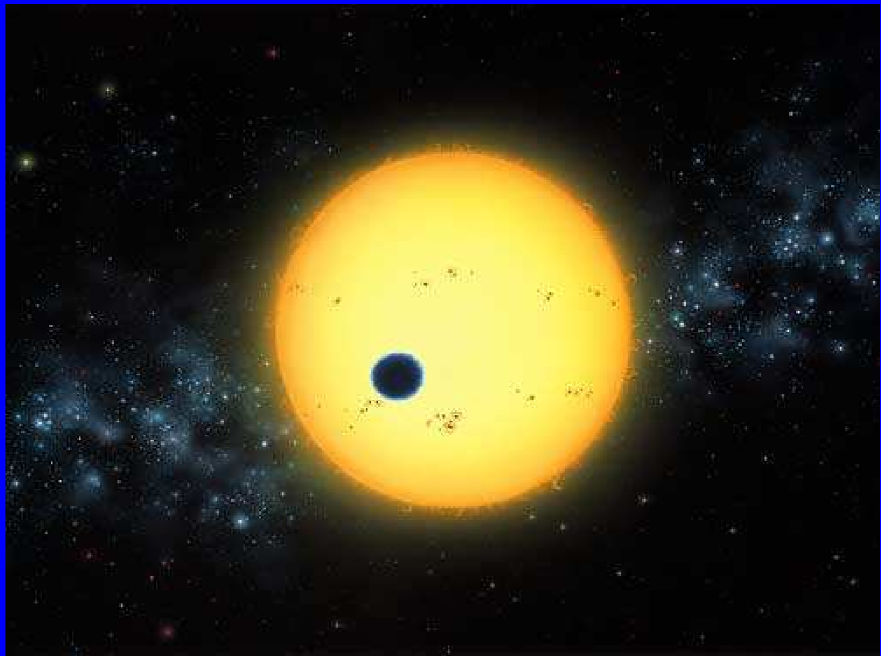
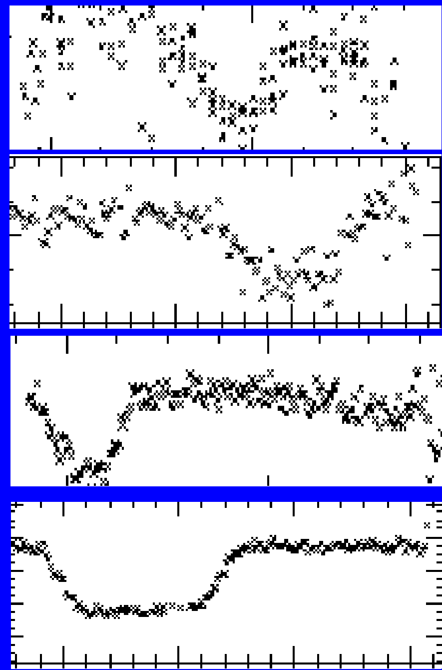
The Future of Extrasolar Planet Detection and Characterization



Lynnette Cook



Gabriela Mallén-Ornelas
Harvard-Smithsonian Center for Astrophysics

Facing the Future: A Festival for Frank Bash. UT Austin, October 2003

The Future of Extrasolar Planet Detection and Characterization

Known Planetary Systems

Characterizing Extrasolar Planet via Transits

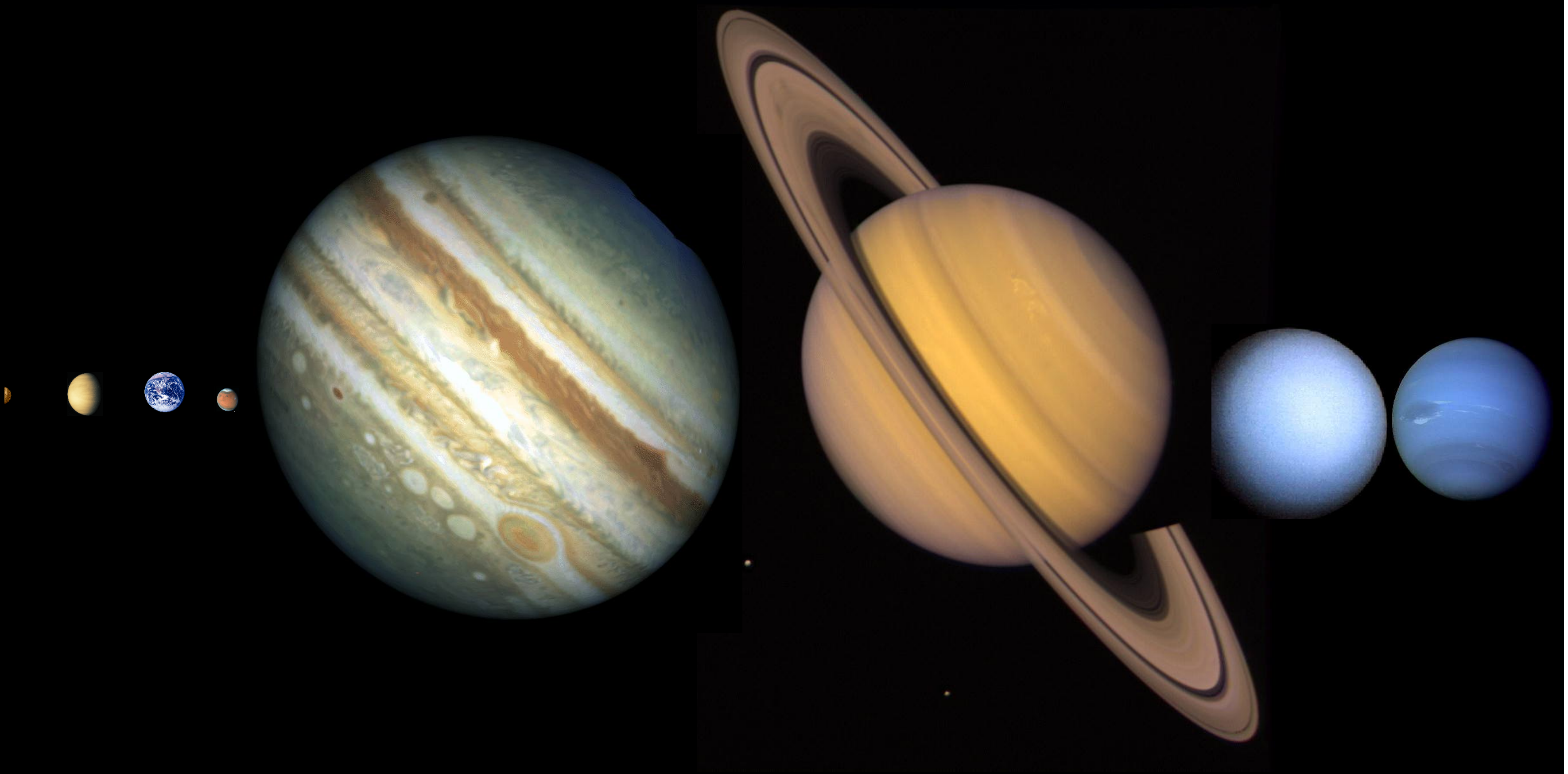
Ground-based Transit Searches

Space-based Searches: Transits and Reflected Light

Summary

The Solar System

Planet sizes are to scale. Separations are not.



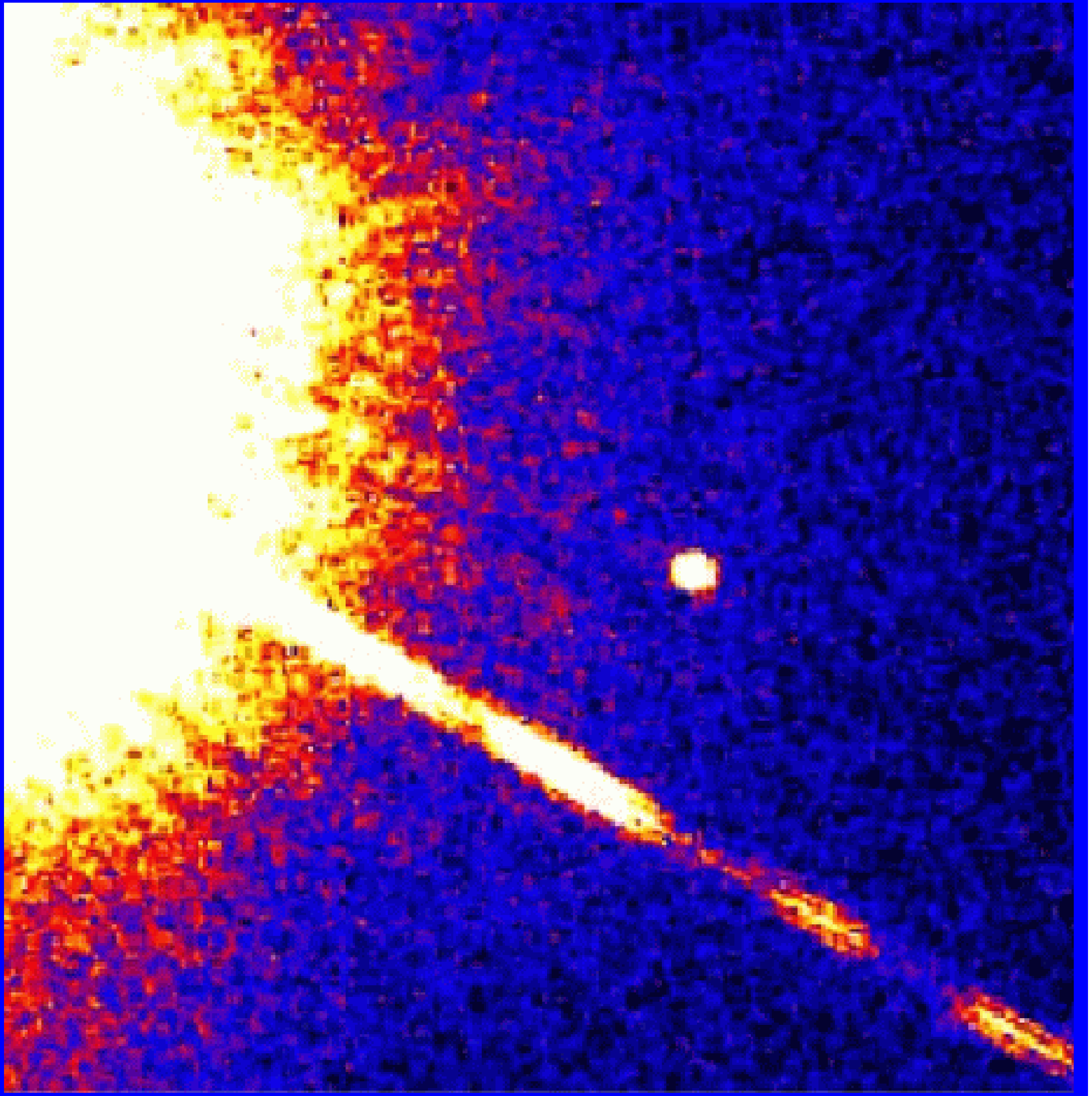
Planets too faint and too close to stars to see

Nearby star with
faint companion star

Earth would be:

* 50 times closer in

* 1 000 000 times
  fainter



Gliese 229 and 229b - Hubble Space Telescope

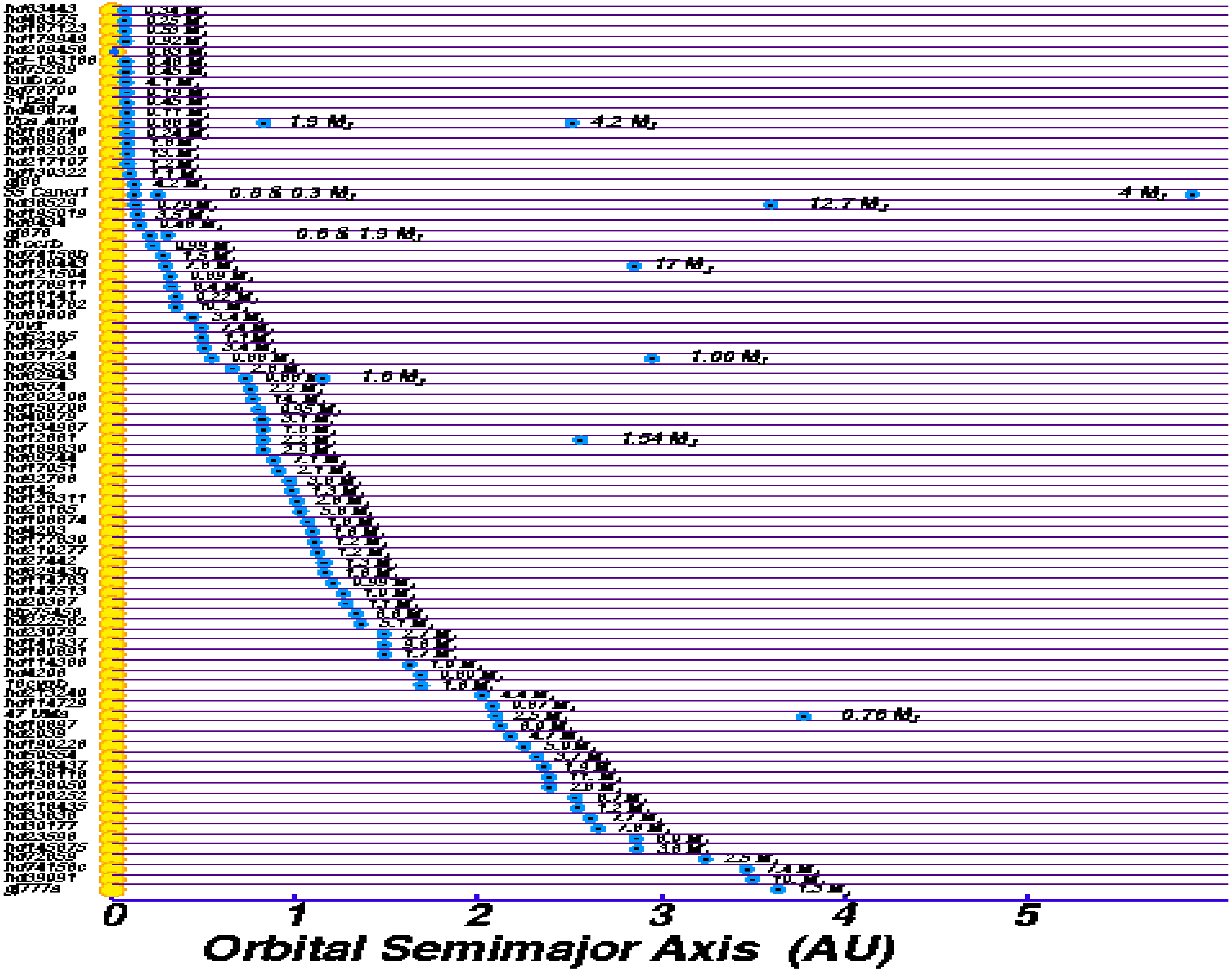
Known Extrasolar Planets

- 1995: discovery of 51 Peg b, the first extrasolar planet found orbiting a sun-like star

- 117 planets orbiting single sun-like stars

- 14 planets with orbital periods < 5 days

- All but one discovered with the radial velocity method www.exoplanets.org



Extrasolar Planetary Systems

Radial velocity tells us minimum mass (M sin i), orbital period and eccentricity

Giant planets exist at all orbital distances probed

Close-in giant planets 7 x closer than Mercury to the Sun

Multiple planet systems

Almost all planets at > 0.2 AU have eccentric orbits

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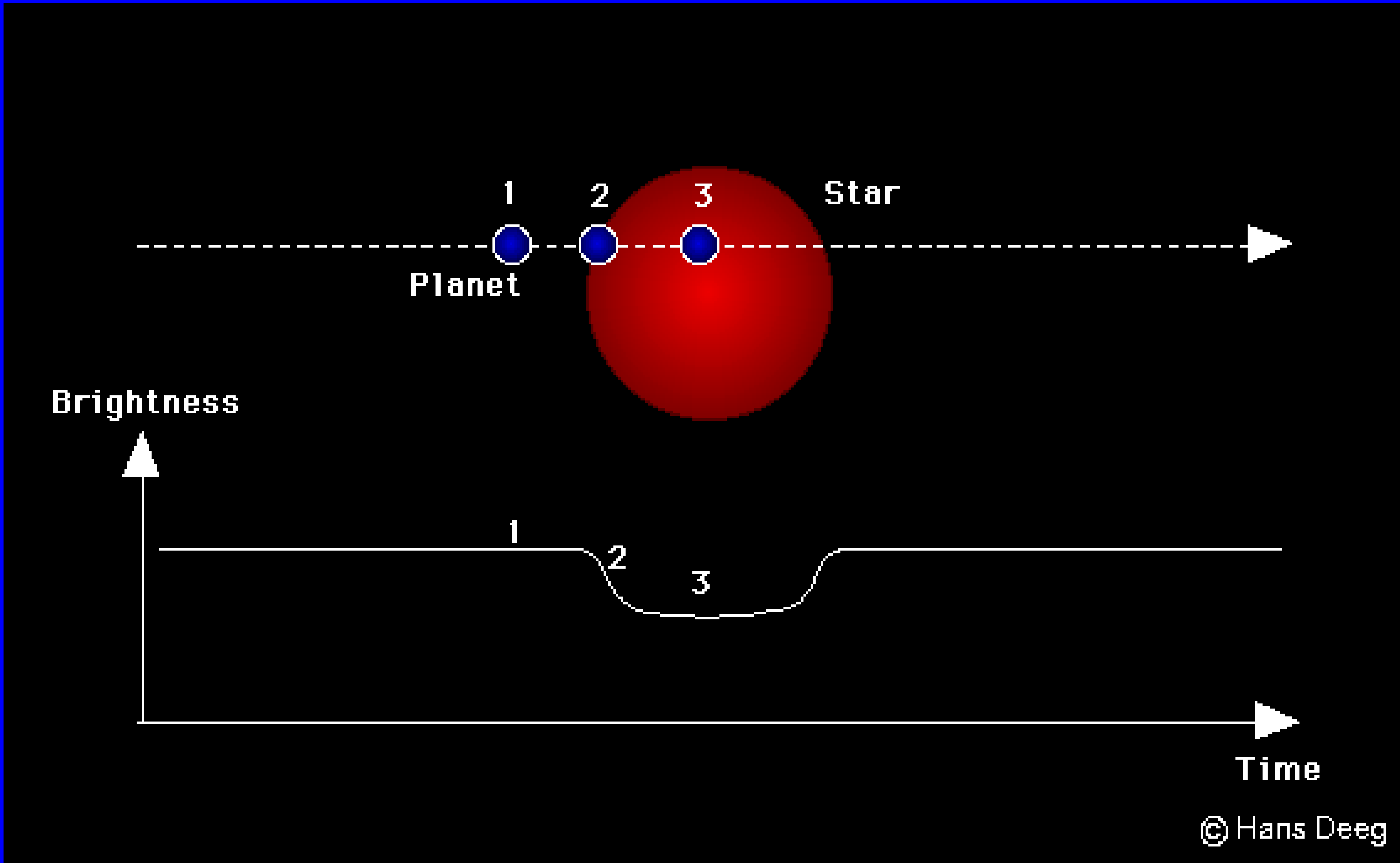
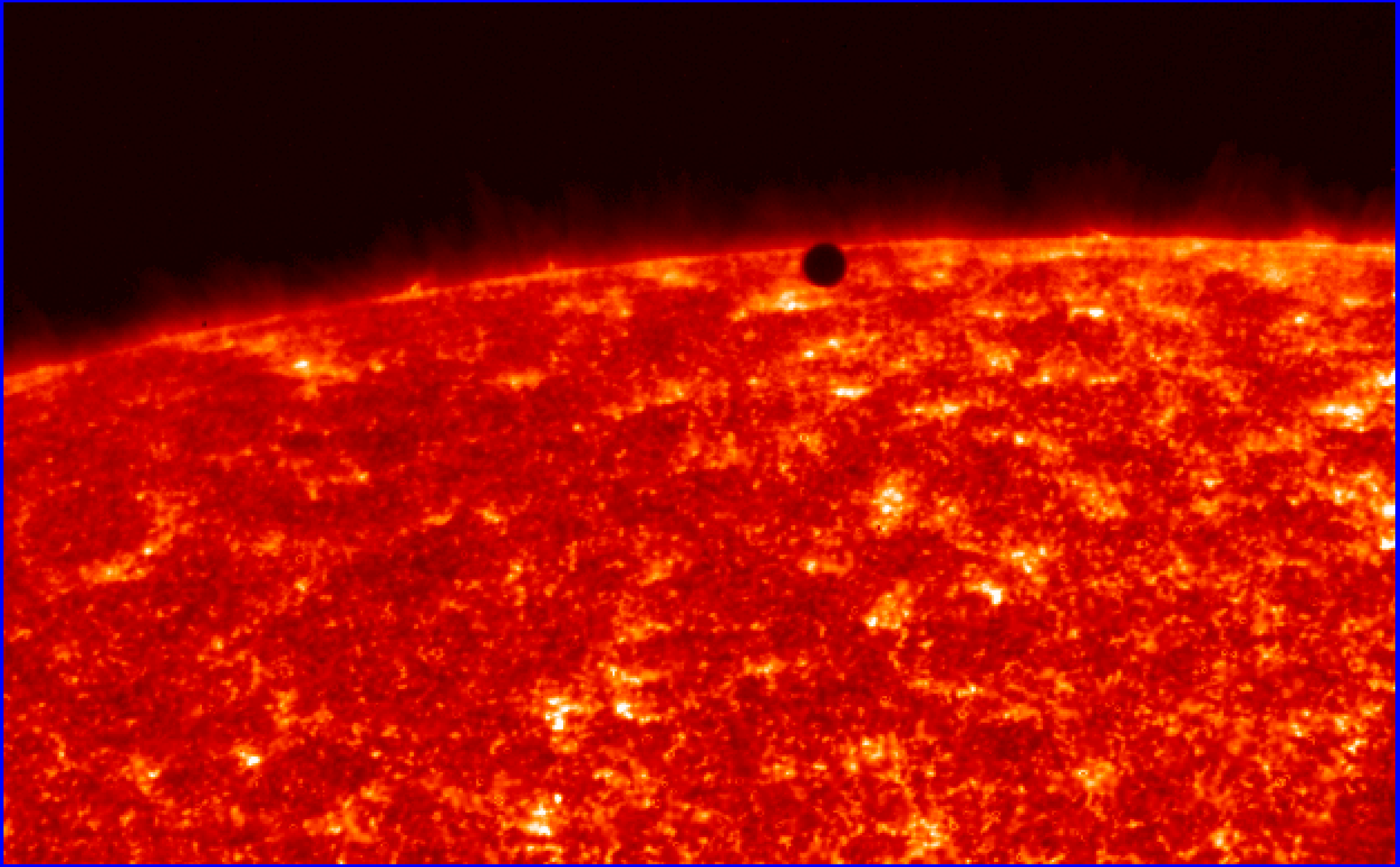
Planet Transits

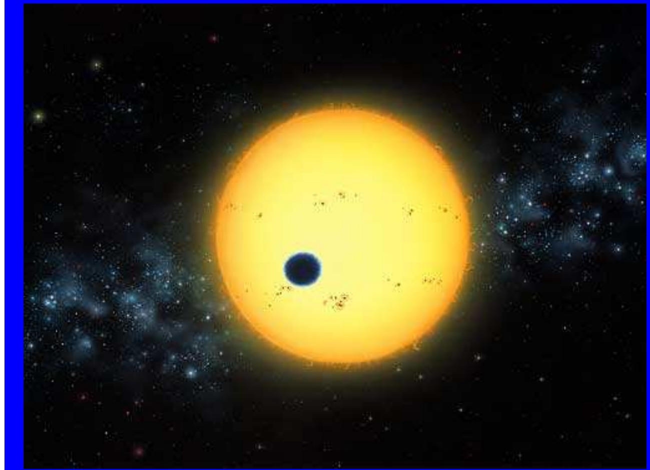


Planet Transits



Mercury transiting the Sun, November 1999 TRACE satellite

The First Transiting Planet



Lynnette Cook

Found as a follow-up to radial velocity searches

Tells us:

DIRECTLY:

Planet radius 1.347 +/- 0.060R_J

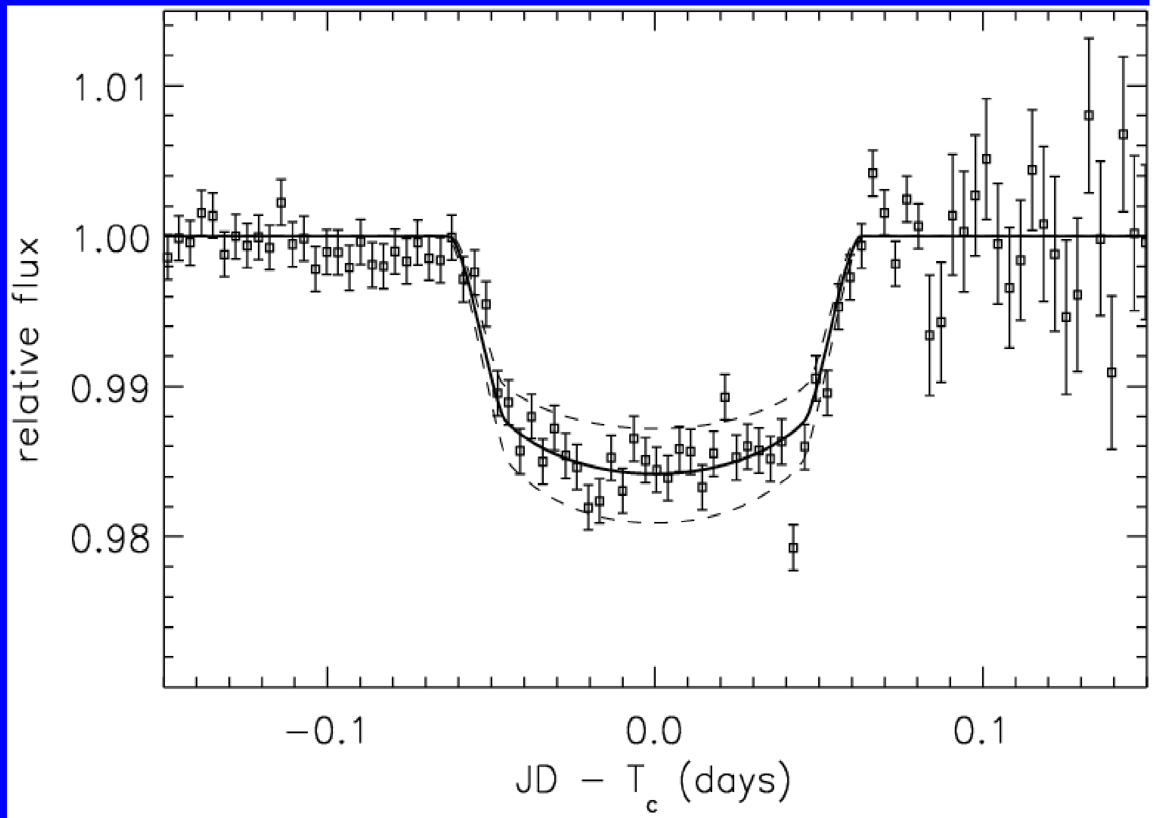
INDIRECTLY:

Planet mass: 0.69 +/- 0.05 M_J

Planet density

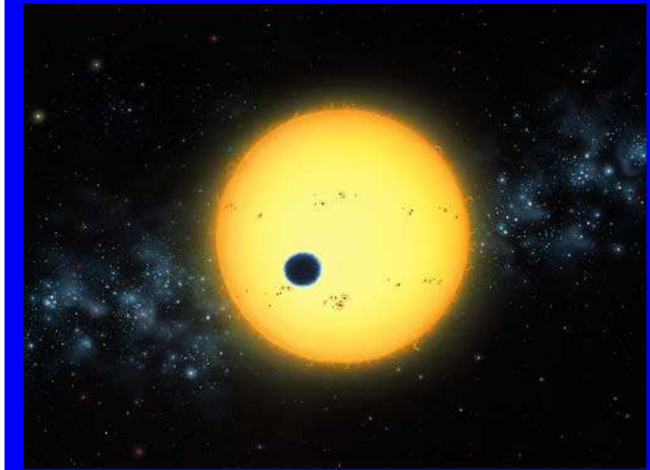
0.31+/- 0.07 g cm^{-3}

Planet composition



Charbonneau, Brown, Latham, Mayor & Mazeh 2000

The First Transiting Planet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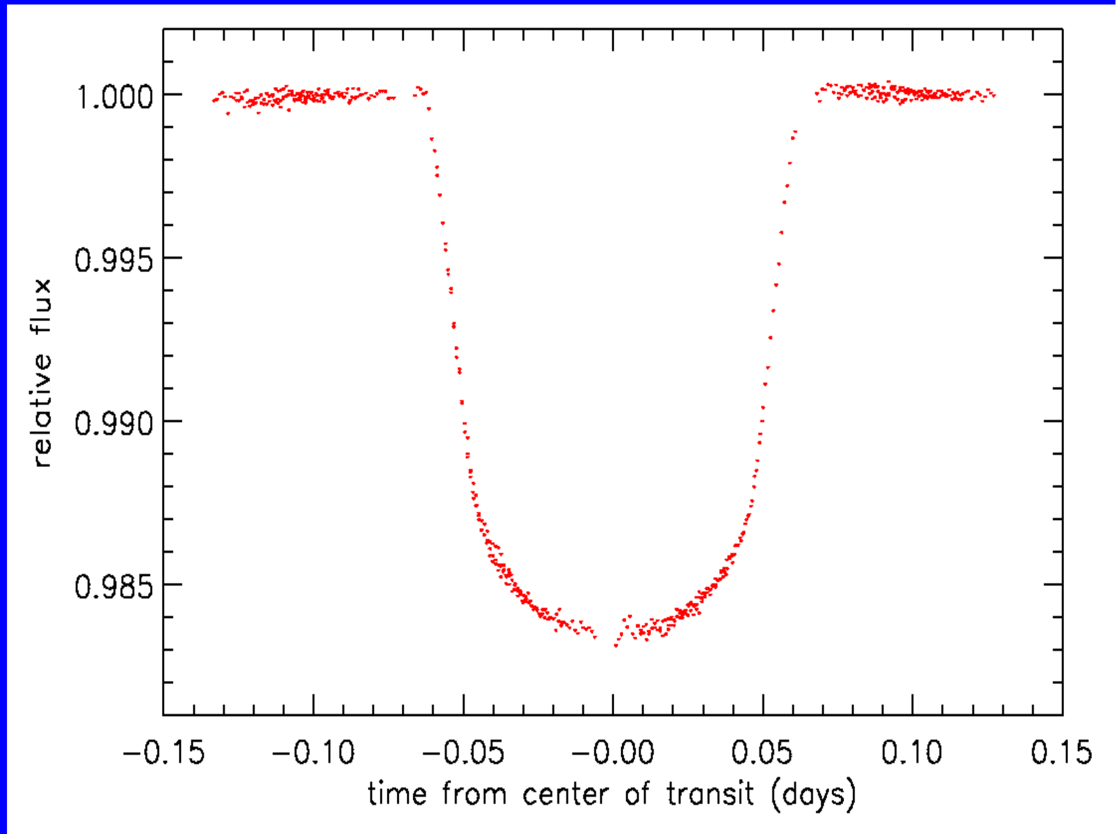

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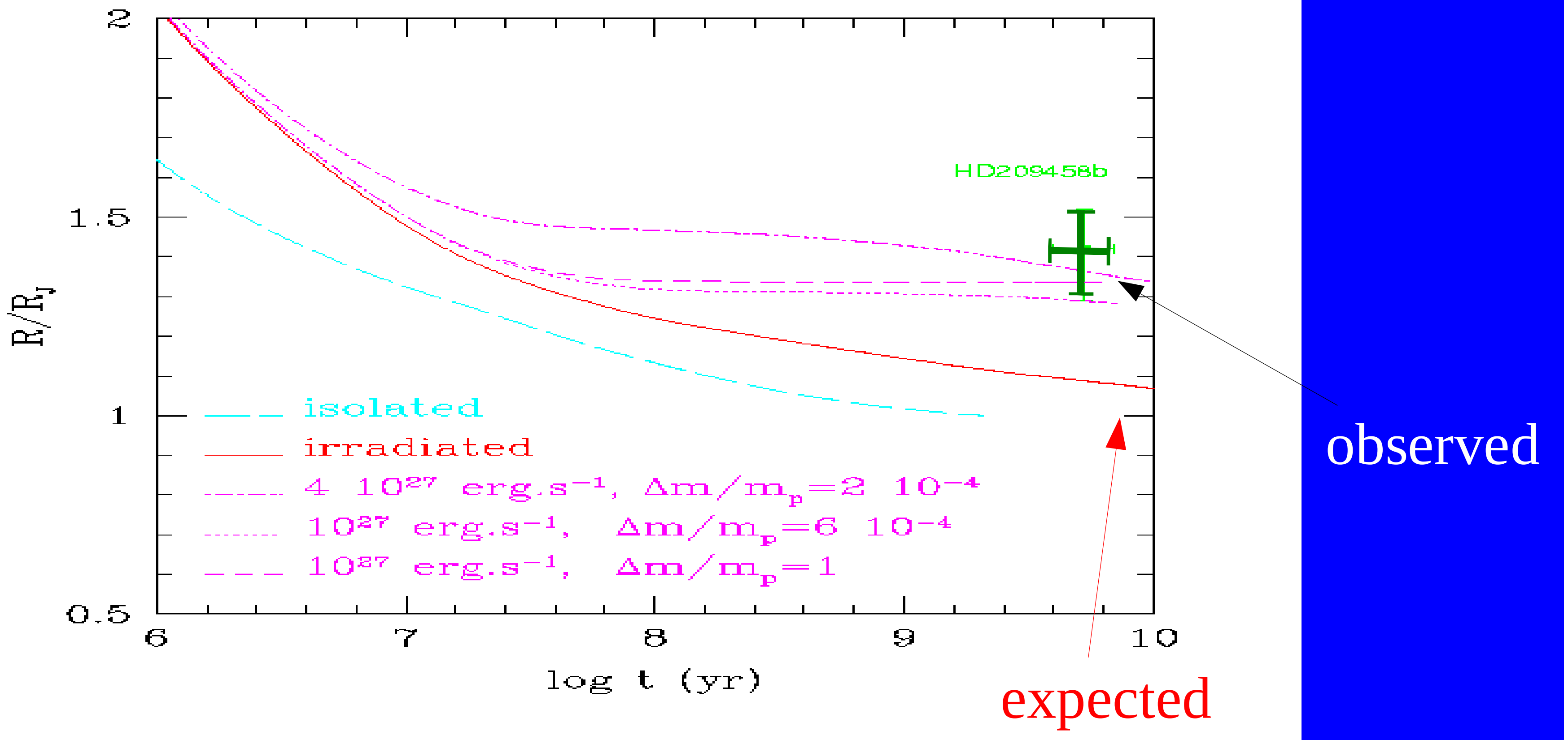
Planet composition

Brown , Charbonneau, Gilliland, Noyes & Burrows 2001

Some Potential Follow-ups

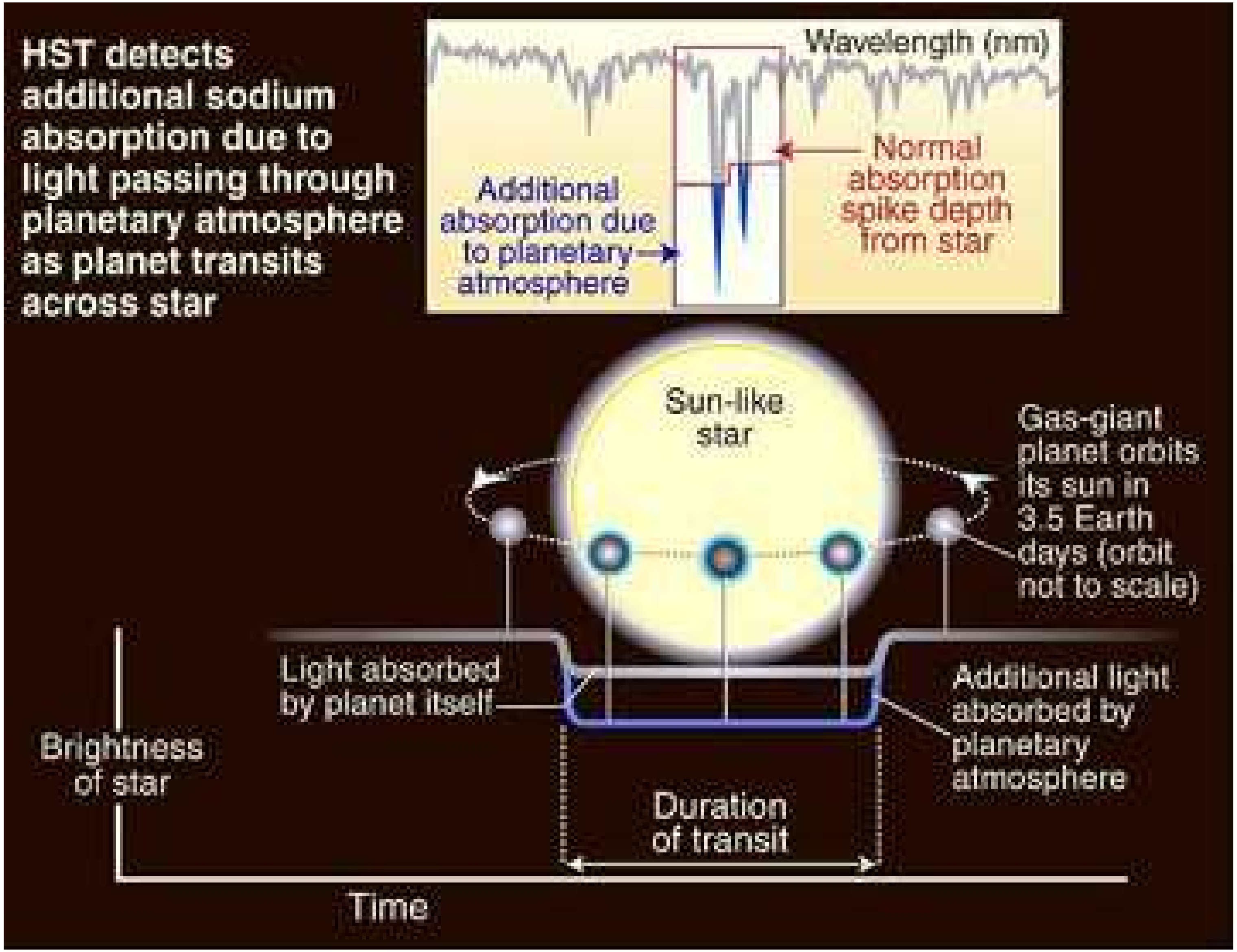
- Planet radius measurement
- Transmission spectra
- Rings or moons in transit
- Temperature determination
- Oblateness/Rotation

The Importance of Planet Radii



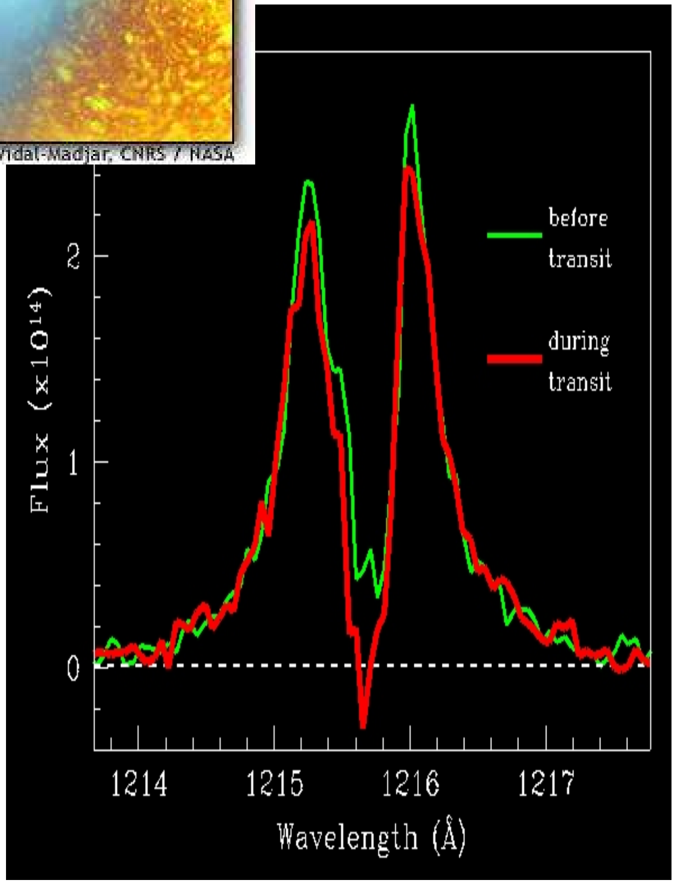
Baraffe et al. 2003

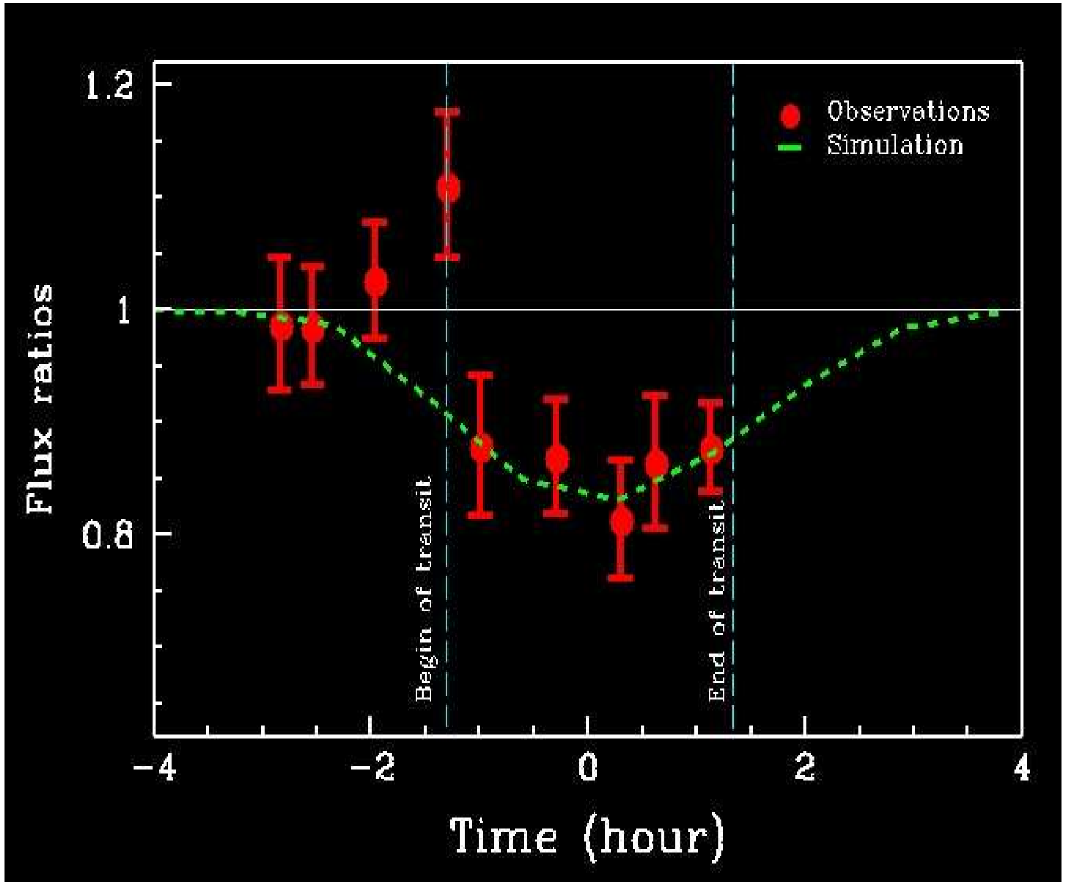
Atmosphere Detection



Charbonneau, Brown, Noyes & Gilliland 2002

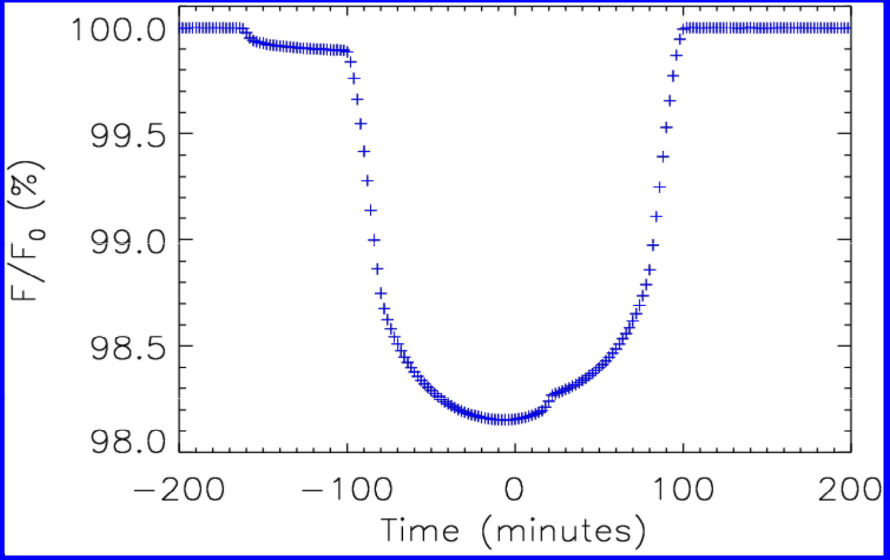
Exosphere Lyα Detection



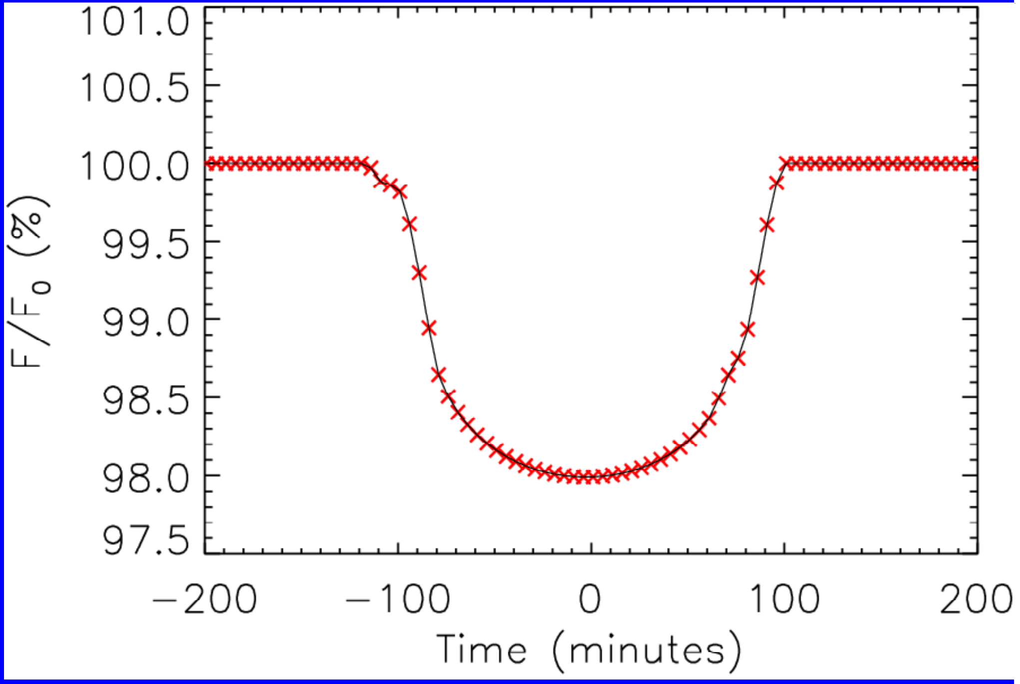


Vidal-Madjar et al, 2003, Nature

Theoretical Planet + Moon Transit Curve



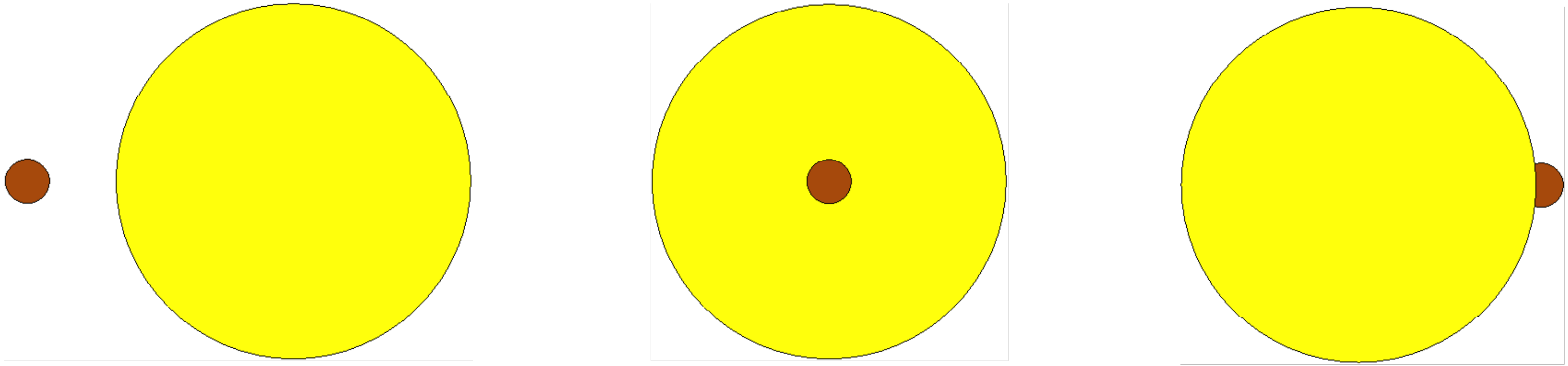
CEGP with leading 0.25*Rp moon



CEGP with leading Earth-sized moon

S. Seager

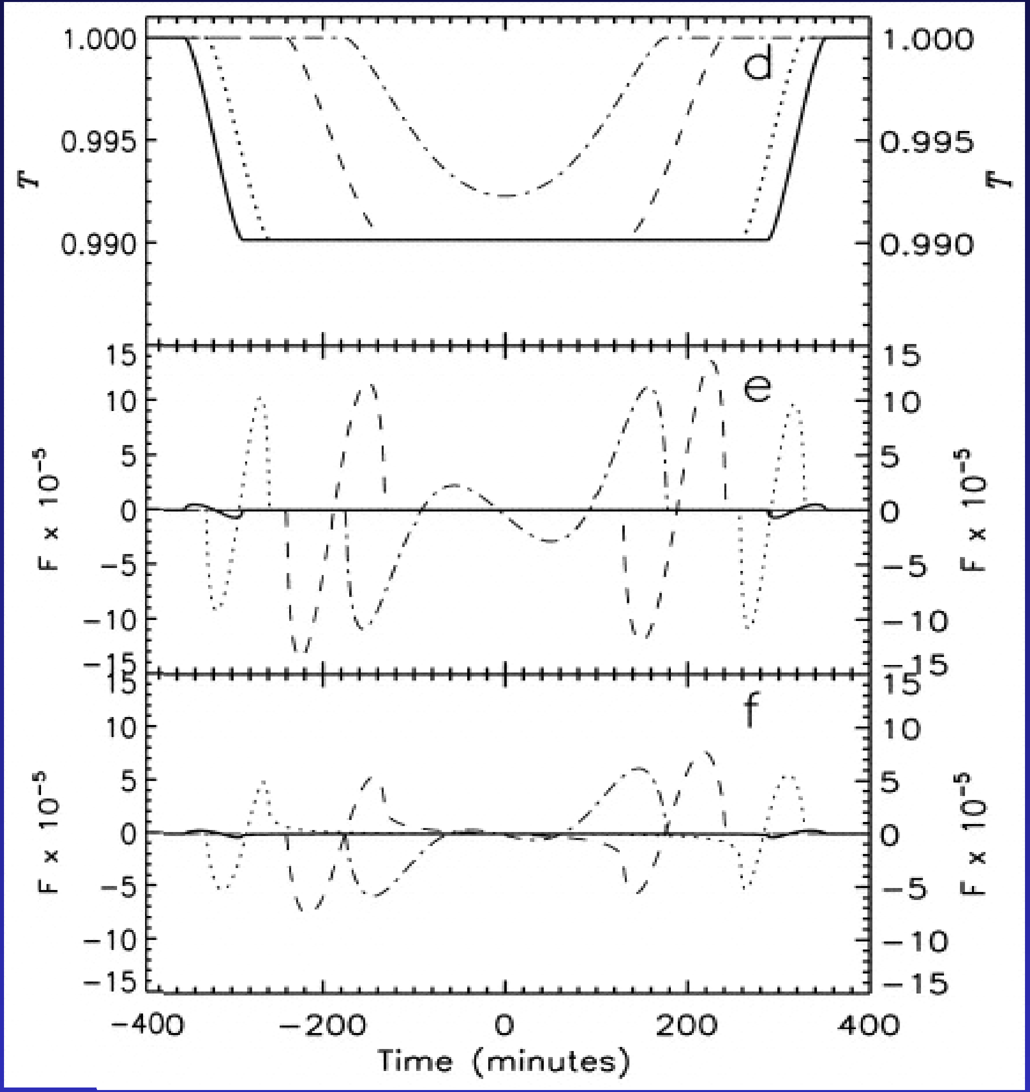
Temperature Determination

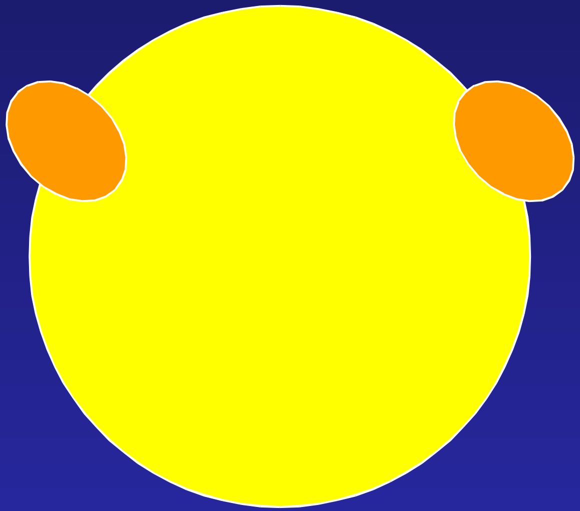


no eclipse primary eclipse secondary eclipse

- Infrared wavelengths
- Close-in planets are tidally locked
- May have different day and night side temperatures
- S/N of 5000 to 10000 over 2.5 hours is needed

Planet Oblateness





- Note asymmetry
- Depends on synchronization timescale

a = 0.2 AU, b = 45, Saturn's oblateness
Seager & Hui 2002

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Characterizing Extrasolar Planet via Transits

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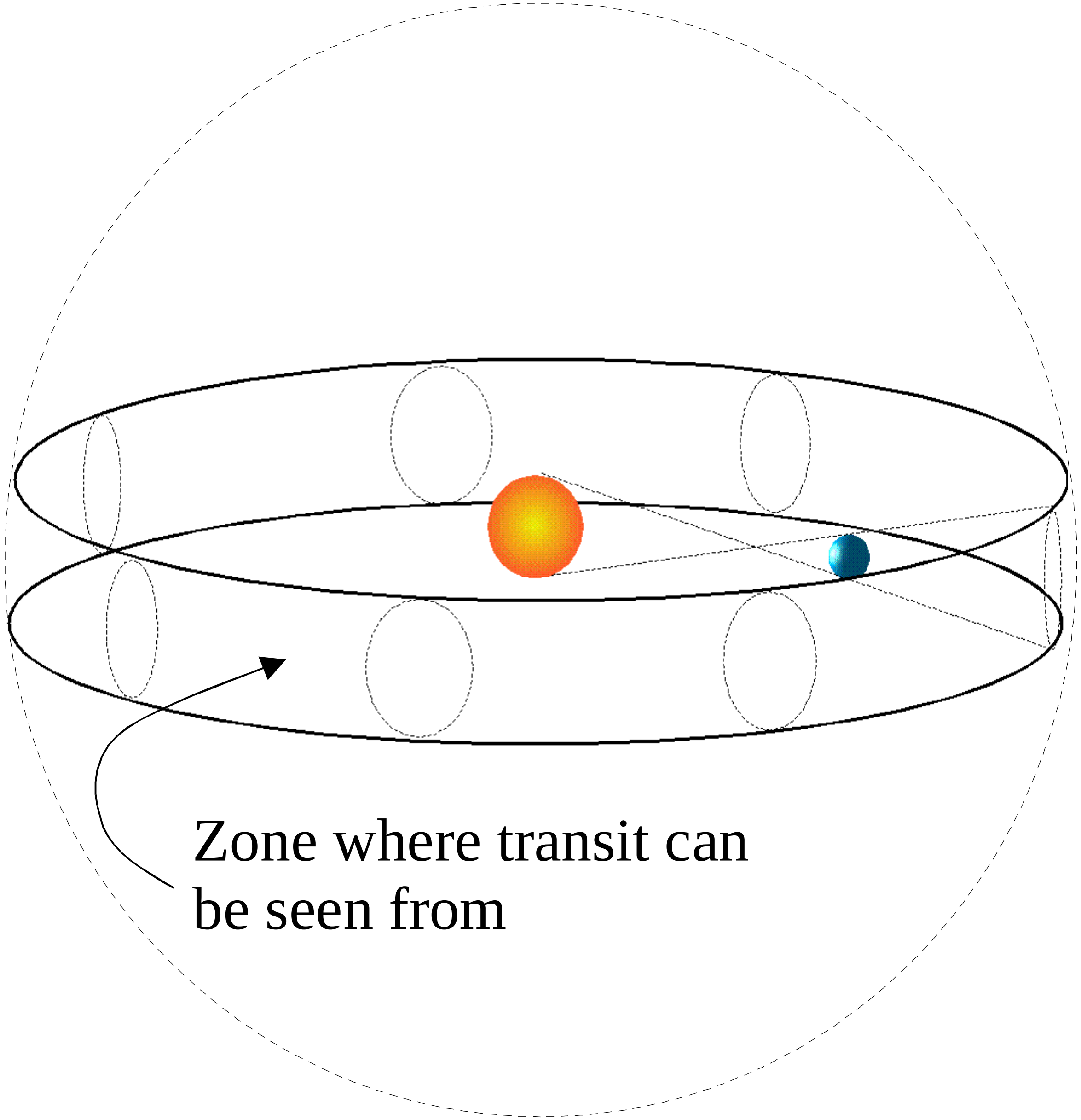
Summary

Using Transits as a Search Method

- Transiting planets give important constraints
  - radius -> physics of giant planets
  - absolute mass (with radial velocities)
- Probes a new area of parameter space
  - more distant stars, different environments
  - different types of stars
- Suitable for follow-up observations

Probability to Transit



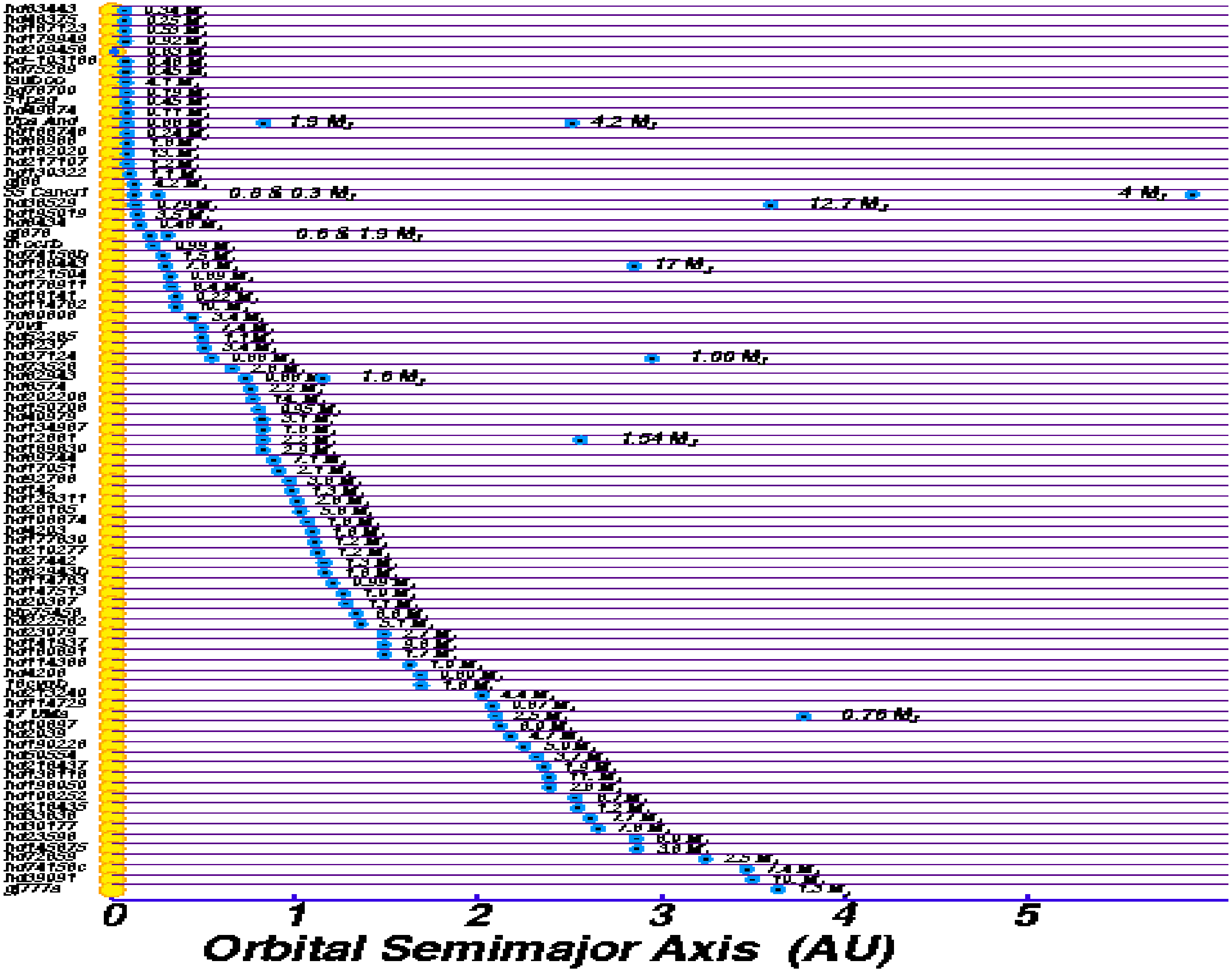
P ~ (R_*/D)

0.05 AU: 10%

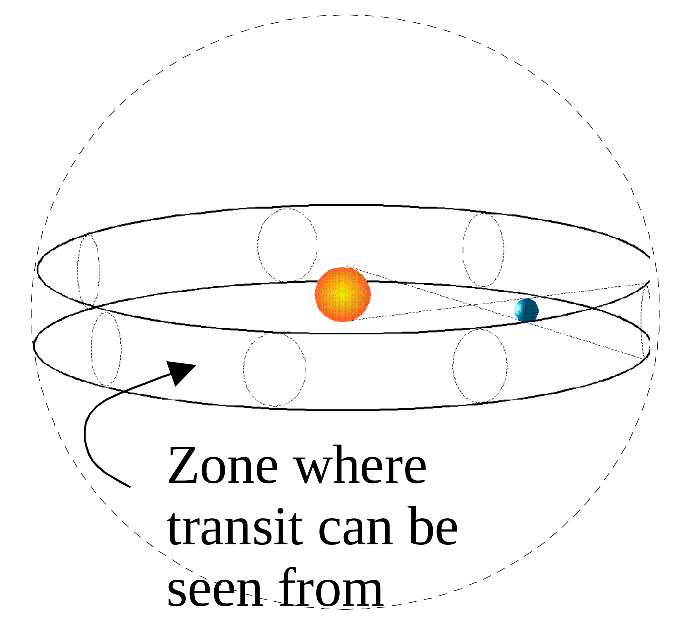
1 AU: 0.5%

Close-in planets make transit searches viable!

www.exoplanets.org



Probability to Observe a Transit



- 10% geometric probability (~R/a)
- 0.7 % frequency of CEGPs around sun-like stars
- 50% binary fraction

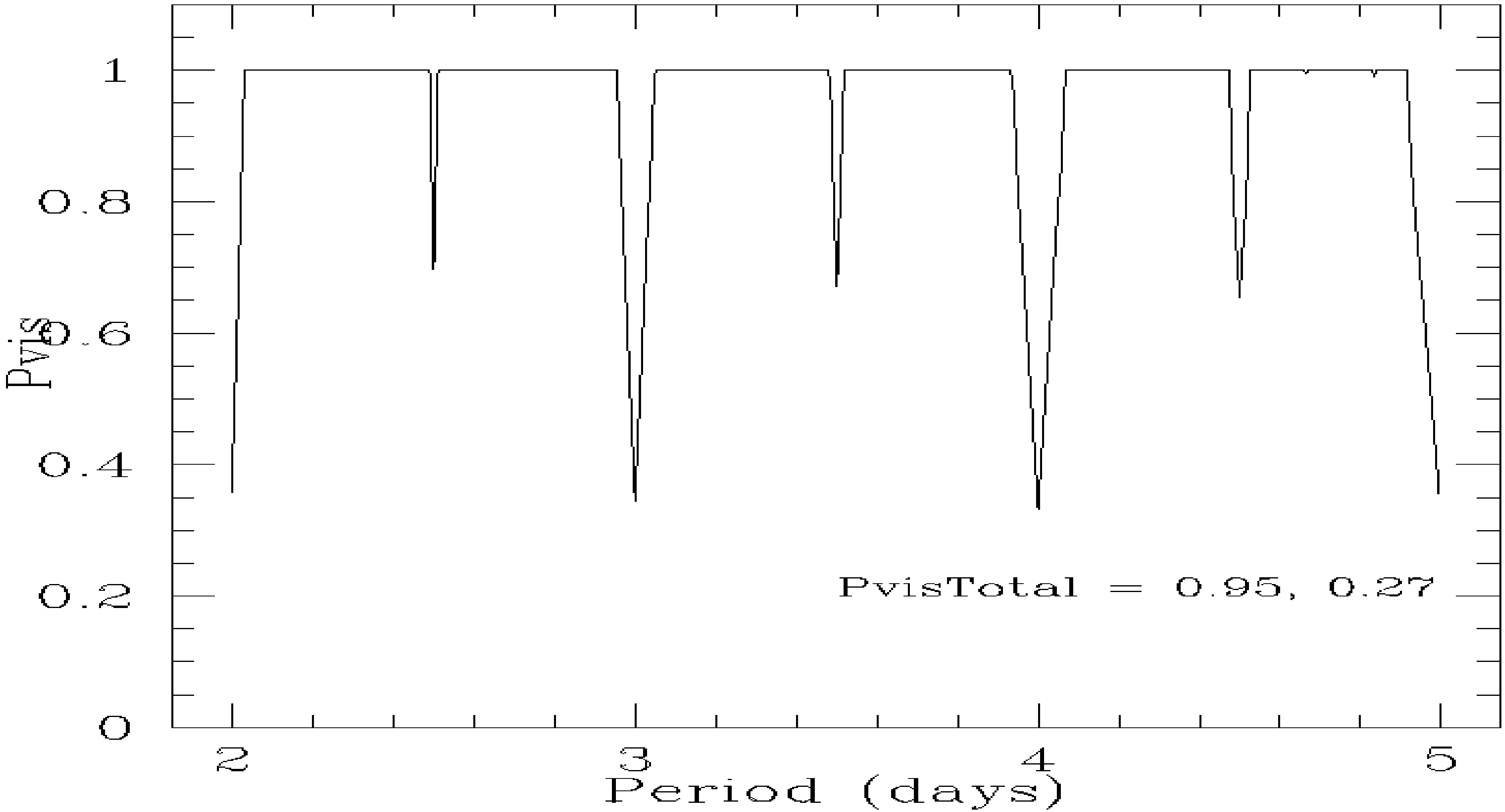
1 in 3000 stars is likely to have a transiting CEGP

Many transits not detected since some transits happen during the day --> need ~20 nights for maximum detection efficiency per night, Pvis ~50-60% yield

The Visibility Function

- Probability to *observe* transits is much lower than 1/3000

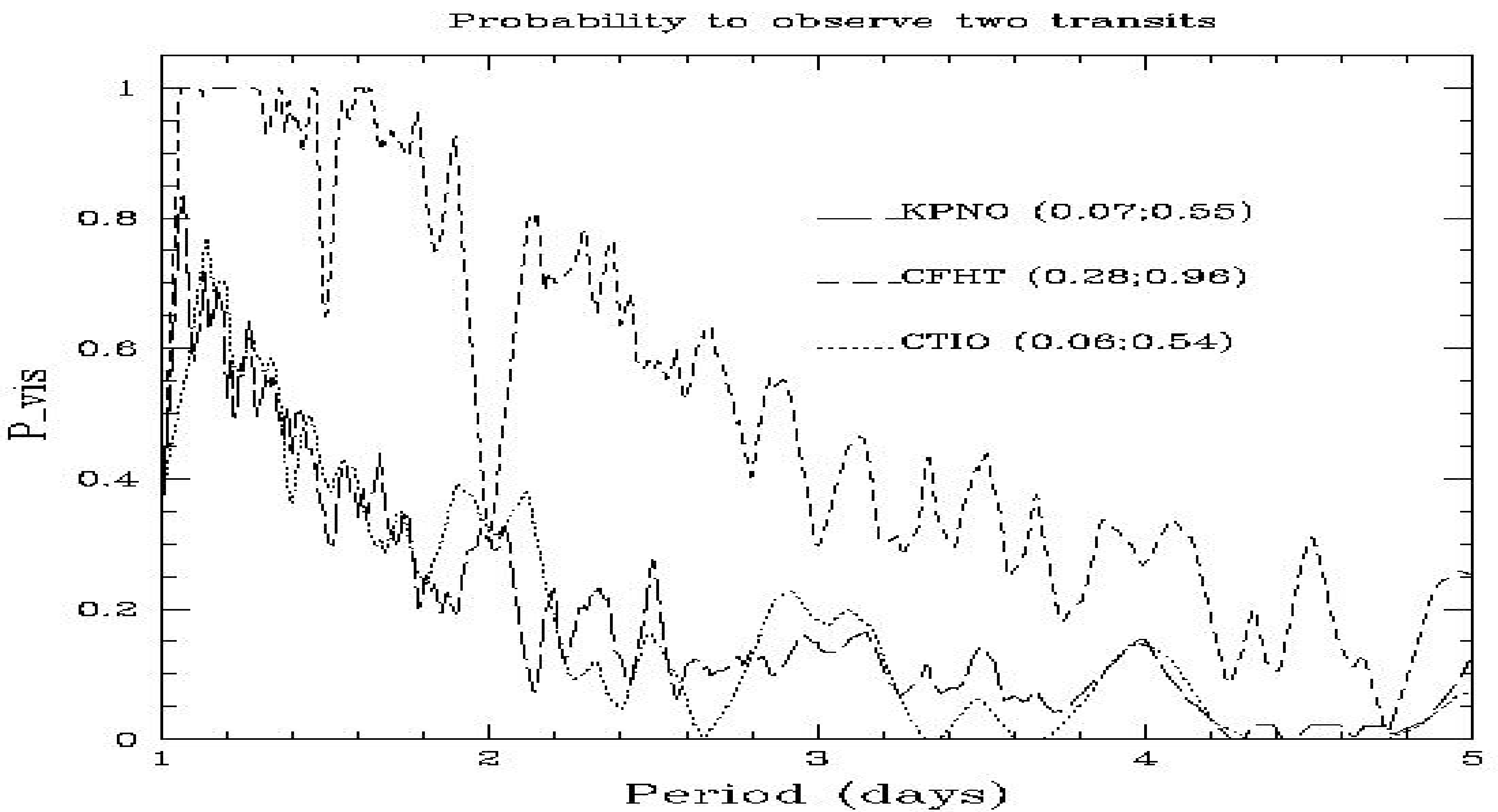
50 nights for 10.8 hours each night



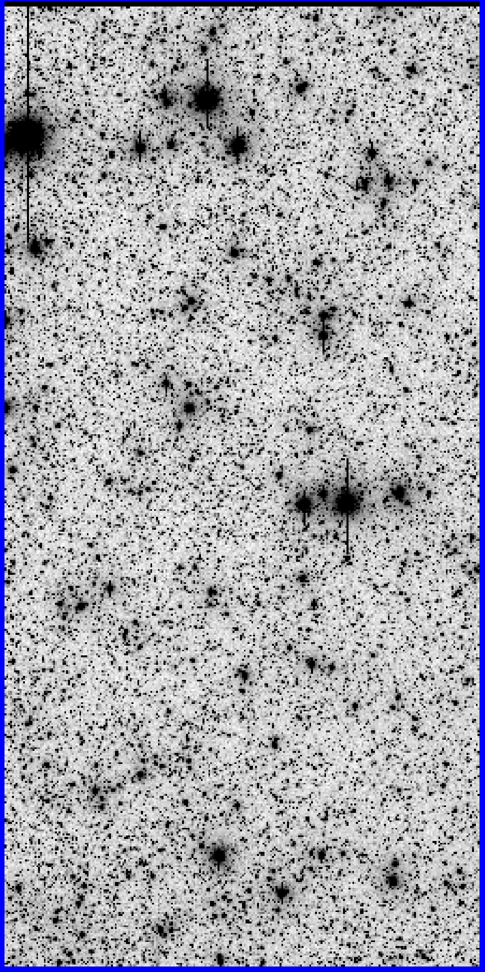
The Visibility Function

- Probability to *observe* transits is much lower than 1/3000

Pvis for real observing runs with 6 to14 clear nights



Maximizing Detection Efficiency

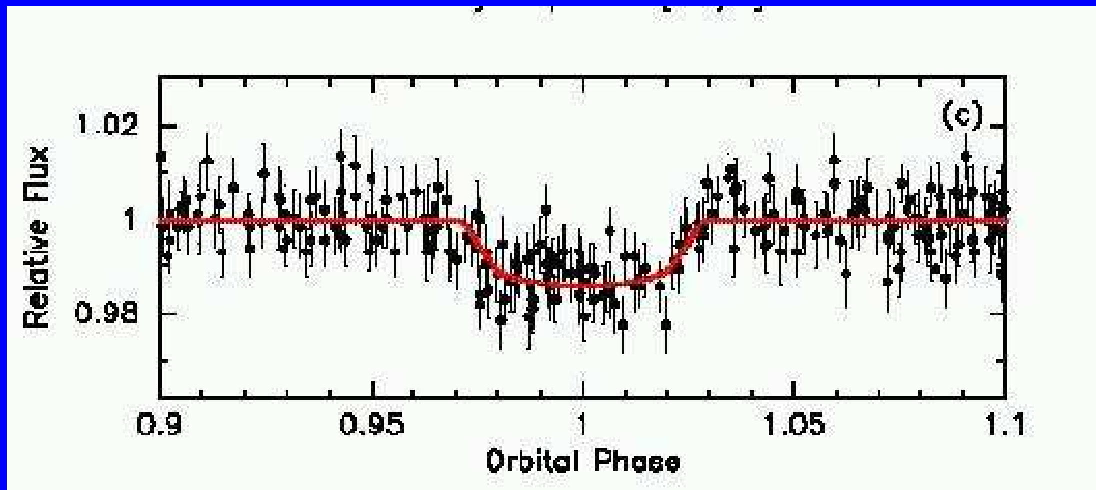


- many clear *consecutive* nights
- long nights
- high time sampling
- high photometric precision per star
- *many stars!*

A Breakthrough Discovery

The first confirmation of a planet *discovered* via transits
announced 6 Jan 2003 at the AAS Meeting in Seattle

OGLE-TR-56
Udalski et al 2002



One of almost 60 stars showing shallow eclipses
50,000 light curves

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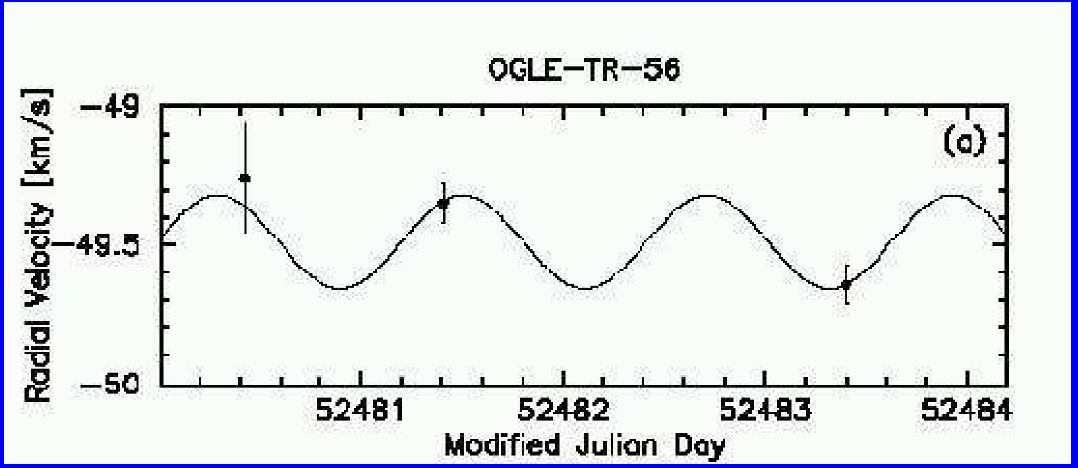
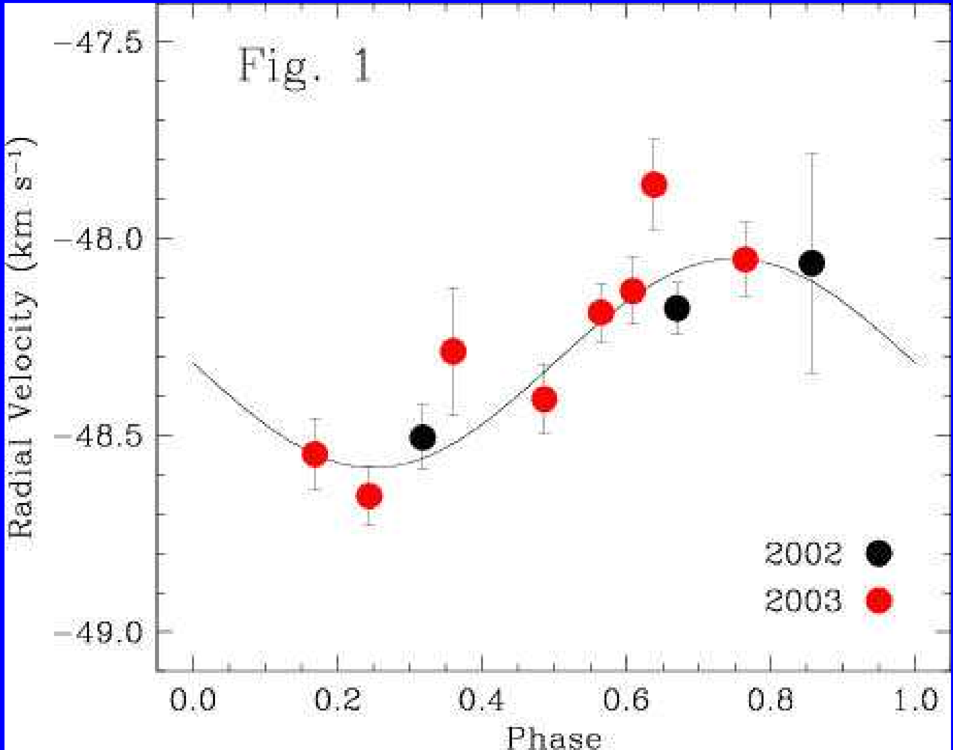
OGLE-TR-56

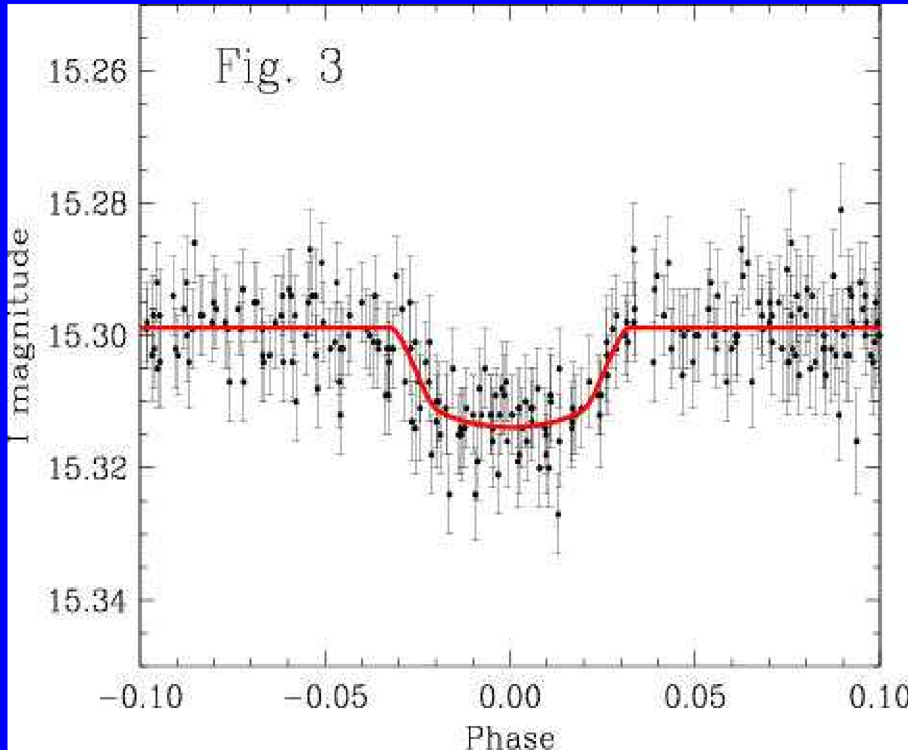
Konacki, Torres, Jha, Sasselov 2003, Nature



P = 1.2 days, M = 0.9 M_{Jup} R = 1.3 R_{Jup}

A Breakthrough Discovery



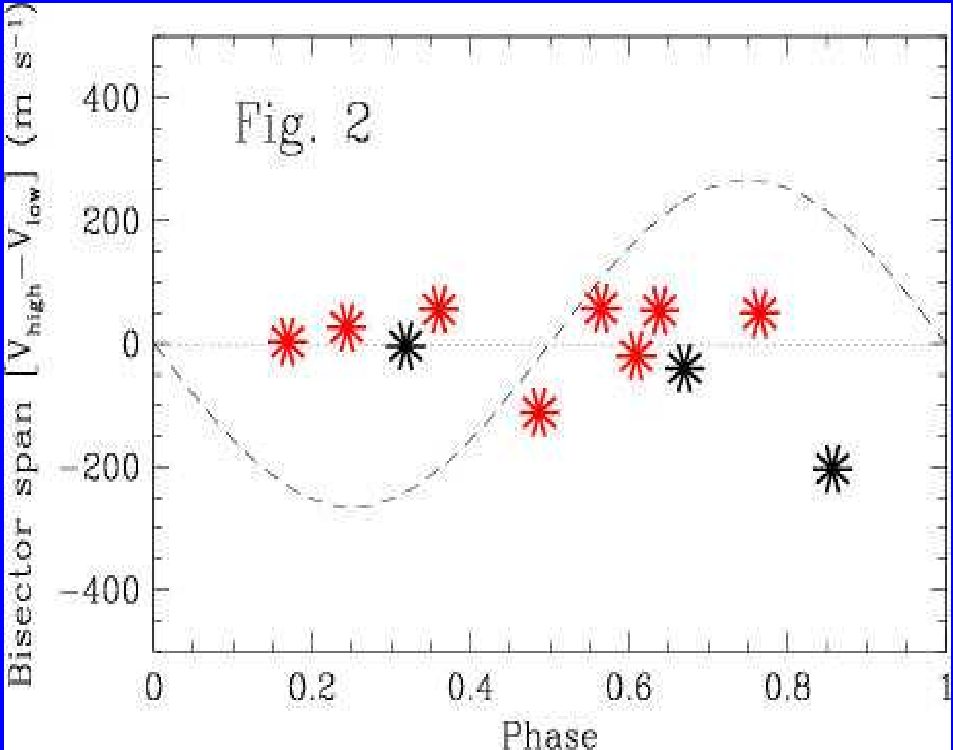


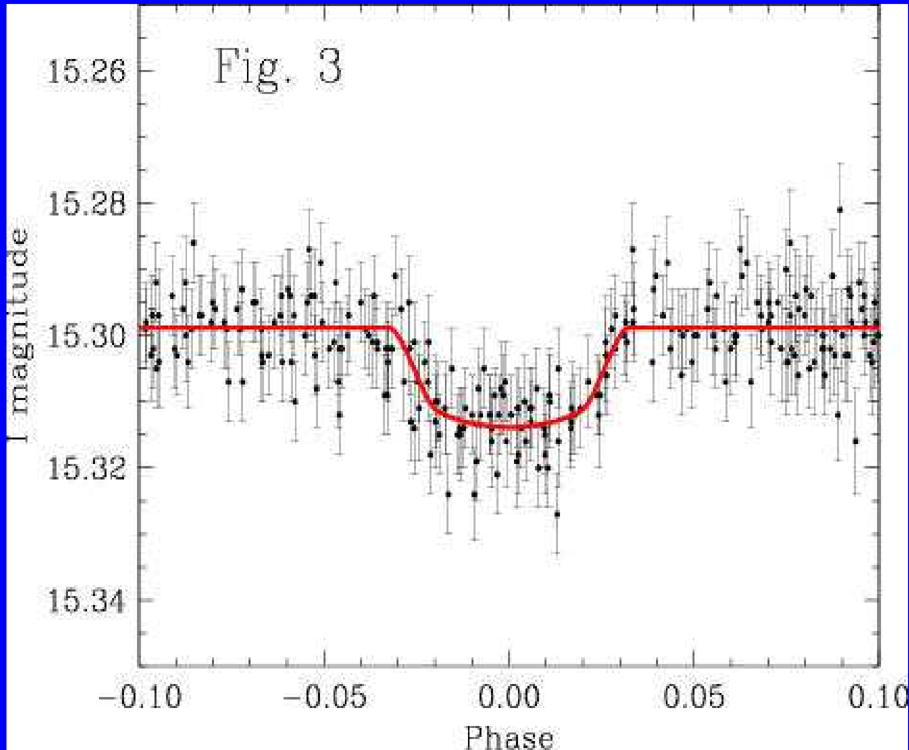
OGLE-TR-56

P = 1.2 days, M = 1.45 M_{Jup} R = 1.23 R_{Jup}

Torres, Konacki, Sasselov & Jha 2003, astro-ph/031011

A Breakthrough Discovery





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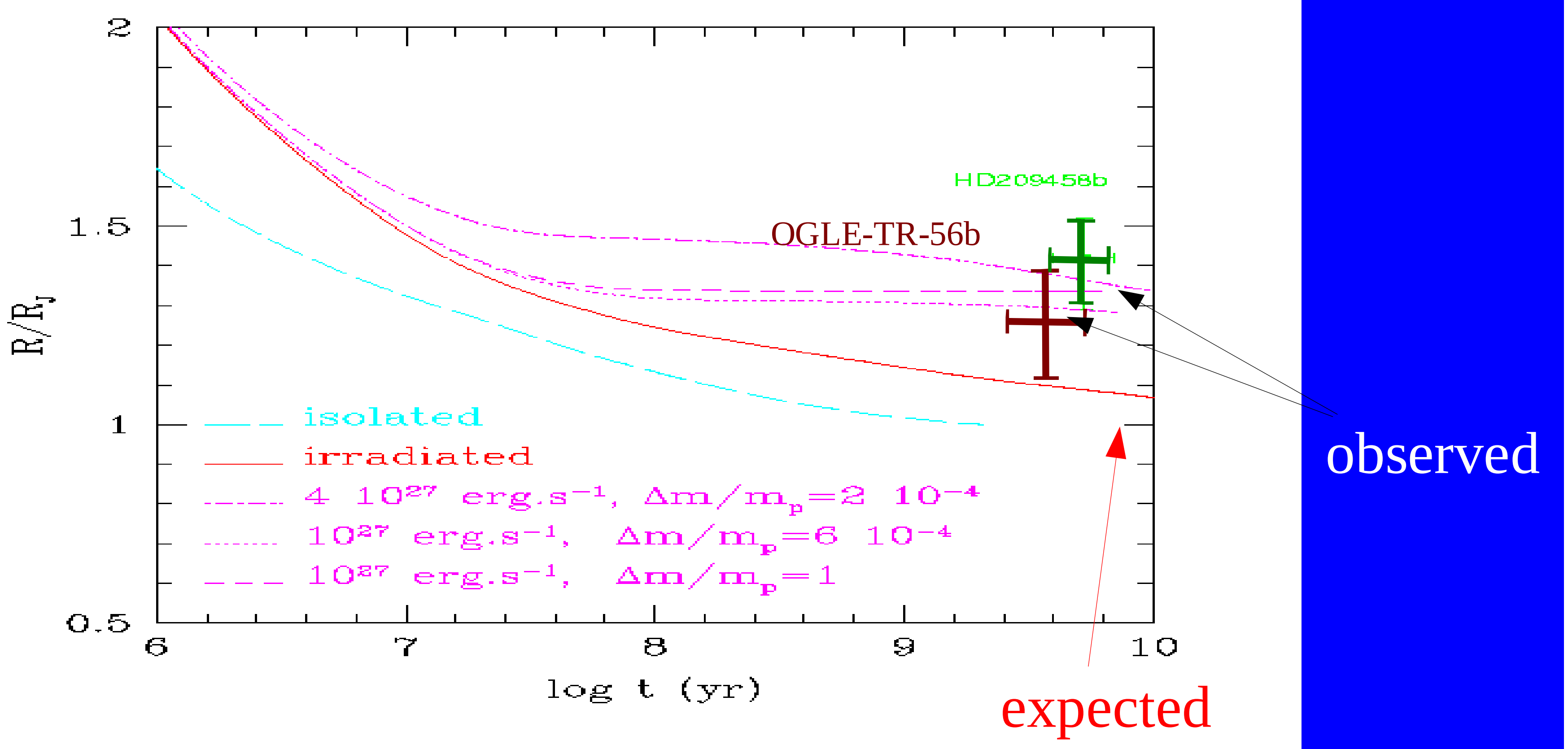
The Importance of Planet Radii



Baraffe et al. 2003

A Breakthrough Discovery

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OGLE-TR-56

P = 1.2 days, M = 1.45 M_{Jup} R = 1.23 R_{Jup}

(Torres, Konacki, Sasselov & Jha 2003, astro-ph/031011)

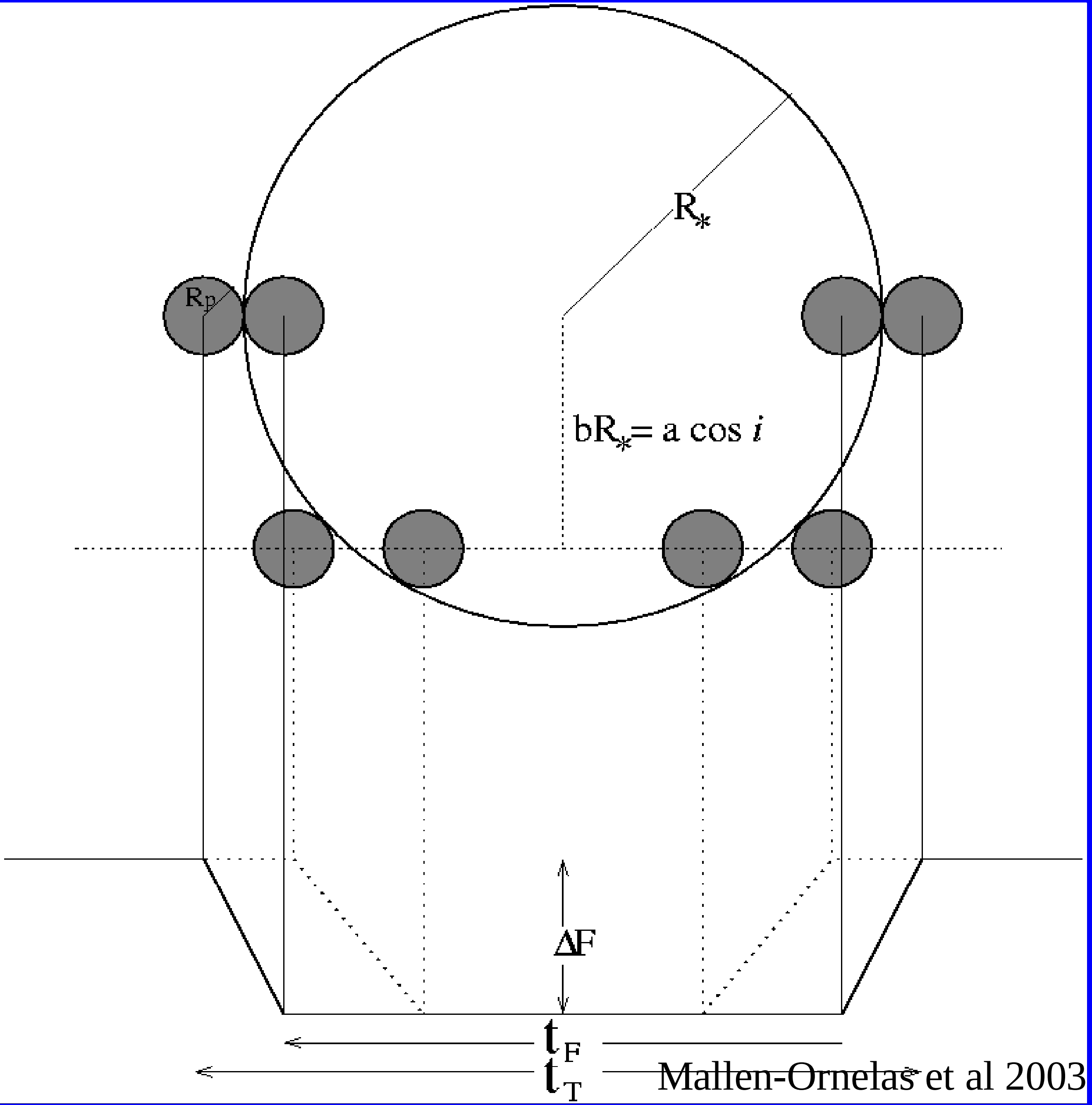
Beginning of a new era in extrasolar planet discovery and characterization.

No planets have been found before with P <<3 days out of >2000 stars surveyed by RV searches

a new class of planets?

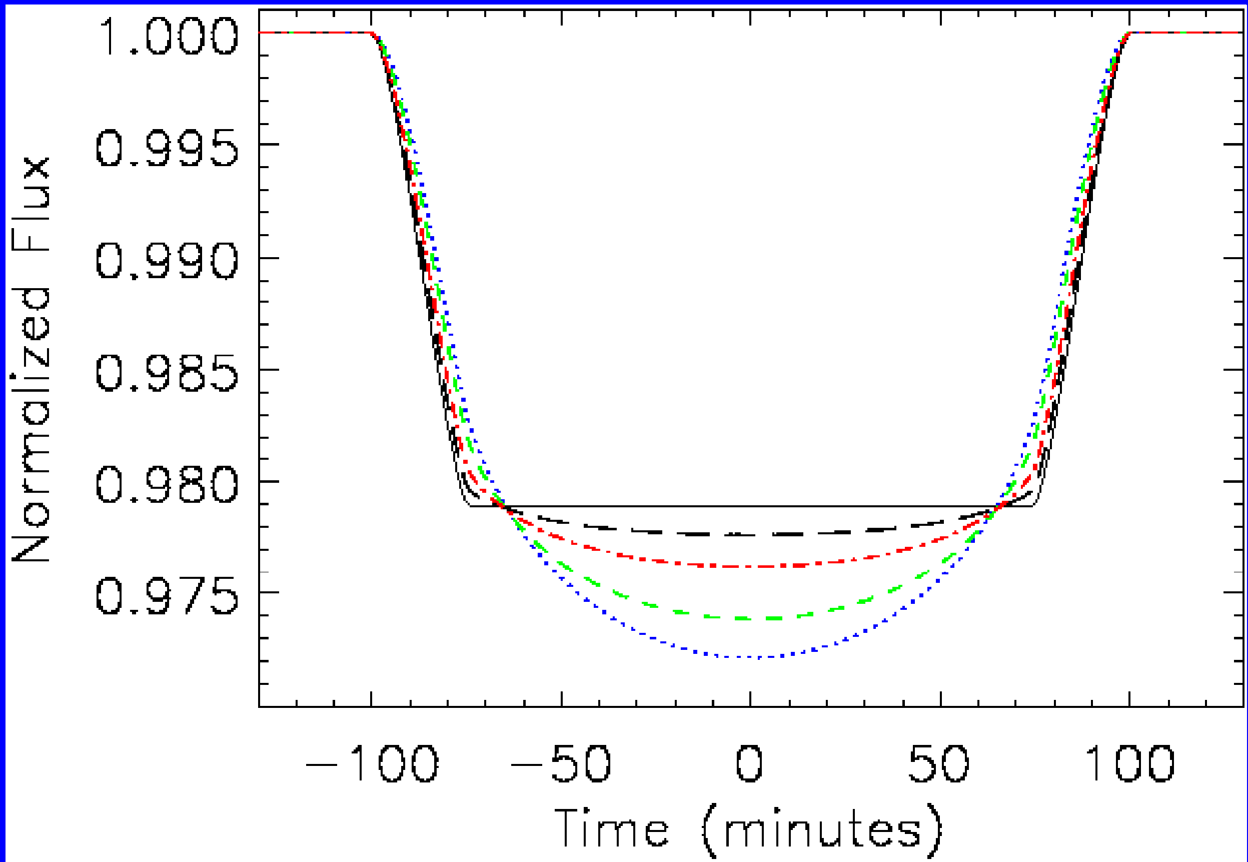
What can we learn from transits?

Anatomy of a Transit



Mallen-Ornelas et al 2003

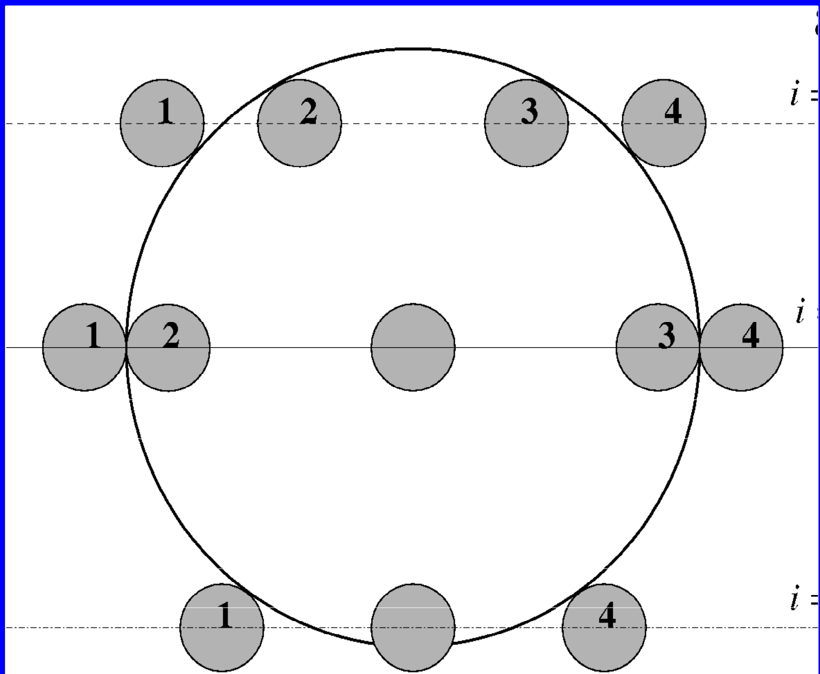
Limb Darkening

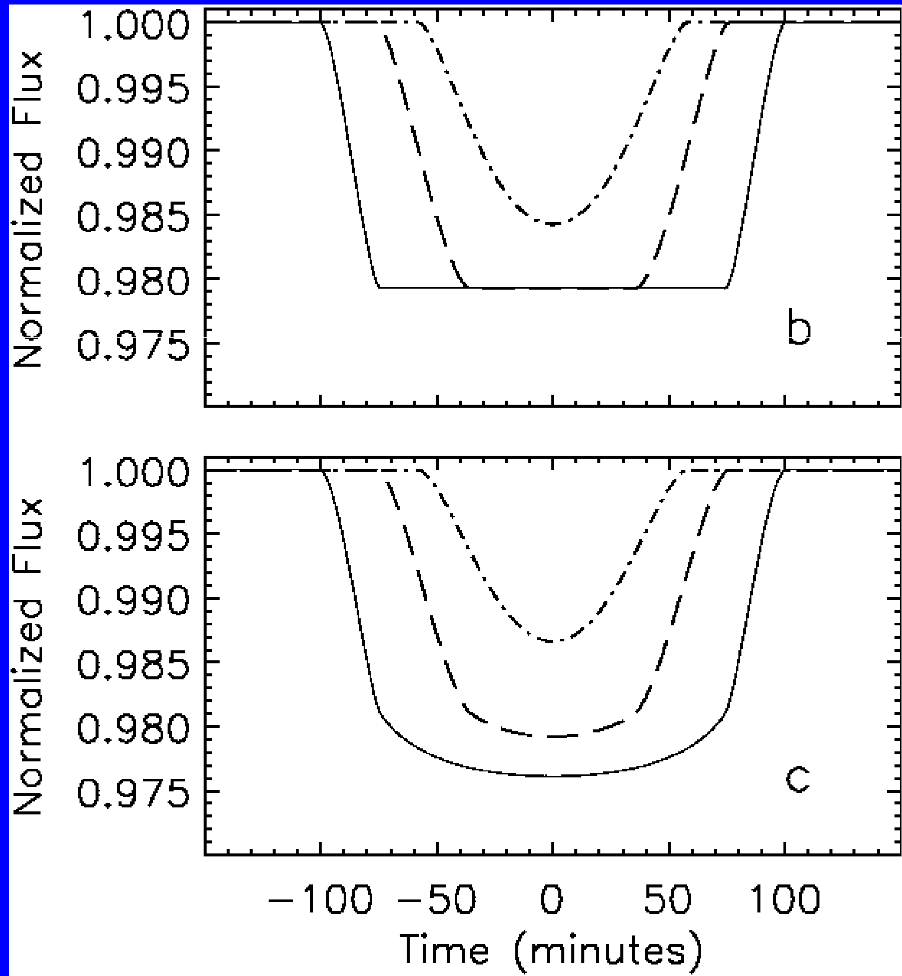


Limb darkening at 3, 0.8, 0.55, 0.45 microns

Mallen-Ornelas et al 2003

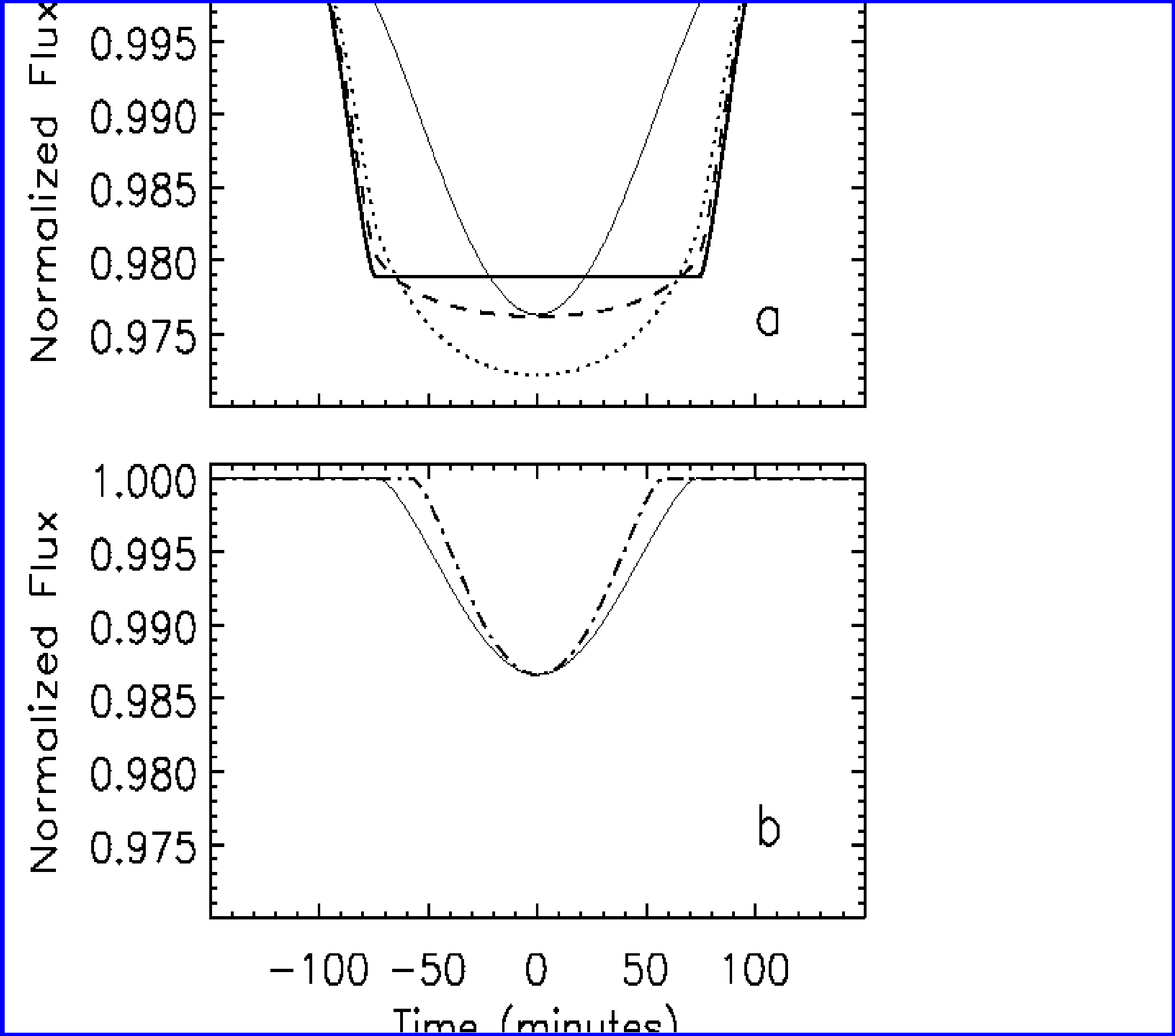
Inclination Dependence





Mallen-Ornelas et al 2003

Inclination Dependence

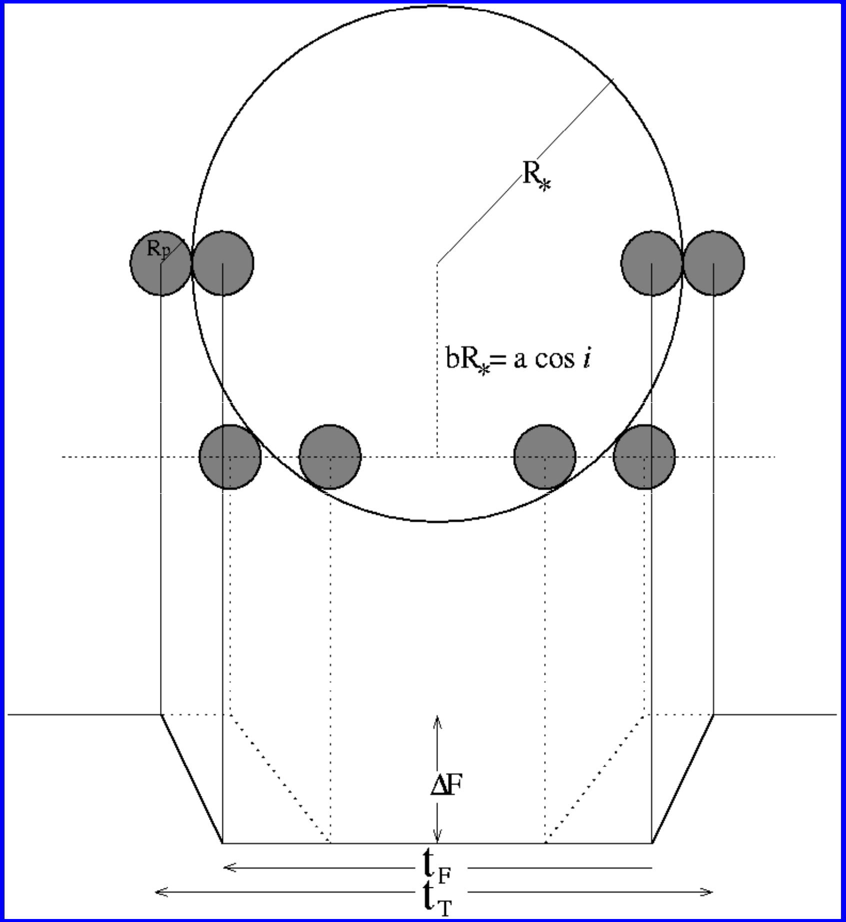


Mallen-Ornelas et al 2003

Transit Light Curves are Unique

- Transit depth
- Transit shape
- Transit duration
- Keplers Third Law
- (Stellar M/R relation)

$M_* \; R_* \; R_p \; a \; i$



- for a planet in circular orbit
- limb darkening is negligible
- stellar companion is dark
- high precision photometry

Seager & Mallen-Ornelas, 2003, ApJ

General Equations

1. Transit Depth

$$\Delta F = \left(\frac{R_p}{R_*}\right)^2;$$

2. Transit Shape

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

3. Transit Duration

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

4. Kepler's Third Law

$$P^2 = \frac{4\pi^2 a^3}{G(M_* + M_p)};$$

5. Stellar Mass-Radius Relation

$$R_* = k M_*^x,$$

Seager & Mallen-Ornelas 2003, ApJ

Analytic Solution

1. Stellar Mass

$$M_* = \left[k^3 \frac{4\pi^2}{P^2 G} \frac{\left[(1-\sqrt{\Delta F})^2 - b^2(1-\sin^2\frac{t_T\pi}{P})\right]^{3/2}}{\sin^3\frac{t_T\pi}{P}} \right]^{\frac{1}{1-3x}}$$

2. Stellar Radius

$$R_* = k M_*^x$$

3. Orbital Distance

$$a = \left[\frac{P^2 G M_*}{4\pi^2}\right]^{1/3}$$

4. Orbital Inclination

$$i = \cos^{-1}\left(b\frac{R_*}{a}\right)$$

5. Planetary Radius

$$R_p = R_*\sqrt{\Delta F} = k\left[\left[\frac{4\pi^2}{P^2 G}\right] \frac{\left[(1+\sqrt{\Delta F})^2 - b^2(1-\sin^2\frac{t_T\pi}{P})\right]^{3/2}}{\sin^3\frac{t_T\pi}{P}}\right]^{\frac{1}{3(1-3x)}} \sqrt{\Delta F}$$

$$b = \left[\frac{(1-\sqrt{\Delta F})^2 - \frac{\sin^2\frac{t_F\pi}{P}}{\sin^2\frac{t_T\pi}{P}}(1+\sqrt{\Delta F})^2}{1-\frac{\sin^2\frac{t_F\pi}{P}}{\sin^2\frac{t_T\pi}{P}}}\right]^{1/2}$$

Seager & Mallen-Ornelas 2003, ApJ

Stellar Density

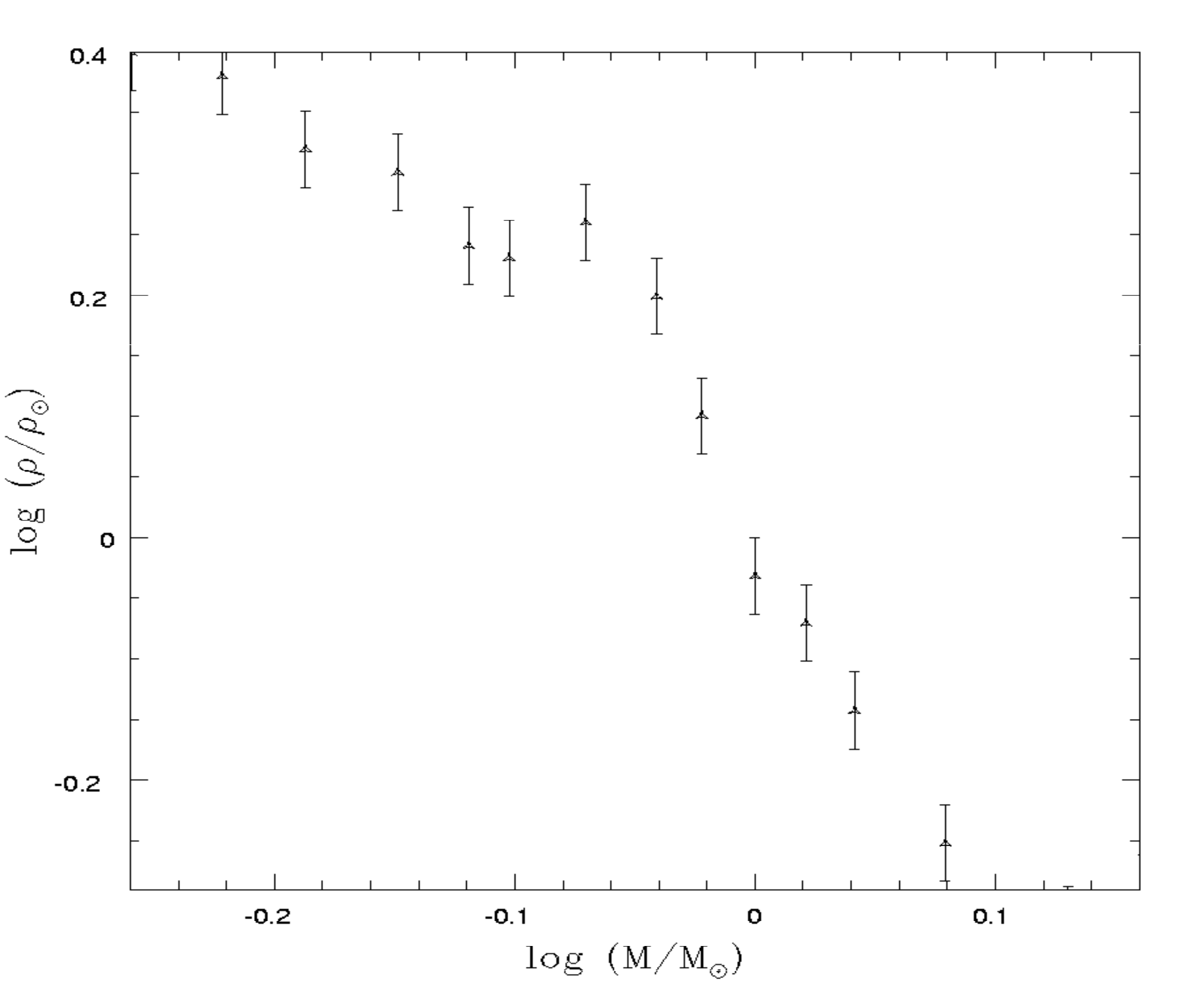
1. General Solution

$$\rho_* \equiv \frac{M_*}{R_*^3} = \left[\frac{4\pi^2}{P^2 G}\right] \frac{\left[(1-\sqrt{\Delta F})^2 - b^2\left(1-\sin^2\frac{t_T\pi}{P}\right)\right]^{3/2}}{\sin^3\frac{t_T\pi}{P}}$$

$$b = \left[\frac{(1-\sqrt{\Delta F})^2 - \frac{\sin^2\frac{t_F\pi}{P}}{\sin^2\frac{t_T\pi}{P}}(1+\sqrt{\Delta F})^2}{1-\frac{\sin^2\frac{t_F\pi}{P}}{\sin^2\frac{t_T\pi}{P}}}\right]^{1/2}$$

2. Simplified Solution

$$\rho_* = \left[\frac{4\pi^2 P}{G}\right]\left[\frac{1}{t_T\pi}\right]^3\left[\frac{4\sqrt{\Delta F}}{1-\left(\frac{t_F}{t_T}\right)^2}\right]^{3/2}$$



No mass-radius relation is needed!

Seager & Mallen-Ornelas 2003, ApJ

Transit Searches

More than twenty ongoing ground-based transit searches

Open clusters (e.g., PISCES, STEPSS, EXPLORE-OC, etc.)

Field stars

Small telescopes (e.g., HAT, STARE etc, Vulcan, WASP, KELT)

Medium telescopes (e.g. TeMPEST, most OC searches)

Large telescopes (e.g., EXPLORE, OGLE)

HST transit search:

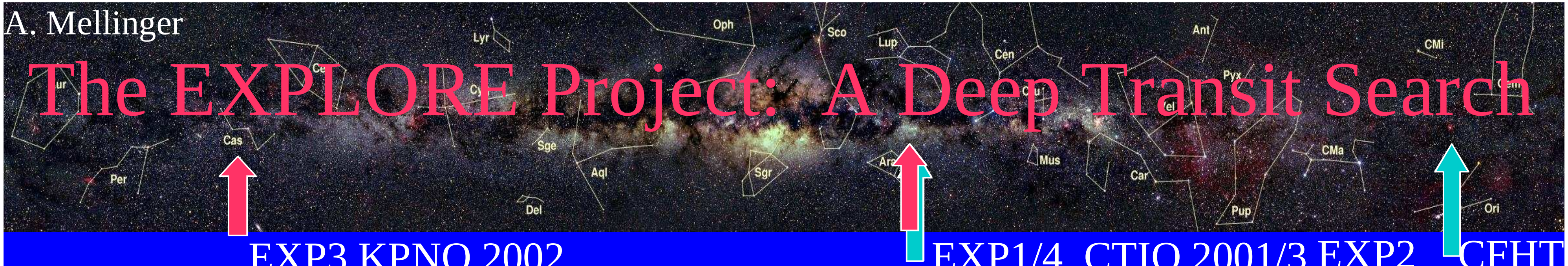
Globular cluster (47 Tuc, Gilliland et al.)

Approved program with the Advanced Camera to look at bulge & disk stars (K. Sahu et al.)


The EXPLORE Project
We use mosaic CCD cameras on 4m-class telescopes
to monitor a single stellar field in the Galactic Plane

A. Mellinger

The EXPLORE Project: A Deep Transit Search



EXP3 KPNO 2002 EXP1/4, CTIO 2001/3 EXP2 CFHT 2001

EXPLORE I, Jun 2001:

- CTIO 4m + VLT, 6 clear nights (Pvis~0.06), 40000 stars < 1%
- 1 good planet candidate
- 1 possible planet candidate
- 1 planet expected

EXPLORE II, Dec 2001/Jan 2002:

- CFHT 3.6m + Keck , 14 clear nights, (Pvis~0.28), 10000 stars < 1%
- 2 promising planet candidates
- 1 planet expected

EXPLORE III NOAO Survey Project, Oct 2002:

- KPNO 4m, 6 clear nights (Pvis~0.07), 18000 stars < 1%
- <1 planet expected
- 4 flat-bottomed shallow eclipse systems but no good candidates

EXPLORE IV NOAO Survey Project, Jun 2003:

- CTIO 4m, 7 clear nights (Pvis~0.08), expect 40000 stars < 1%
- ~1 planet expected
- data reduction in progress

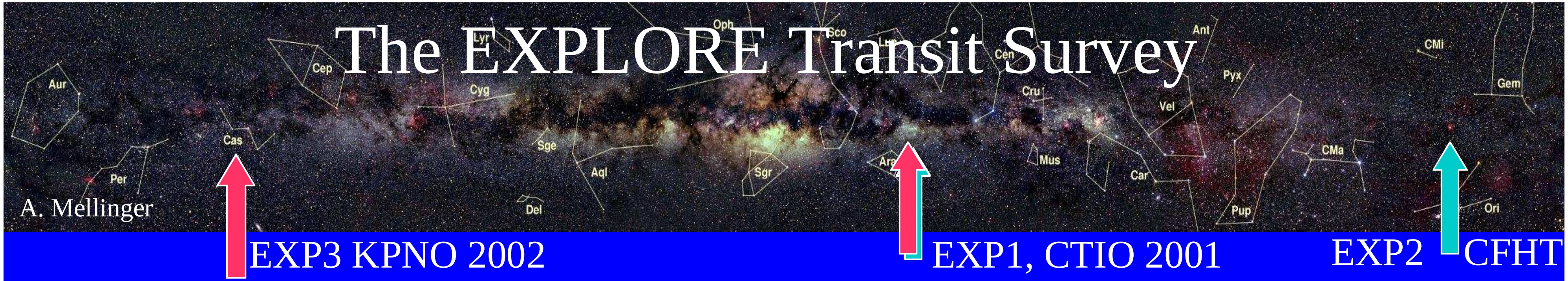
PHOTOMETRY PIPELINE

- Automatic pre-processing program does crosstalk correction, overscan and bias subtraction, flatfielding, image splitting

- Aperture photometry (PPPLT) uses a sinc-shift algorithm to center apertures to a very high accuracy from frame to frame. Currently merging with DAOPHOT to improve photometry of stars with close neighbours. Non-parametric aperture photometry helps improve precision.

- Iterative relative photometry chooses the most stable local stars to compute zero-points.

The EXPLORE Transit Survey



EXP3 KPNO 2002

EXP1, CTIO 2001

EXP2 CFHT 2001

Sample Lightcurves

1. Common contaminants
   - Grazing binary
   - Large star primary with small star secondary
   - Shallow eclipse due to blended light

2. Planet candidates

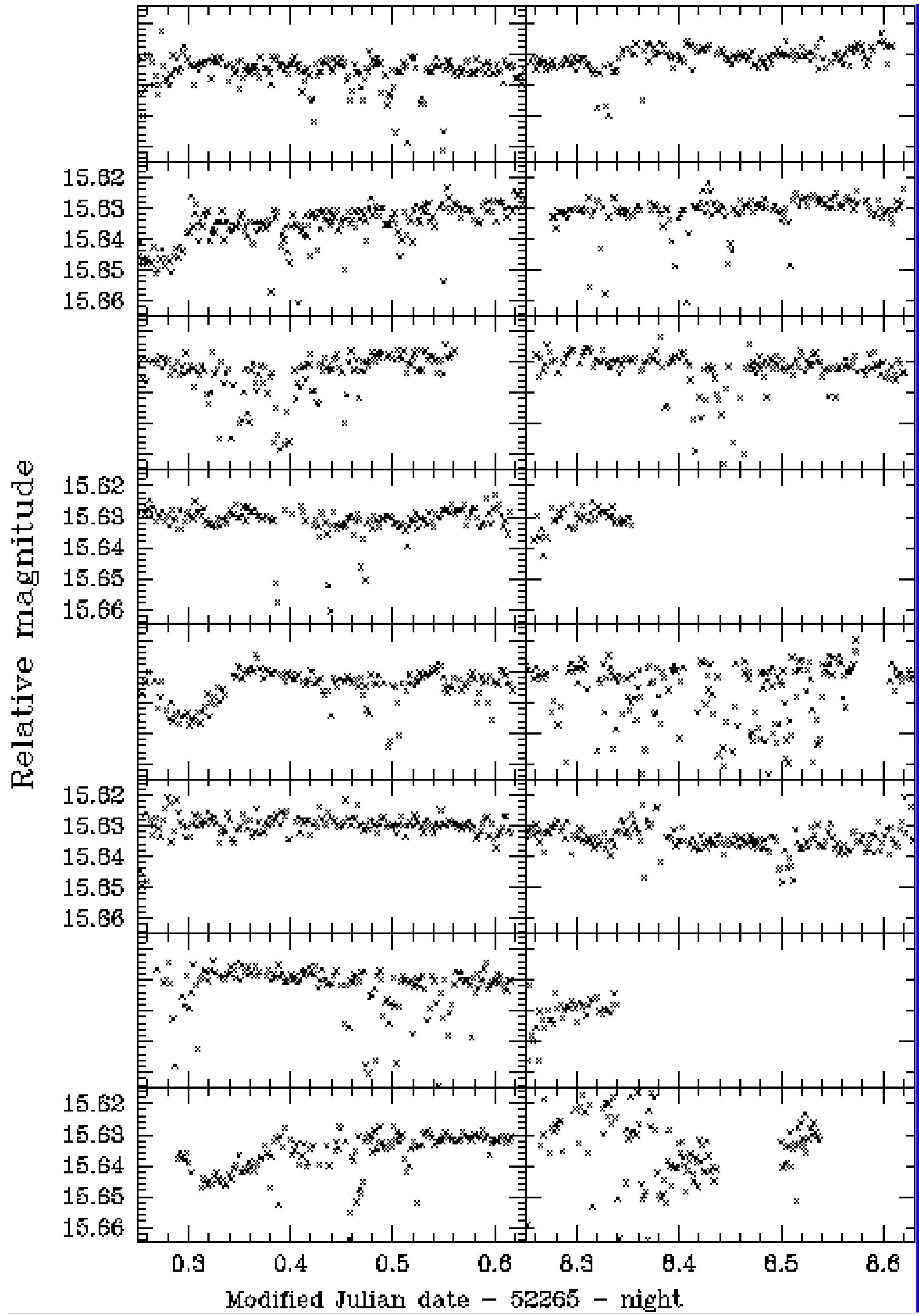
High photometric precision and time sampling allows selection of a clean set of candidates for Radial Velocity follow-up

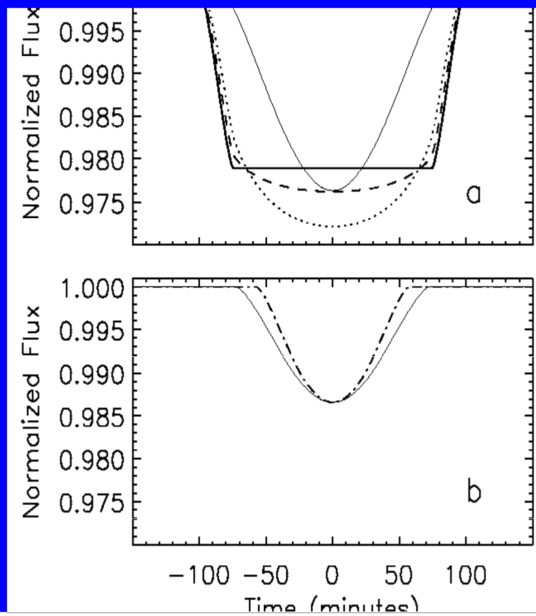
EX2-1731: Grazing Binary

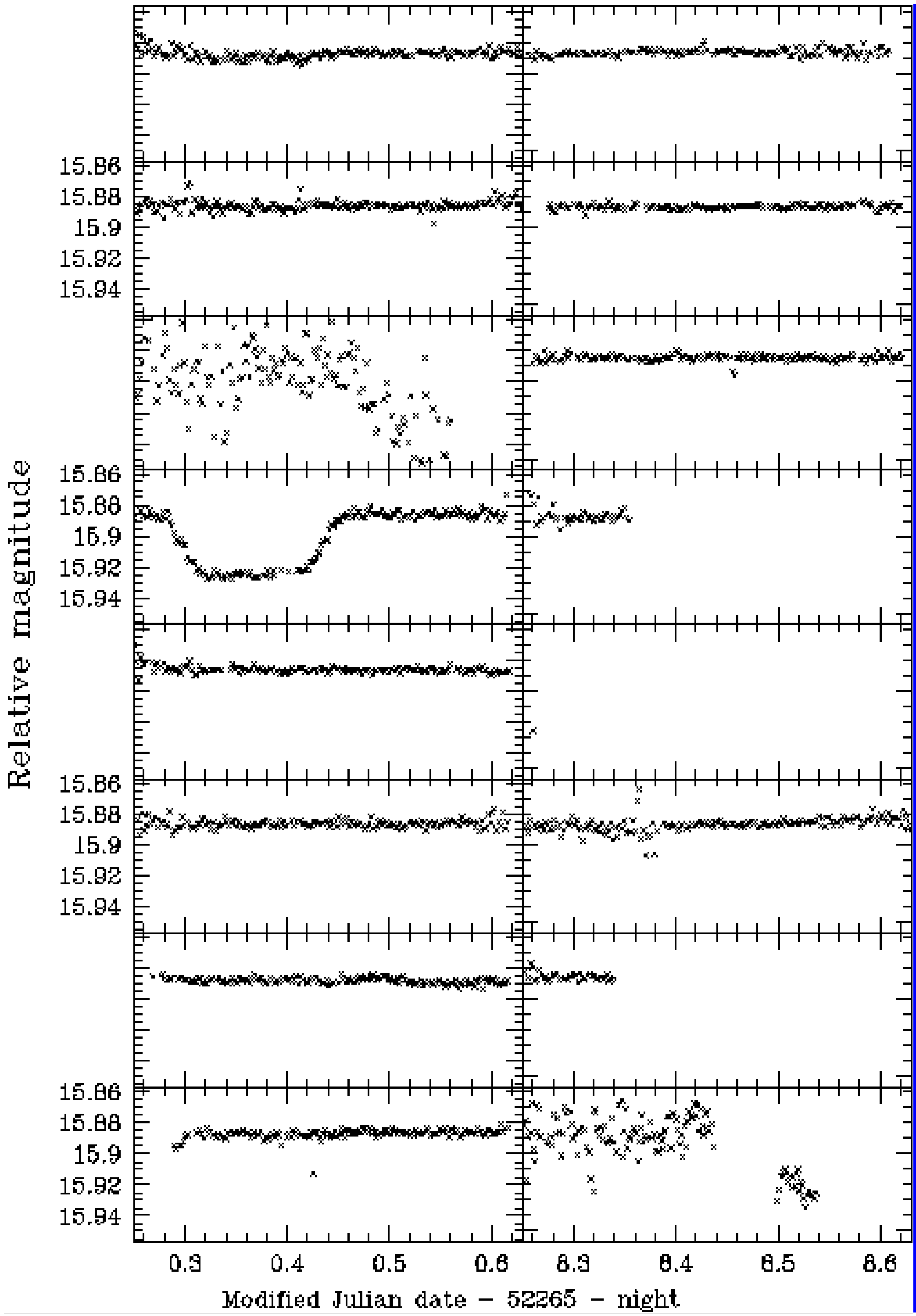
- Eclipses have *round bottom*
- 3% eclipse depth

- P = 2.9 days
- I = 16.6, V = 18.5

- Radial-velocity data show *two cross-correlation peaks of equal strengths*





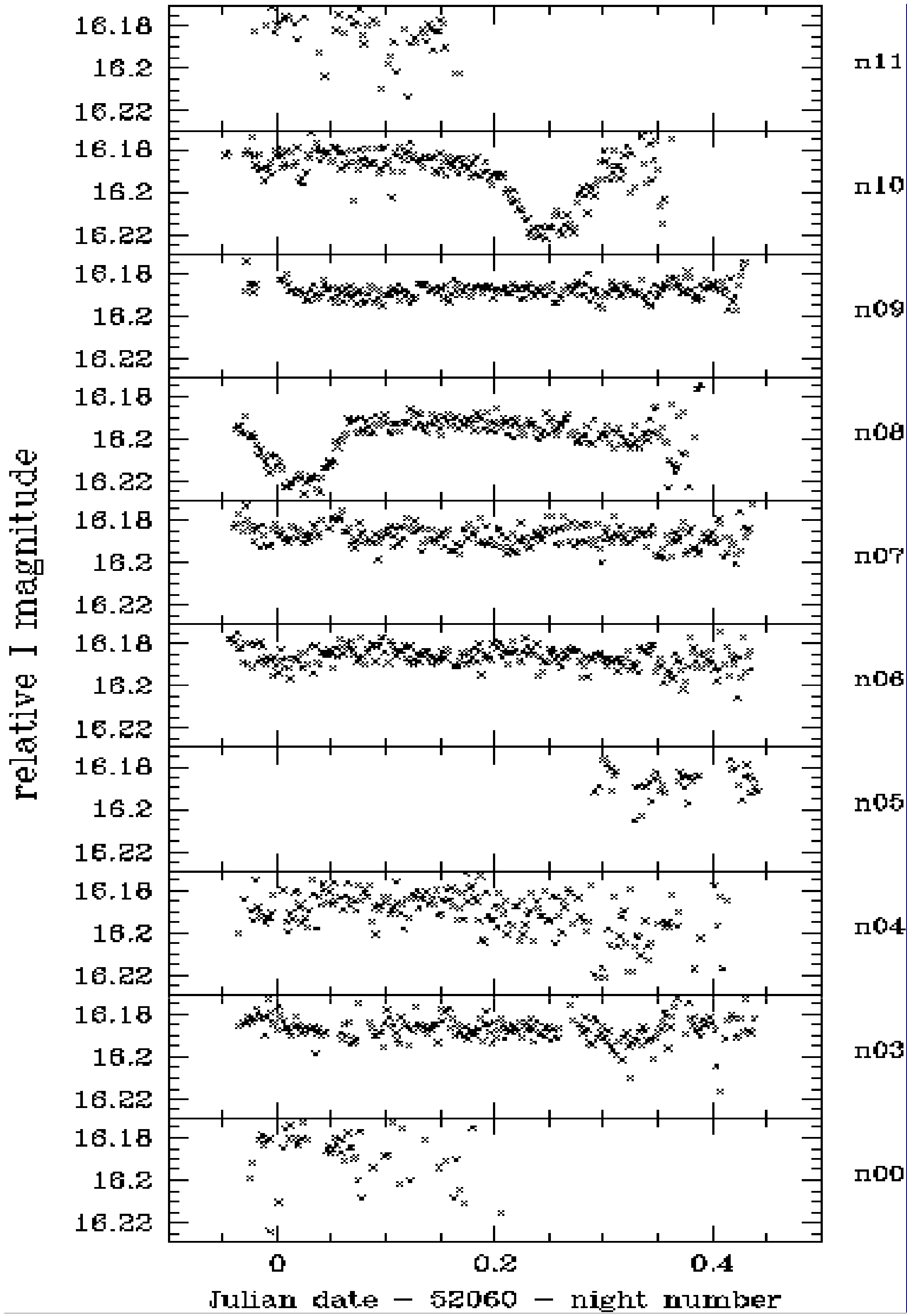


EX2-5494: Binary with a Large Primary Star

- Eclipse has flat bottom, but has *long duration*
- 3% eclipse depth

- P = 4.2 days?
- I = 16.9, V = 18.8

- Radial-velocity data show one cross correlation peak *which shifts with time*

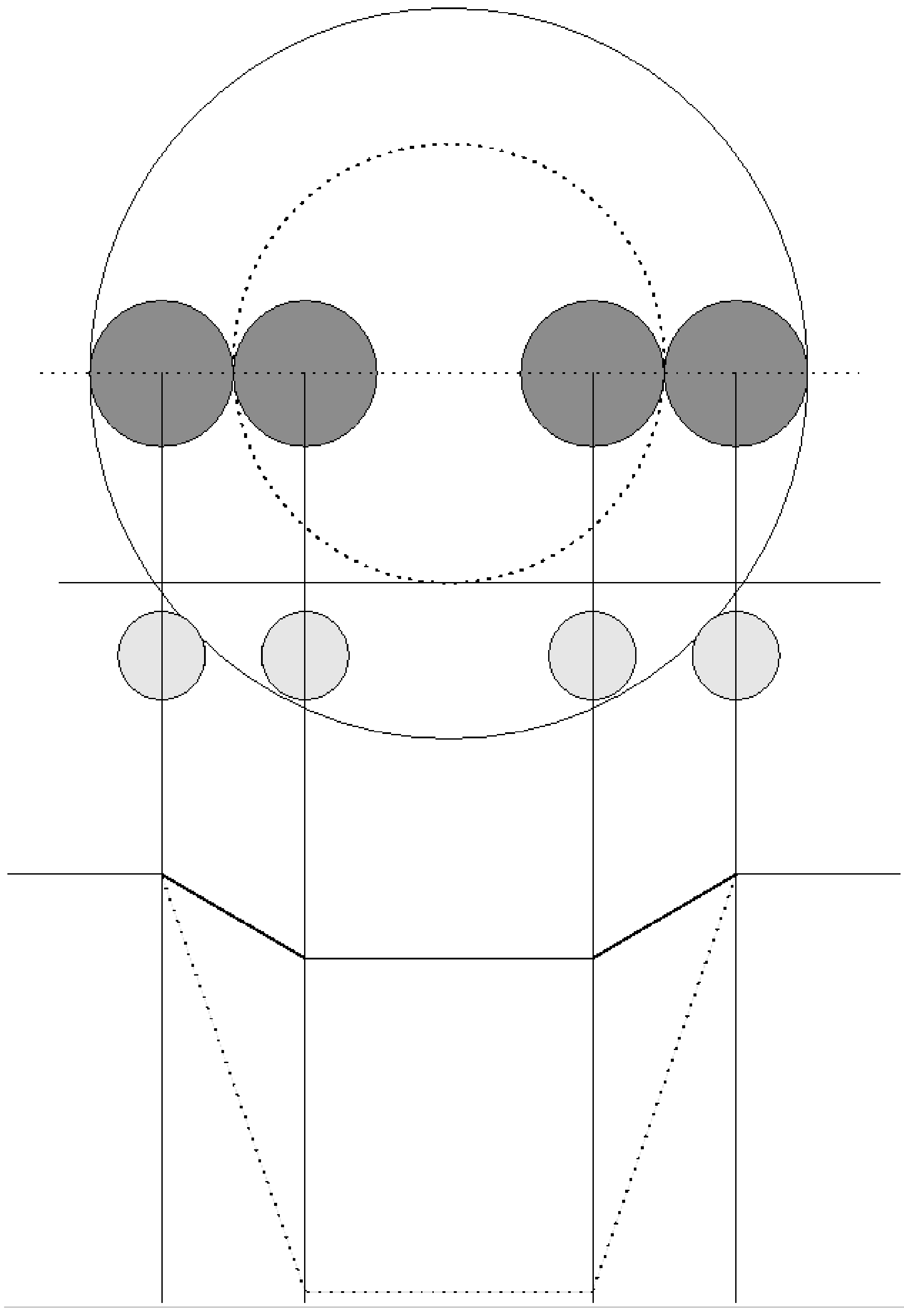


EX1-4343: Contaminating light from a blended star / triple system

- Eclipses have flat bottom and are short, *but ingress/ egress are long.*
- 3% eclipse depth

- P = 2.3 days
- I = 16.2, V = 17.9

- Radial-velocity data show a strong cross correlation peak, *and a second weaker broad peak which shifts with time*

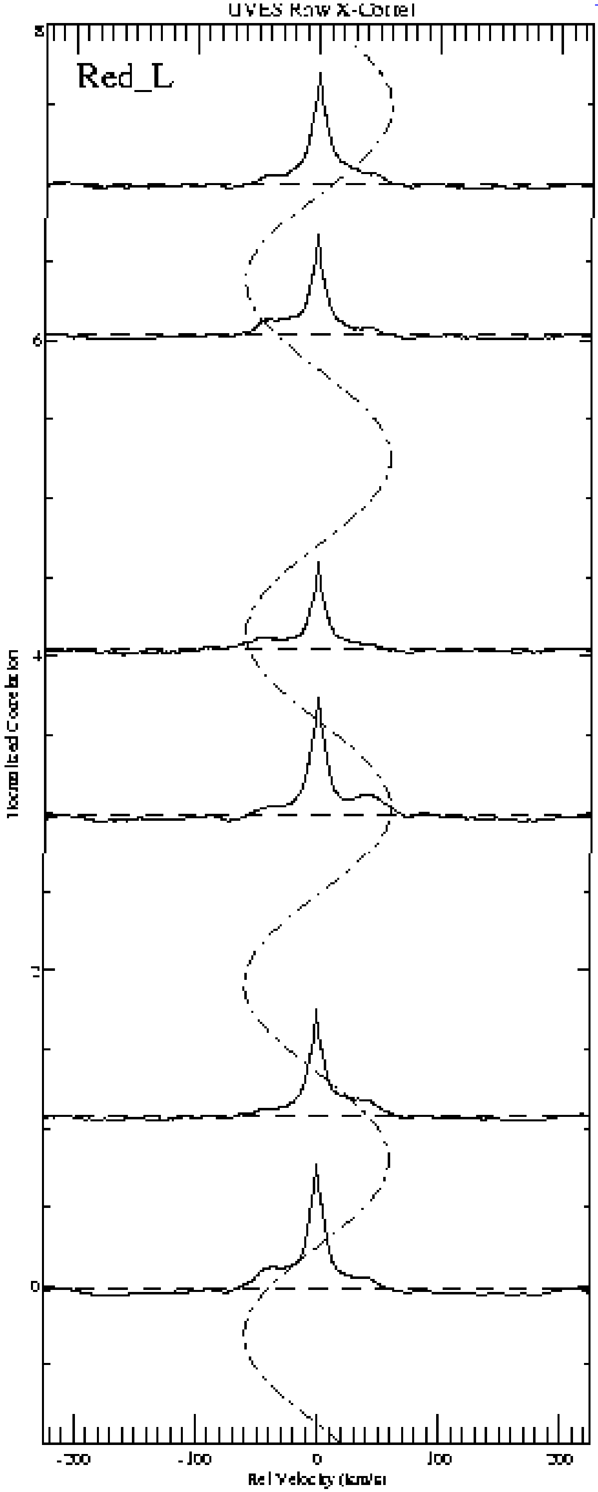


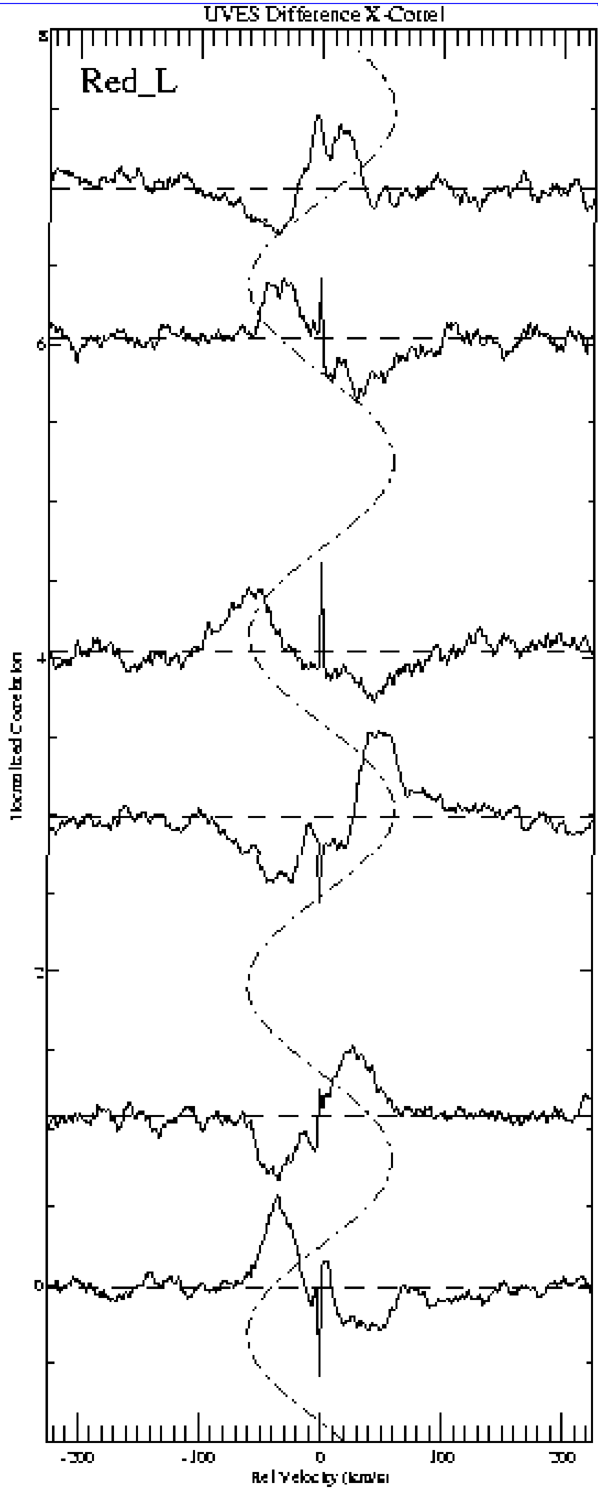
EX1-4343: Contaminating light from a blended star / triple system

- Eclipses have flat bottom and are short, *but ingress/ egress are long*.
- 3% eclipse depth

- P = 2.3 days
- I = 16.2, V = 17.9

- Radial-velocity data show a strong cross correlation peak, *and a second weaker broad peak which shifts with time*



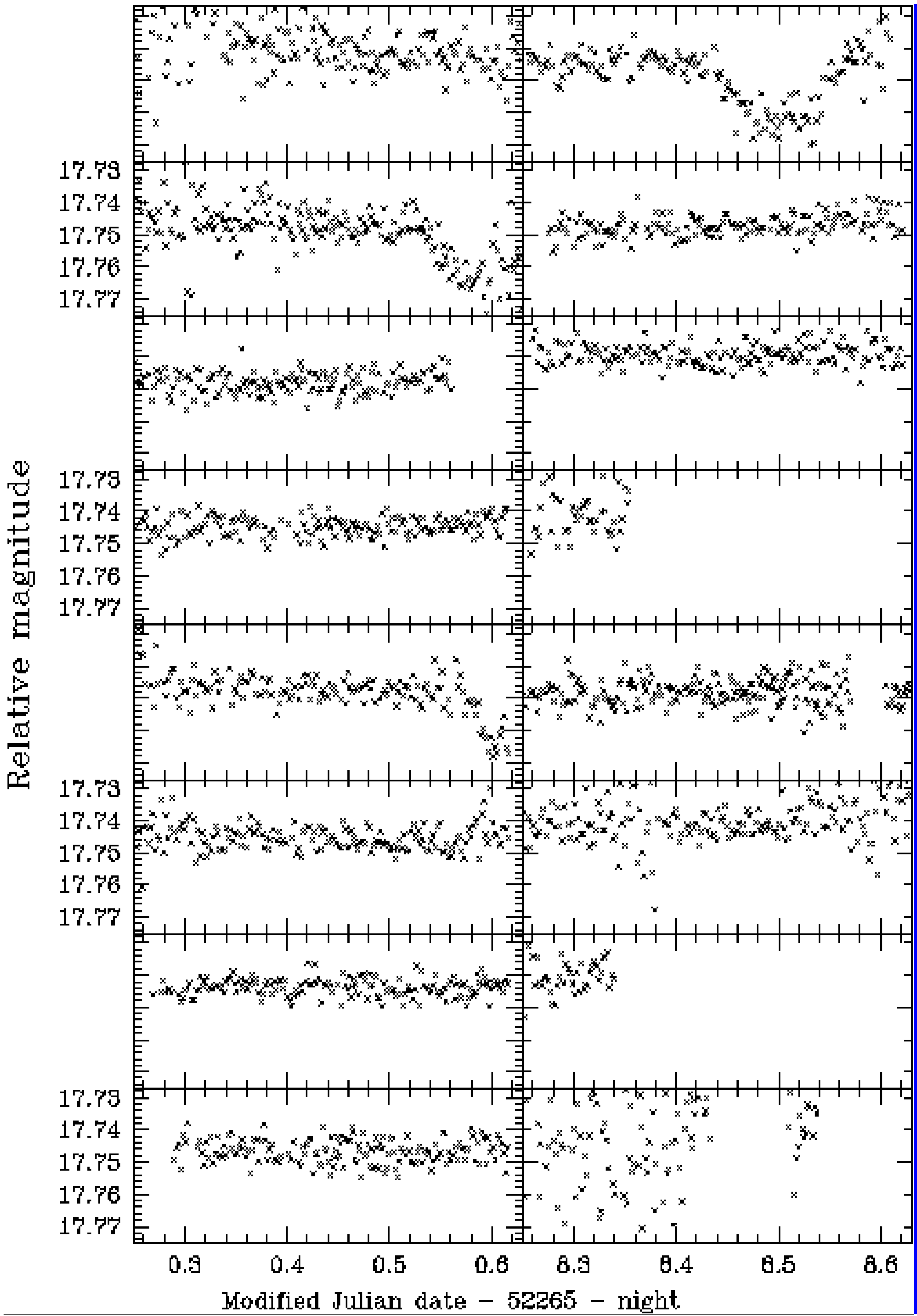


EX1-4343:
contaminating
light from a blended
star / triple system

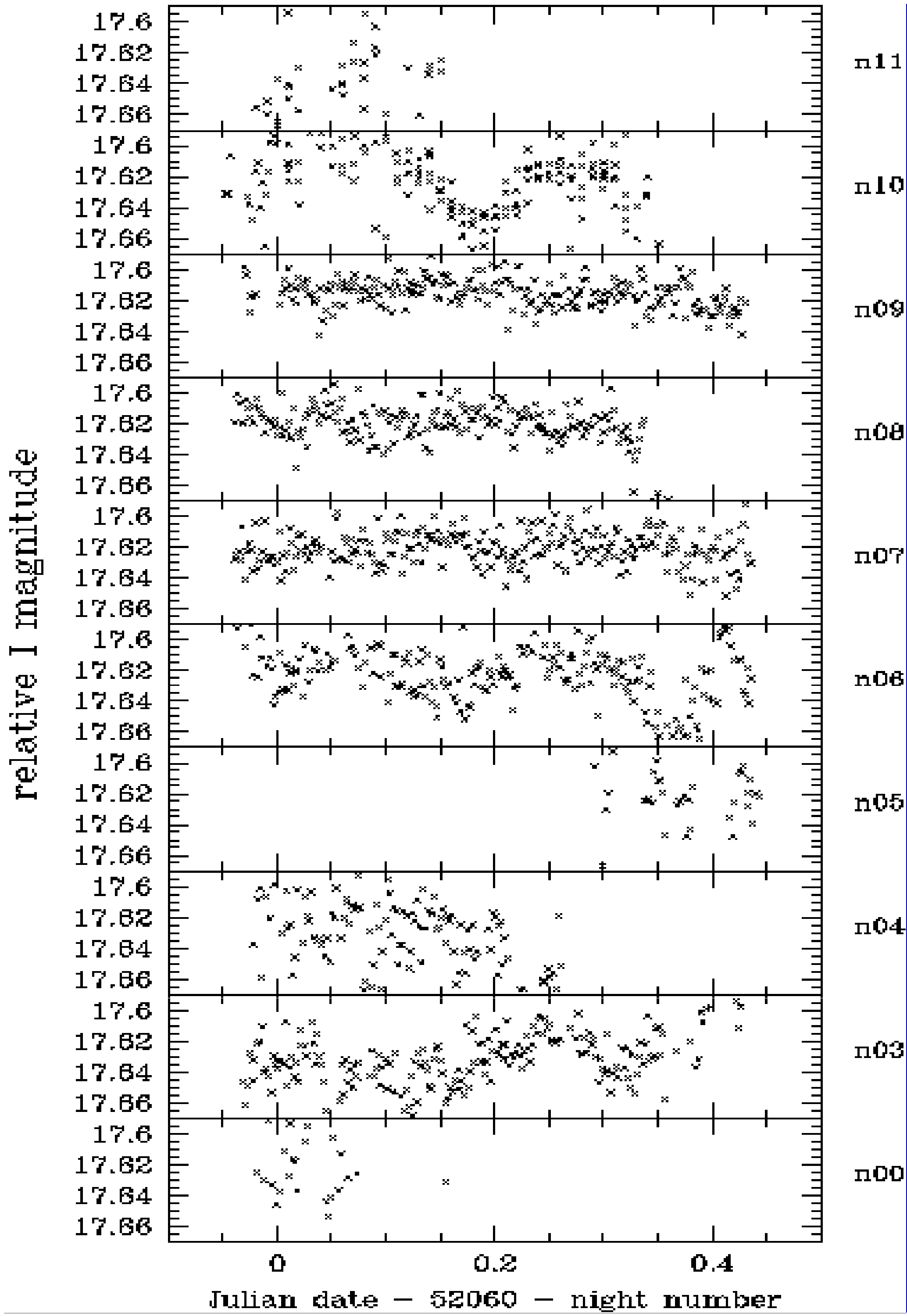
L: cross correlation
of raw spectra

R: cross correlation
of moving component

EX2-4809: Planet Candidate



- Eclipses have flat bottom and are short. Ingress/egress are not inordinately long
- 1.7% eclipse depth
- P = 2.97 days
- I = 18.3, V = 20.2
- Radial-velocity data show only one cross correlation peak. *Only 2 RV points, taken at the same phase, so there is no information on dark companions mass*

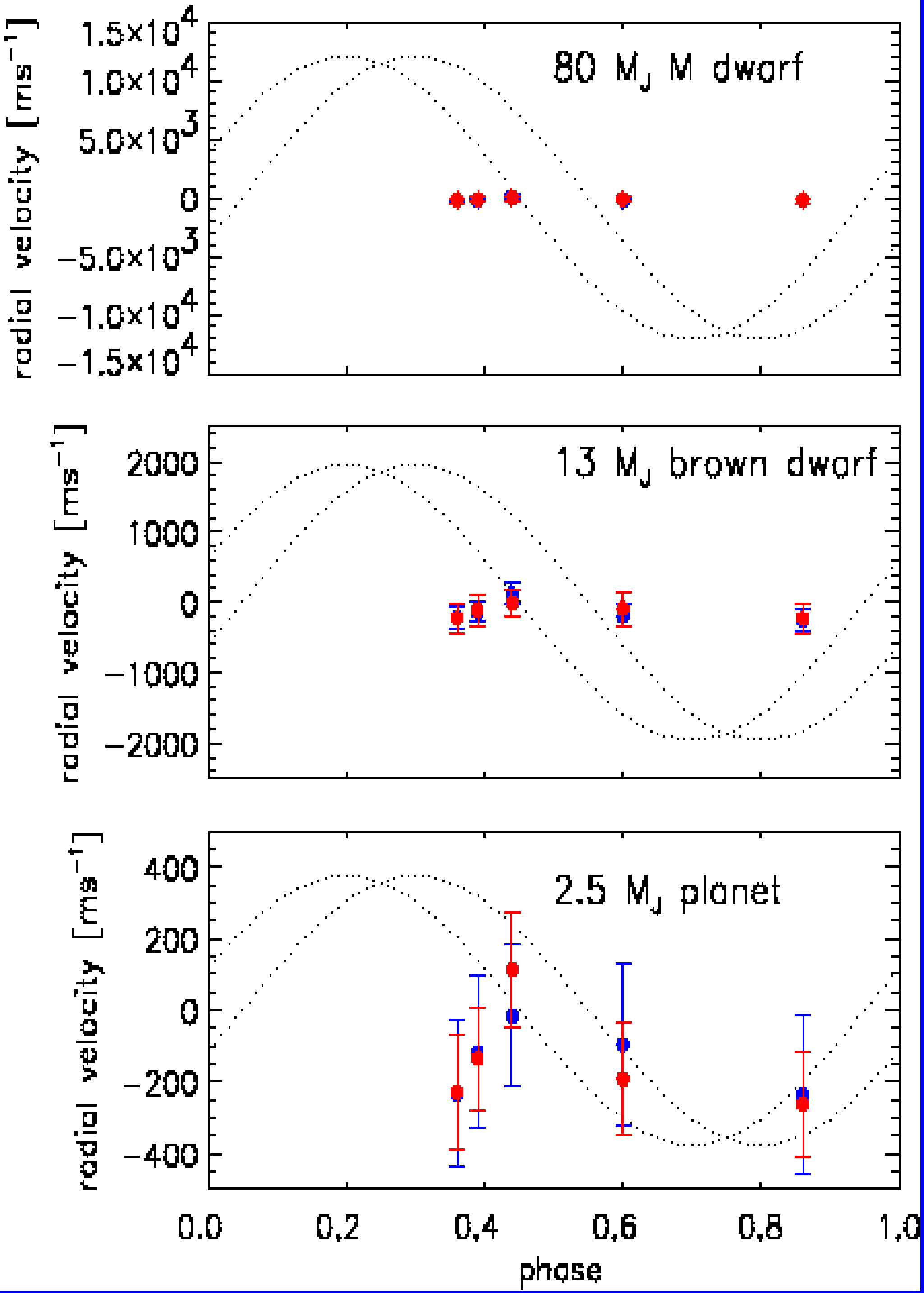


EX1-109: Planet Candidate

- *Eclipses are noisy*
- 2.5% eclipse depth

- P = 3.8 days
- I = 17.6, V = 19.4

- Radial-velocity data show only one cross correlation peak. There is no radial velocity variation within 200 m/s error bars.



EX1-109: Planet Candidate

- *Eclipses are noisy*
- 2.5% eclipse depth

- P = 3.8 days
- I = 17.6, V = 19.4

- Radial-velocity data show only one cross correlation peak. There is no radial velocity variation within 200 m/s error bars.

Ground Based Transit Searches

Ground-based transit searches have the potential for finding many planets with measured radii

The main challenge is to get good light curves with good time coverage for enough *small main sequence stars*

*Large telescopes
*Small, automated telescopes
*Follow-up of Radial Velocity Planets

Comparison of Search Schemes

Small, automated telescopes	Large telescopes
-Challenging to get enough stars	-Many stars, many pixels, many more candidates
-Dedicated telescopes	-Telescope time may be expensive
-Easy RV follow-up	-RV follow-up needs largest telescopes
-Contamination by large stars	-Smaller fraction of large stars
-Blends are common (large pixels)	-Easier to avoid blends
-Planets around bright stars facilitates other follow-up observations	-Difficult to follow-up beyond radius measurement
-Fewer planets with better data	-More planets, radii and masses only

Follow-up of Radial Velocity Planets

Requires RV observations of *many* stars

Requires single-object photometric follow-up

Sample of non-transiting close-in planets

Brighter stars -> best possibilities for follow-up

The Future of Extrasolar Planet Detection and Characterization

Known Planetary Systems

Characterizing Extrasolar Planet via Transits

Ground-based Transit Searches

Space-based Searches: Transits and Reflected Light

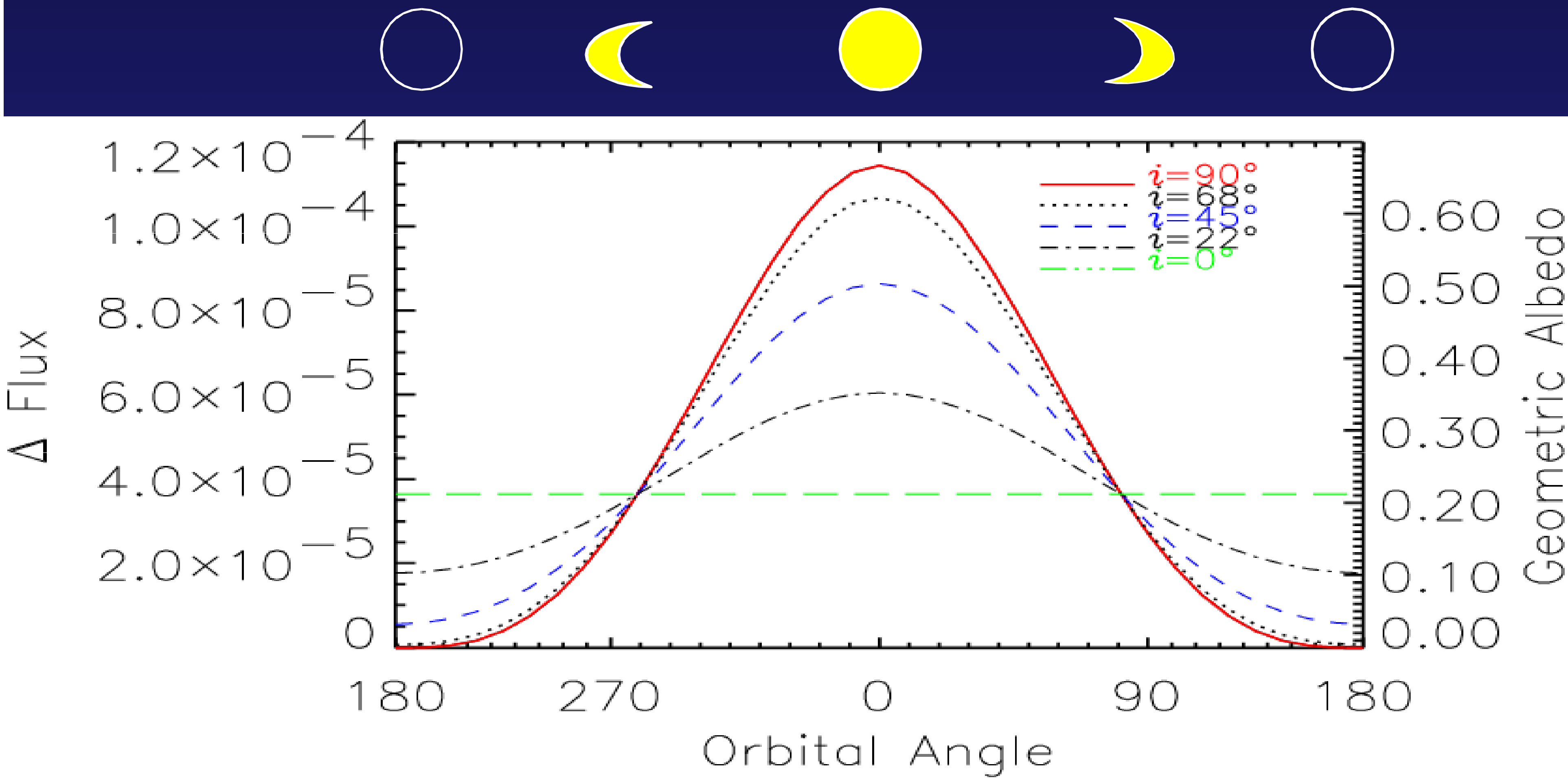
Summary

Beyond Ground Based Transits

High-precision photometry from space

- Transits
- Scattered light from giant planets

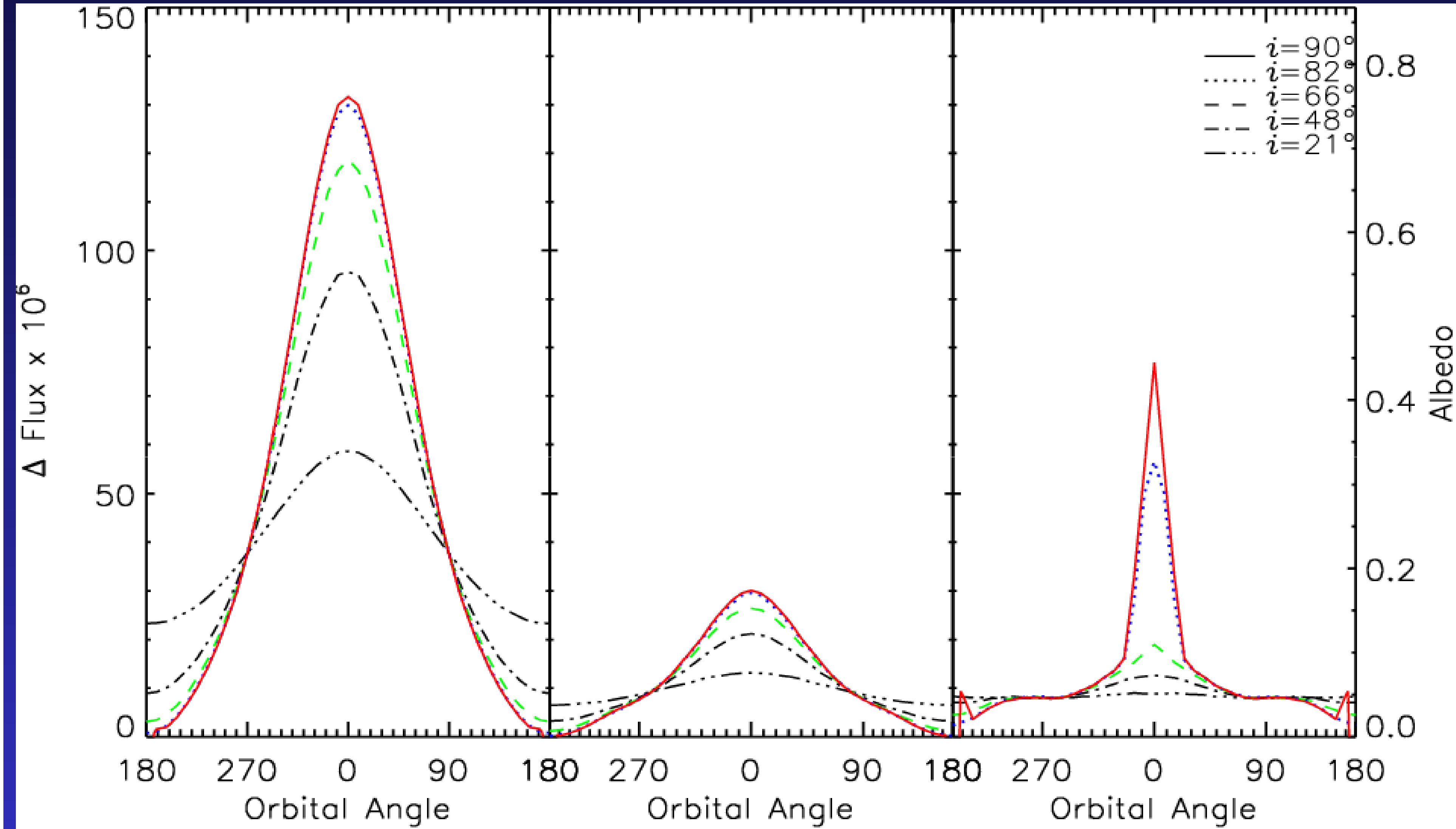
Orbital Light Curves



Lambert sphere

Seager, Whitney, & Sasselov 2000

Scattered Light Curves



51 Peg @ 550 nm

Seager, Whitney, & Sasselov 2000

Albedo for transiting planets

Beyond albedo?

Beyond Ground Based Transits

MOST working now!

15 cm telescope. 1 ppm photometry.

Asteroseismology and reflected light curves

COROT 2005/2006

27 cm telescope; 2.5 year mission

Asteroseismology and transits. Two bandpasses.

P < 50 days, many hot Jupiters

Beyond Ground Based Transits

Kepler 2007

95 cm telescope with CCD array

1000 giant planets reflected light

100 giant planet transits

50-600 terrestrial inner-orbit transits

Earth-like planets in habitable zone

Eddington 2008

0.764 sq metre collecting area

5 year mission (3 years for planets)

Terrestrial planets

Giant planet radii as a function of irradiation

Beyond Ground Based Transits

Other search techniques:

SIM (2009) and GAIA (2010) will do high-precision astrometry (up to 1 micro arcsec).

Astrometry can give orbital elements for multiple planet systems

A large-scale microlensing search? (e.g., Gould and Gaudi, in prep)

Microlensing has the potential to yield the best *statistics* about earth-mass planets.

Direct Detection of Earths

Terrestrial Planet Finder / Darwin (2015)

Interferometer and coronograph designs
Spectra of Earth analogs. Search for biomarkers:

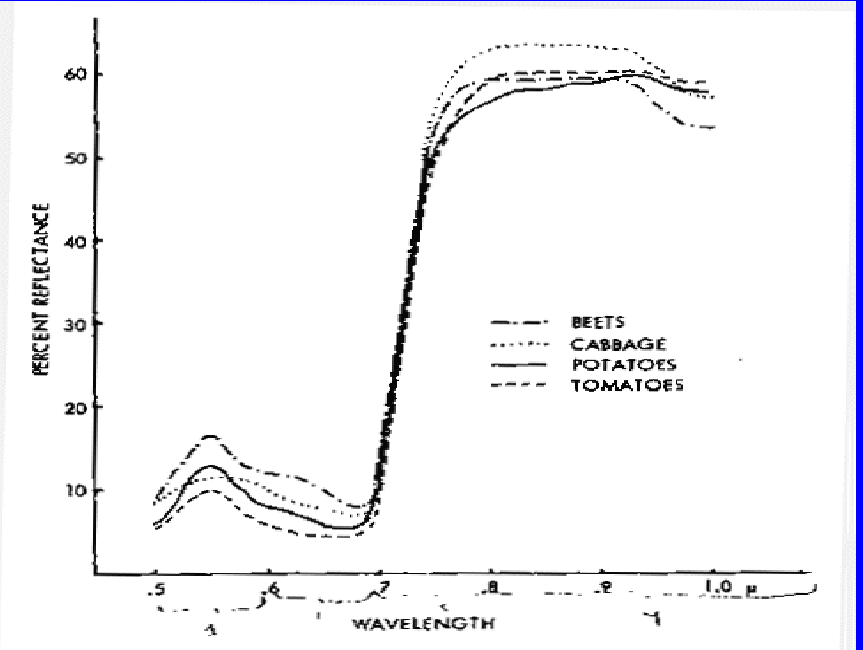


Fig. 2-87. Similar Signatures.

O_2 O_3 H_2O
CH_4 N_2O

The red edge

Signs of non-equilibrium

The Future of Extrasolar Planet Detection and Characterization

Known Planetary Systems

Characterizing Extrasolar Planet via Transits

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Summary

SUMMARY

Radial Velocity searches have dramatically improved
our knowledge of extrasolar planetary systems over
the last decade

Characterization of extrasolar planets requires new
techniques

Transit searches are challenging, but hold great promise
over the next few years: planet radius is very important

Exciting and surprising discoveries guarranteed: stay tuned!