Paper Due Tue, Feb 23

Seager & Mallen-Ornelas 2003 ApJ 585, 1038.

"A Unique Solution of Planet and Star Parameters
from an Extrasolar Planet Transit Light Curve"

Exoplanet Discovery Methods

(1) Direct imaging

(2) Astrometry → position

(3) Radial velocity → velocity

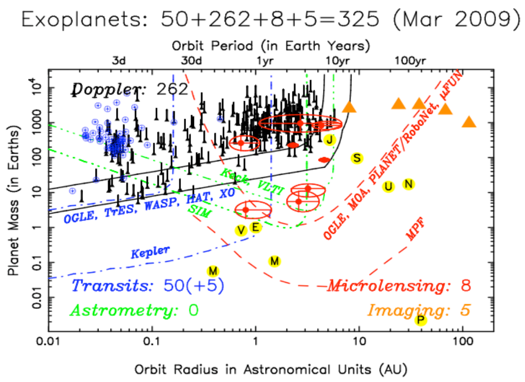
Today:

(4) Transits

Later:

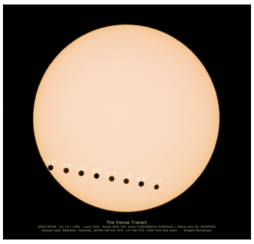
(5) Gravitational microlensing

(6) Pulsar timing



Transits

Simplest method: look for drop in stellar flux due to a planet transiting across the stellar disc

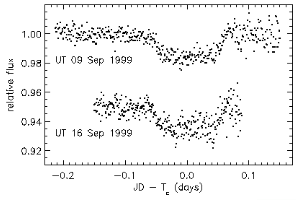


Venus Transit in 2004

International Space Station and Space Shuttle crossing the disk of the Sun

Needs luck - transits only occur if the orbit is almost edge-on

1999 *First Transiting Exo-Planet*



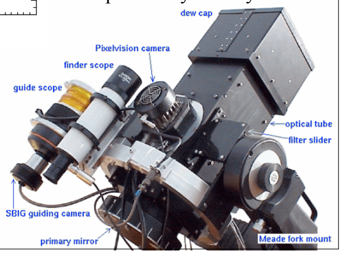
Charbonneau & Brown (2000)

STARE **10 cm telescope**

**A Very Big Discovery
by a grad student using
a Very Small Telescope!**

HD 209458
V=7.6 mag

1.6% “winks”
last 3 hours
repeat every 3.5 days

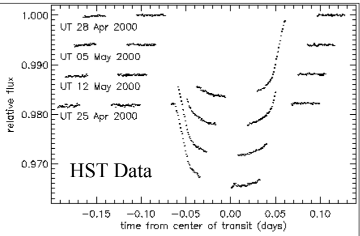


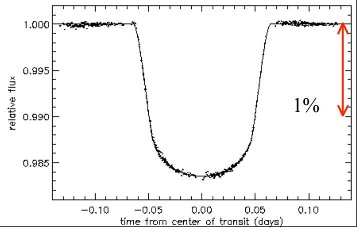
HD 209458 Transits HST/STIS

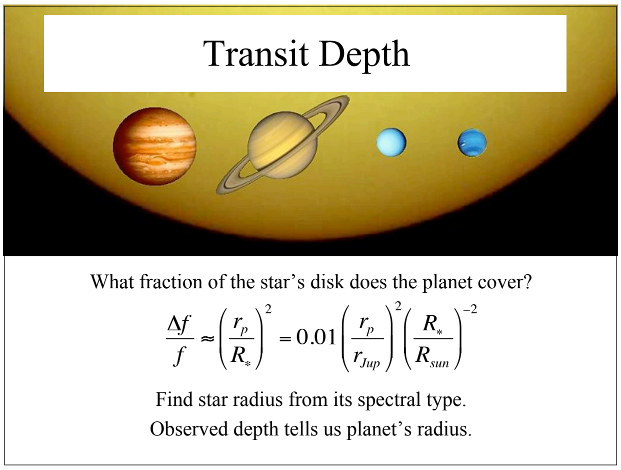
Brown et al. (2001)

$P = 3.52$ d $a = 0.046$ AU
$m_V = 7.8$
$\Delta f / f = 0.017$ mag (1.6%)
$i = 86°.6 \pm 0°.2$
$r_p = 1.35 \pm 0.06\ r_J$

From radial velocities
$m \sin i = 0.69\ m_J$
$\Rightarrow$ “bloated” gas giant





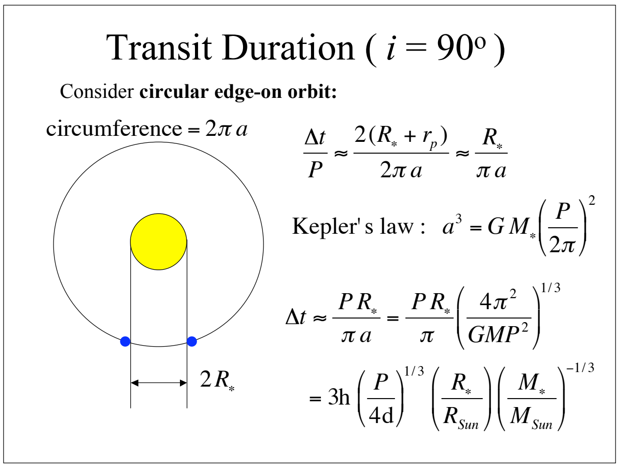


Transit Depth

What fraction of the star’s disk does the planet cover?

$$\frac{\Delta f}{f} \approx \left(\frac{r_p}{R_*}\right)^2 = 0.01\left(\frac{r_p}{r_{Jup}}\right)^2\left(\frac{R_*}{R_{sun}}\right)^{-2}$$

Find star radius from its spectral type.
Observed depth tells us planet’s radius.



Transit Duration ($i = 90^o$)

Consider **circular edge-on orbit:**

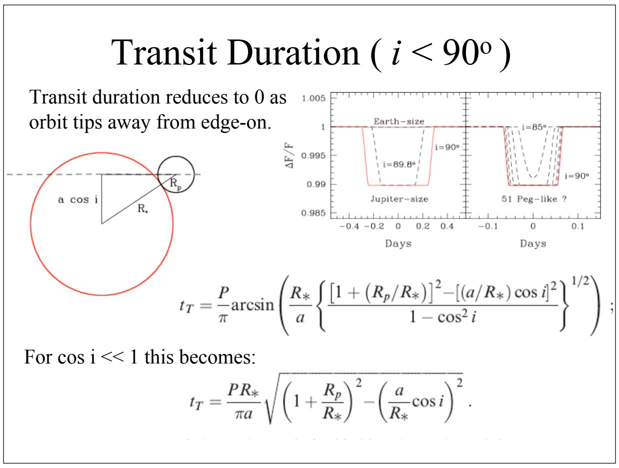
circumference $= 2\pi a$

$$\frac{\Delta t}{P} \approx \frac{2(R_* + r_p)}{2\pi a} \approx \frac{R_*}{\pi a}$$

$$\text{Kepler's law: } \quad a^3 = G M_* \left(\frac{P}{2\pi}\right)^2$$

$$\Delta t \approx \frac{P R_*}{\pi a} = \frac{P R_*}{\pi}\left(\frac{4\pi^2}{GMP^2}\right)^{1/3}$$

$$= 3\text{h}\left(\frac{P}{4\text{d}}\right)^{1/3}\left(\frac{R_*}{R_{Sun}}\right)\left(\frac{M_*}{M_{Sun}}\right)^{-1/3}$$



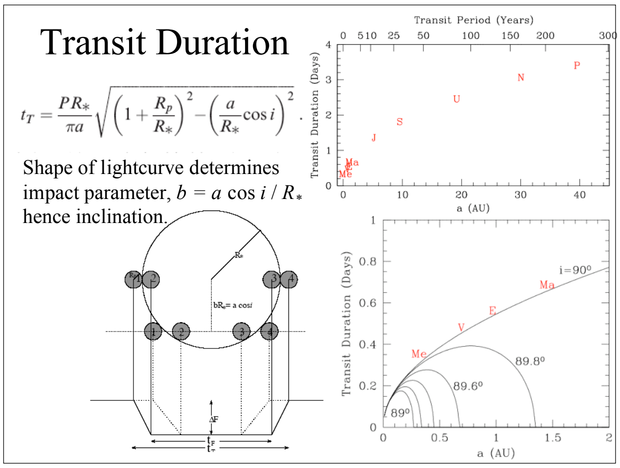
Transit Duration ($i < 90^o$)

Transit duration reduces to 0 as orbit tips away from edge-on.

$$t_T = \frac{P}{\pi}\arcsin\left(\frac{R_*}{a}\left\{\frac{[1+(R_p/R_*)]^2 - [(a/R_*)\cos i]^2}{1-\cos^2 i}\right\}^{1/2}\right);$$

For cos i << 1 this becomes:

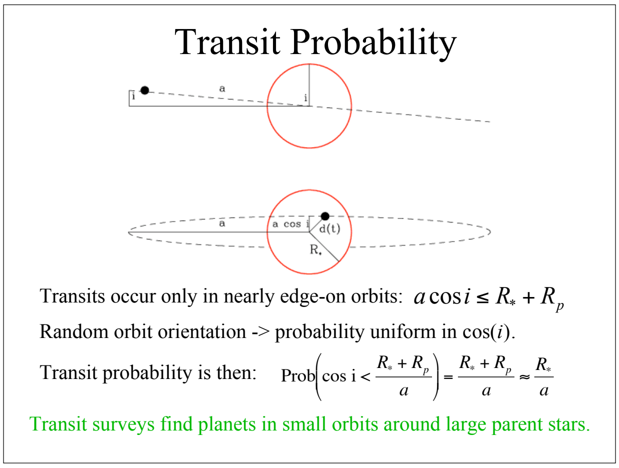
$$t_T = \frac{PR_*}{\pi a}\sqrt{\left(1+\frac{R_p}{R_*}\right)^2 - \left(\frac{a}{R_*}\cos i\right)^2}.$$



Transit Duration

$$t_T = \frac{PR_*}{\pi a}\sqrt{\left(1+\frac{R_p}{R_*}\right)^2 - \left(\frac{a}{R_*}\cos i\right)^2}.$$

Shape of lightcurve determines impact parameter, $b = a \cos i / R_*$ hence inclination.



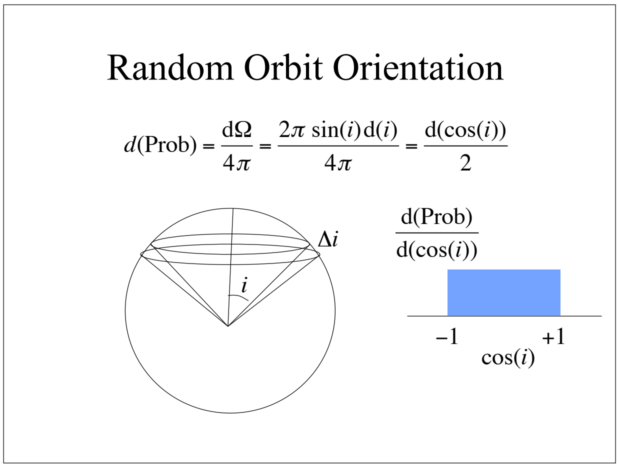
Transit Probability

Transits occur only in nearly edge-on orbits: $a \cos i \le R_* + R_p$

Random orbit orientation -> probability uniform in cos(i).

Transit probability is then: $\text{Prob}\left(\cos i < \frac{R_* + R_p}{a}\right) = \frac{R_* + R_p}{a} \approx \frac{R_*}{a}$

Transit surveys find planets in small orbits around large parent stars.

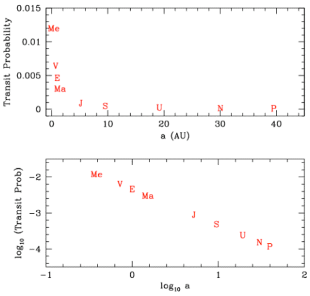


Random Orbit Orientation

$$d(\text{Prob}) = \frac{d\Omega}{4\pi} = \frac{2\pi\,\sin(i)\,d(i)}{4\pi} = \frac{d(\cos(i))}{2}$$

Transit Probability

$$\text{Prob} \approx \frac{R_*}{a} \approx 0.005 \left(\frac{R_*}{R_{sun}}\right)\left(\frac{1AU}{a}\right)$$



- Hot planets more likely to be detected.
- Prob = 0.5 % at 1 AU, Prob = 0.1 % at 5 AU (Jupiter’s orbit)
- Prob = 10% at 0.05 AU (Hot Jupiters)
- Thousands of stars must be monitored to discover planets by spotting their transits.

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(1) Spectral Type gives star mass and radius.

(2) Period (+ Kepler’s law) gives orbit size.

(3) Depth of transit gives planet radius.

Models of planets with masses between ~ 0.1 M_J and 10 M_J, have almost **the same radii** (i.e. a flat mass-radius relation).

-> Giant planets transiting solar-type stars expected to have transits depths of around 1%

(4) Impact parameter $b = a \cos(i)/R_*$, determined from the shape of the transit, gives a measure of inclination angle.

(5) Bottom of light curve is not flat in all wave bands, providing a measure of stellar limb-darkening

(6) Since inclination is measured, can measure mass, not just lower limit $m_p \sin(i)$, from the radial velocity data.

Photometry at better than 1% precision is possible (not easy!) from the ground.

By 2000, over 20 independent ground-based searches for transiting planets were started.

SuperWASP, Tres, XO, HAT, OGLE have detected nearly all transiting planets. Mostly gas giant planets.

Transit depth for an Earth-like planet is:

$$\left(\frac{R_{\text{Earth}}}{R_{\text{Sun}}}\right)^2 \approx 8 \times 10^{-5}$$

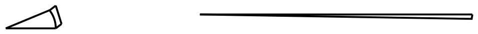
Photometric precision of ~ 10^{-5} can be achieved from space.

May provide first detection of habitable Earth-like planets

French satellite *Corot - launched 2006.*
NASA’s *Kepler* mission - *launched 2009.*
ESA mission PLATO - under review.

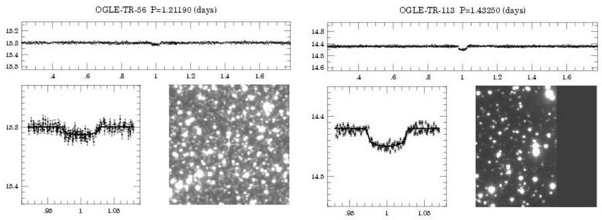
Transit Surveys

Wide vs Deep



$D \sim 10$ cm $\quad \theta \sim 10^\circ$	$D \sim 1-4$ m $\quad \theta < 1^\circ$
$d \sim 300$ pc $\quad \Delta\theta \sim 30$ arcsec	$d \sim 1-4$ kpc $\quad \Delta\theta \sim 1$ arcsec
All-sky surveys	Galactic plane fields
Small wide-angle cameras survey bright nearby stars	**Larger telescopes (narrow fields) survey faint distant stars**

OGLE III Deep Transit Survey



1.3m microlens survey telescope Las Campanas, Chile.
Mosaic 8-chip CCD camera. 2001 Galactic Bulge -- 64 candidates
2002 Carina -- 73 candidates

Spectroscopic follow-up of OGLE-TR-56b
confirms it is a planet with $m_p = 0.9\ m_J$ and $P = 1.2$ days

⇒ first exoplanet discovered using transits.

Wide-Angle Transit Surveys
Discovery Potential:

Assume HD 209458 (V=7.6 mag) is brightest.

mag	8	9	10	11	12	13
all sky	1	4	16	64	256	1024 Hot Jupiters!

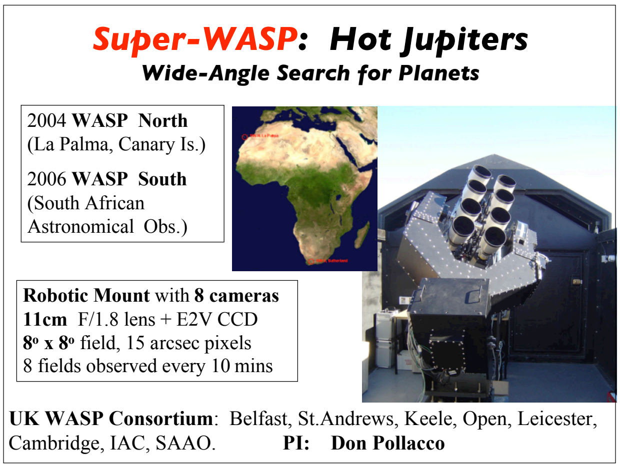
100 x fainter -> 10 x farther -> 1000 x more targets.

How long to find them ?

All sky = 600 8°x8° fields x 2 months / field

~ 100/N years $\quad N$ = number of 8°x8° cameras

Need ~6 years for N=16



Super-WASP: *Hot Jupiters*

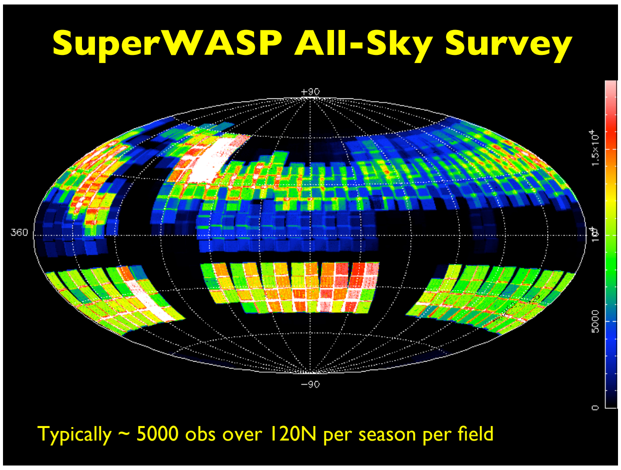
Wide-Angle Search for Planets

2004 **WASP North**
(La Palma, Canary Is.)

2006 **WASP South**
(South African
Astronomical Obs.)

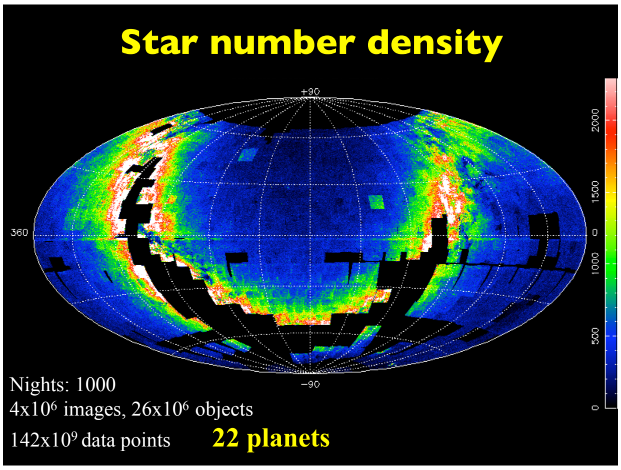
Robotic Mount with **8 cameras**
11cm F/1.8 lens + E2V CCD
8º x 8º field, 15 arcsec pixels
8 fields observed every 10 mins

UK WASP Consortium: Belfast, St.Andrews, Keele, Open, Leicester, Cambridge, IAC, SAAO. **PI: Don Pollacco**



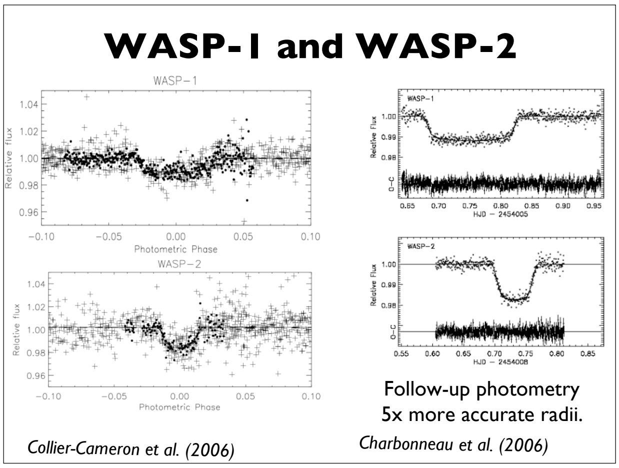
SuperWASP All-Sky Survey

Typically ~ 5000 obs over 120N per season per field



Star number density

Nights: 1000
4x10⁶ images, 26x10⁶ objects
142x10⁹ data points **22 planets**

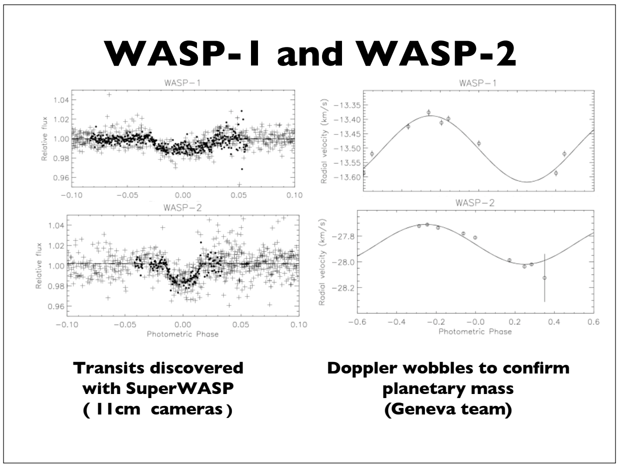


WASP-1 and WASP-2

Follow-up photometry
5x more accurate radii.

Collier-Cameron et al. (2006)

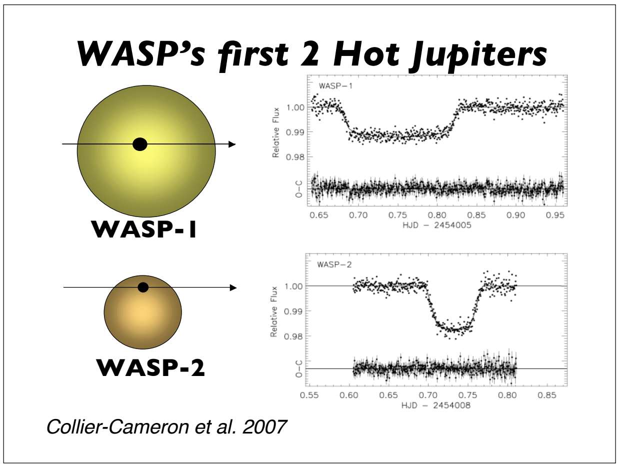
Charbonneau et al. (2006)



WASP-1 and WASP-2

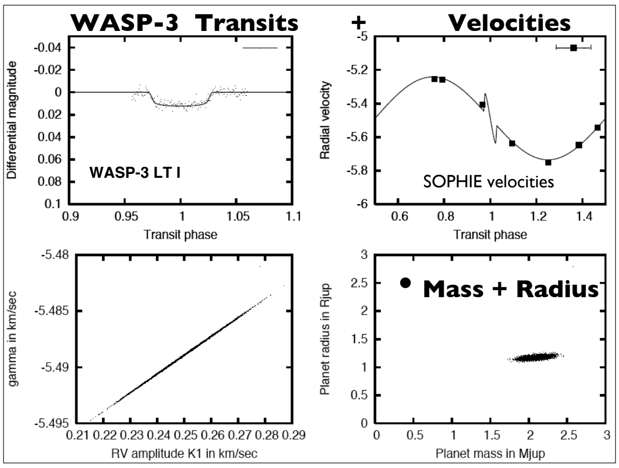
Transits discovered with SuperWASP (11cm cameras)

Doppler wobbles to confirm planetary mass (Geneva team)



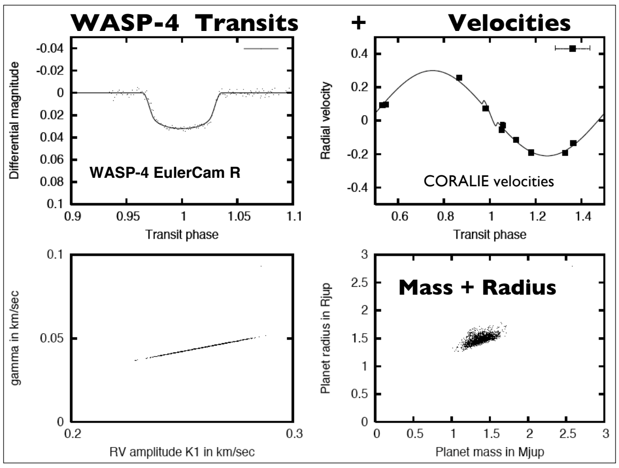
WASP's first 2 Hot Jupiters

Collier-Cameron et al. 2007



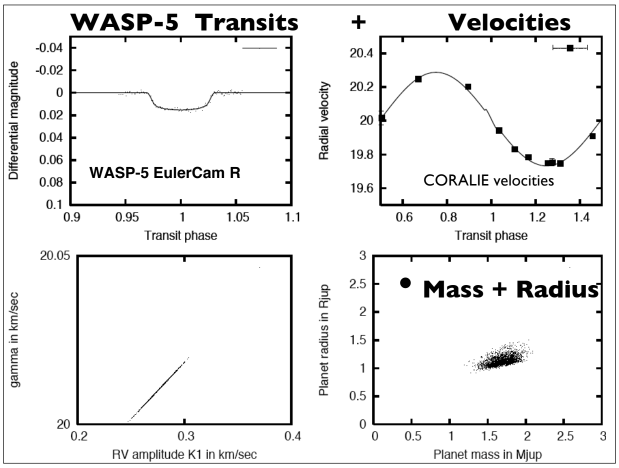
WASP-3 Transits + Velocities

Mass + Radius



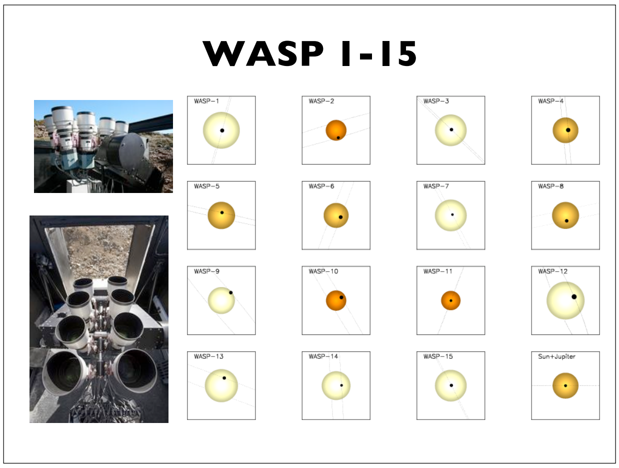
WASP-4 Transits + Velocities

Mass + Radius

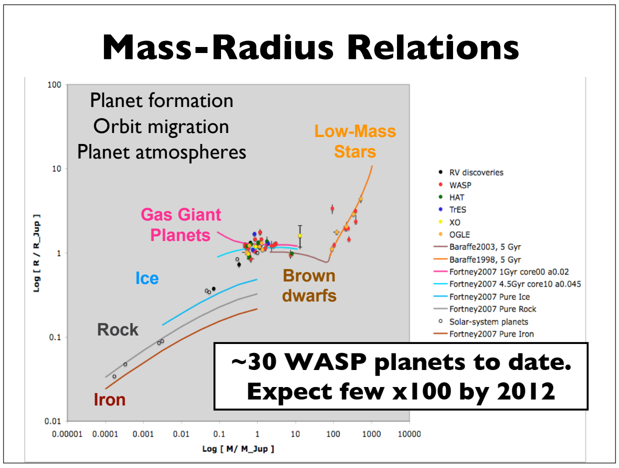


WASP-5 Transits + Velocities

Mass + Radius



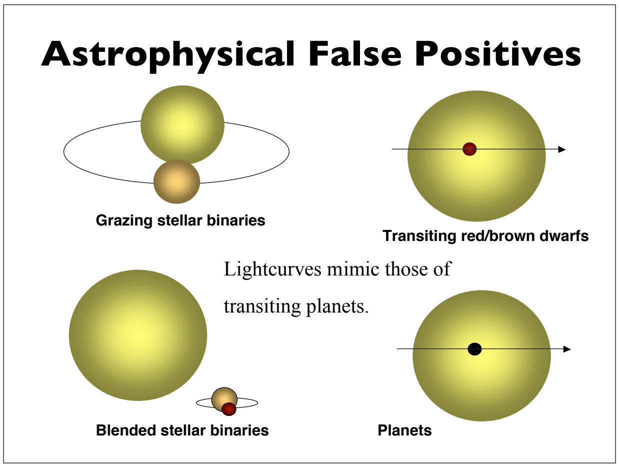
WASP 1-15



Mass-Radius Relations

Planet formation
Orbit migration
Planet atmospheres

~30 WASP planets to date.
Expect few x100 by 2012

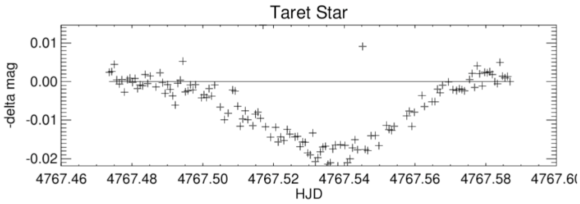


Astrophysical False Positives

Lightcurves mimic those of transiting planets.

Grazing binary

2 equal mass, equal size stars that just barely eclipse eachother. This causes a small dip in brightness which is approximately planet sized. However, the transit is V-shaped.

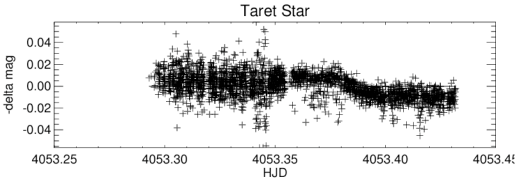


Observations taken with the JGT in St Andrews

M-dwarf secondary

Main sequence primary star, but massive M-dwarf secondary star (rather than planet mass secondary). Light curve is indistinguishable from a planet transit since late M-dwarfs are the same size as gas giant planets ($R_* \sim 0.1\ R_{sun} \sim 1\ R_J$).

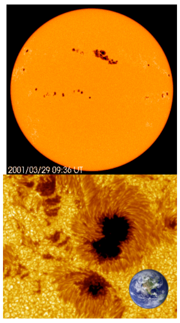
Need RV to determine mass of the secondary object

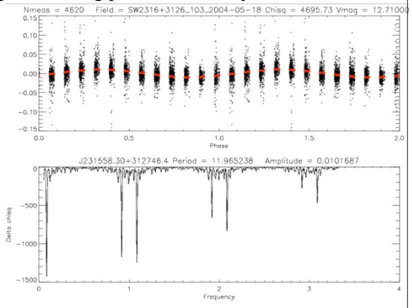


Observations taken with the JGT in St Andrews

Star Spots

Multiple starspots tend to cause sine-like variations, not dips. Starspots come and go, transiting planets are always there.





Makes detection of Earth sized planets more difficult

Sources of confusion

- A stellar binary can have an inclination such that the eclipsing secondary *grazes* the primary causing photometric dips very similar to those expected from planetary transits. Resolvable with multi-colour observations and spectroscopy
- Massive M-dwarf secondary, rather than a planet mass secondary
- Stellar spots – initally confusing but not permanent, different shape than a transit
- Line-of-sight blending with an eclipsing binary
  - blending due to large pixel of survey telescope can be rejected with photometry
  - unresolved blends require RV measurements and show variations with the “line-bisector”
- Giants stars showing dips in brightness. Secondary object would not be planet sized. Colors and proper motion of the star can distinguish giants from main sequence stars