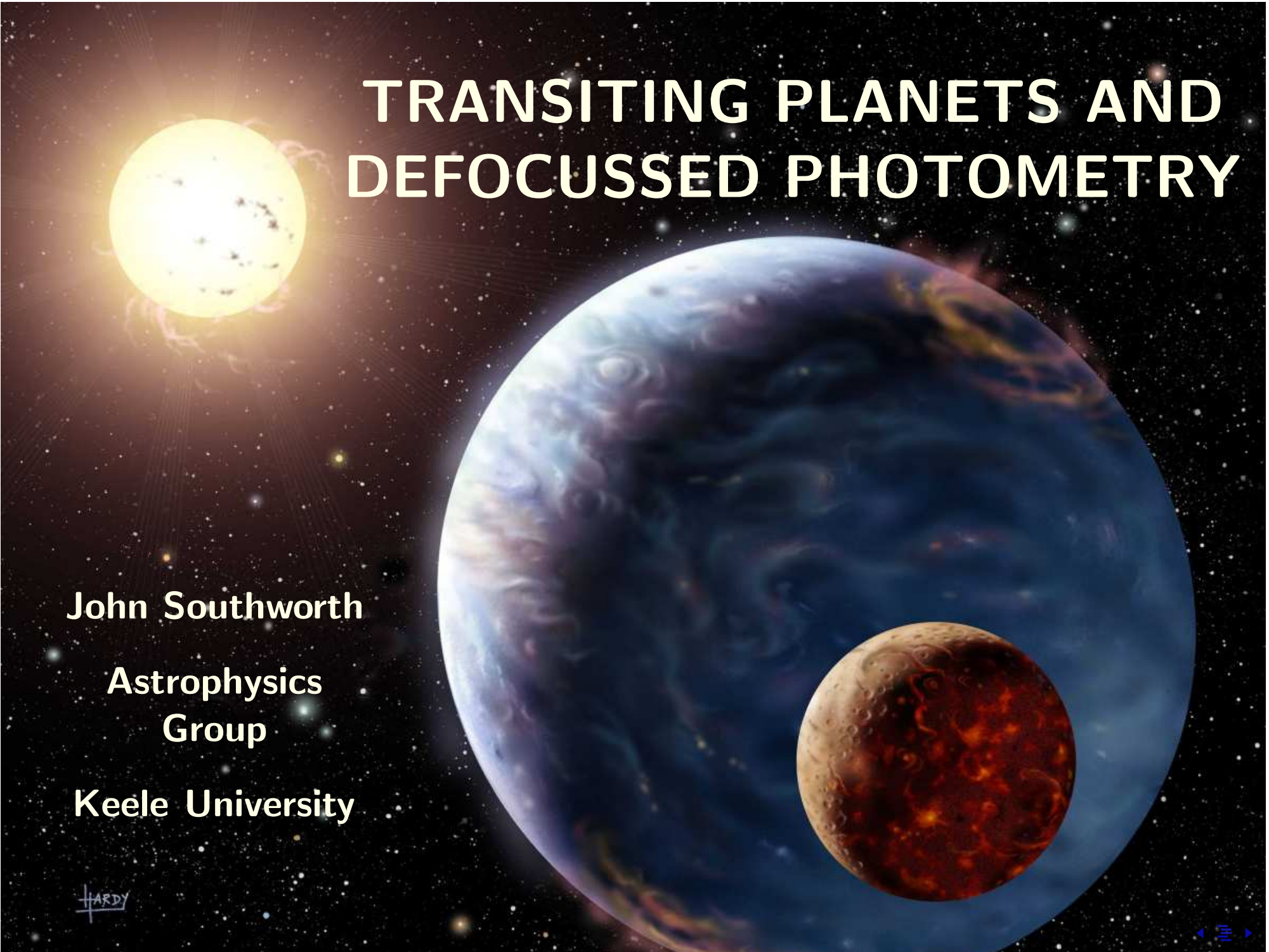
TRANSITING PLANETS AND DEFOCUSSED PHOTOMETRY



John Southworth

Astrophysics Group

Keele University

Extrasolar planets – a history

- 1940s and 1950s: false alarms
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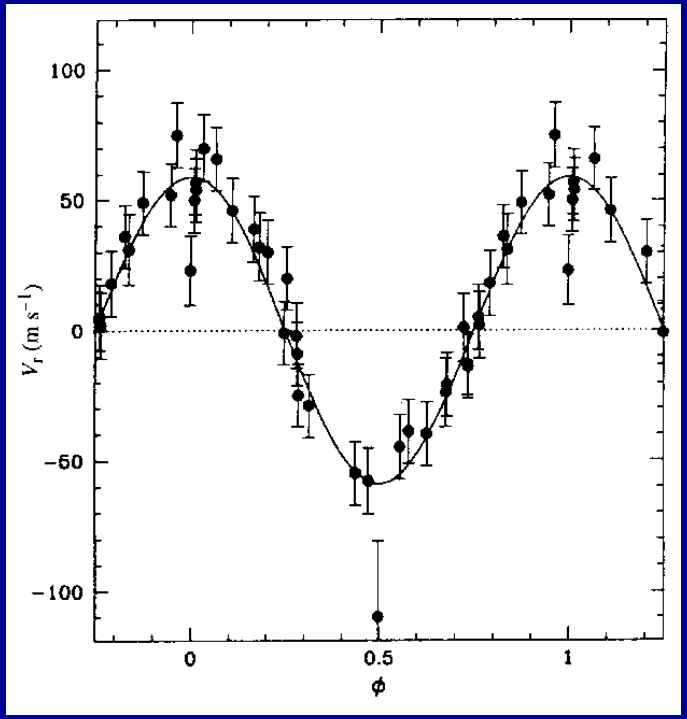

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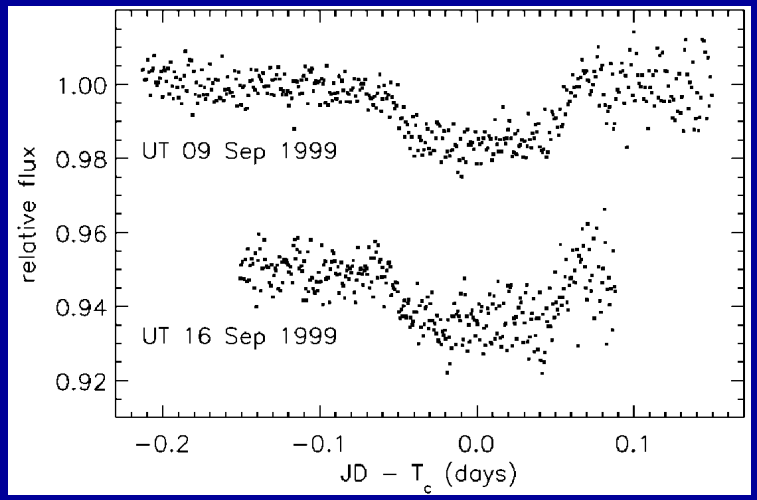

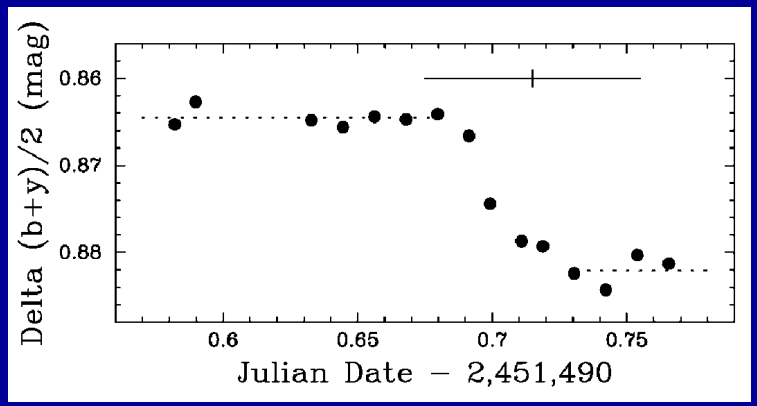

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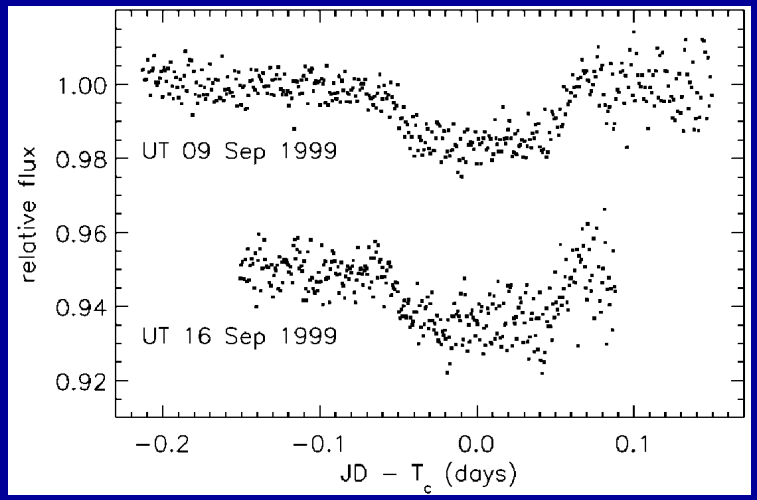

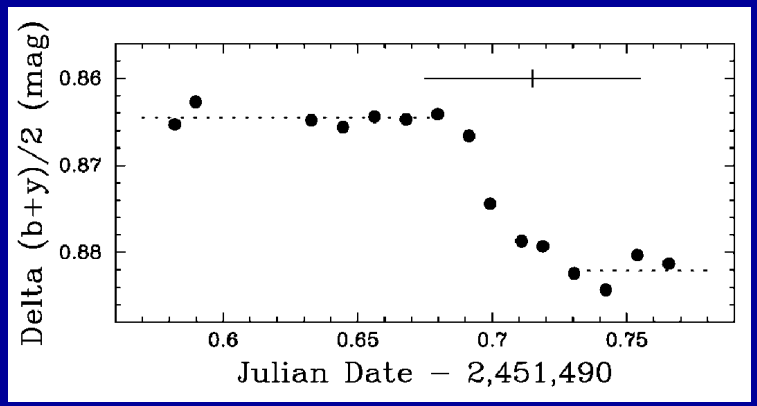

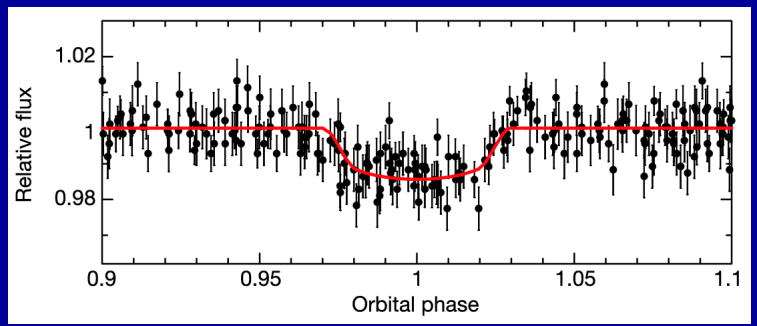

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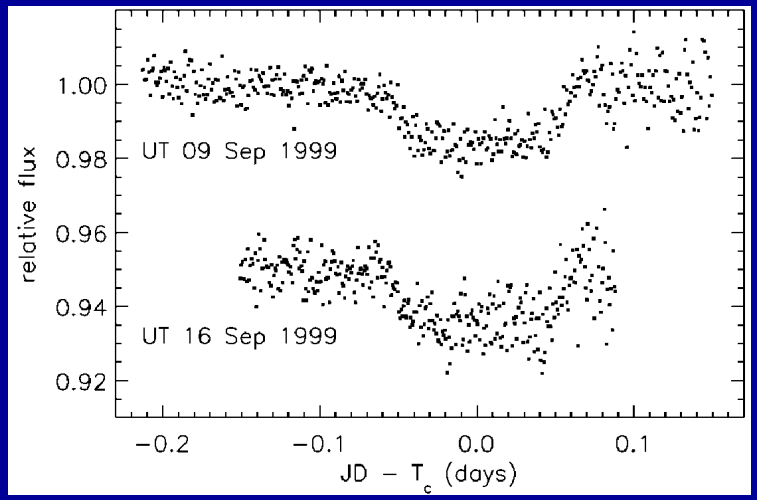
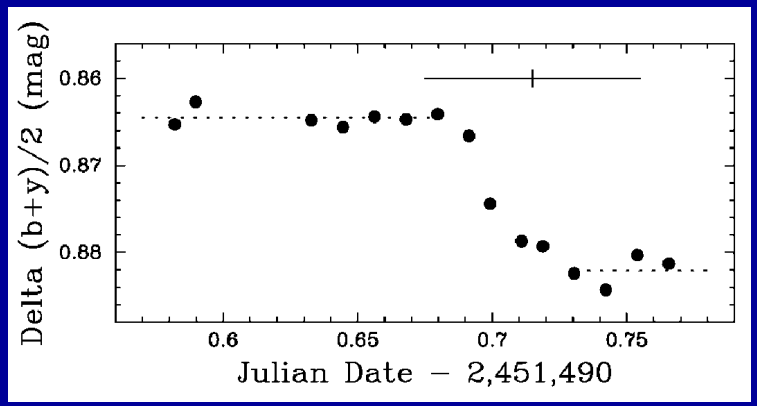
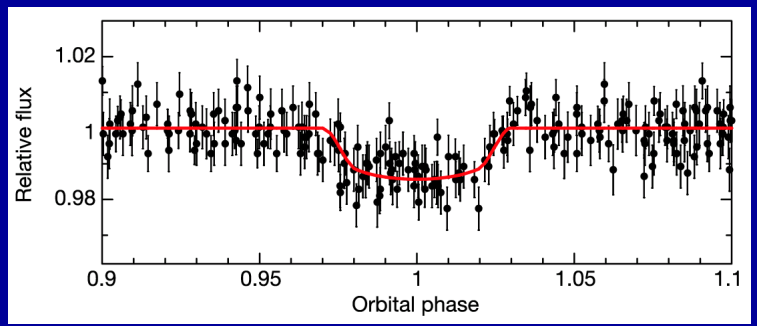
- Current census: 420 + (www.exoplanet.eu)







Transiting planets – discovery surveys

- Monitor millions of stars for months
- Detect periodic transit events

WASP-South installation (South Africa)

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- Monitor millions of stars for months
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- Follow up candidates
  - Radial velocity confirmation
  - High-quality transit light curves
  - High-resolution imaging

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Transiting planets – discovery surveys

- Monitor millions of stars for months
- Detect periodic transit events
- Follow up candidates
  - Radial velocity confirmation
  - High-quality transit light curves
  - High-resolution imaging
- Successful surveys:
  - SuperWASP (UK)
  - HAT (US/Hungary)
  - OGLE (myriad)
  - XO (US)
  - TrES (US/Spain)

WASP-South installation (South Africa)

Transiting planets – current status

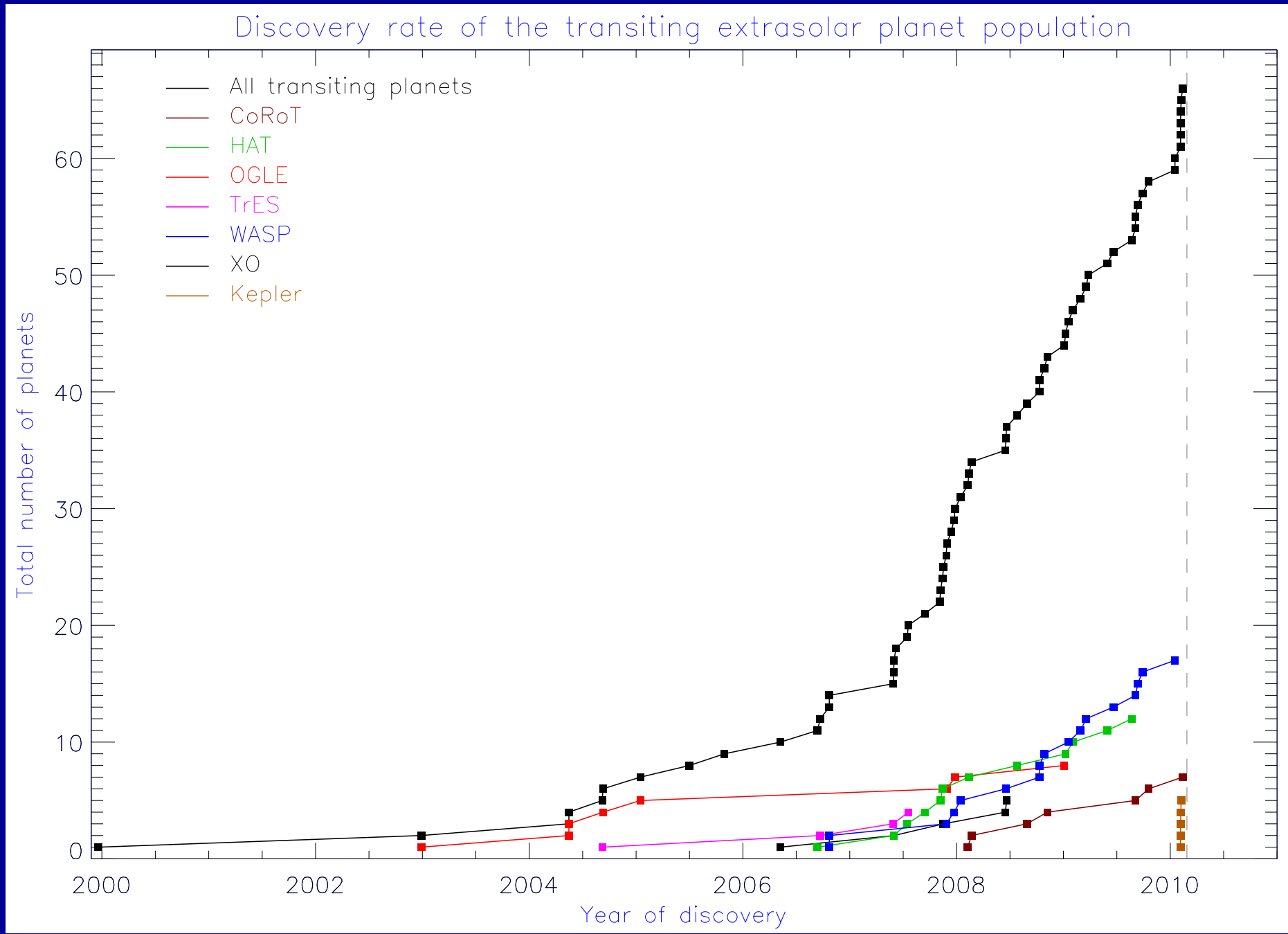
- Roughly 60 known transiting extrasolar planets

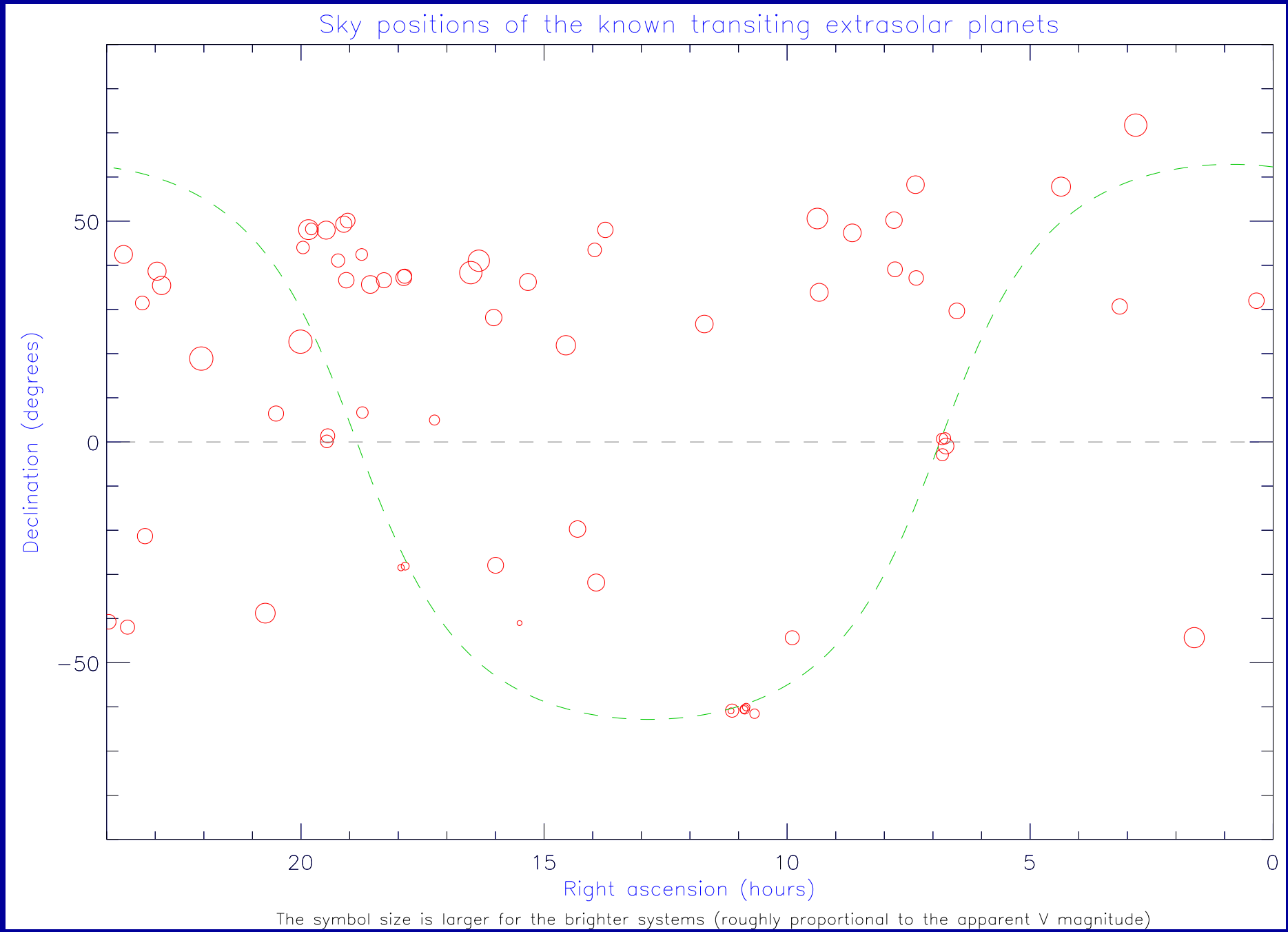
WASP-South installation (South Africa)

Transiting planets – current status

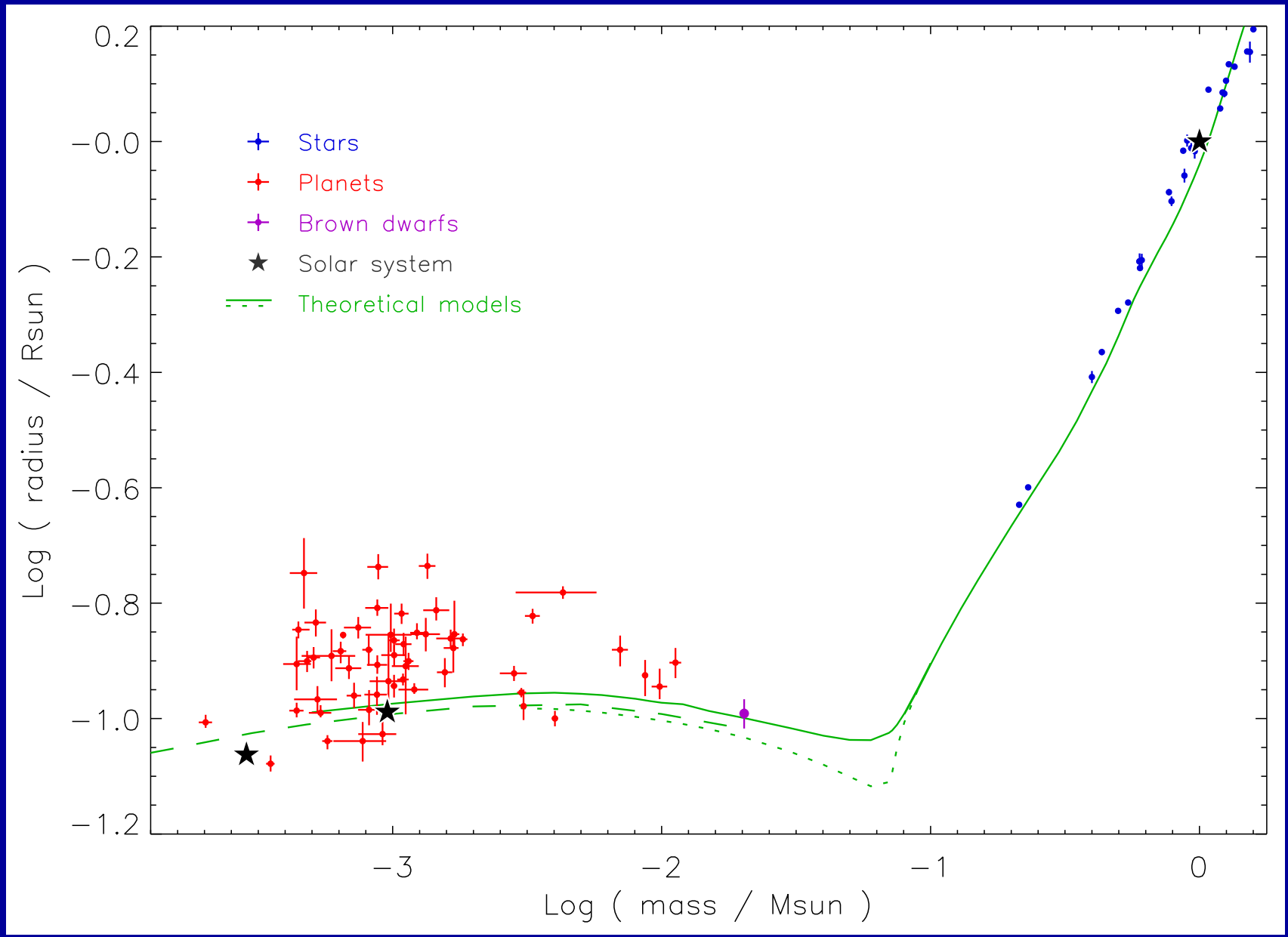
- Roughly 60 known transiting extrasolar planets
- Dedicated ground-based transiting planet surveys:
  - SuperWASP: 17 published
  - HAT: 12
  - OGLE: 8
  - XO: 5 (survey stalled)
  - TrES: 4 (survey finished?)
- Dedicated space-based surveys:
  - CoRoT (France): 7
  - *Kepler* (US): 5

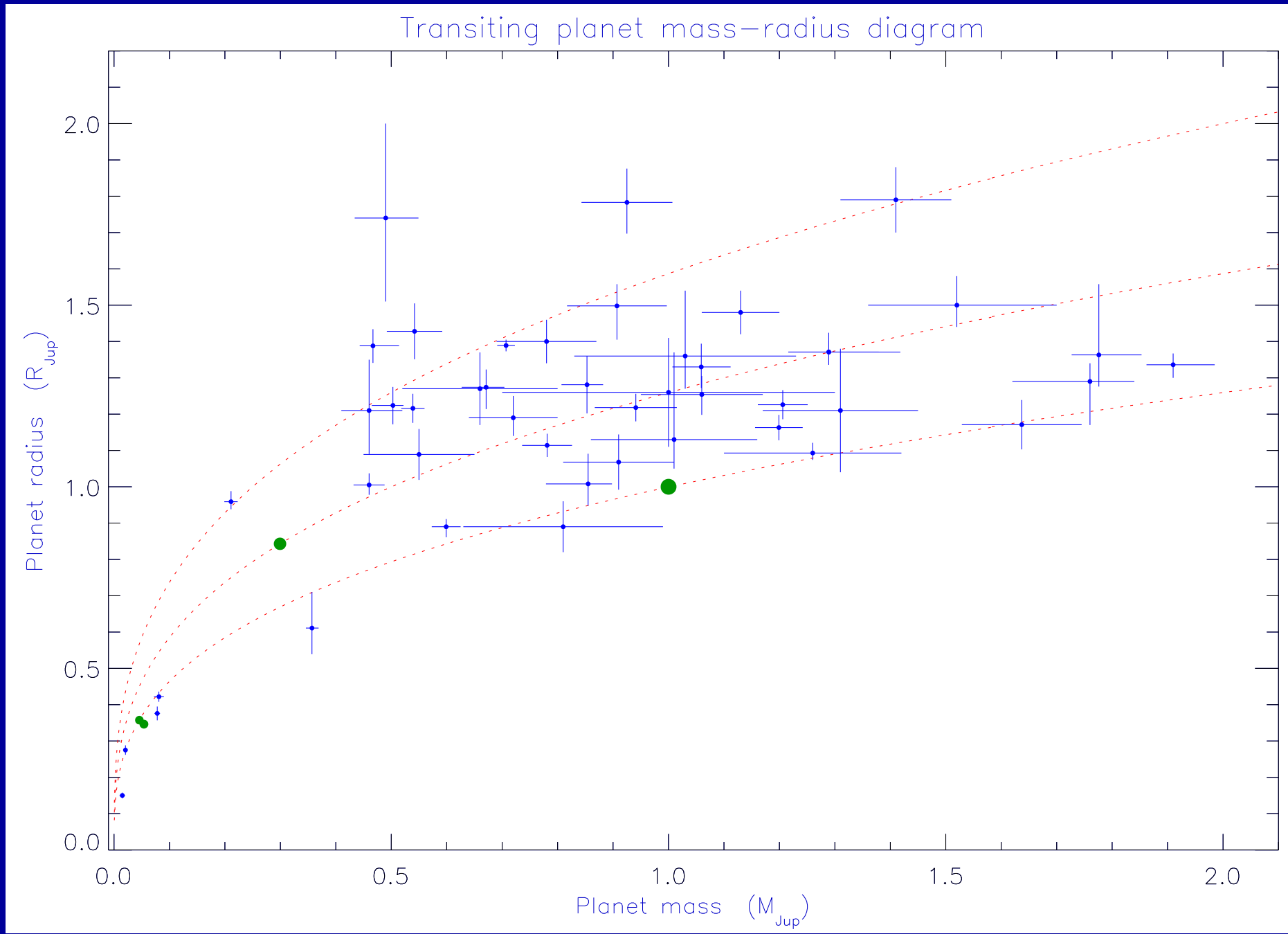
WASP-South installation (South Africa)


Discovery rate of the transiting extrasolar planet population
All transiting planets
CoRoT
HAT
OGLE
TrES
WASP
XO
Kepler
Total number of planets
0
10
20
30
40
50
60
2000
2002
2004
2006
2008
2010
Year of discovery

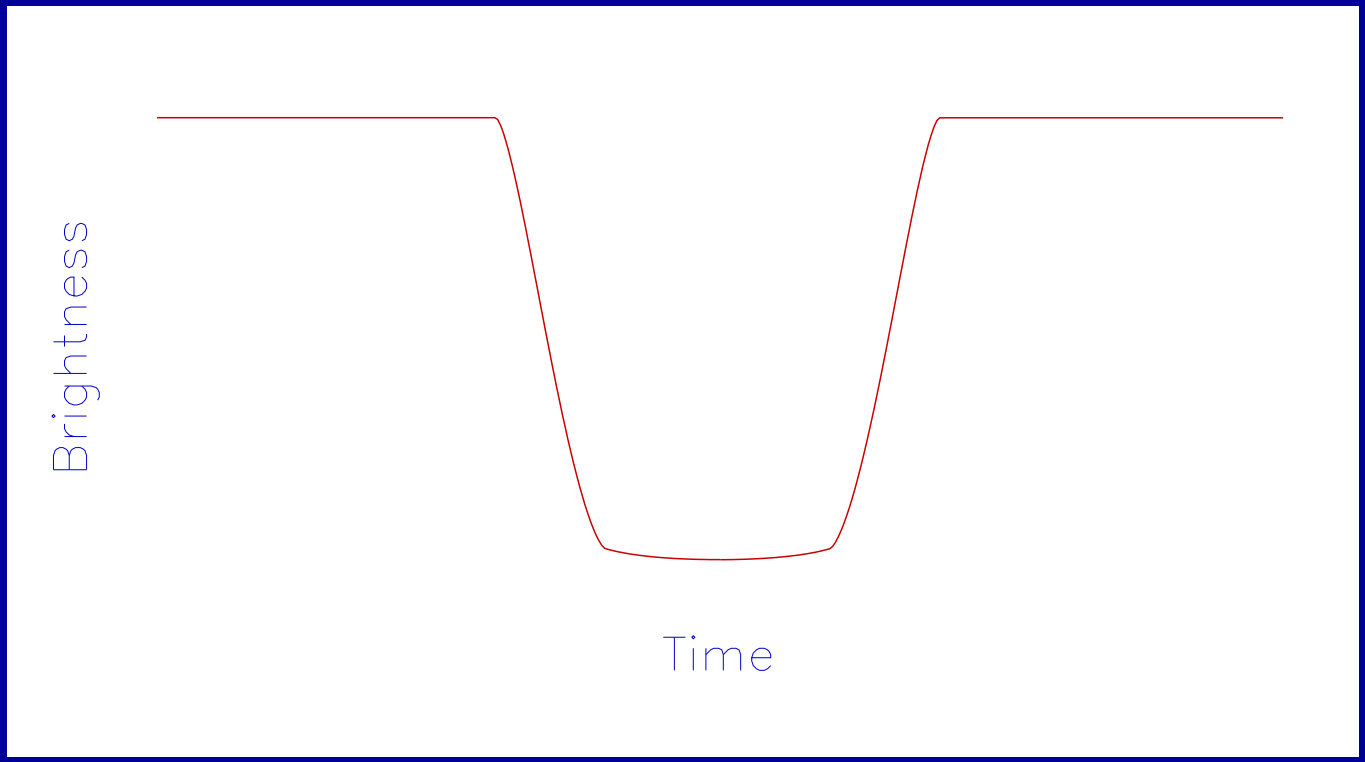

Sky positions of the known transiting extrasolar planets
50
0
−50
Declination (degrees)
20
15
10
5
0
Right ascension (hours)
The symbol size is larger for the brighter systems (roughly proportional to the apparent V magnitude)

The end of the main sequence... and beyond




Transiting planet mass–radius diagram
Planet radius (R_Jup)
Planet mass (M_Jup)
0.0
0.5
1.0
1.5
2.0

Anatomy of a transit light curve



Light curve gives: $P_{\rm orb}$ orbital period

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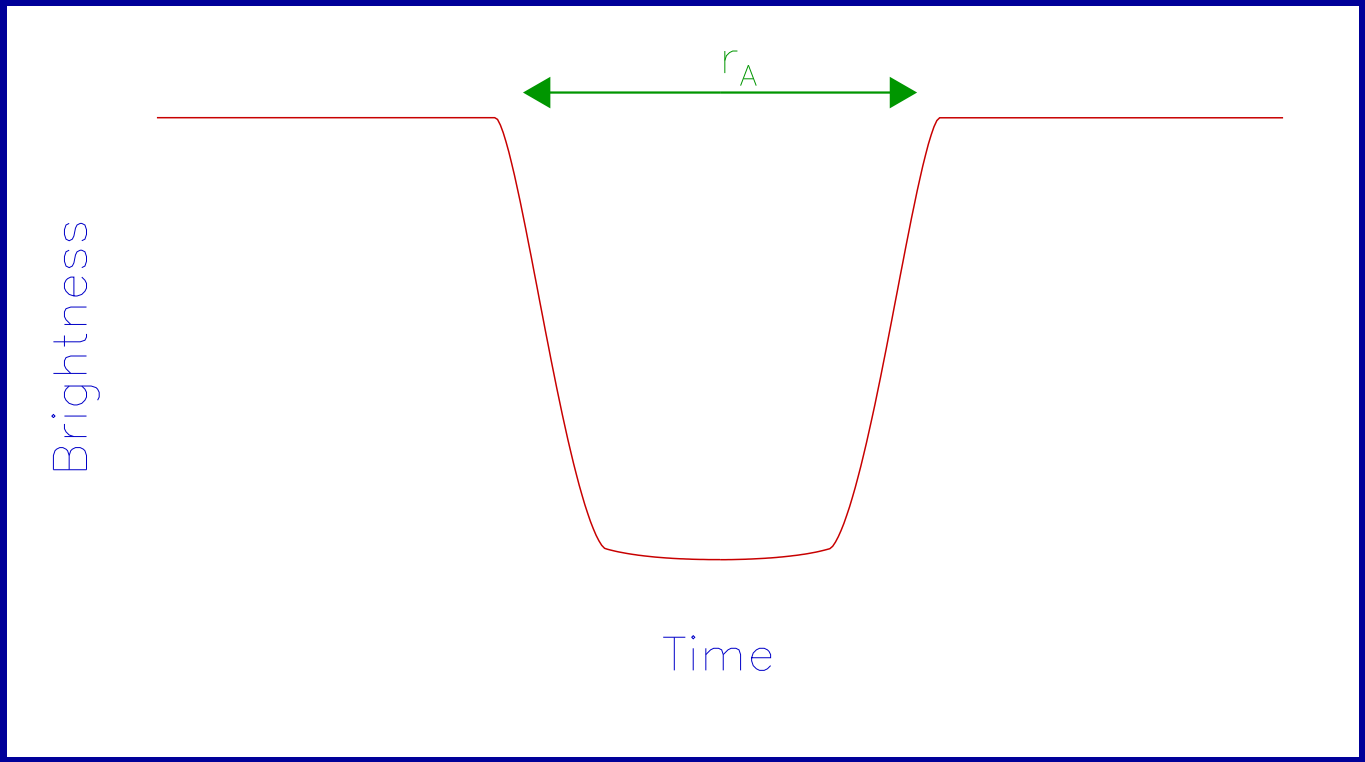

Light curve gives:

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$r_{\rm A} = R_{\rm A}/a$	fractional radius of star

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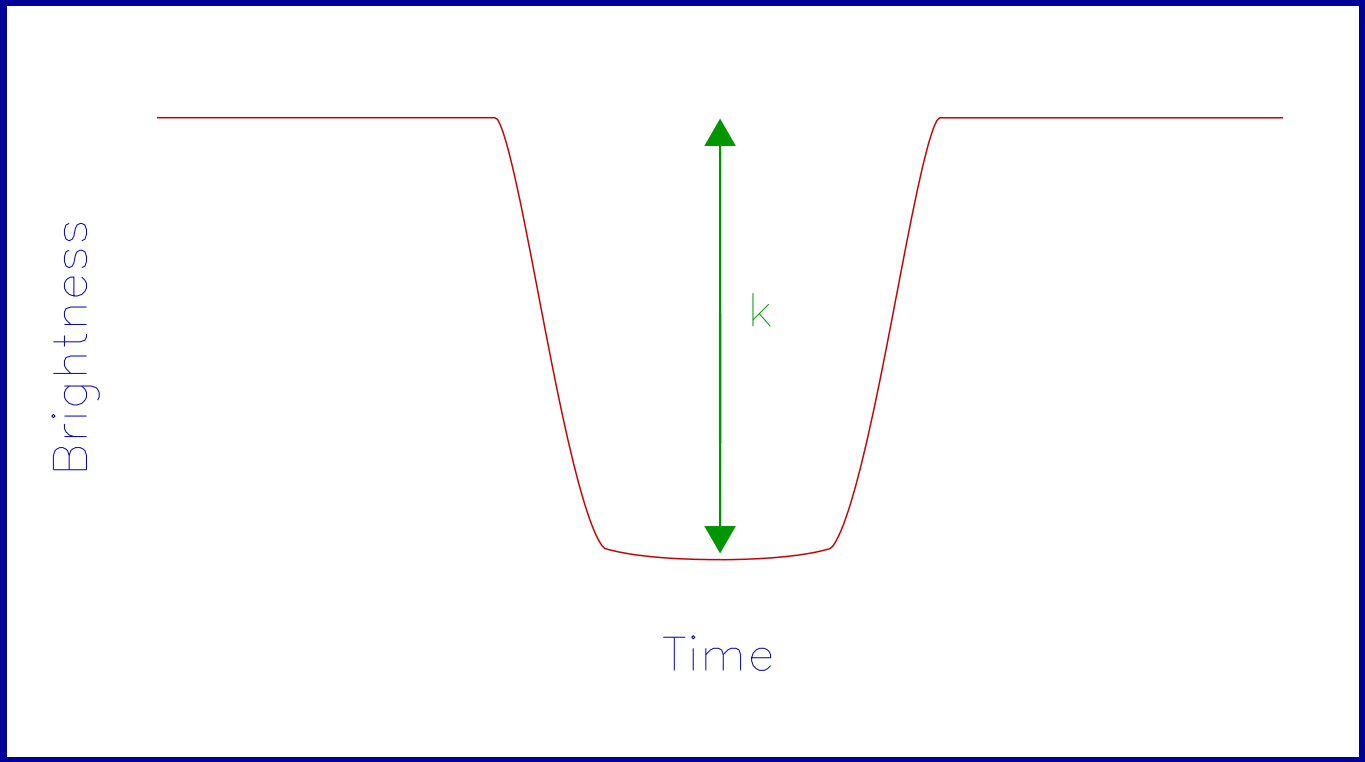

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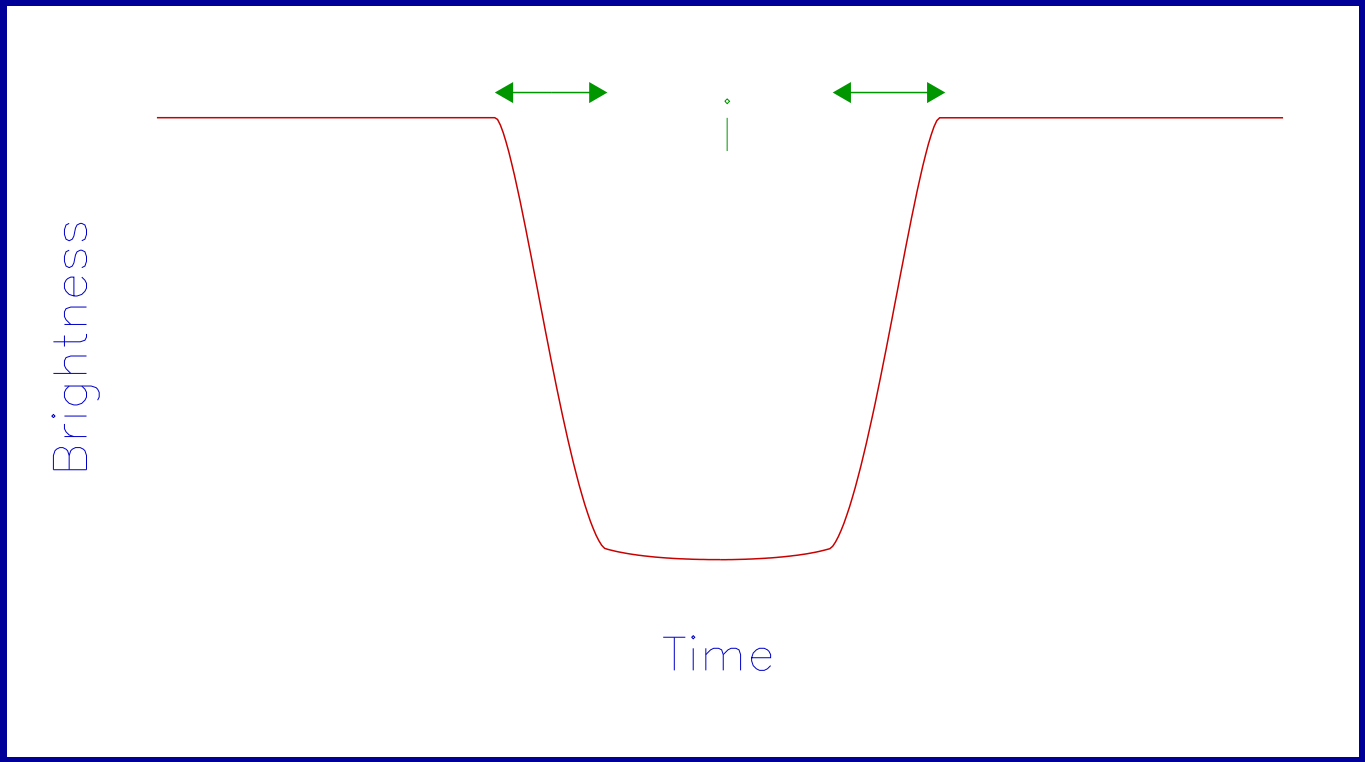

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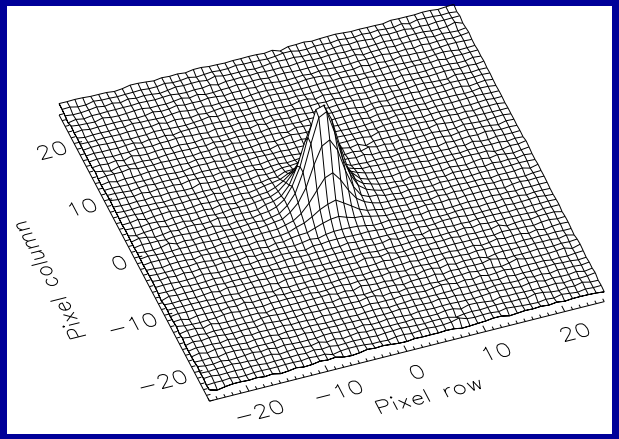
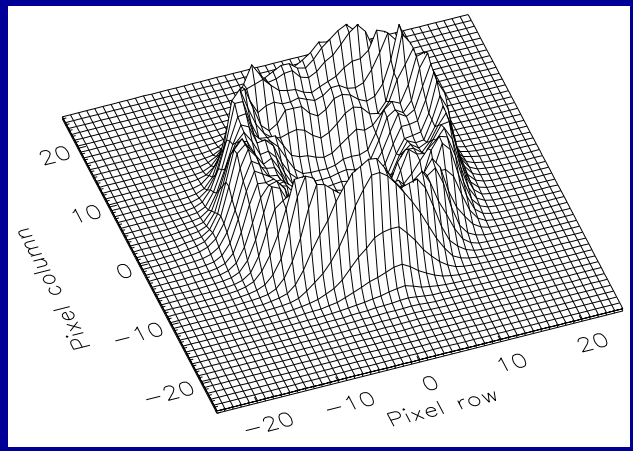
Defocussed photometry

- Look at a bright star with a large telescope:
  - long-ish exposure times: 120 s maximum
  - defocus PSF to cover thousands of pixels



Focussed PSF for WASP-4



Defocussed PSF for WASP-5

Defocussed photometry

- Look at a bright star with a large telescope:
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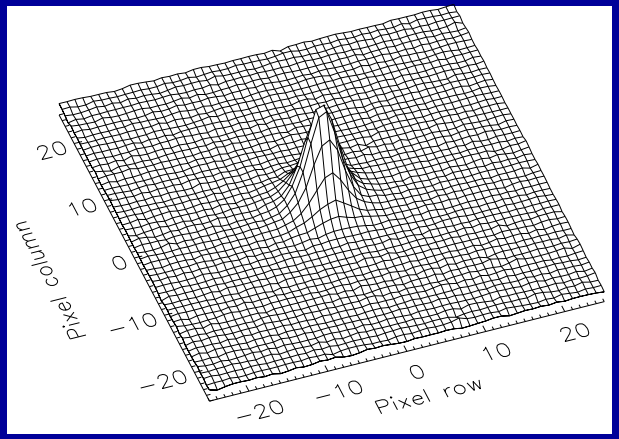
  - defocus PSF to cover thousands of pixels
- Advantages:
  - large PSF $\Rightarrow$ low flatfielding noise
  - long exposure times $\Rightarrow$ less time lost to CCD readout
  - less CCD readout $\Rightarrow$ more photons, less scintillation



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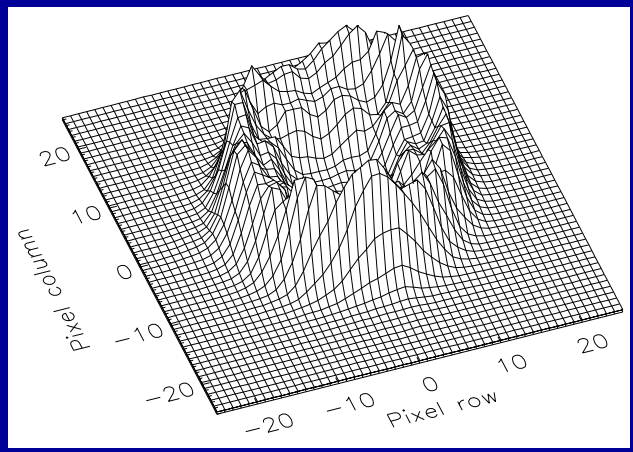

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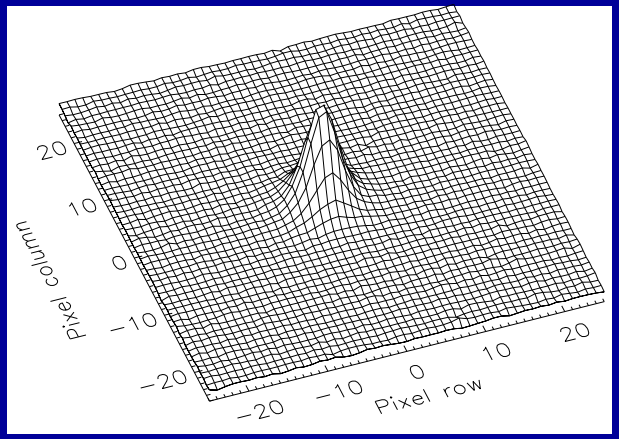
- Disadvantages:
  - lower time resolution $\Rightarrow$ 120 s is good enough for planets
  - higher background $\Rightarrow$ not important for bright stars
  - still need good weather...



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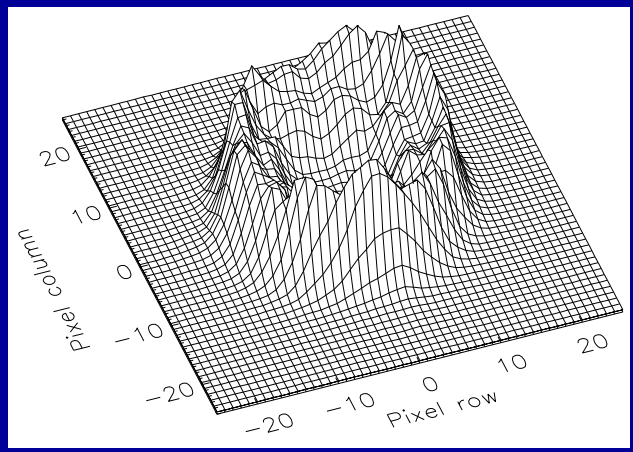
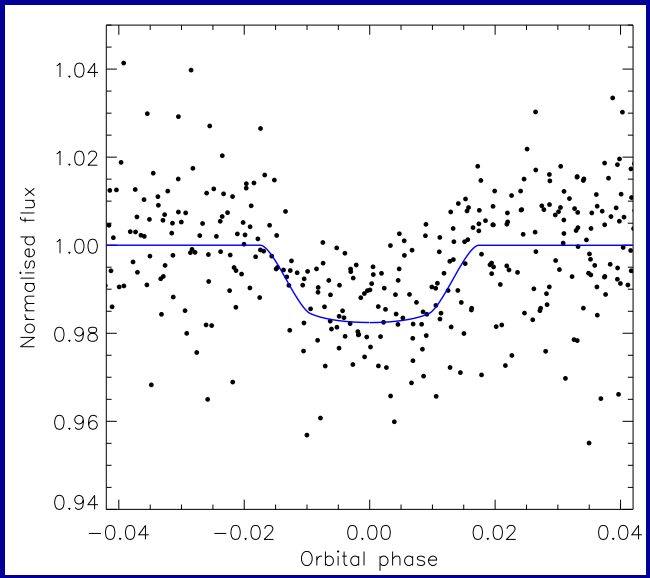


Defocussed PSF for WASP-5

Example: WASP-2



Collier Cameron et al.
(2007, MNRAS, 375, 951)
20cm telephoto lens

- Problem: want to measure planet radius to a few percent
- Consequence: need $r_{\rm A}$ and $r_{\rm b}$ to a few percent
- Answer: Defocus!

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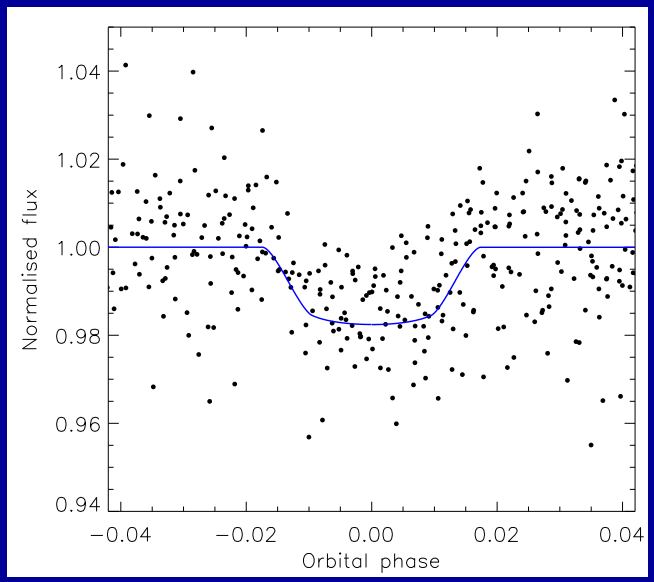

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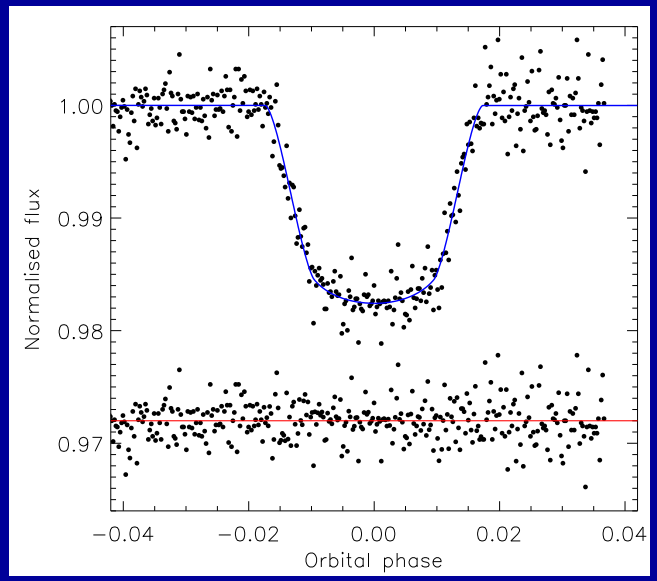

Charbonneau et al.,
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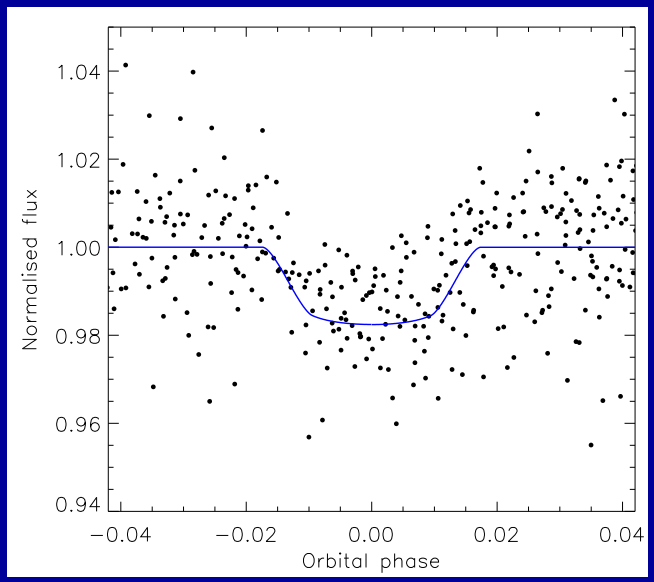

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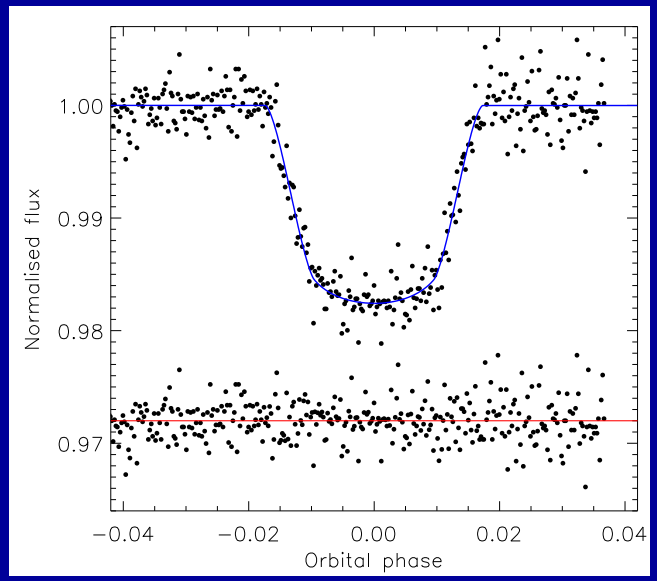

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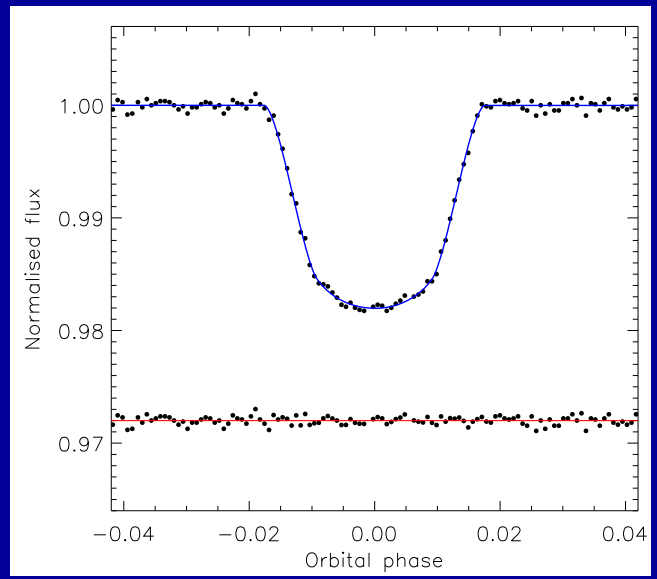
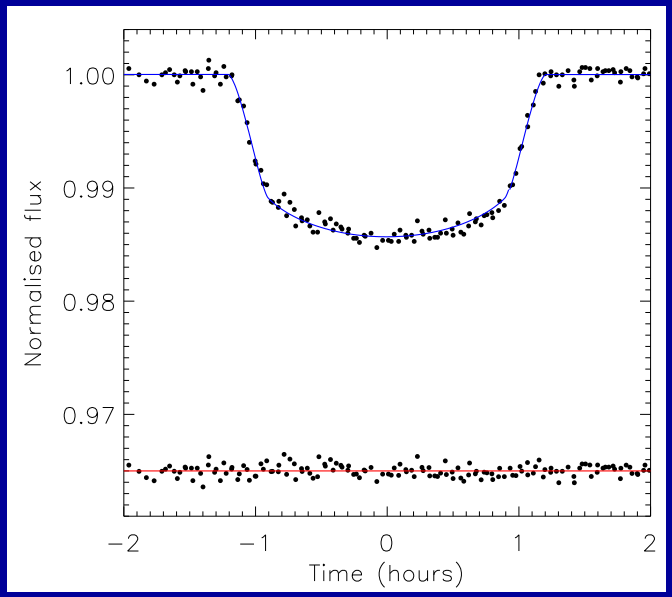


My observations
(telescope defocussing)
1.5 metre telescope

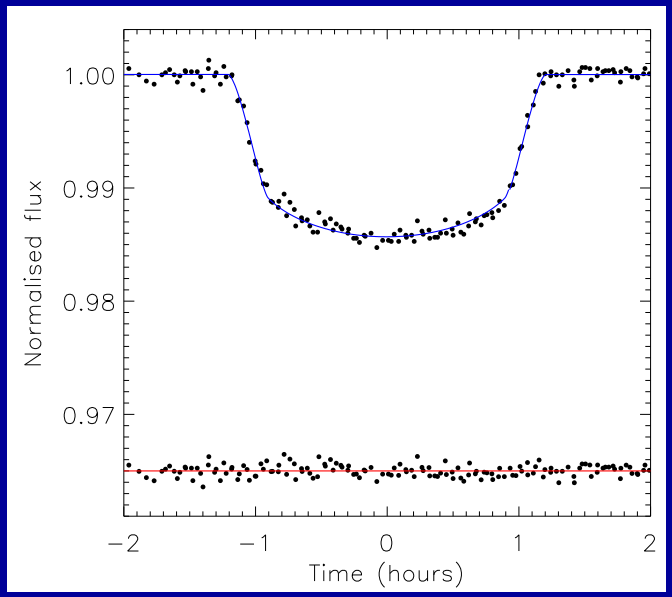
- Problem: want to measure planet radius to a few percent
- Consequence: need $r_{\rm A}$ and $r_{\rm b}$ to a few percent
- Answer: Defocus!

More examples



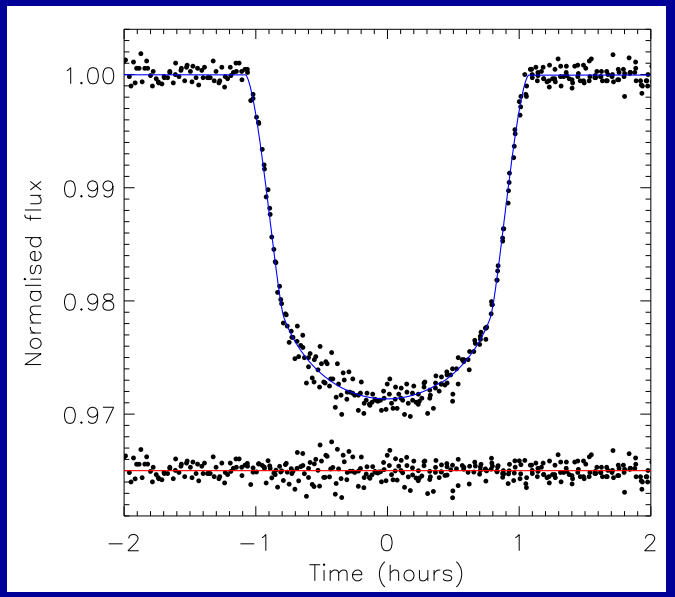
WASP-5
2009, MNRAS, 396, 1023

More examples



WASP-5
2009, MNRAS, 396, 1023

WASP-4
2009, MNRAS, 399, 287



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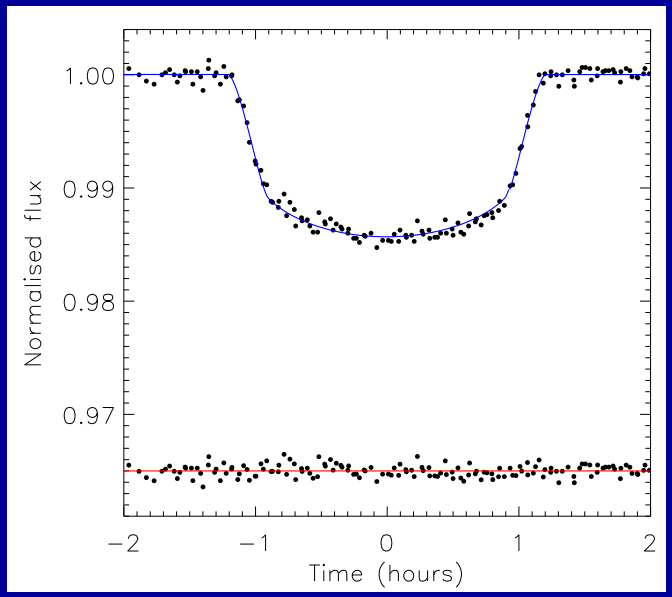

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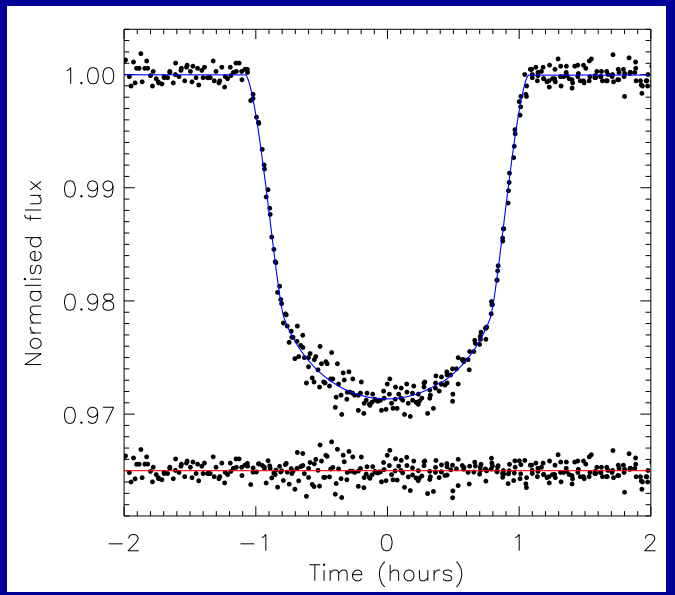
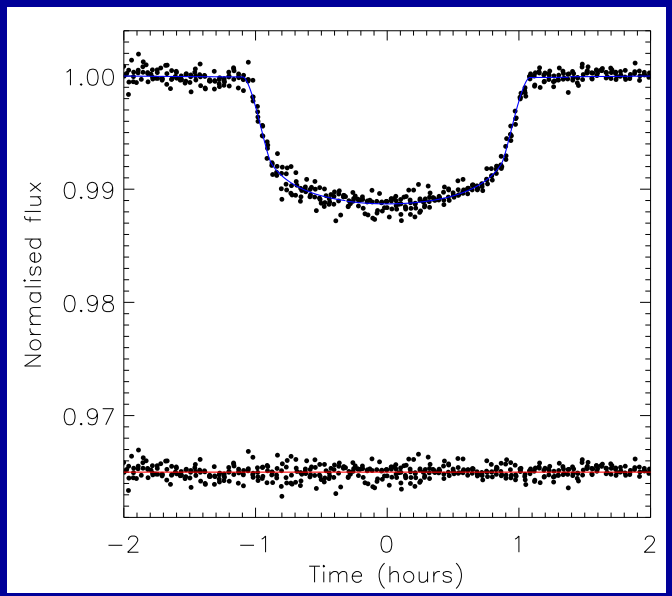
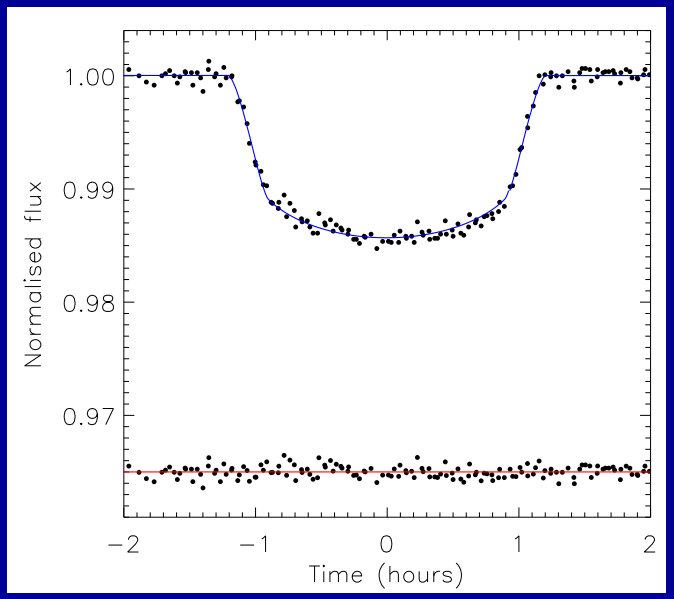


WASP-4
2009, MNRAS, 399, 287

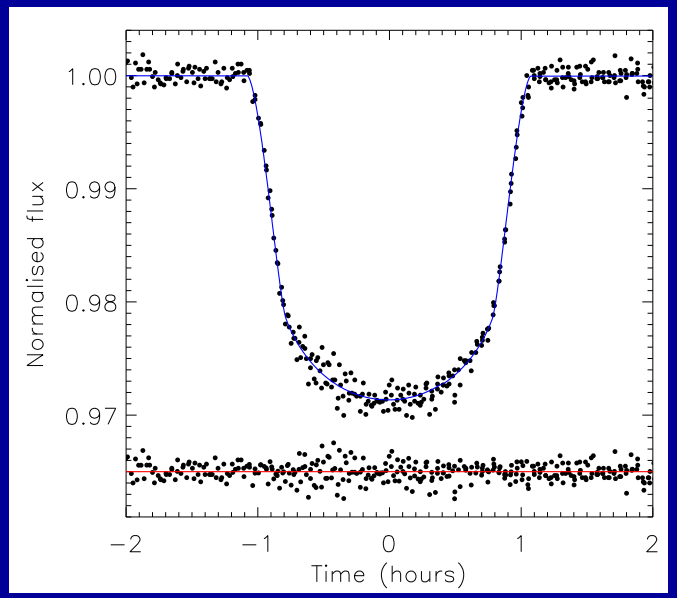


WASP-18
2009, ApJ, 707, 167

More examples



WASP-5
2009, MNRAS, 396, 1023



WASP-4
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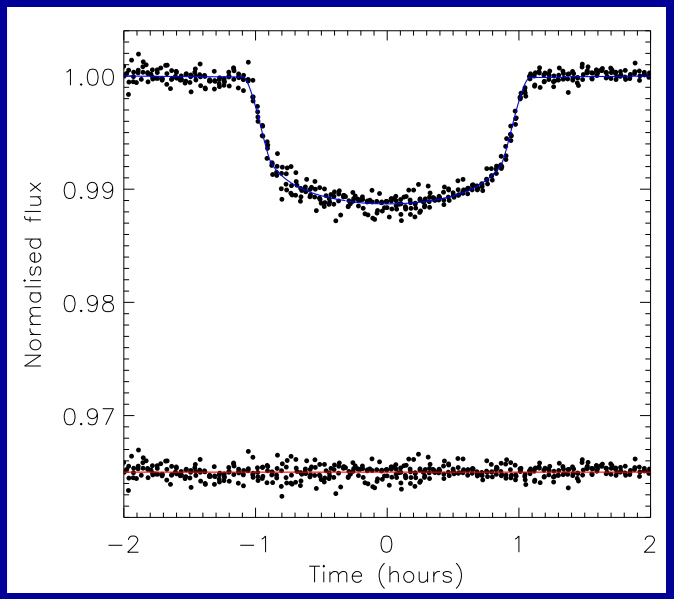

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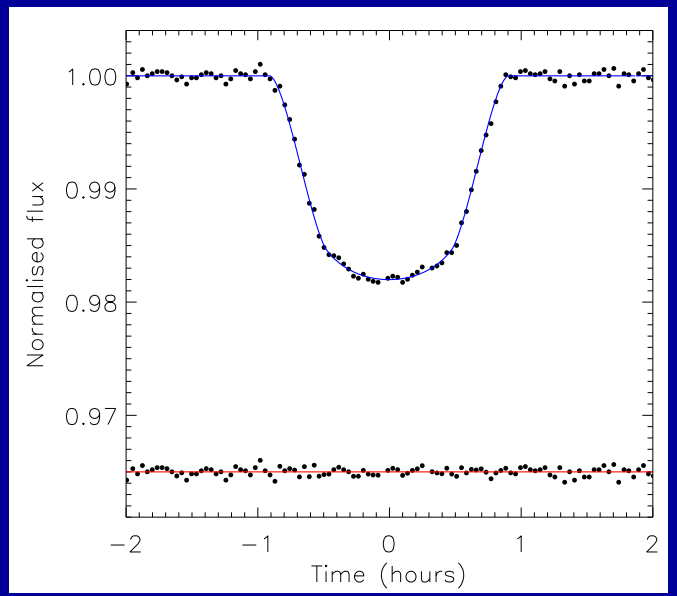

WASP-2
(in preparation)

Transiting planet properties

- Light curve: $P_{\rm orb}$ $r_{\rm A}$ k i

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  - get density $\Rightarrow$ composition and core size
  - composition and core size $\Rightarrow$ formation scenario

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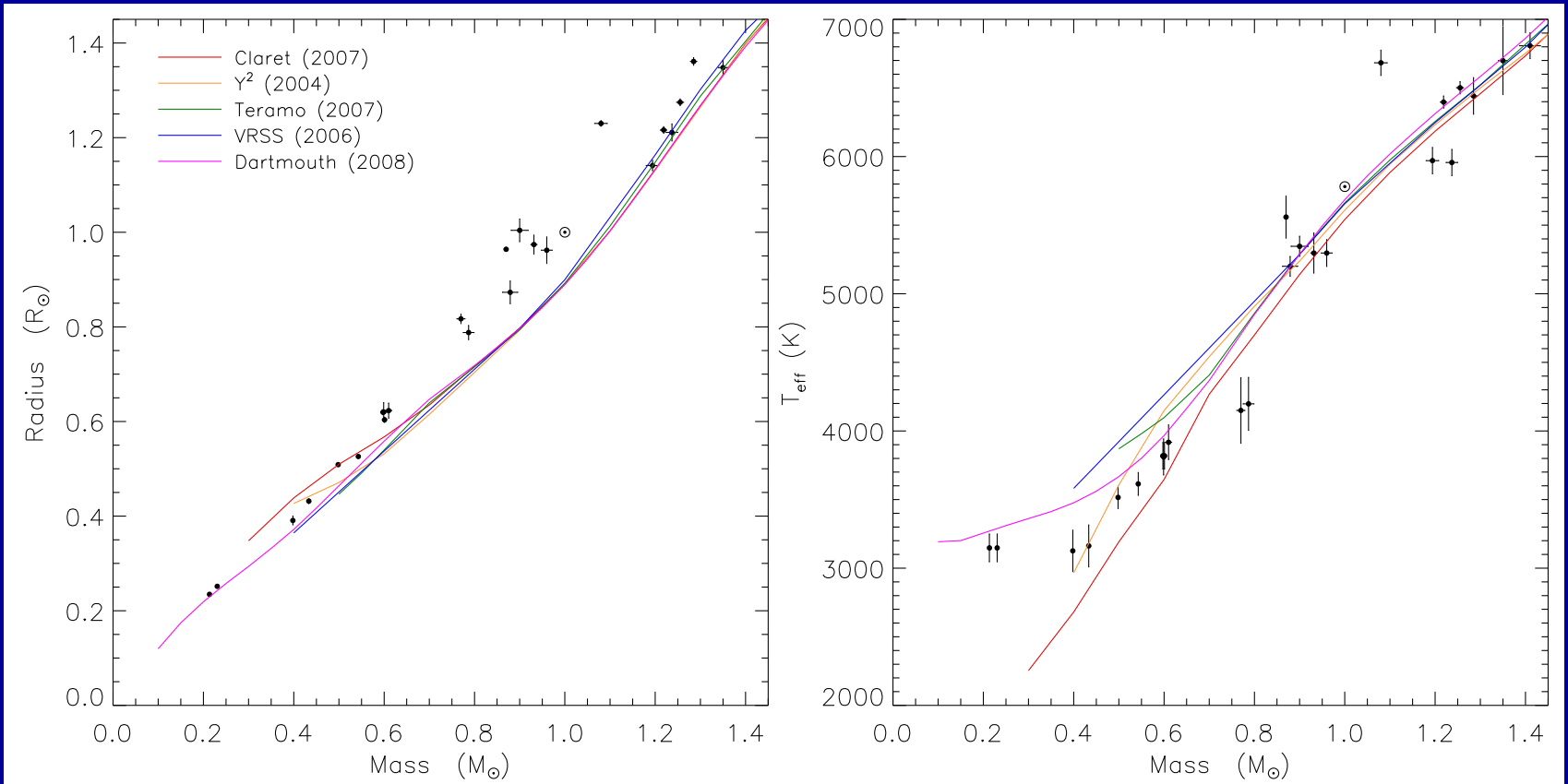
  - composition and core size $\Rightarrow$ formation scenario

Stellar models v. observations



- Plot masses, radii and $T_{\rm eff}$s for eclipsing binary star systems
  - masses and radii can be measured directly and to 1%
- Add predictions of stellar models for age 0.5 Gyr and solar $\left[\frac{\rm Fe}{\rm H}\right]$
- Models disagree with observations . . . and with each other

Homogeneous studies of transiting planets

- Problems:
  - People analyse transiting planet light curves in different ways
  - People use a variety of stellar models to get physical properties
  - Results are not consistent
  - Stellar model imperfections are ignored

Southworth (2009, MNRAS, 386, 1644) Southworth (2009, MNRAS, 394, 272)

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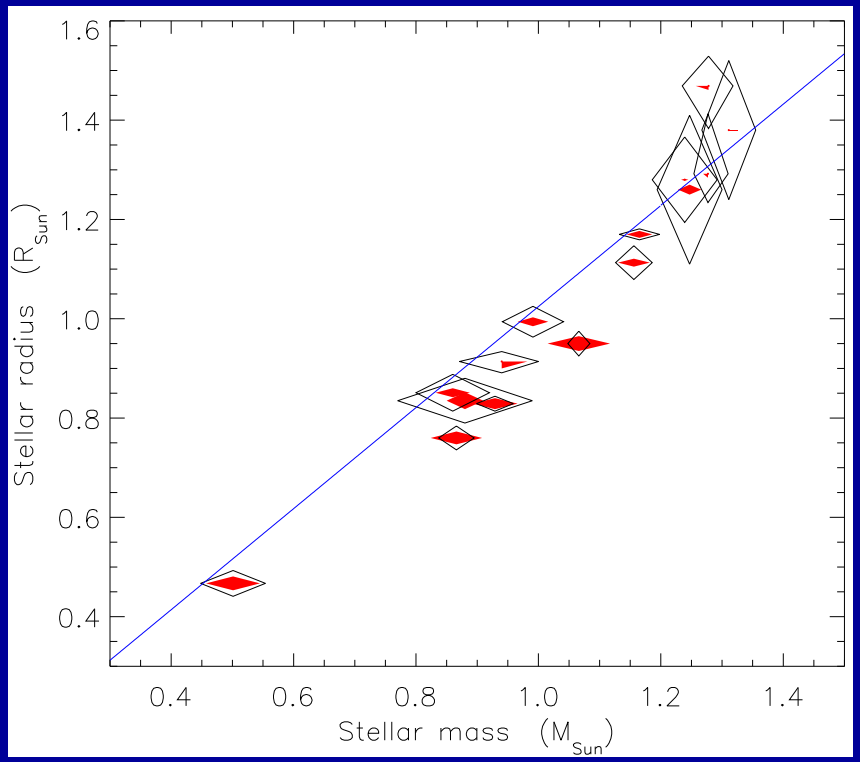
- Step 2: Physical properties
  - Use measured $T_{\rm eff}$, $\left[\frac{\rm Fe}{\rm H}\right]$, $K_{\rm A}$
  - Include five different stellar models
  - Try eclipsing binary mass–radius relation

Southworth (2009, MNRAS, 386, 1644) Southworth (2009, MNRAS, 394, 272)

The disease of systematic errors



- Left: plot of mass versus radius for transiting planet host stars
  - Black diamonds: random errors
  - Red diamonds: systematic errors
  - Blue line: eclipsing binary mass–radius relation

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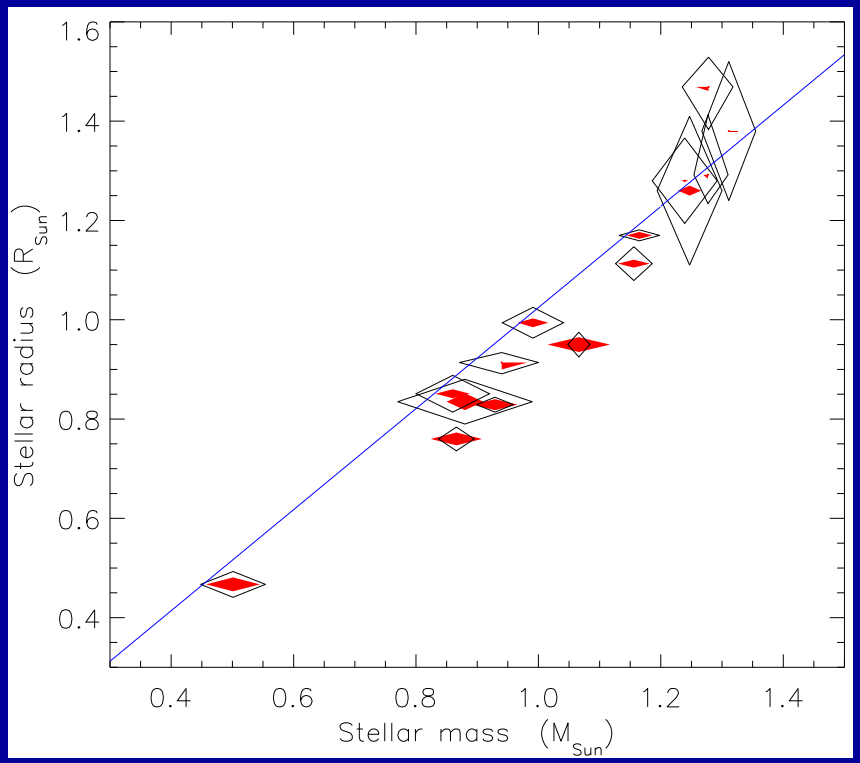

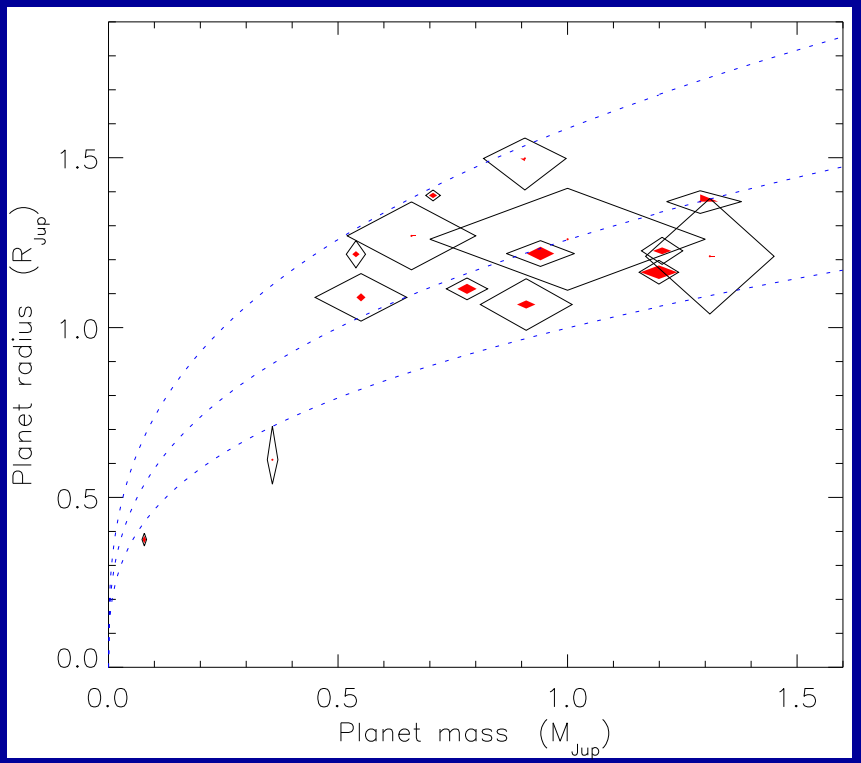

- Left: plot of mass versus radius for transiting planet host stars
  - Black diamonds: random errors
  - Red diamonds: systematic errors
  - Blue line: eclipsing binary mass–radius relation
- Right: plot of mass versus radius for the planets
  - Blue lines: density = 1.0, 0.5, 0.25 $\times$ Jupiter

Southworth (2009, MNRAS, 394, 272)

Surface gravity: immune from the disease

- Planetary surface gravity can be calculated directly:

$$g_{\rm b} = \frac{2\pi}{P_{\rm orb}} \frac{\sqrt{1-e^2}\, K_{\rm A}}{{r_{\rm b}}^2 \sin i}$$

  - e, $K_{\rm A}$ from velocity measurements
  - $P_{\rm orb}$, $r_{\rm b}$, i come from the light curve

Southworth et al (2007, MNRAS, 379, L11)

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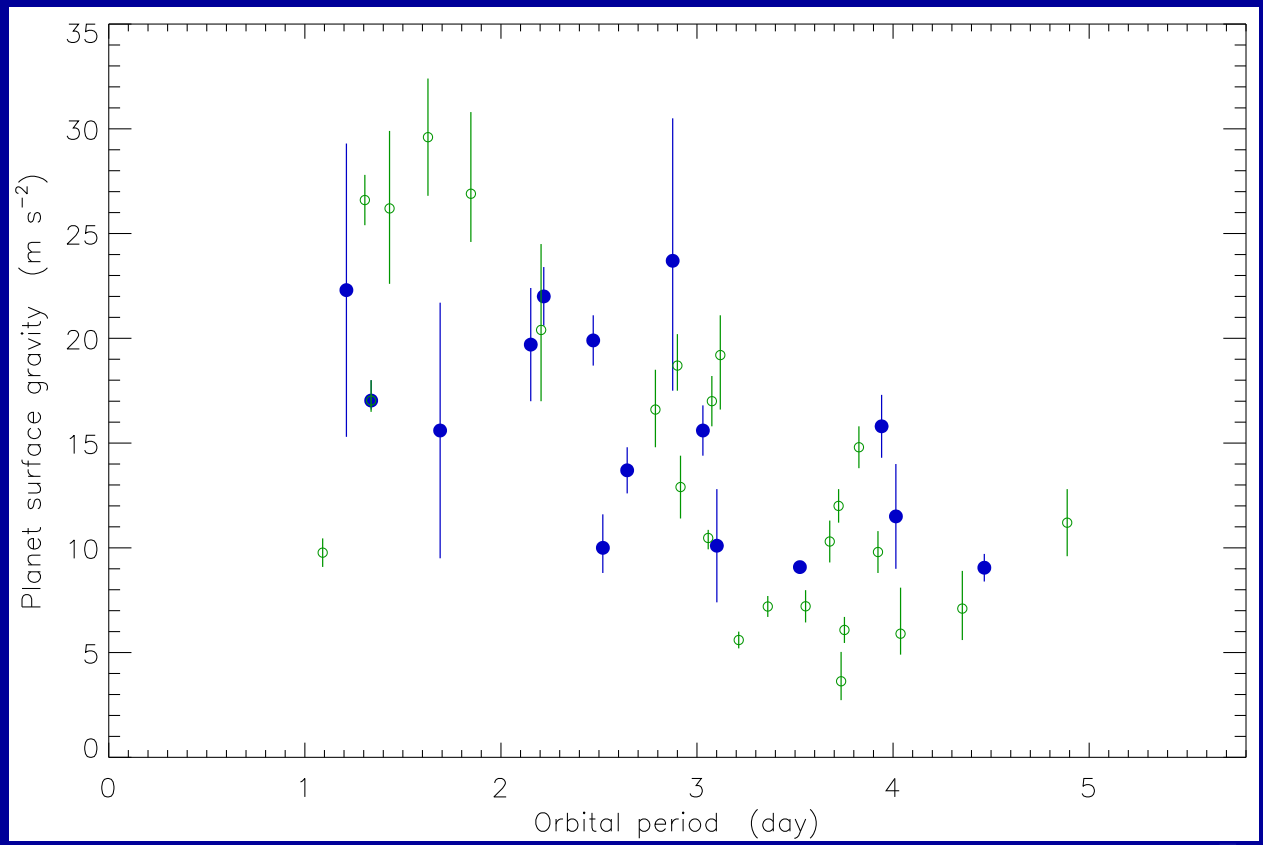
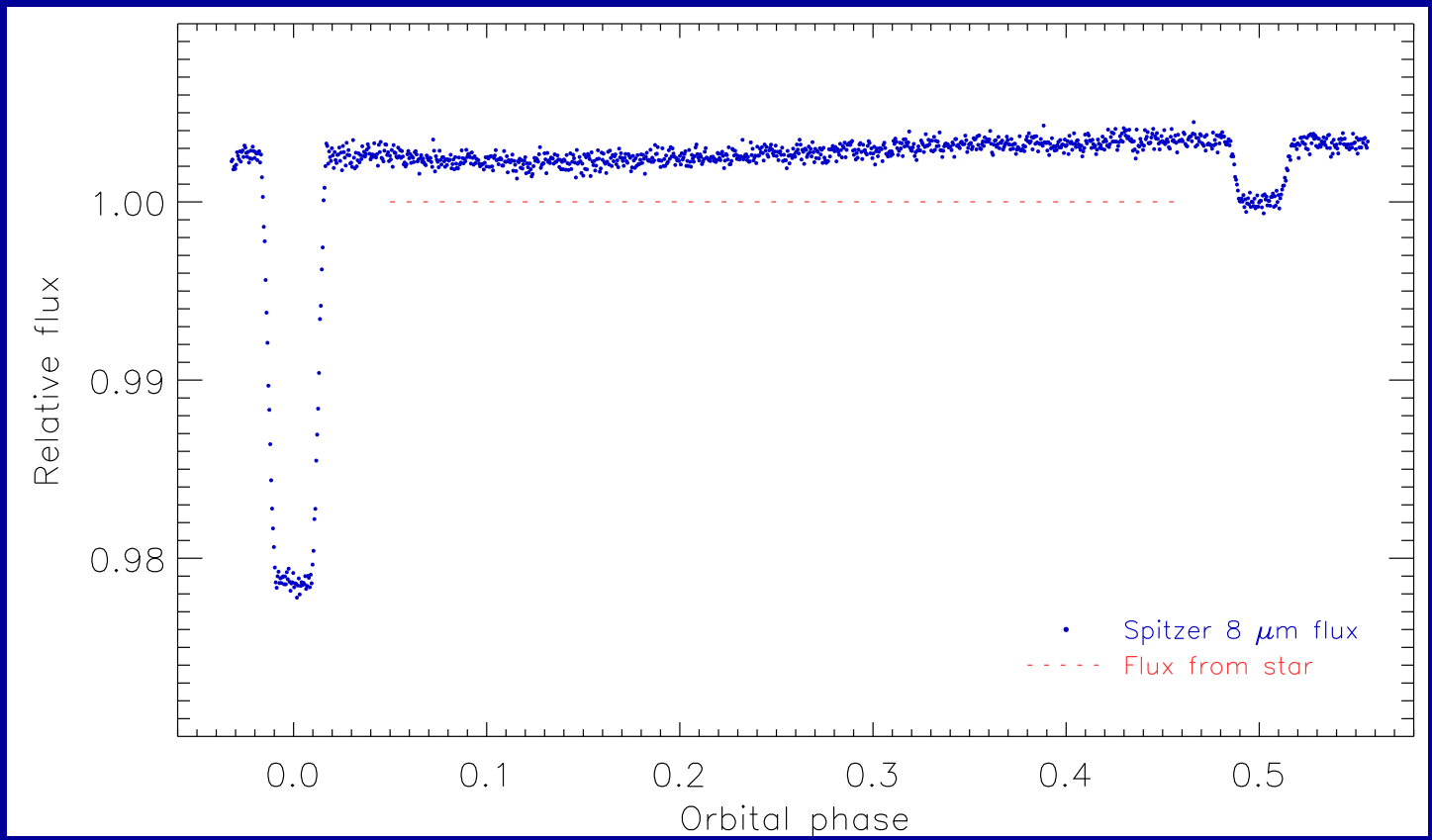
Southworth et al (2007, MNRAS, 379, L11)

- $g_{\rm b}$ correlates with orbital period
  - interesting physics?
  - selection effects?
  - small-number statistics?



Future part 1: secondary eclipse measurements

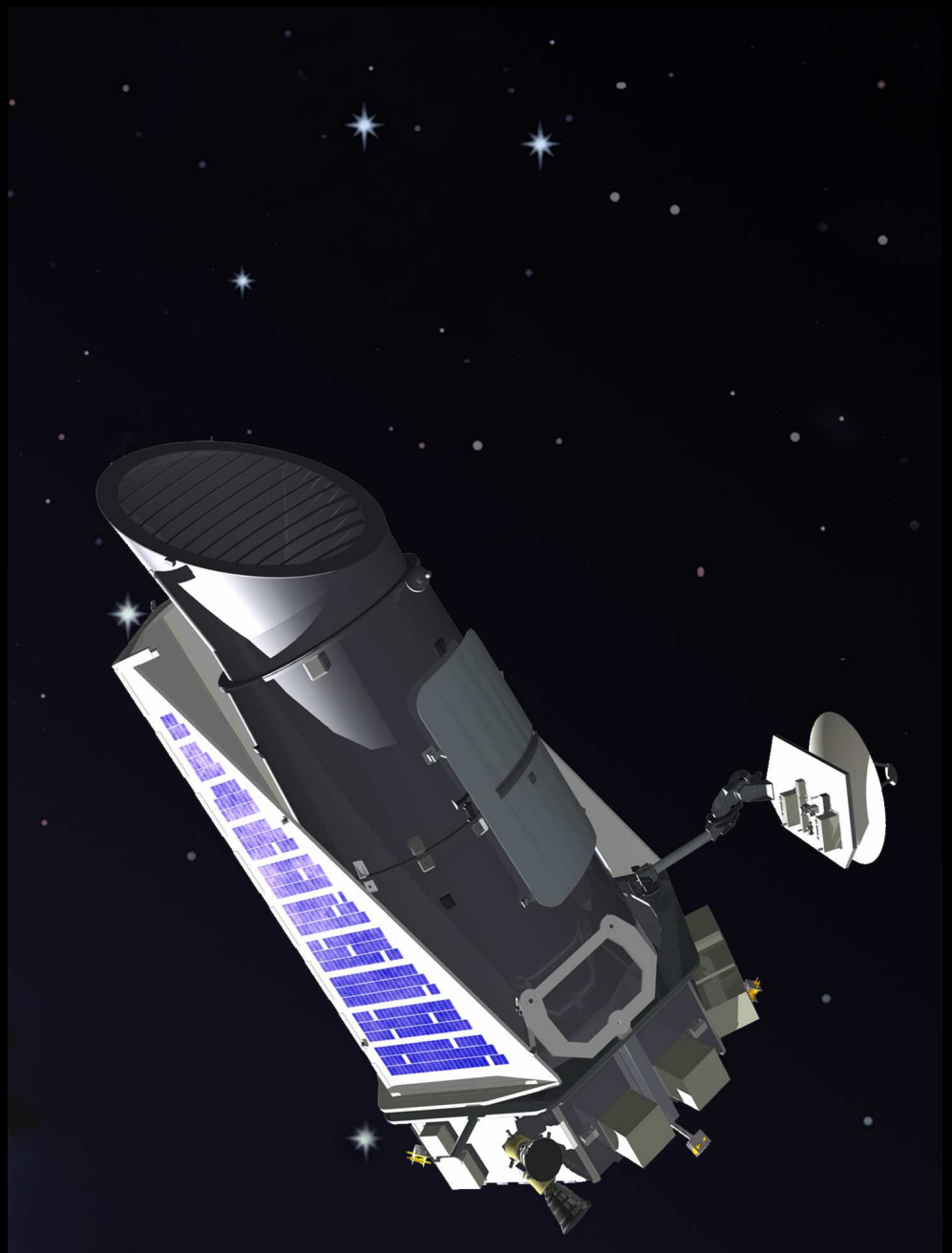
- Secondary eclipses can be measured in the infrared
- Direct detection of light from planet
- Use to measure the infrared spectrum of a planet

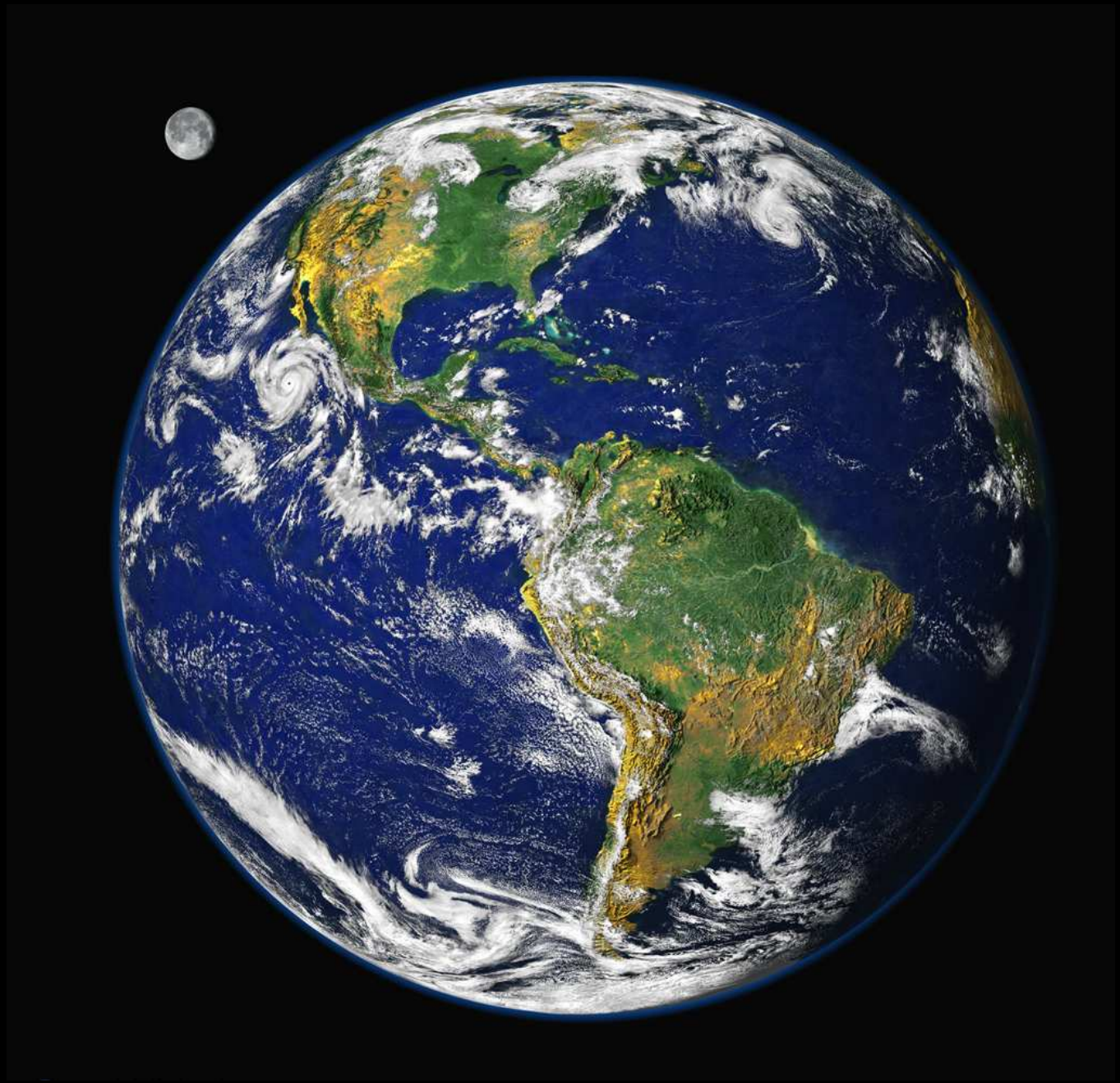


Spitzer Space Telescope
8 μm observations of
HD 189733
(Knutson et al., 2007,
Nature, 447, 183)

Future part 2: transiting Earth-likes

- CoRoT and *Kepler* satellites
  - launched 2006/12 and 2009/03
  - can detect 1–2 $\mathrm{R}_\oplus$ planets
  - CoRoT-7: mass 4.8 $\mathrm{M}_\oplus$, radius 1.7 $\mathrm{R}_\oplus$
- *Kepler* could detect something like Earth, far enough from its star to be habitable . . .





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