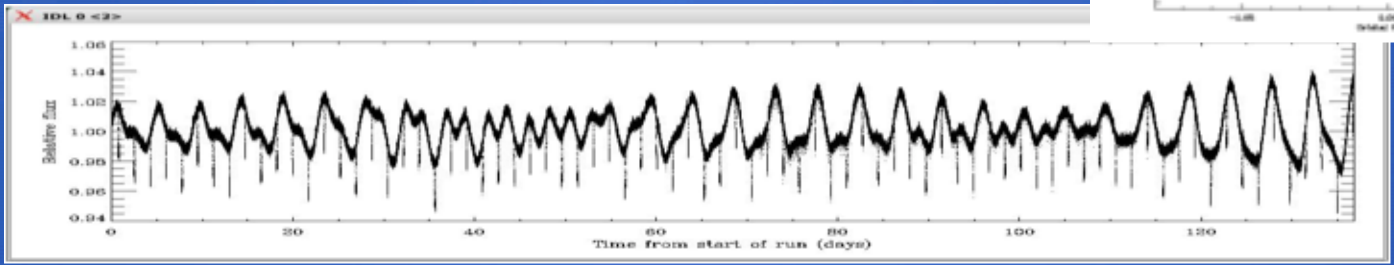


CoRoT-1 Phased Curve
(Barge et al. 2007)

CoRoT: Jupiters around Active Stars

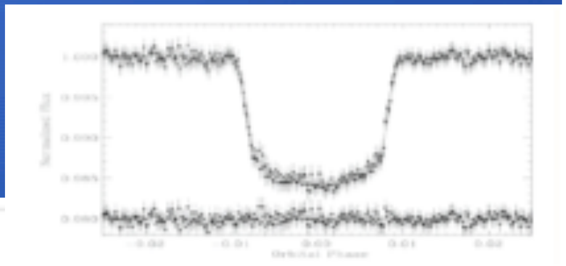
- CoRoT-2b
  - Period: 1.7 d; Radius: 1.5 R_J; Mass: 3.3 M_J;
  - Rotation of the star 4.5 d (G7V)

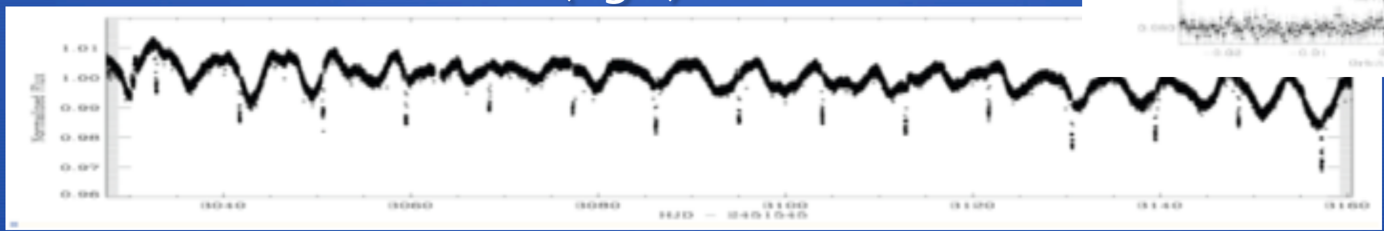




Alonso et al. 2008

- CoRoT-6b
  - Period: 8.9 d; Radius: 1.2 R_J; Mass: 3.3 M_J;
  - Rotation of the star 6 d (F5V)

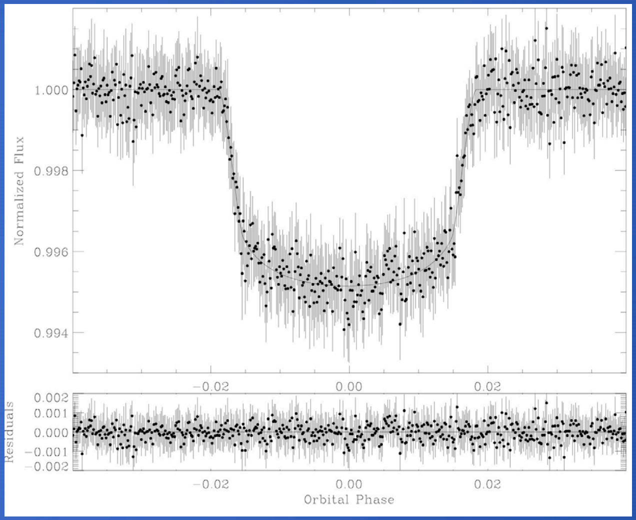




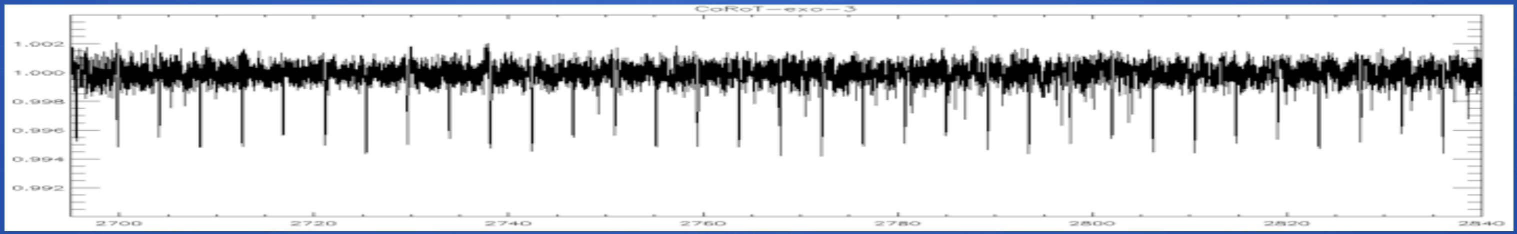
Fridlund et al. 2009

CoRoT: Planet or Brown Dwarf

- CoRoT-3b
  - P = 4.26
  - M = 21.7 M_{Jup}; R = 1.01 R_{Jup}
  - Star Rotation = 4 d (F3V)
- CoRoT-15b
  - P = 3.1 d
  - M = 60 M_{Jup}; R = 1.15 R_{Jup}
- Above the traditional BD/Planet mass limit of 13 M_{Jup}
  - But how did it get in such a short orbit?
  - Did it form like a planet or like a star?
  - Gas accretion plus migration?

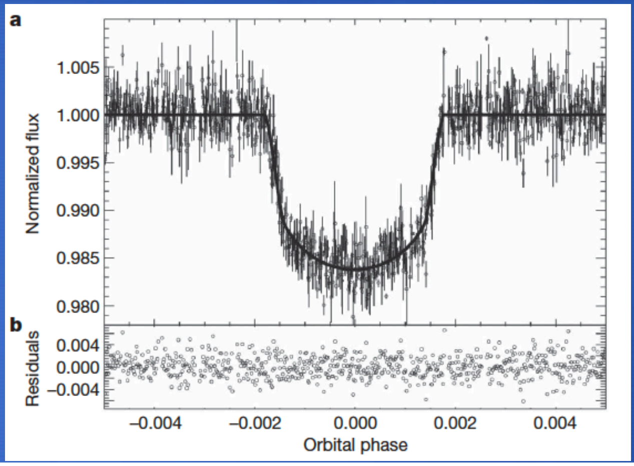


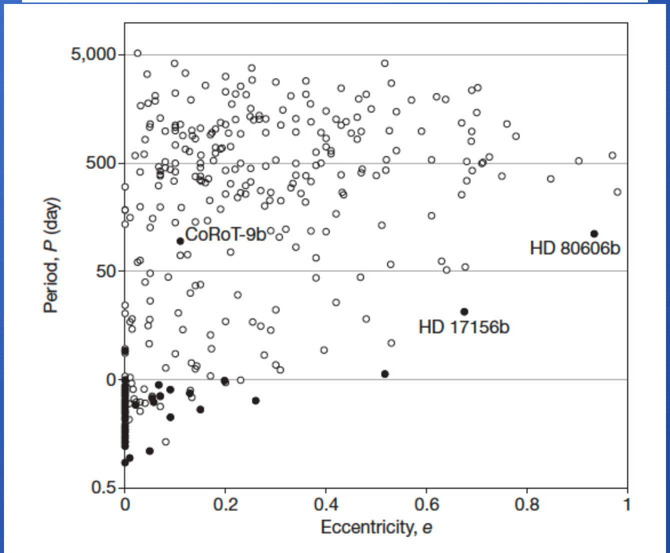
Deleuil et al. 2008



CoRoT: A temperate gas giant

- CoRoT-9b
  - $P = 95.27$, $e = 0.11$
  - $M = 0.84\ M_{Jup}$; $R = 1.1\ R_{Jup}$
  - Non-active G3V star ($M \sim 0.9\ M_{sun}$)
  - $T_{equilibrium} = 350$ K
    - At time of discovery, the longest known orbital period of the known transiting planets with very modest eccentricity
    - Composition H + He + 20 M_{earth} core



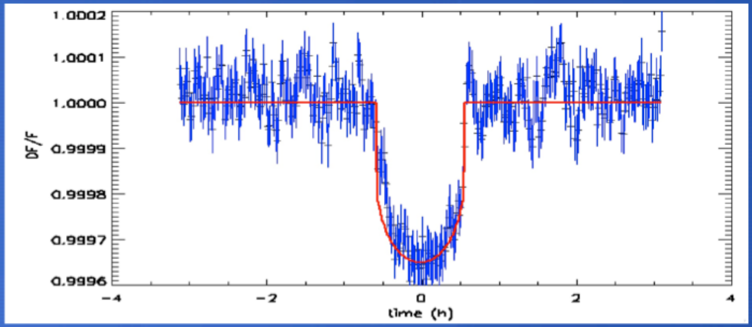


Deeg et al. 2010

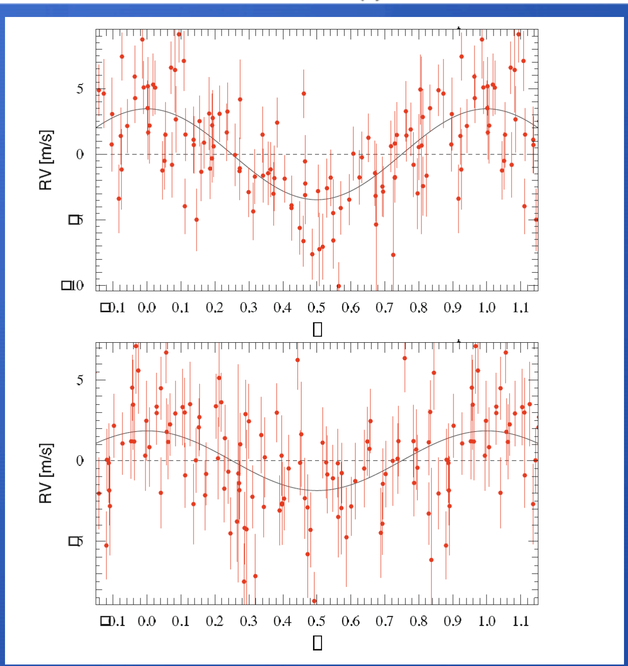
CoRoT: The Smallest Transiting Planet

- CoRoT-7b
  - P = 0.85 days
  - M = 4.8 M_{earth}; R = 1.7 R_{earth}
  - Active G9V star Prot = 23 days
  - Rocky planet

Leger et al. 2009

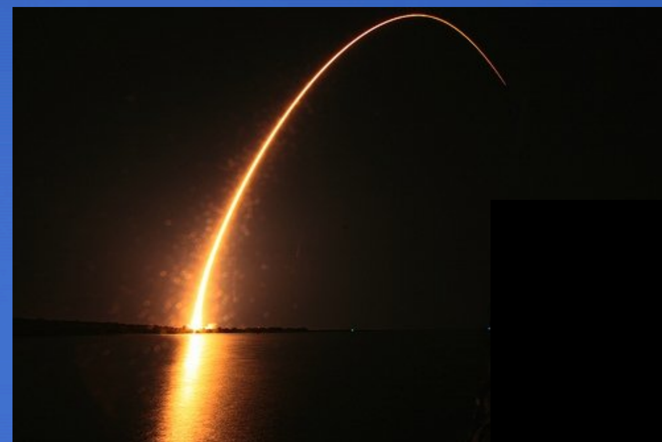


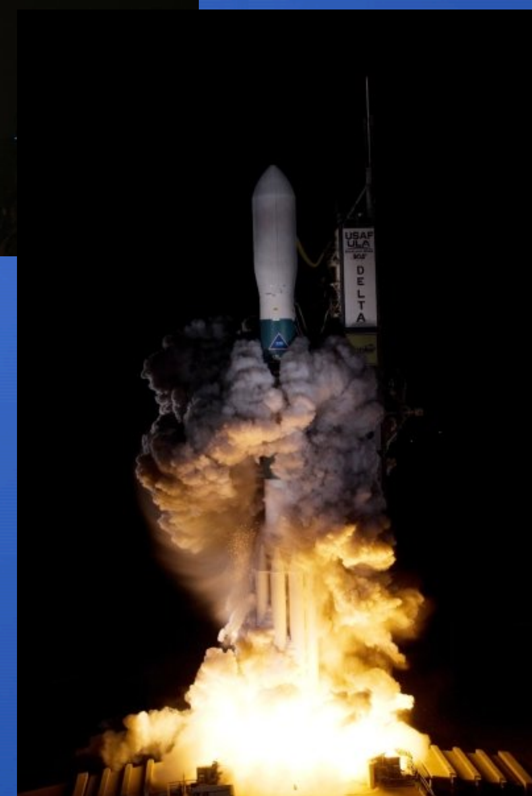
- Radial velocity very challenging because of stellar activity
  - Stellar activity ~ 5 m/s
  - 100+ RV observations
  - see Suzanne Aigrain's Talk
- RV Discovery of second (non-transiting) planet CoRoT-7c
  - P = 3.7 days
  - M = 8.4 M_{earth}



Queloz et al. 2010

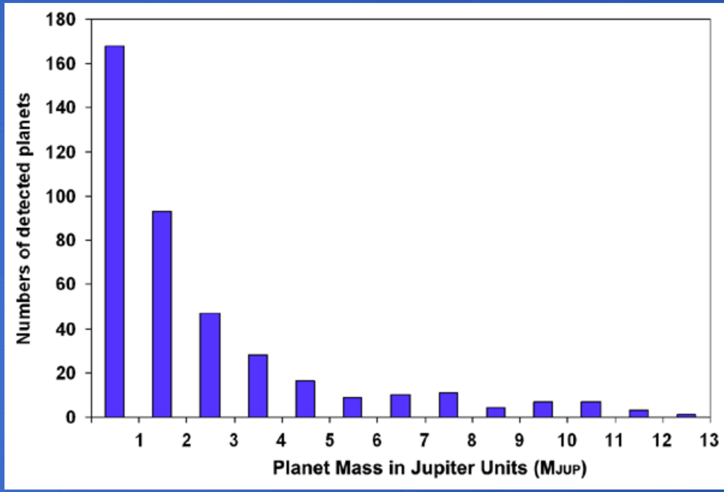
- NASA's first mission dedicated to the exploration of exoplanets
- The first space-mission designed solely for the detection of earth-like planets around sun-like stars
- Launched: 7 March 2009

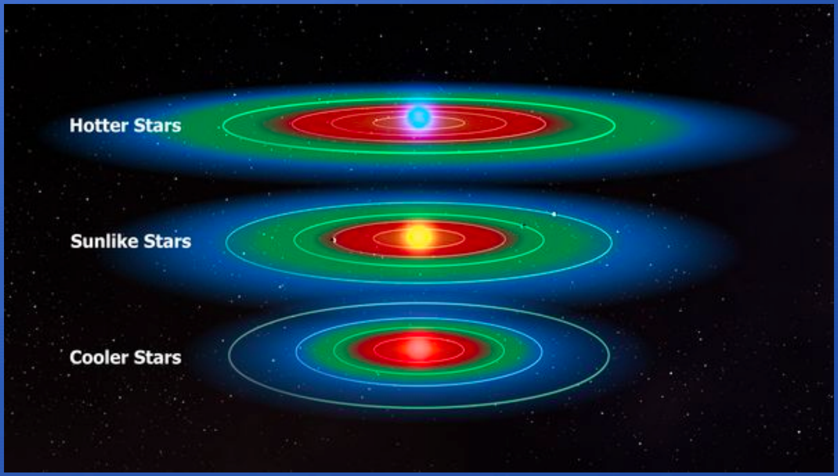




Kepler: Mission Goals

- Determine the frequency of planets in the habitable zones around a variety of stellar types
- Related Goals
  - Determine frequency of planets
  - Determine orbital distributions of planets
  - Determine physical characteristic distributions of planets
  - Determine the properties of exoplanet-hosting stars



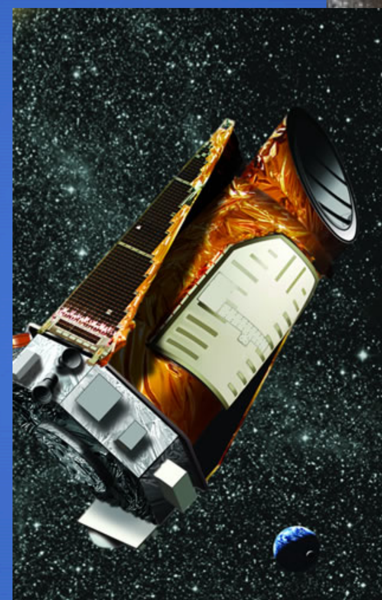


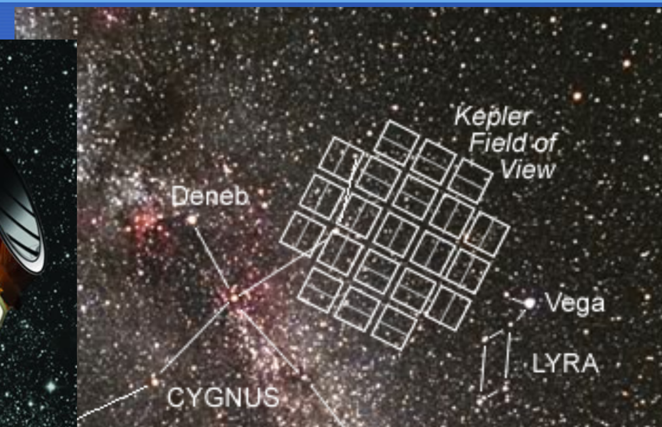
Kepler: Requirements

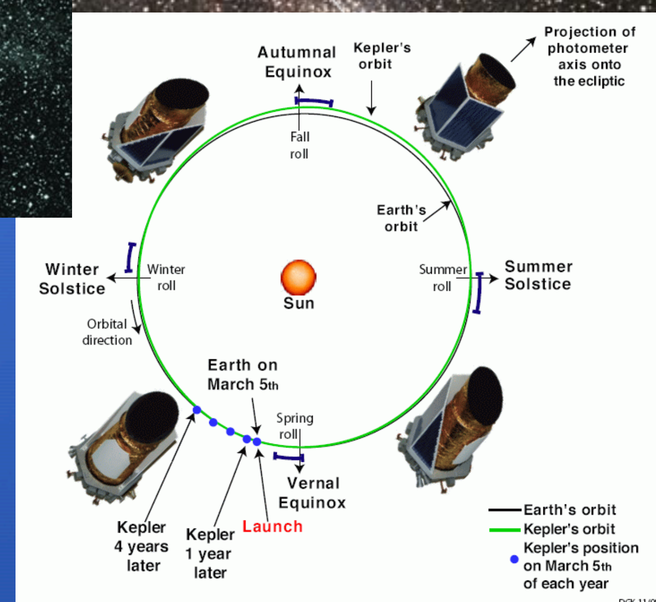
- 150,000 stars measured at precisions of 10^{-6}
  - Relatively faint stars (V = 10 – 16 mag)
  - Very large area of the sky
- Long duration observations (3+ years)
- Resulted in
  - Extremely large focal plane array
  - Earth-trailing solar orbit

Kepler: Telescope & Orbit

- 1.4 m (0.95m clear aperture) Schmidt telescope
- 42 2200 × 1024 CCDs
  - 4″ per pixel
  - 100 □ deg on CCDs
- Field Center in Cygnus
  - α~19.5h, δ~44.5°
  - b~13°; β~65°
- Earth-trailing solar-orbit enables uninterrupted staring of single field
  - Every 20 days – body point for download
  - Every 3 months spacecraft rolls 90° to maintain solar panels on Sun

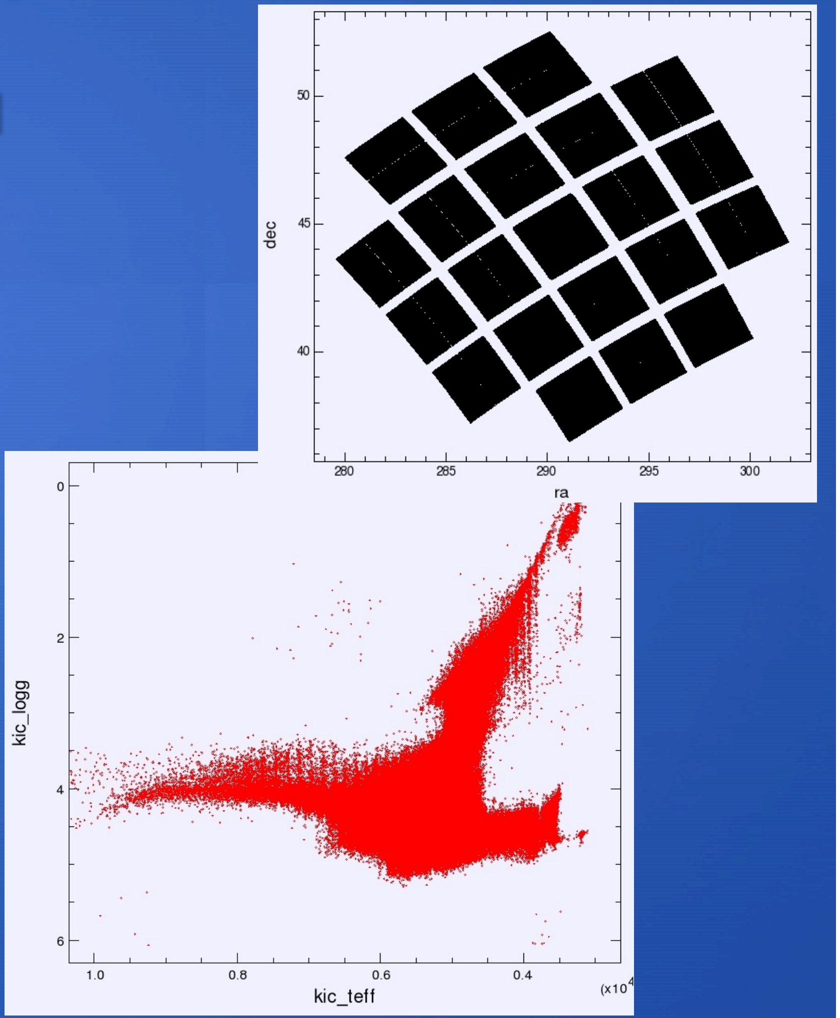






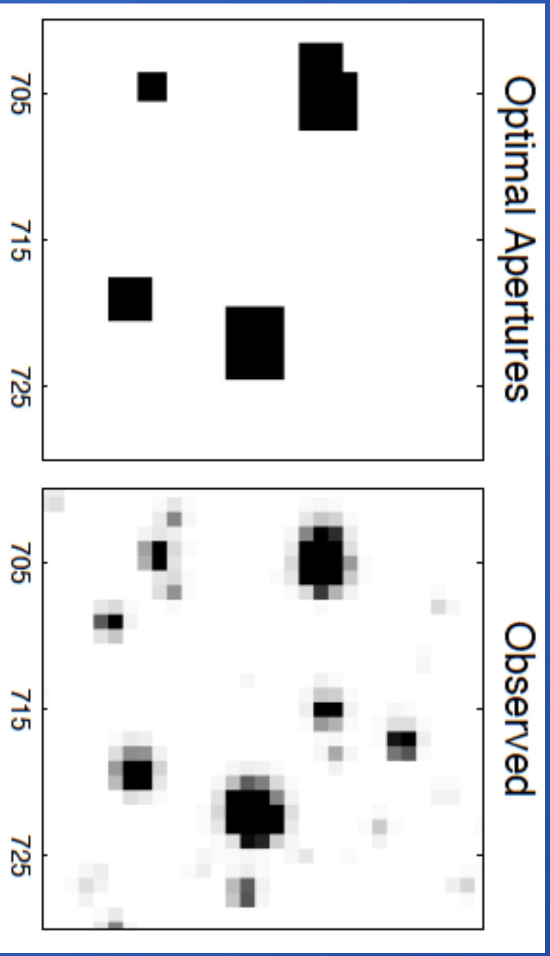
Kepler: Preparatory Program

- Intensive pre-launch preparation and target selection program
- Kepler Input Catalog
  - Imaged entire Kepler field in Sloan filters – coupled to 2MASS (JHKs)
  - Source catalog complete down to Ks~14 mag.
  - 14 million stars in KIC
  - Isochrone-modeling provides stellar parameters for catalog stars
- Used for Final Target Selections



Kepler: Survey Strategy

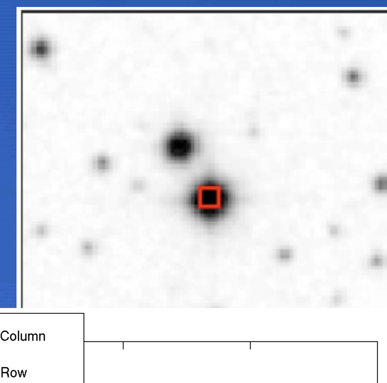
- Single field observed for 3.5 years
- Only interruptions to cadence
  - 20-day download (spacecraft body point to Earth)
  - 90-day spacecraft roll (maintain solar power)
- Monitor 170,000 stars
  - Down select target list to 150,000 after first year
- 1 minute integrations coadded on-board for 30 minute cadence
  - 1 minute cadence available for small subset of stars
- Download postage stamp images for each target

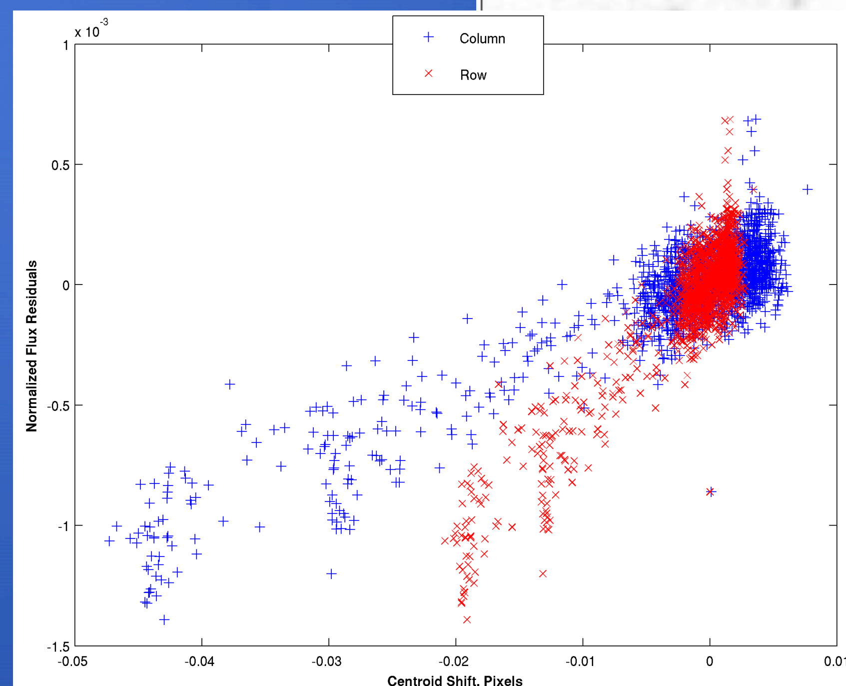


Batalha et al. 2010

Kepler: Follow-Up Work

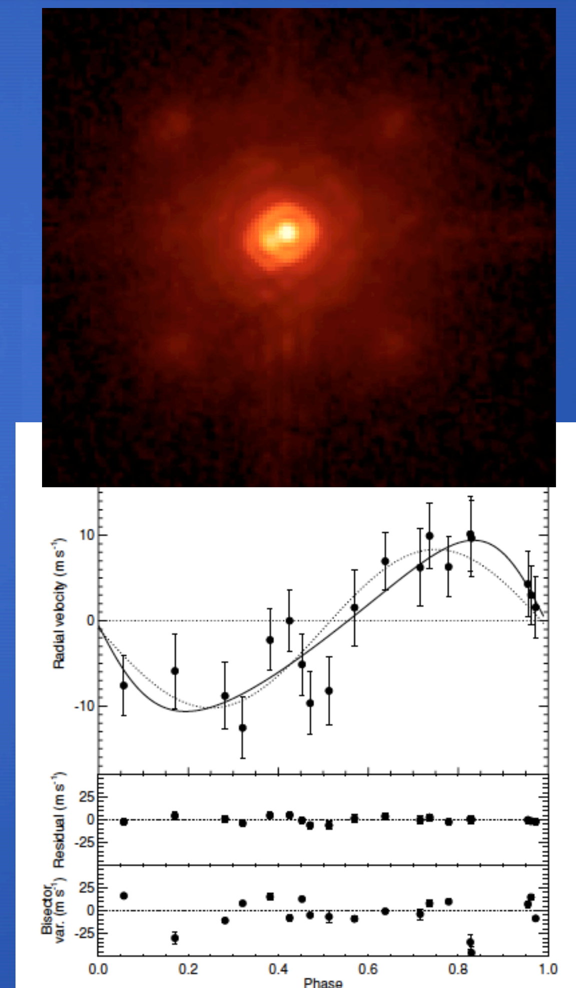
- Kepler downloads the pixels
  - Enables centroid measurements of center of light in photometric aperture
  - Centroids are good to a milli-pixel (0.004")
- Centroid shift during transit
  - Flux vs. Centroid Position (rain plots)
  - Need to know light distribution in aperture
  - Large rain plot shifts usually big warning sign





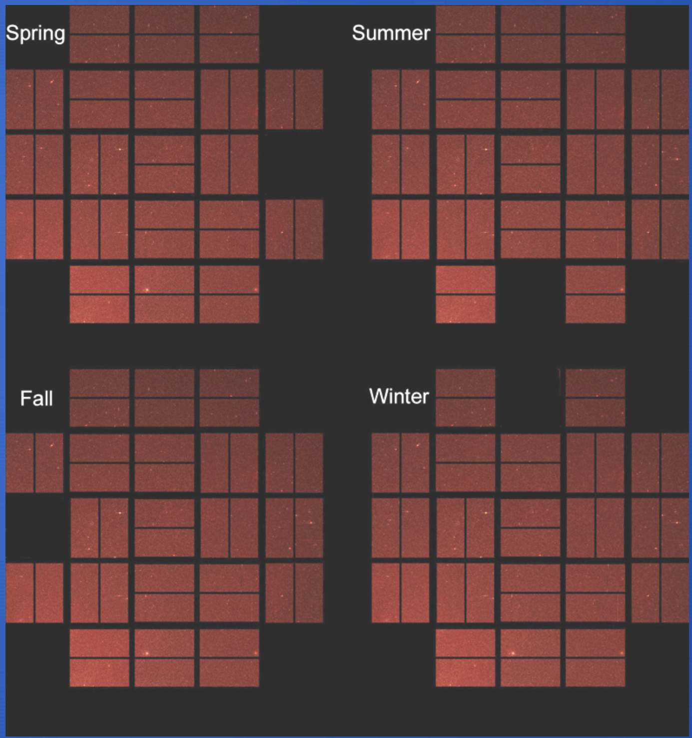
Kepler: Follow-Up

- First line of Vetting: Kepler data
  - Modeling of light curve and searching for secondary eclipse
  - Rain Plots
- Moderate precision spectroscopy to eliminate binary stars
- AO and speckle imaging
  - Nearby companions
  - Interpret rain plots
- Then: high precision RV follow-up



Kepler: Challenges

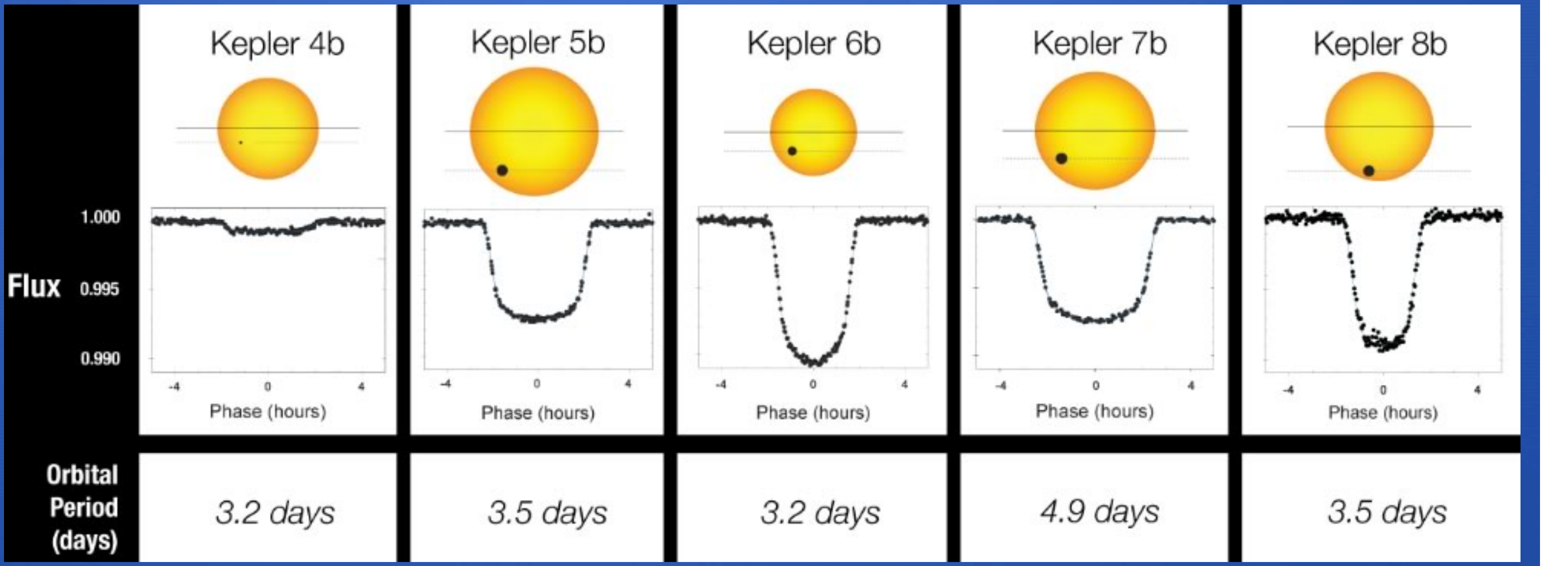
- Lost module
  - Spring 2010 1 of 21 modules failed
  - Module position rotates with quarterly rolls
- CCD issues (Caldwell et al. 2010)
  - "Argabrightening"
  - Various CCD artifacts and cross-talk
- Smallest planets detectable by Kepler are beyond the ability of the ground-resources to follow-up
  - Primary targets are faint (V= 12 – 15 mag)
  - Blend EB is 8-9 mag fainter
  - RV signature of an Earth around a Sun (1-3 m/s)
- Manpower
  - This is always an issue!



Kepler: First Planets

- Initial Batch of planets (January 2010)
  - $M = 0.08 - 2.0\ M_{Jup}$: $R = 0.3 - 1.4\ _{Rjup}$; $P = 3.2 - 5$ days
  - Kepler-4: Neptune-sized
  - Kepler-6,7,8: Saturn-sized
  - Kepler-5: Jupiter-sized

Borucki et al 2010
Koch et al. 2010
Dunham et al. 2010
Latham et al. 2010
Jenkins et al. 2010



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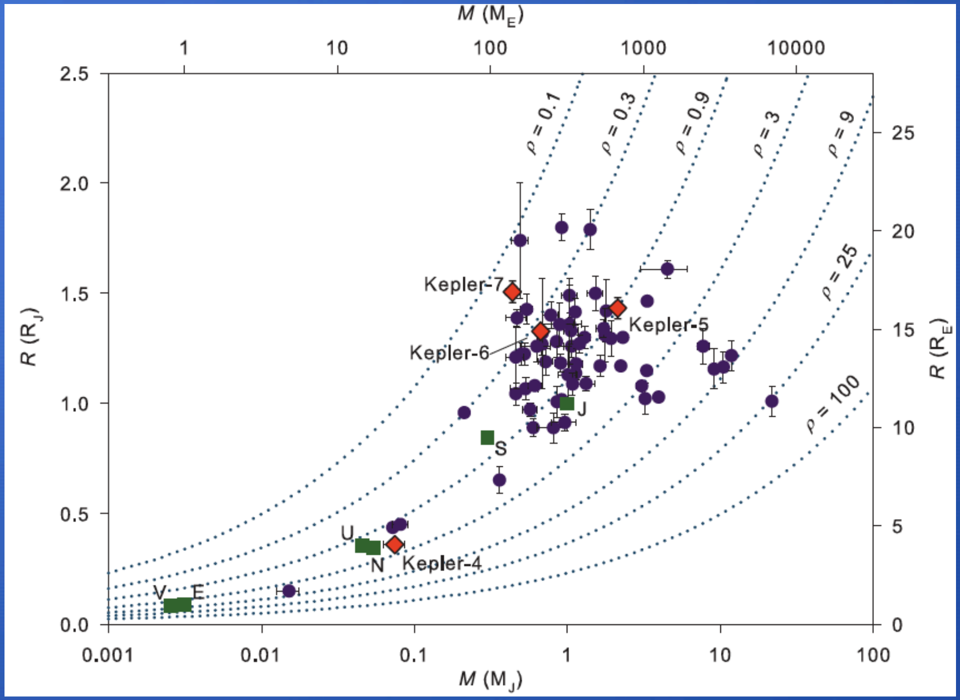
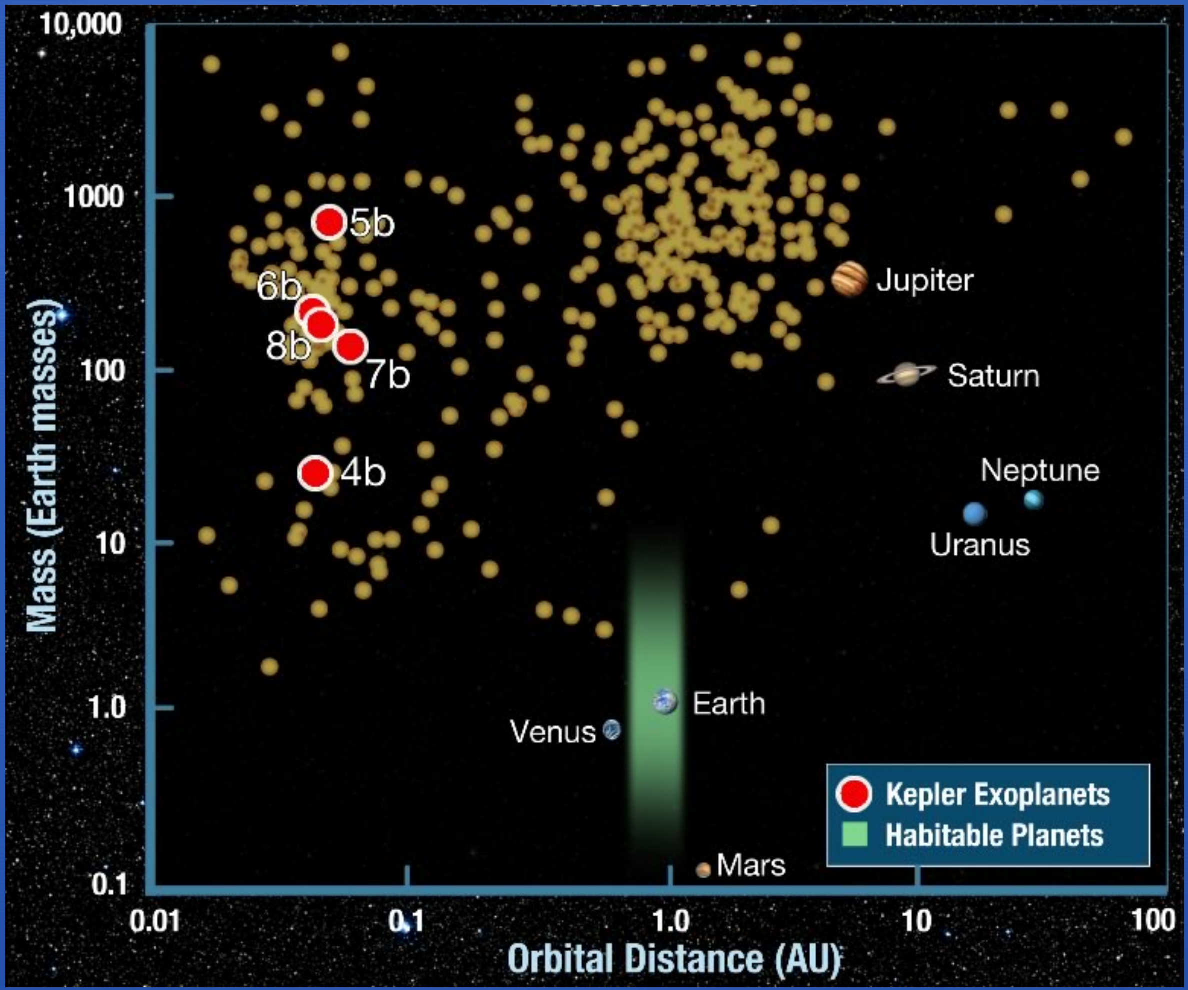


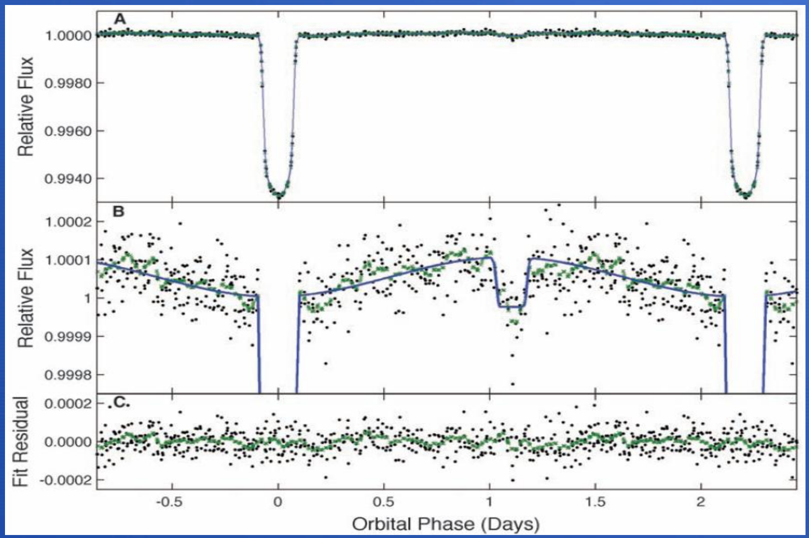
Latham et al. 2010

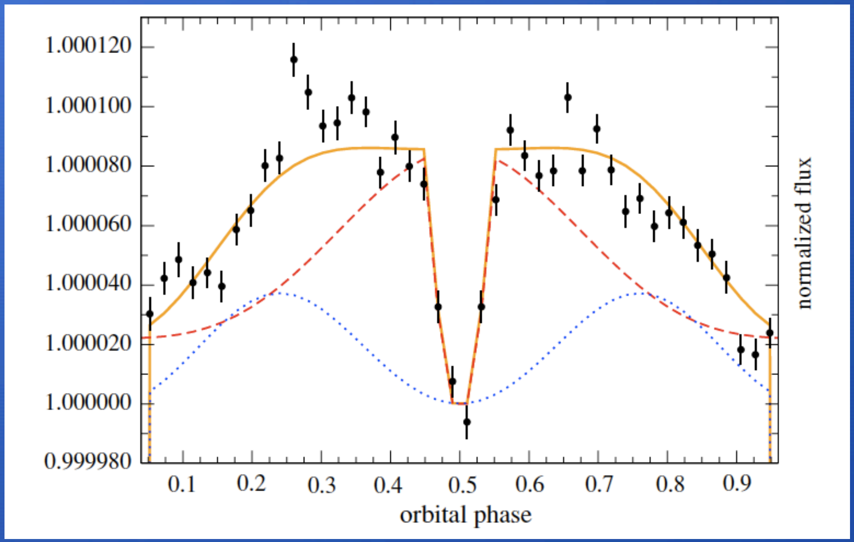
Kepler: First Planets



Kepler: Characterization

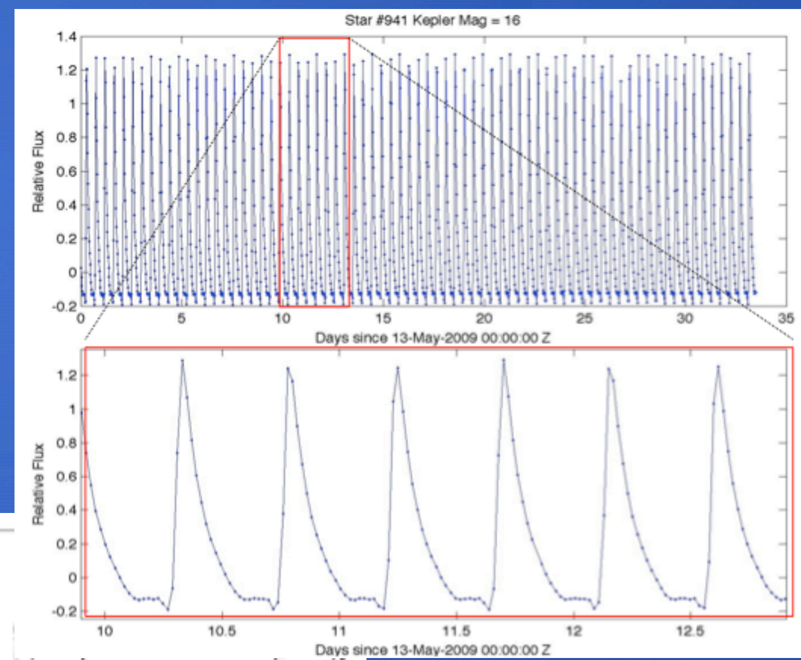
- HAT-P7-b: HATNet discovered planet in Kepler Field
  - Kepler measured the secondary eclipse, planet phase variations, and stellar ellipsoidal variations induced by the planet.
  - Teq ~ 2500 K (night) – 2900 K (day)
  - Star ellipsoidal variations of $\Delta R/R \sim 10^{-4}$

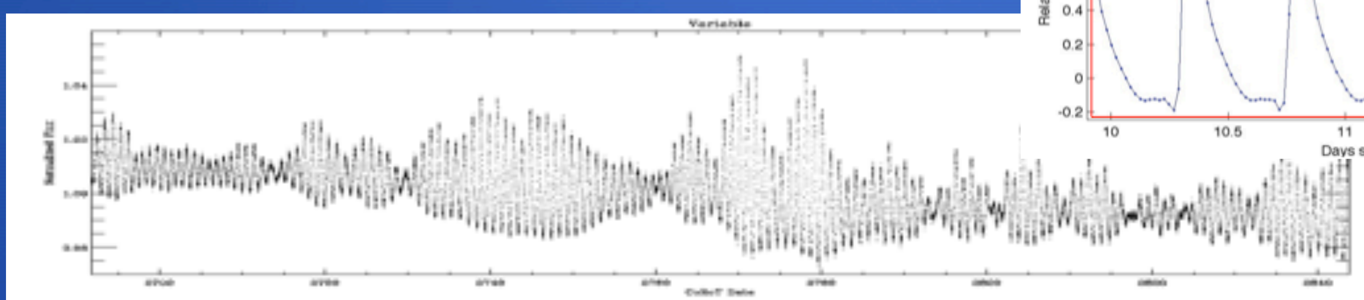




And …

- I haven't even talked about all the other astrophysics that can be accomplished with these data
  - Binary stars
  - Pulsating stars
  - Seismology
  - Eruptive Variables





Where do we go next?

- CoRoT and Kepler keep going
  - CoRoT just approved for 3 year extended mission
  - Kepler has only completed 1 yr of 3.5 year mission
  - More planets across a more diverse parameter space
    - Smaller planets
    - Longer Orbits
    - Multiple Systems – from transits and transit time variations
- Next Steps after CoRoT & Kepler
  - All-sky bright star transit survey
  - Provide targets for detailed planet characterization

In Closing …

- CoRoT and Kepler have redefined the boundaries of exoplanetary astrophysics – and astrophysics in general
- Truly a phenomenal and opportunistic time …