Extrasolar Transiting Planets: Detection and False Positive Rejection

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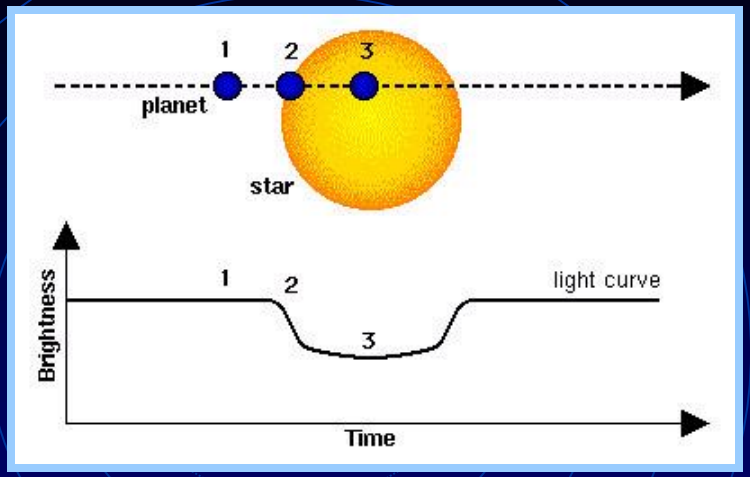
The Transit Technique



- Recent development (~10 yr)
- Provides crucial information for studying extrasolar planets
  - Inclination angle → absolute mass of the planet
  - Radius → mean density: probes internal structure and composition
- Requires high photometric precision (few mmag) to find shallow drops in brightness of ~1% or less
- Transits are rare phenomena: only ~10% chance of occurrence for P = 4 days: need to look at many stars
  - Searches with small telescopes: wide field, shallow
  - Searches with larger telescopes: narrow field, deep

Status of Confirmed Detections

Survey	Detections*
SuperWASP	29 ‡
HATNet	26 ‡
CoRoT	13
OGLE	8
Kepler	7
XO	5
TrES	4
Other	7
Total	99

* Excludes companions with $M_p > 13\ M_{Jup}$

‡ One detection shared

Mass range: $M_p = 4.8\ M_\oplus$ to $13\ M_{Jup}$

Radius range: $R_p = 1.7\ R_\oplus$ to $1.81\ R_{Jup}$

Mean density range: $\rho_p = 0.12$ to 13.8 g/cm^3

Orbital period range: $P = 0.79$ to 111.4 days

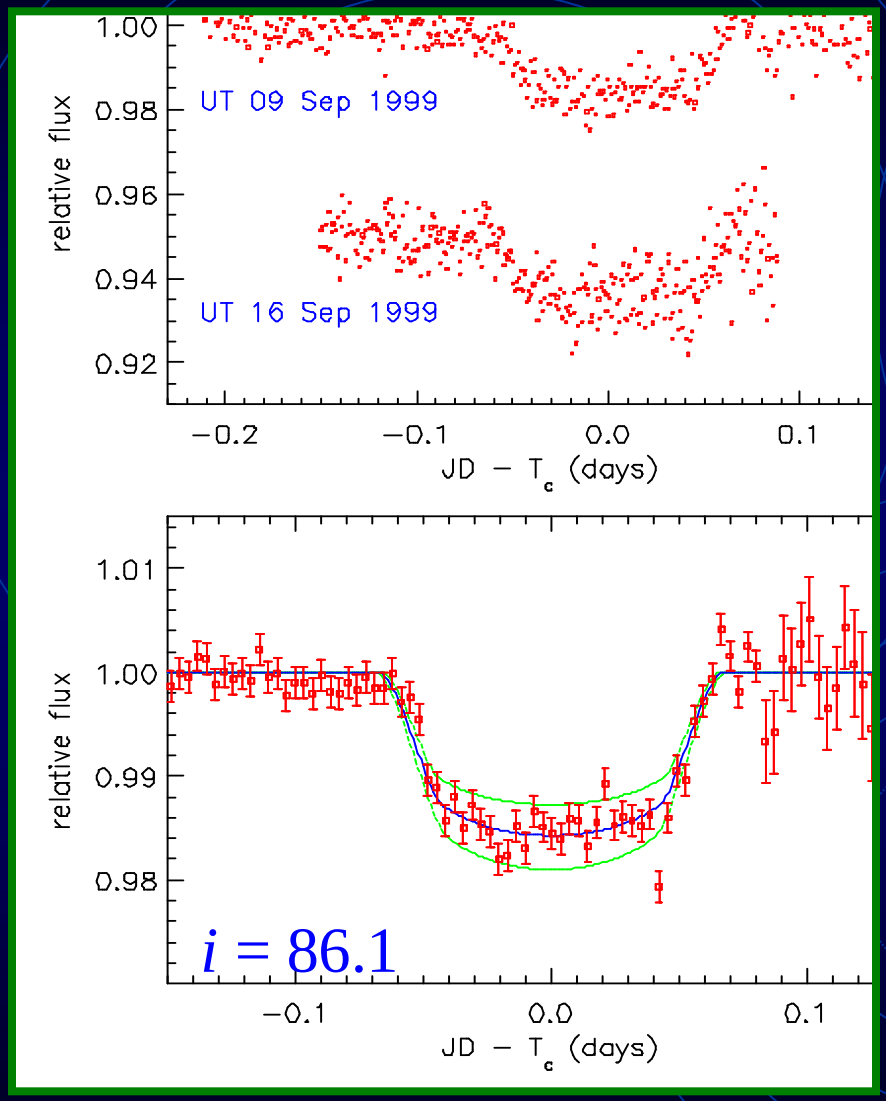
Brightness range: $V = 7.65$ to 16.84

Transit depth range: $\Delta = 0.2$ to 25 mmag

RV semi-amplitude range: K = m/s to km/s

Extrasolar Planets Encyclopaedia: http://exoplanet.eu

HD 209458: first transiting planet discovered



Charbonneau et al. (2000)

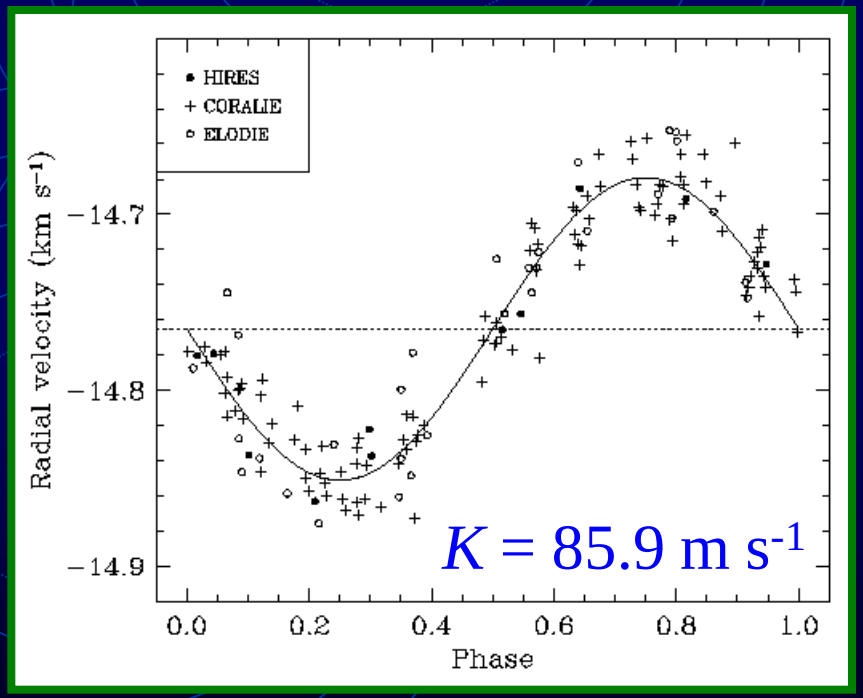
P = 3.52433 days

Planetary mass = 0.69 M_{Jup}

Planetary radius = 1.4 R_{Jup}

Density = 0.31 g cm^{-3}

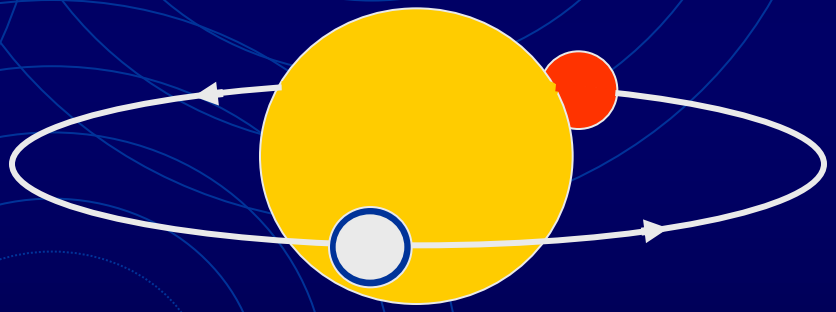
V = 7.65



Mazeh et al. (2000)

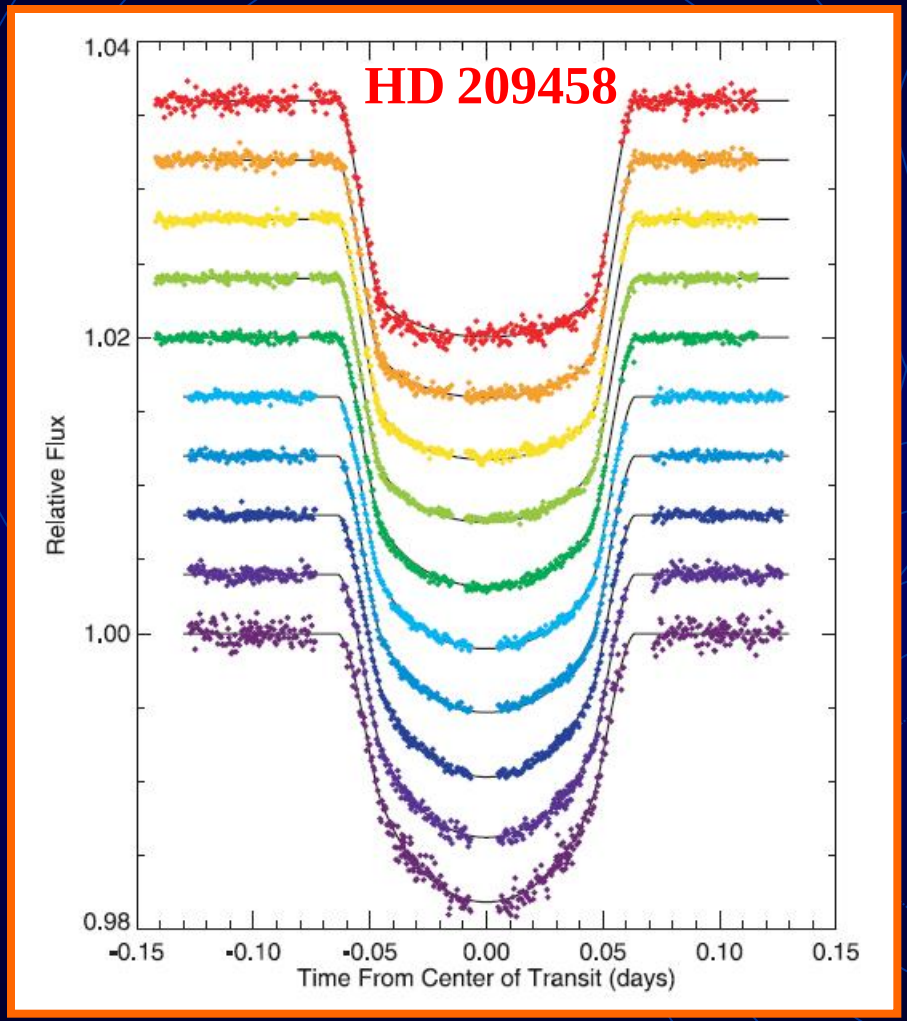
Importance of Brighter Cases

- They enable very detailed follow-up studies that are difficult or impossible for fainter examples
  - Very high-precision light curves (search for satellites and circumplanetary rings, etc.)
  - Transmission spectroscopy (atmospheric studies)
  - Occultation spectroscopy (thermal emission)



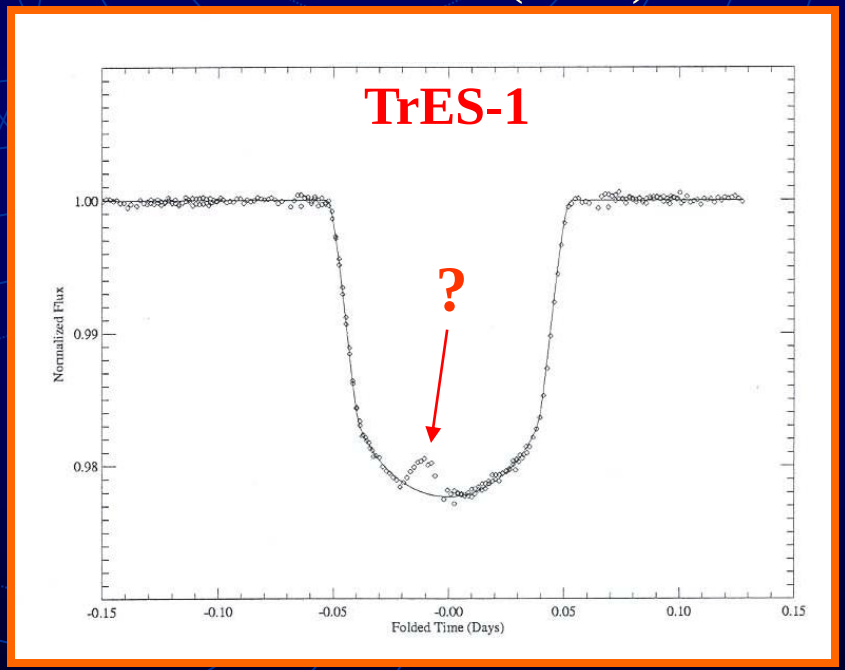
- They advance our theoretical understanding of planets (formation, structure, evolution)

High-Precision Light Curves With HST



Knutson et al. (2007)

Brown et al. (2005)

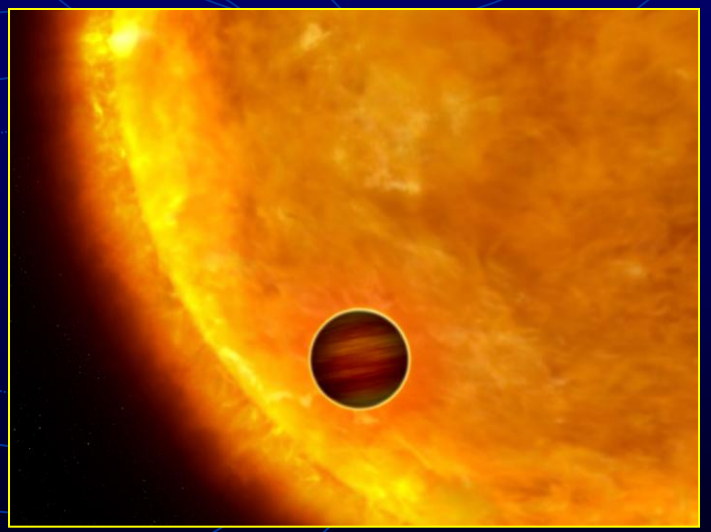


$V = 7.65$, $\sigma = 0.00012$ mag

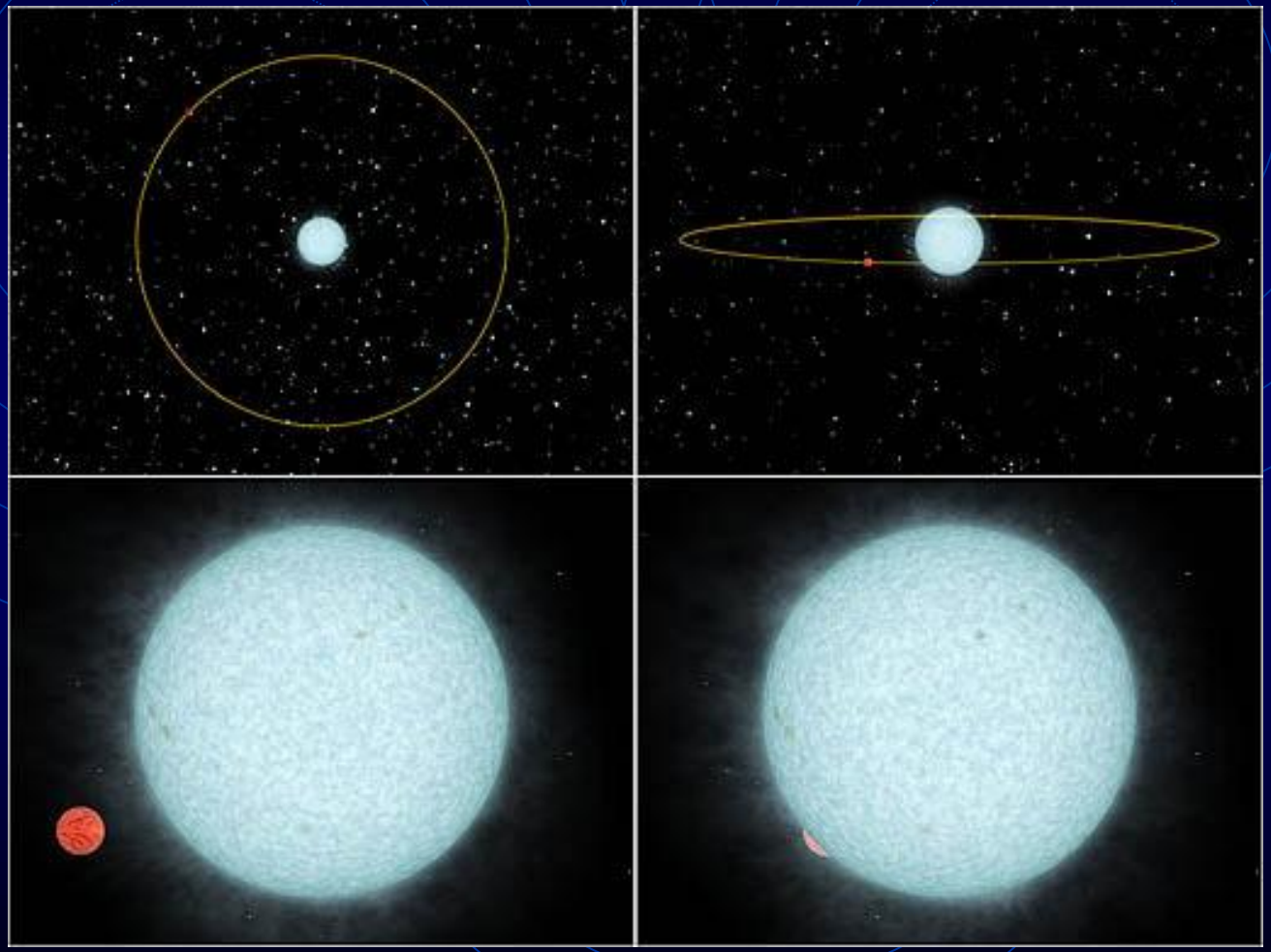
$V = 11.79$, $\sigma \sim 0.0003$ mag

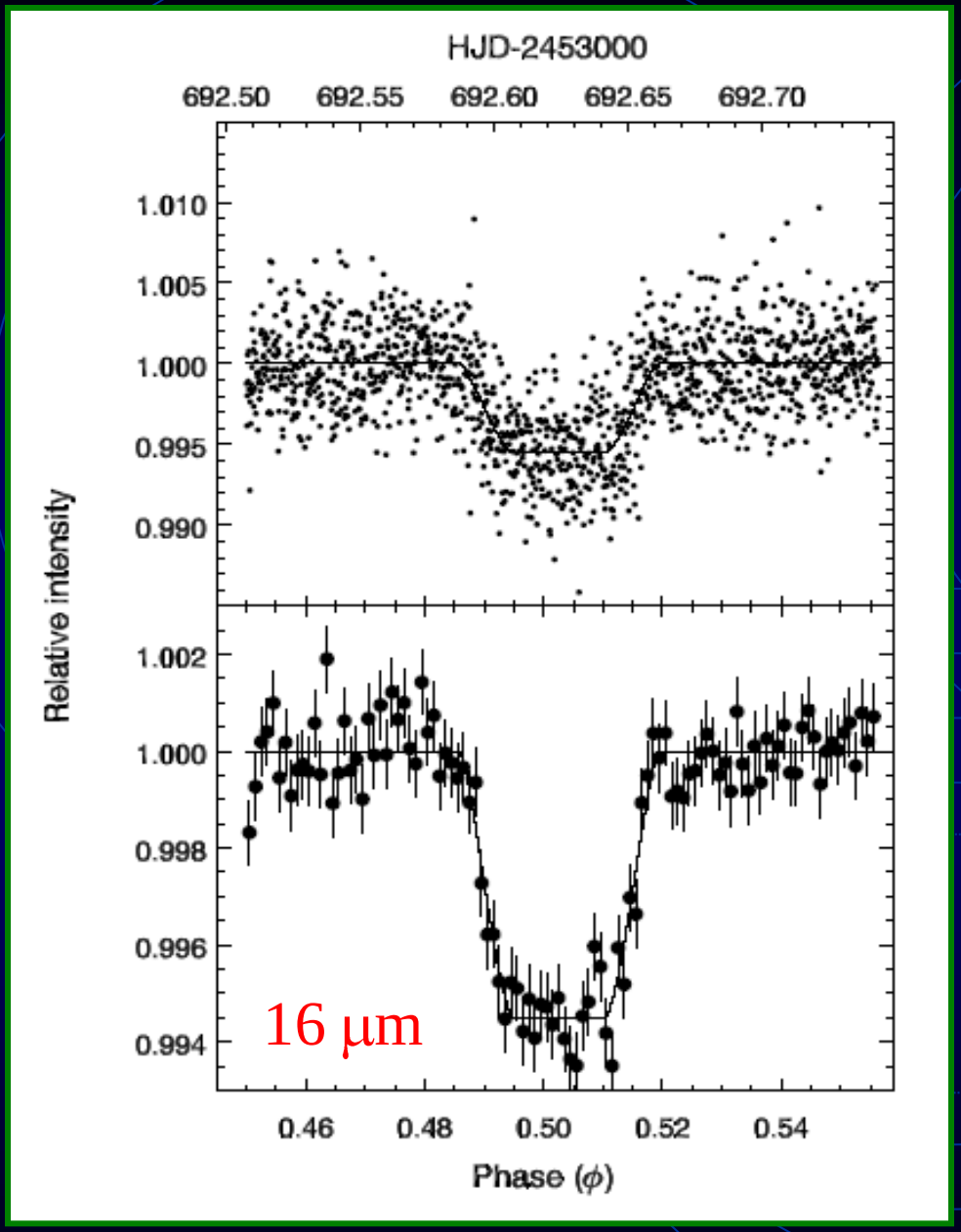
Transmission Spectroscopy With HST and Now Also Ground-Based Telescopes

- Detection of chemical elements in the atmospheres of several transiting planets
  - HD 209458b: Sodium (Charbonneau et al. 2002), hydrogen (Vidal-Madjar et al. 2003), possibly carbon and oxygen (Vidal-Madjar et al. 2004)
  - HD 189733b: Sodium (Redfield et al. 2008)
  - HD 80806b: Potassium (Sing et al. 2010)
  - XO-2b: Potassium (Colón et al. 2010)



Detection of Thermal Emission From an Extrasolar Planet





HD 189733

Observation of the secondary eclipse with the Spitzer Space Telescope

Eclipse depth = 0.55%

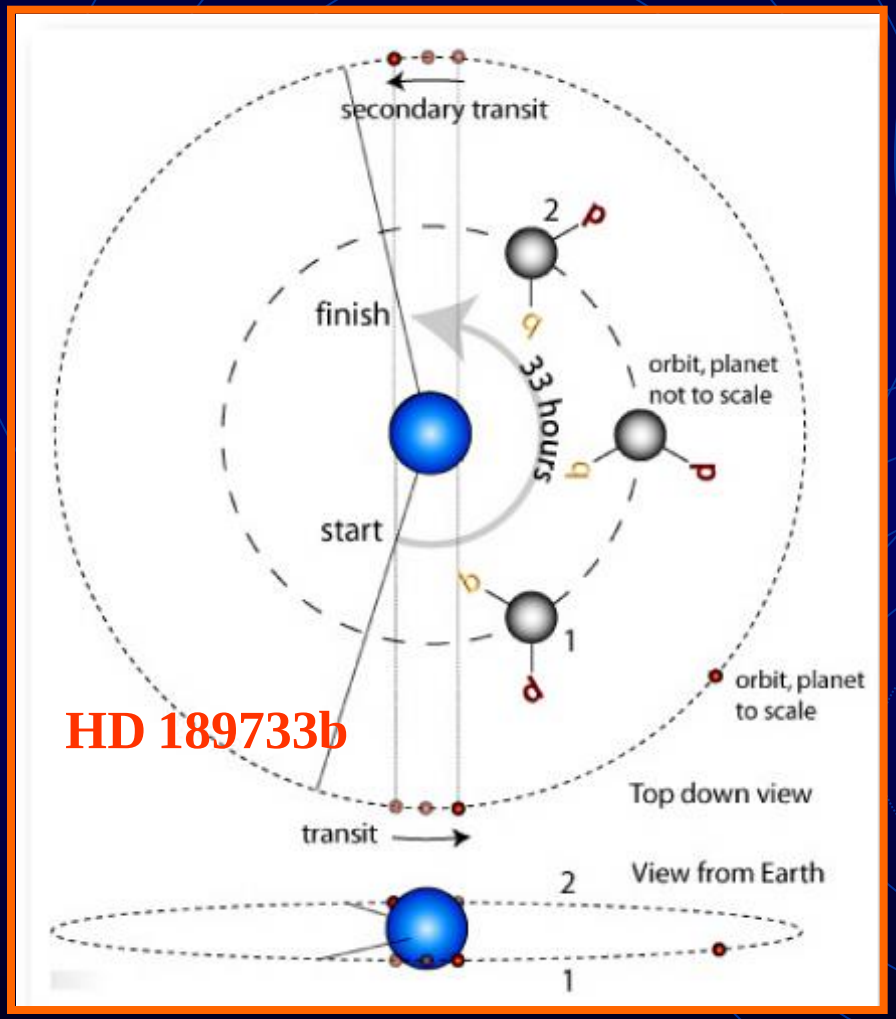
More favorable case than others:

- Smaller parent star (K2 dwarf, $R_* = 0.76\ R_\odot$)
- Closer distance (19 pc)

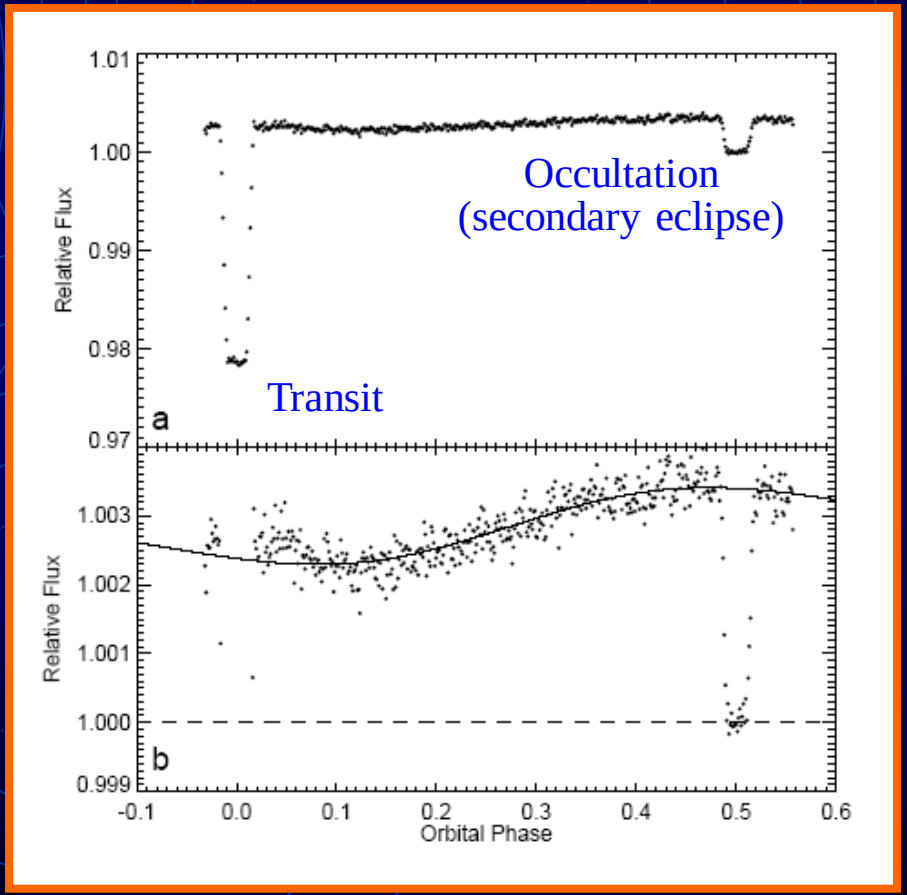
Deming et al. (2006)

A Map of the Day-Night Contrast of an Extrasolar Planet

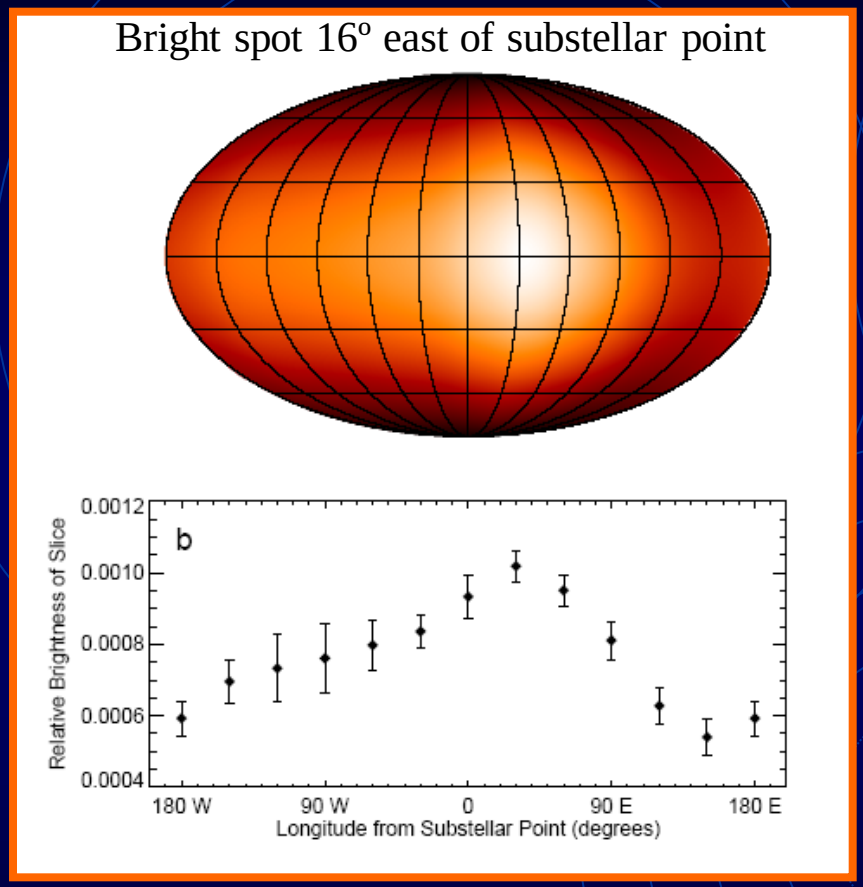
Observing HD 189733b over 62% of its orbit



Light curve obtained with *Spitzer*, at a wavelength of 8 μm

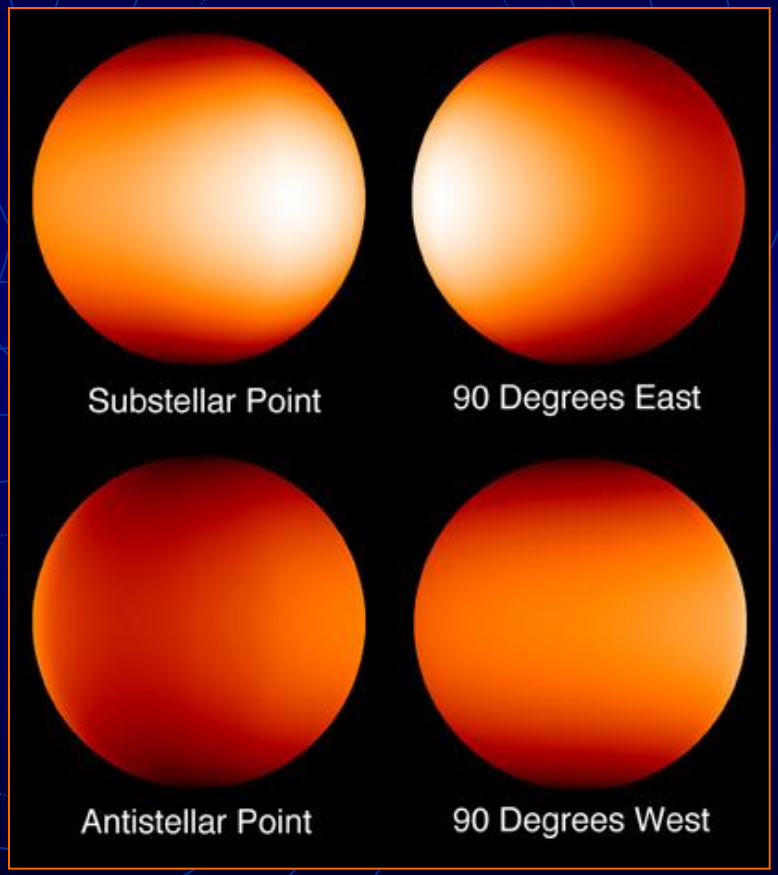


Brightness Distribution on the Surface of the HD 189733b



Temperature of day side = 1212 K

Temperature of night side = 973 K



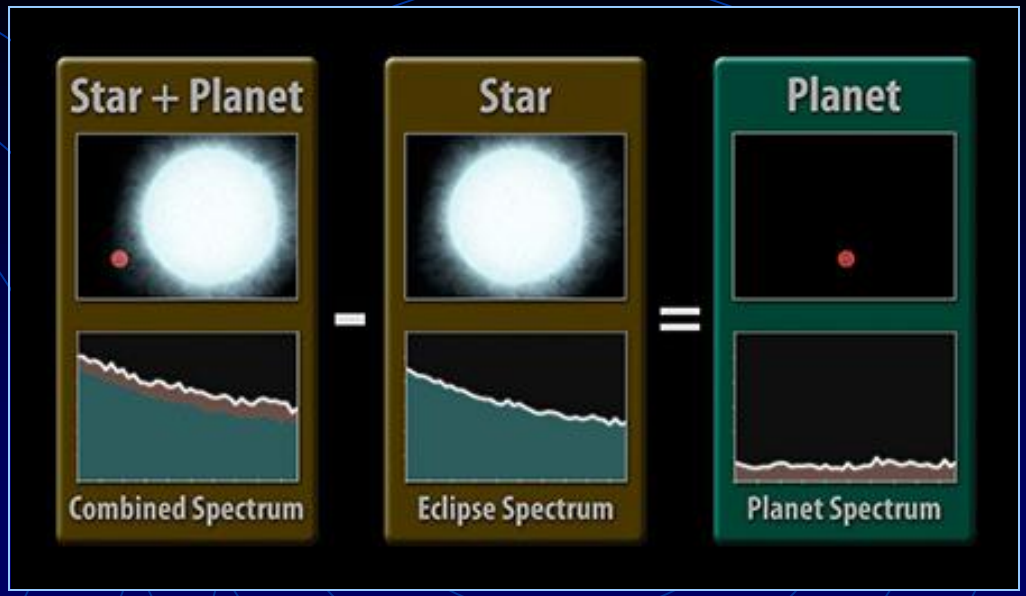
Energy is redistributed quite efficiently throughout the atmosphere from the day side to the night side of the planet.

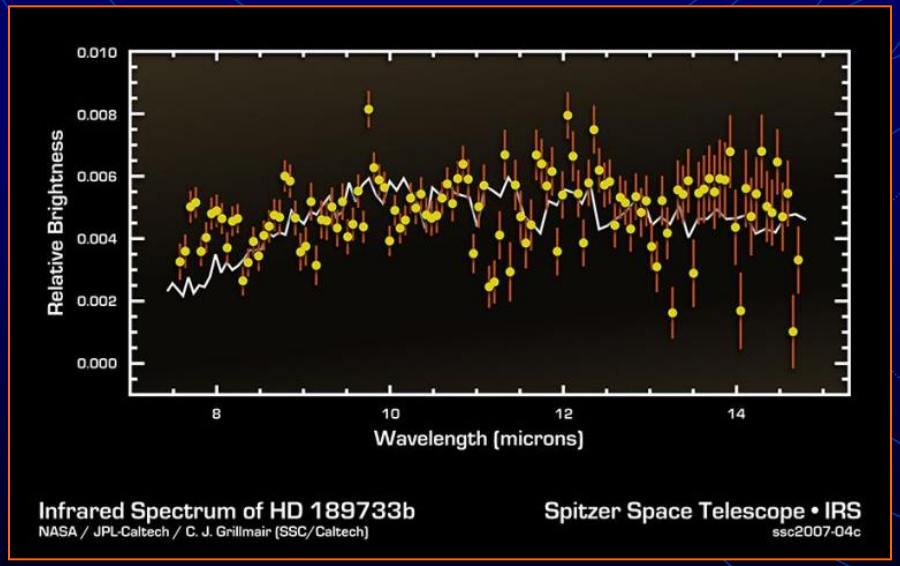
Knutson et al. (2007)

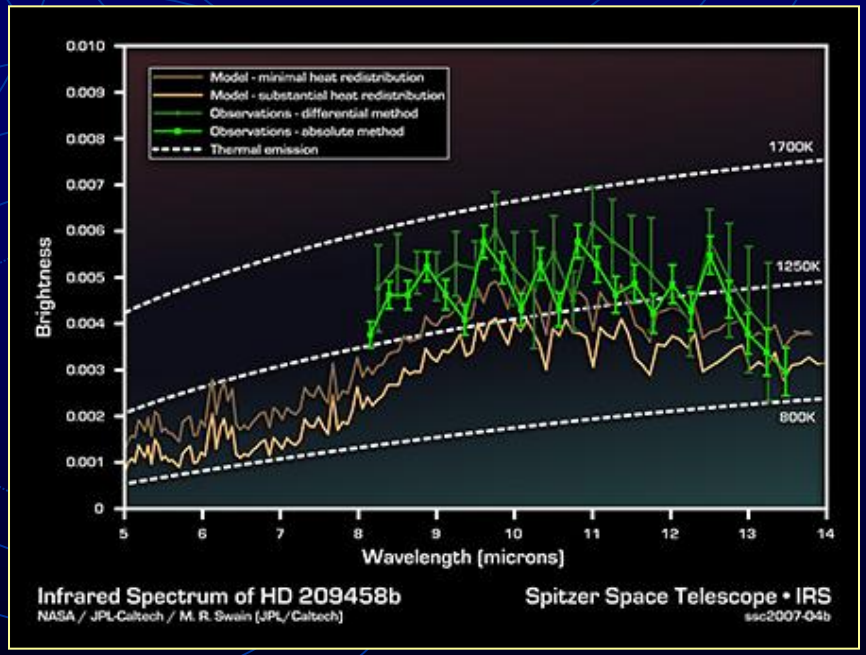
Isolating the Spectrum of an Extrasolar Transiting Planet

HD 189733b: Grillmair et al. (2007)

HD 209458b: Swain et al. (2007)
Richardson et al. (2007)

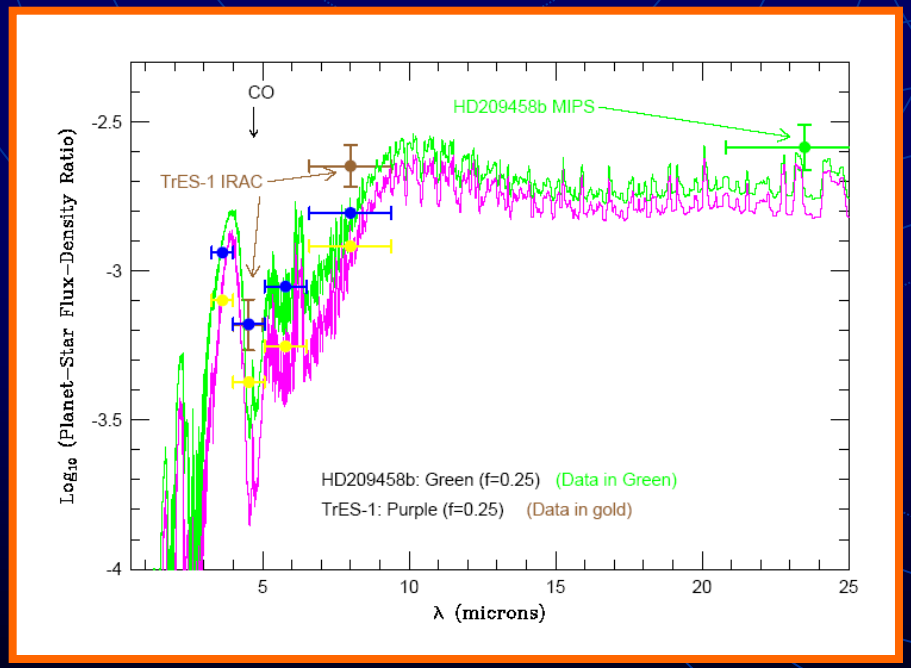


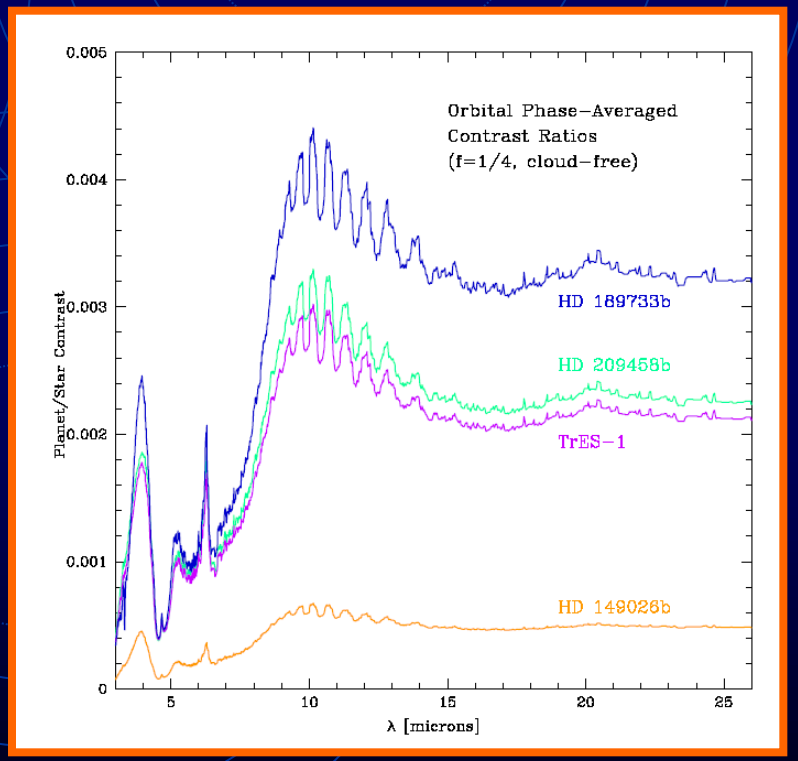


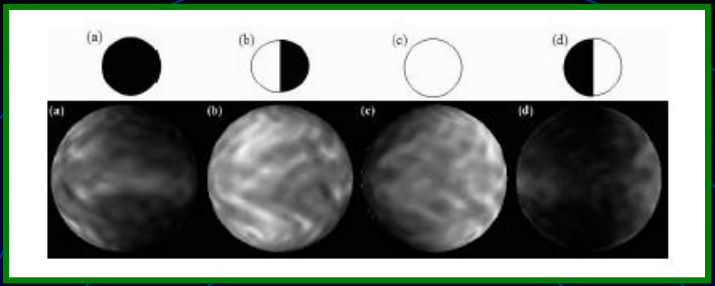


Importance of These Detections for Theory

- Allows study of atmospheric composition, temperature, and global circulation for extrasolar giant planets
- Strong indications of the presence of H_2O and CO
- Indications that the day side is brighter in the infrared than the night side (Burrows et al. 2005)



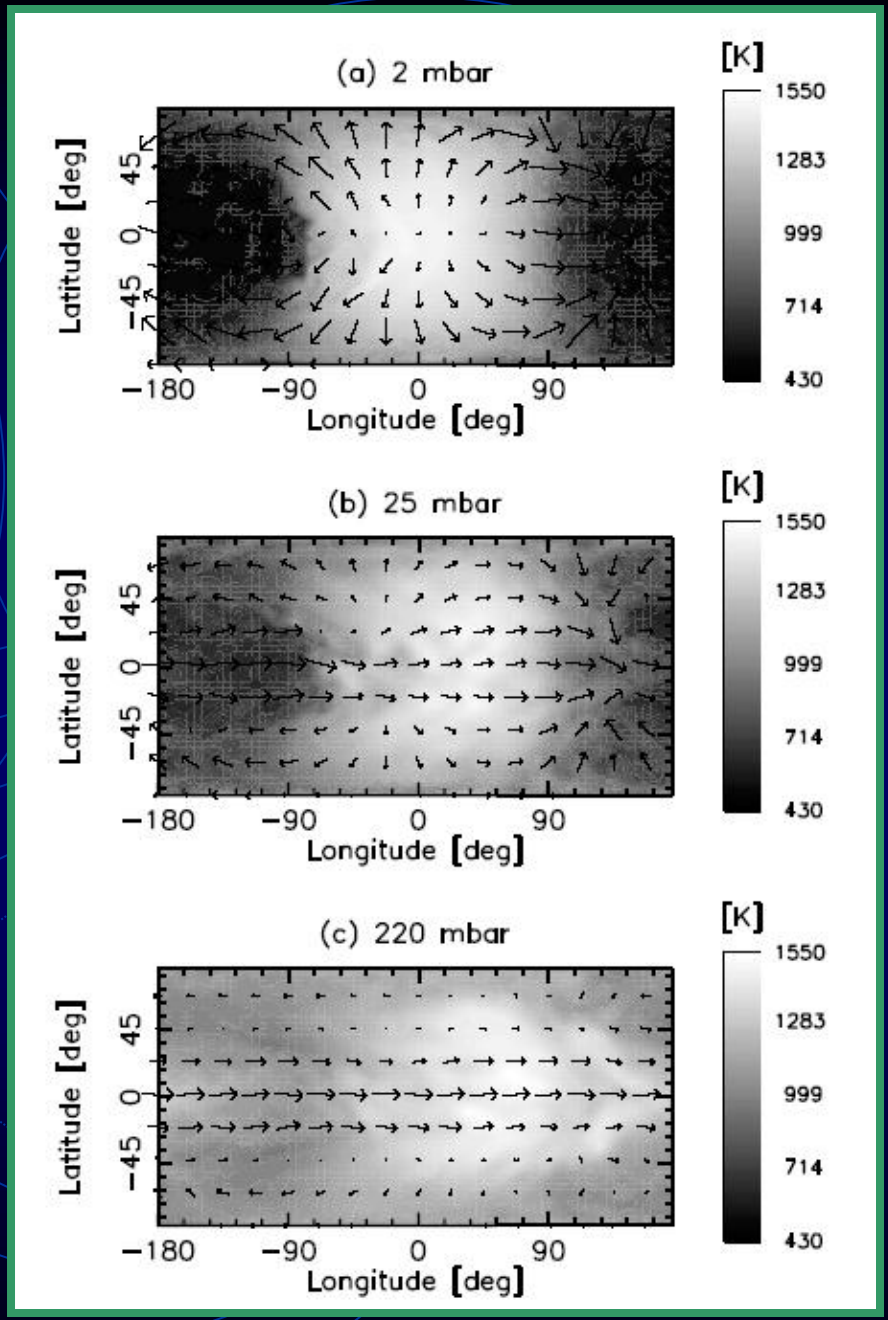




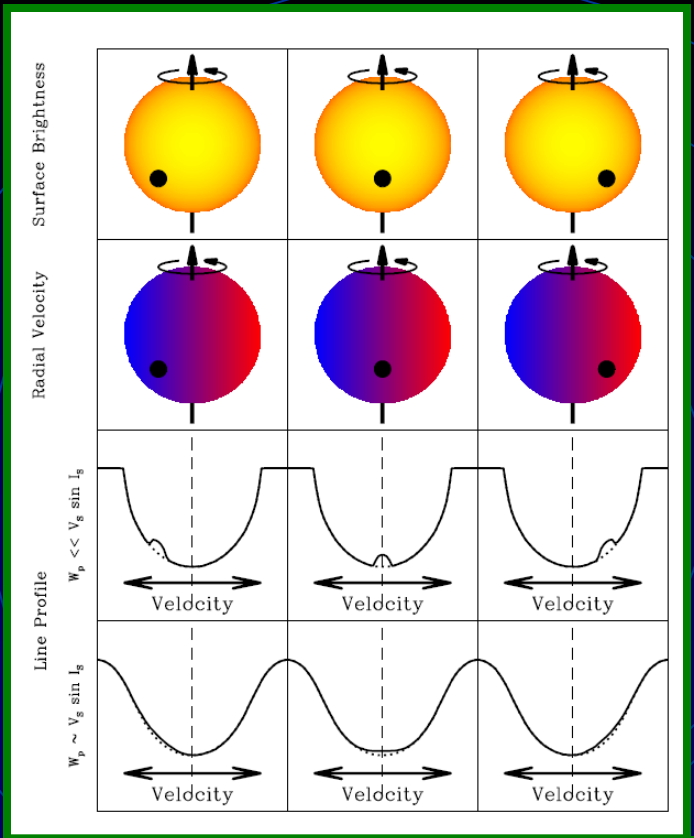
3-D dynamical modeling to understand the structure, winds, and temperature contrasts of the atmosphere of HD 209458b.

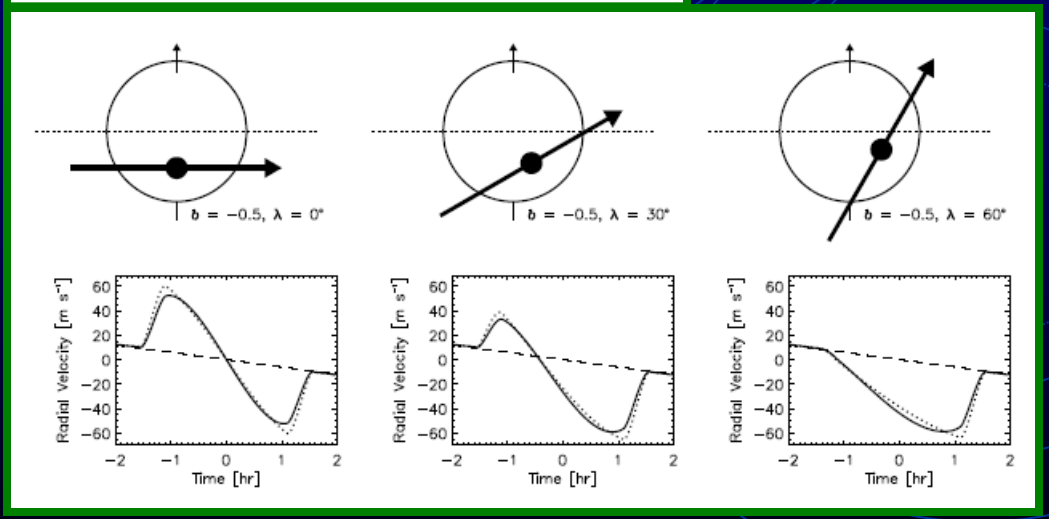
Global temperature and wind map →

Fortney et al. (2006)

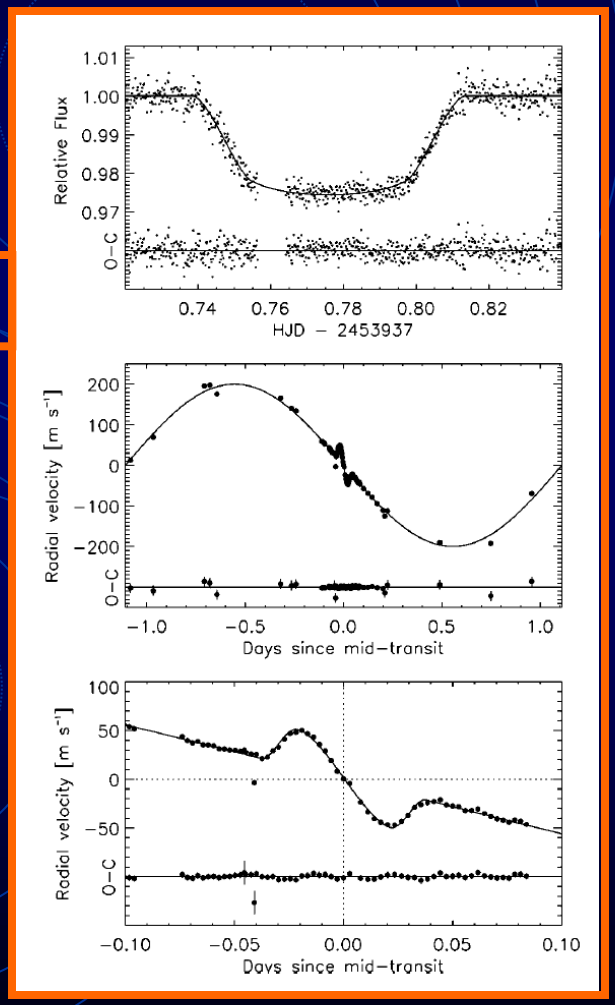


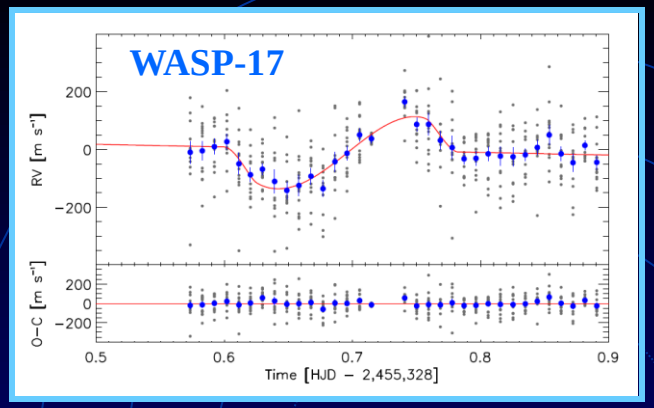
Measuring the Projected Spin-Orbit Angle Through the Rossiter-McLaughlin Effect

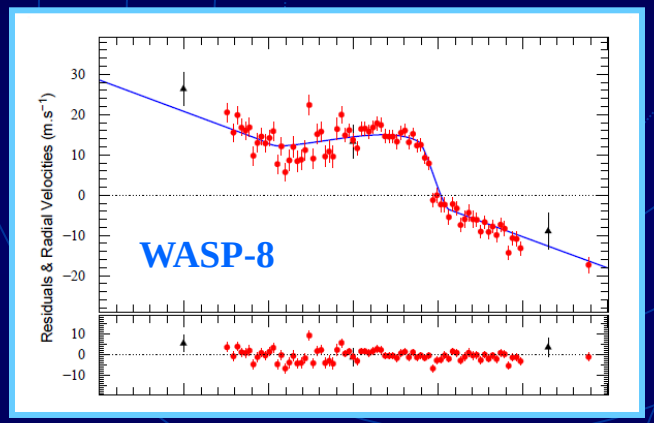


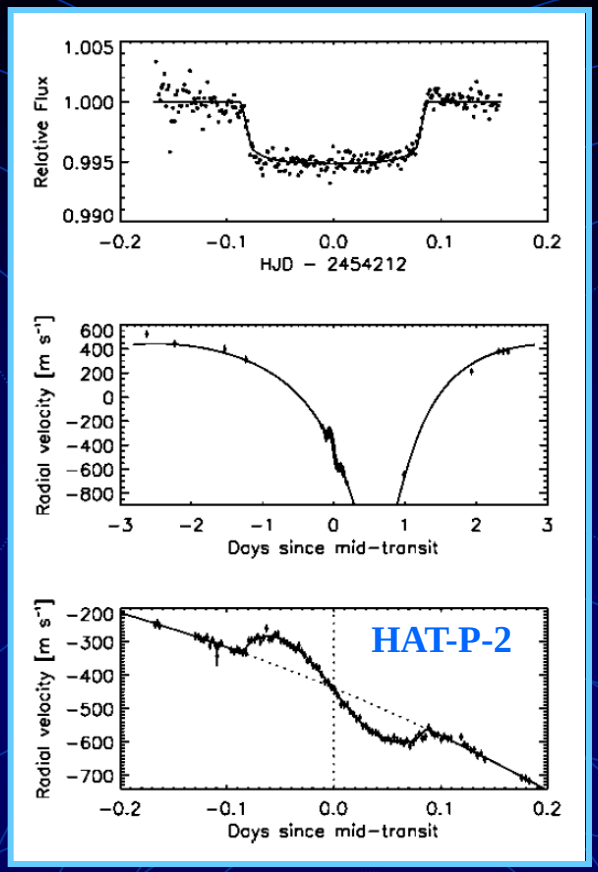


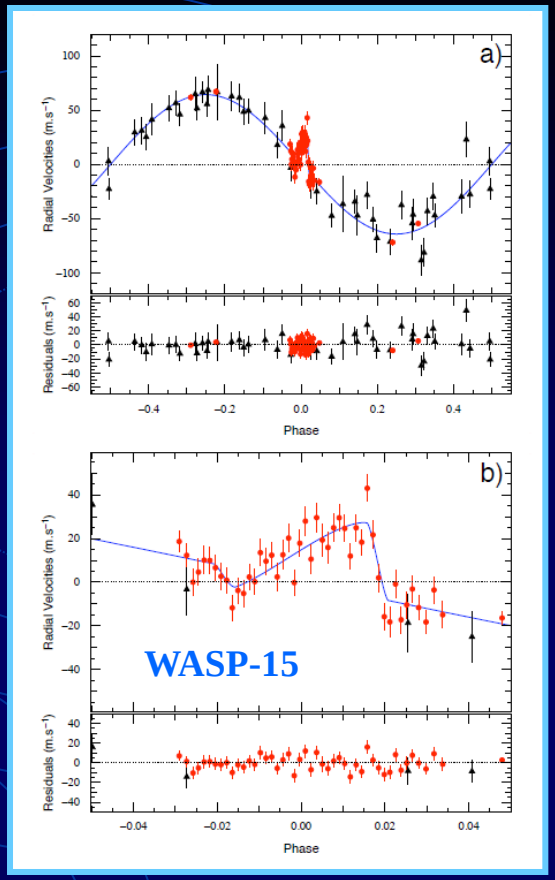
HD 189733

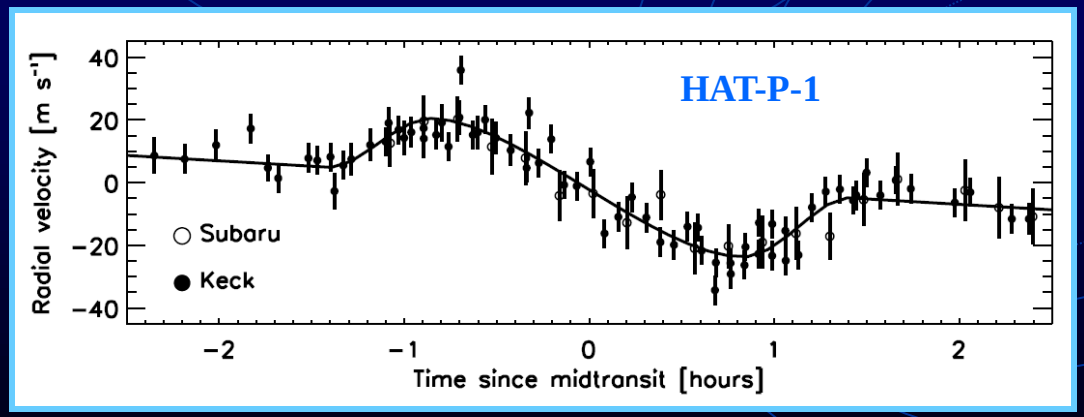


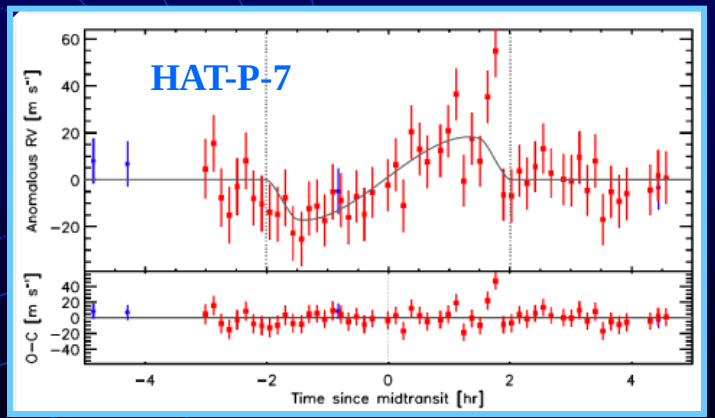

WASP-17
RV [m s⁻¹]
O−C [m s⁻¹]
Time [HJD − 2,455,328]


WASP-8
Residuals & Radial Velocities (m.s⁻¹)


Relative Flux
HJD − 2454212
Radial velocity [m s⁻¹]
Days since mid−transit
HAT-P-2
Radial velocity [m s⁻¹]
Days since mid−transit

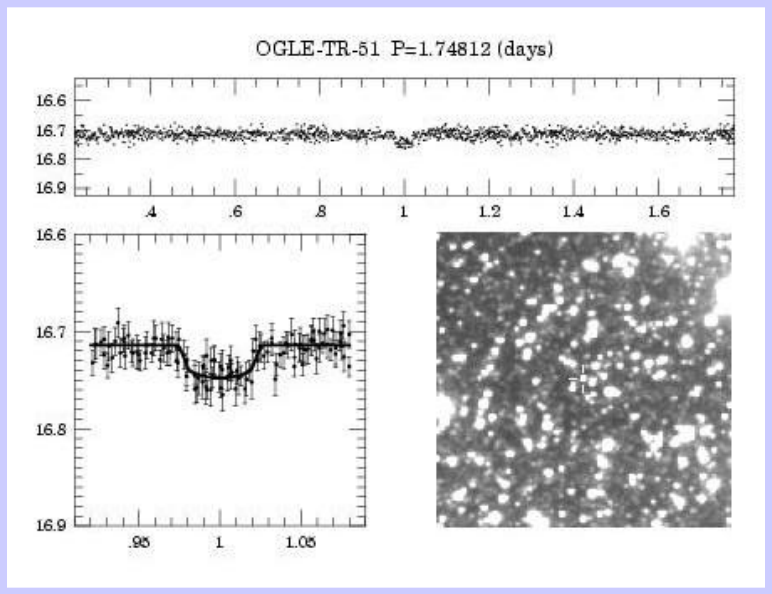

a)
Radial Velocities (m.s⁻¹)
Residuals (m.s⁻¹)
Phase
b)
WASP-15
Radial Velocities (m.s⁻¹)
Residuals (m.s⁻¹)
Phase


HAT-P-1
Radial velocity [m s⁻¹]
Subaru
Keck
Time since midtransit [hours]

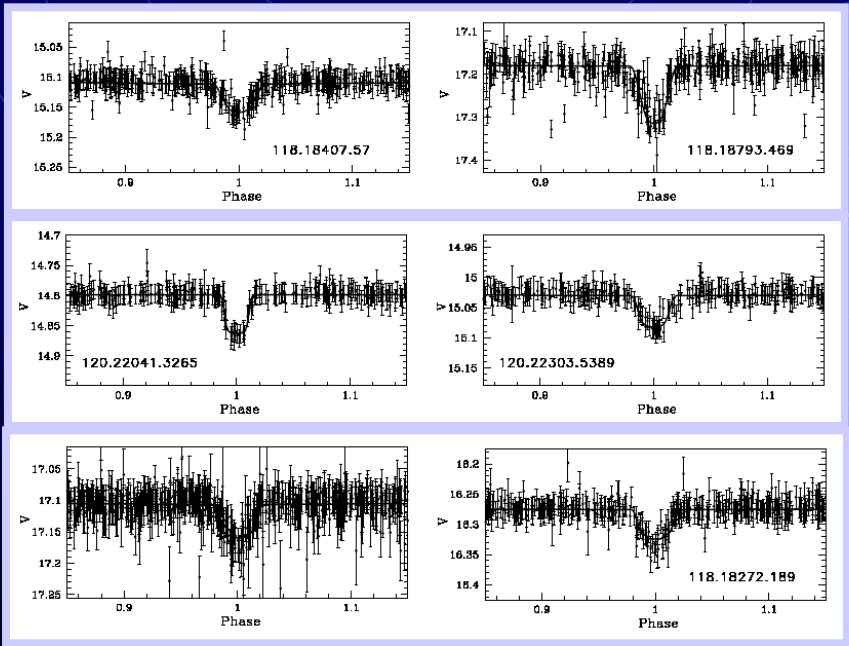

HAT-P-7
Anomalous RV [m s⁻¹]
O−C [m s⁻¹]
Time since midtransit [hr]

Many transiting planet candidates…

Why haven't more been announced?

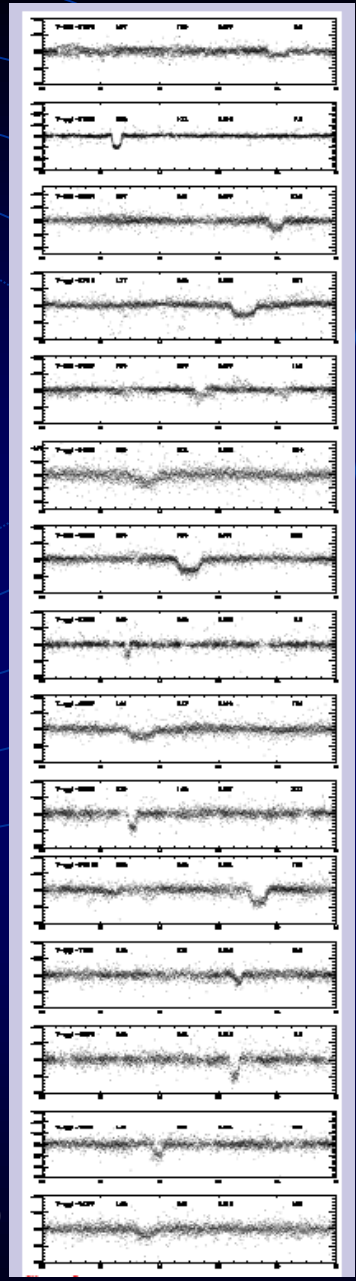


OGLE (Udalski et al. 2002)



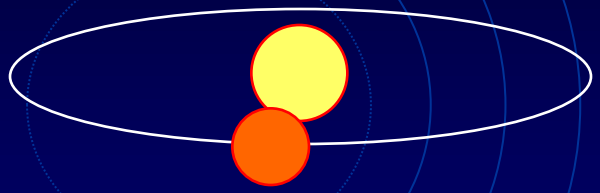
MACHO
(Drake & Cook 2004)

TrES
(O'Donovan et al. 2005)

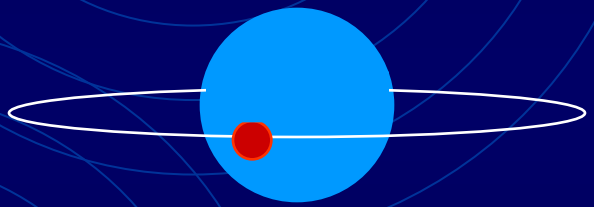


Astrophysical False Positives

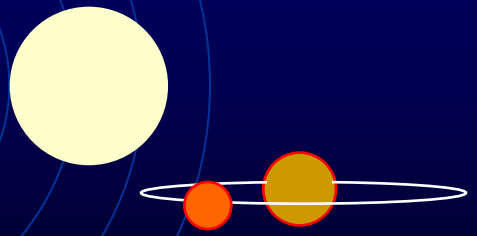
- Eclipsing binary with grazing orientation



- Small star crossing in front of a large star



- Eclipsing binary diluted by the light of a third star (“*blend*”) → trickiest case

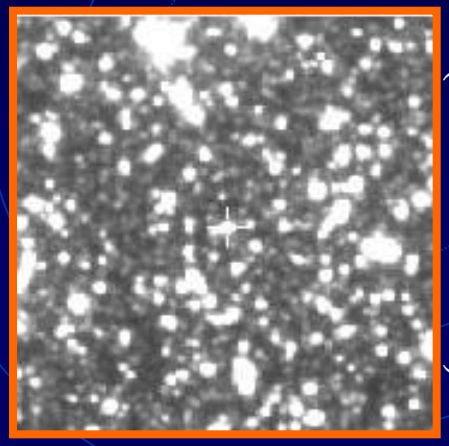


Ruling Out False Positives

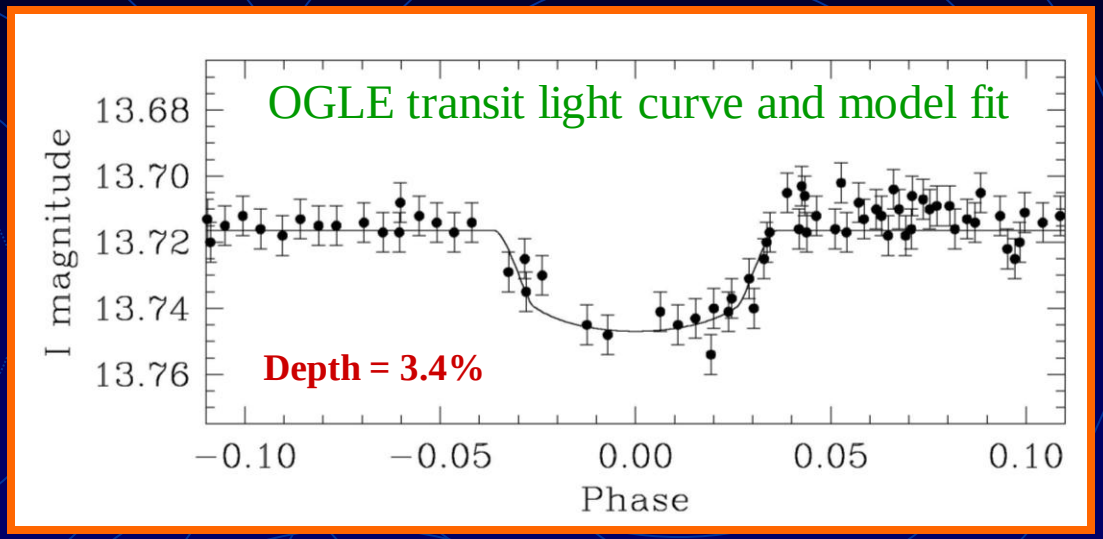
- Signs of another star in the spectrum (optical or NIR)
- Radial velocity monitoring (~1 km/s precision is more than sufficient to detect stellar companions)
- Light curve analysis
  - Curvature outside of eclipse (Drake 2003; Sirko & Paczyński 2003), or presence of secondary eclipses
  - Shape and duration of the transits (Seager & Mallén-Ornelas 2003) must be right for a planet
  - Check for equal depth in alternating transits ($P \rightarrow 2P$?)
  - Multi-color photometry (λ dependence of transit depth)
- Changes in image position or shape
- Spectral line profile (asymmetry) variations

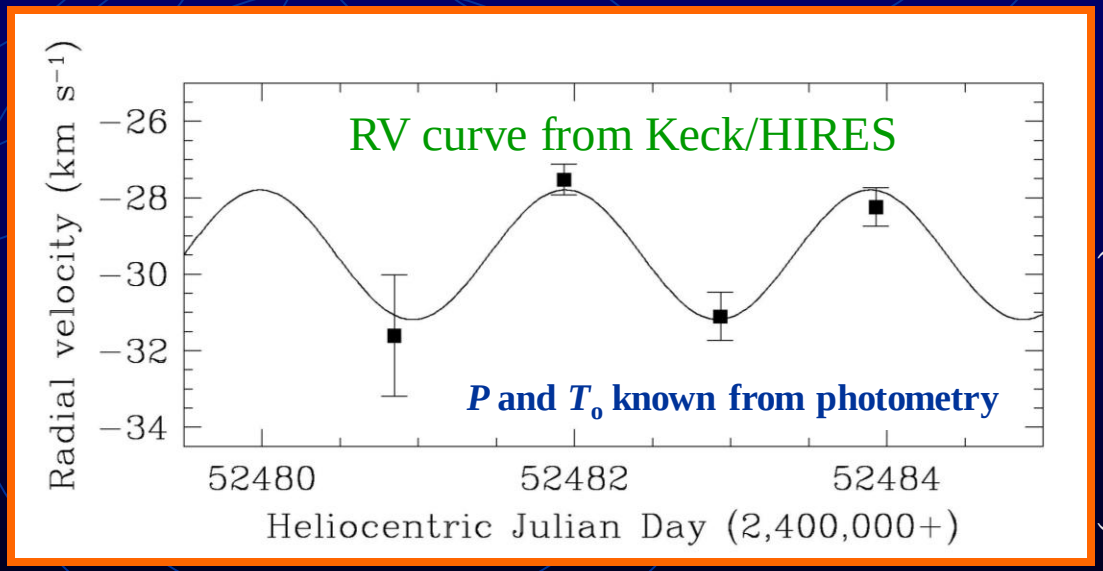
A Promising Candidate: OGLE-TR-33

Transit candidate toward the Galactic center (V = 14.7)



(Udalski et al. 2002)





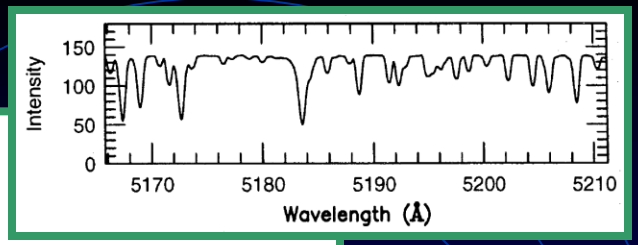
(Torres et al. 2004)

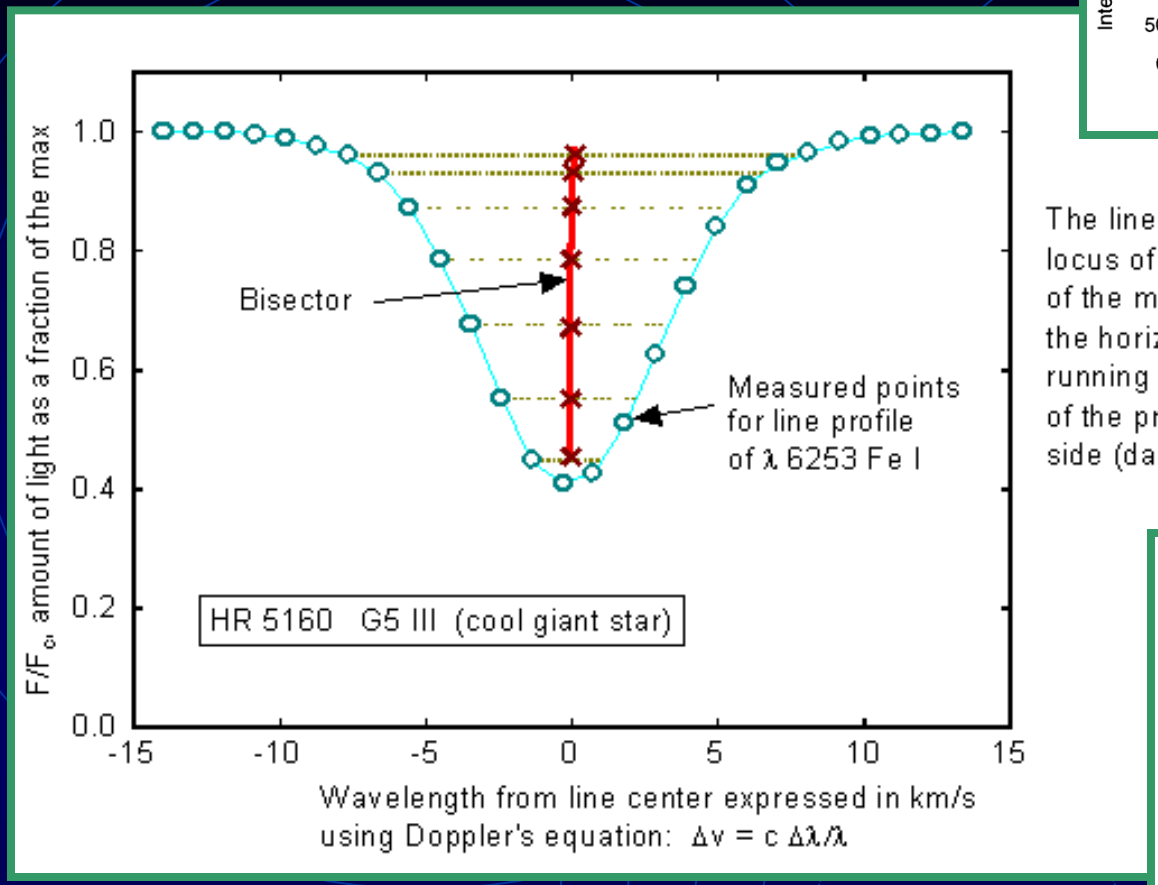
P = 1.95 days

K = 1.70 0.27 km s^{-1}

M_p = 12.6 1.7 $M_{\rm Jup}$

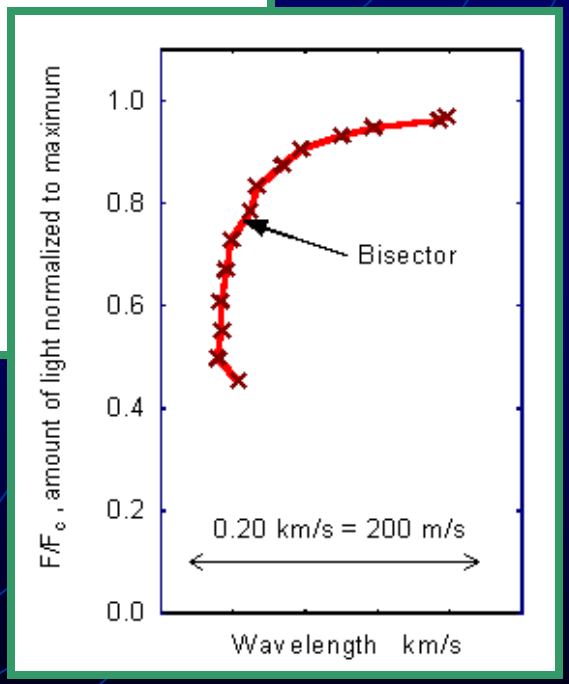
R_p = 2.1 0.1 $R_{\rm Jup}$





The line bisector is the locus of points made up of the midpoints of the the horizontal segments running from the left side of the profile to the right side (dashed lines).

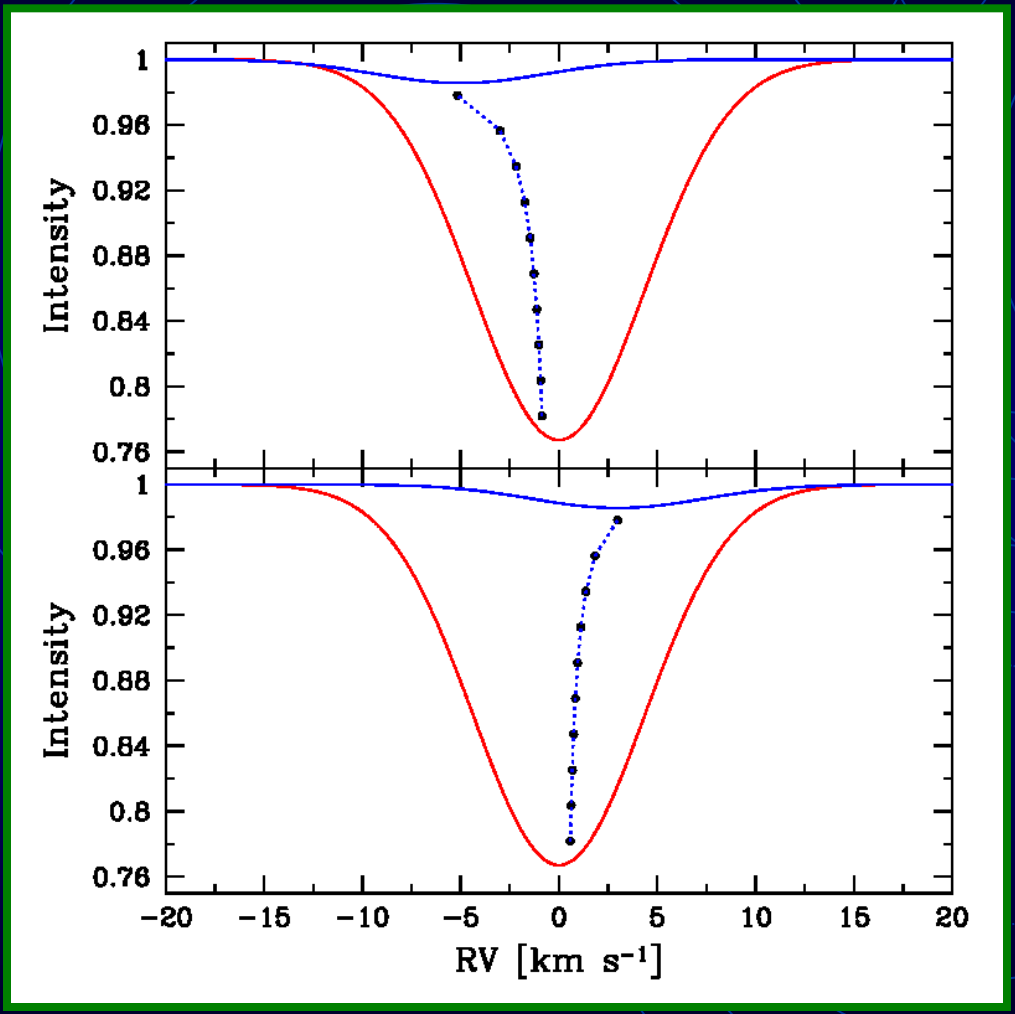
Stellar spectrum



Measuring spectral line asymmetries:

The line bisector

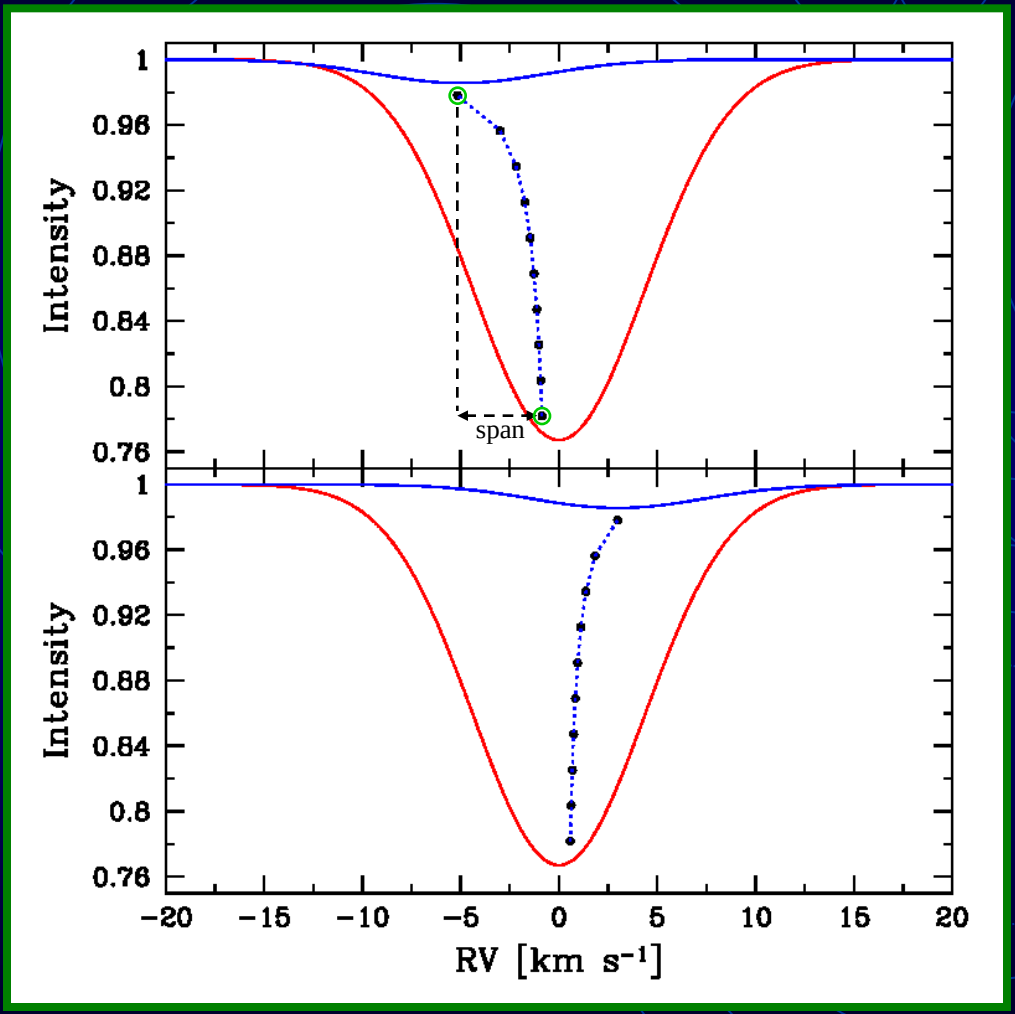
Spectral Line Asymmetries Caused by Blends



The presence of lines of another star in the spectrum (even if it is faint) can cause slight asymmetries in the line profiles.

These asymmetries can be quantified by means of the “bisector spans” (e.g., Queloz et al. 2001; Torres et al. 2004)

Spectral Line Asymmetries Caused by Blends



The presence of lines of another star in the spectrum (even if it is faint) can cause slight asymmetries in the line profiles.

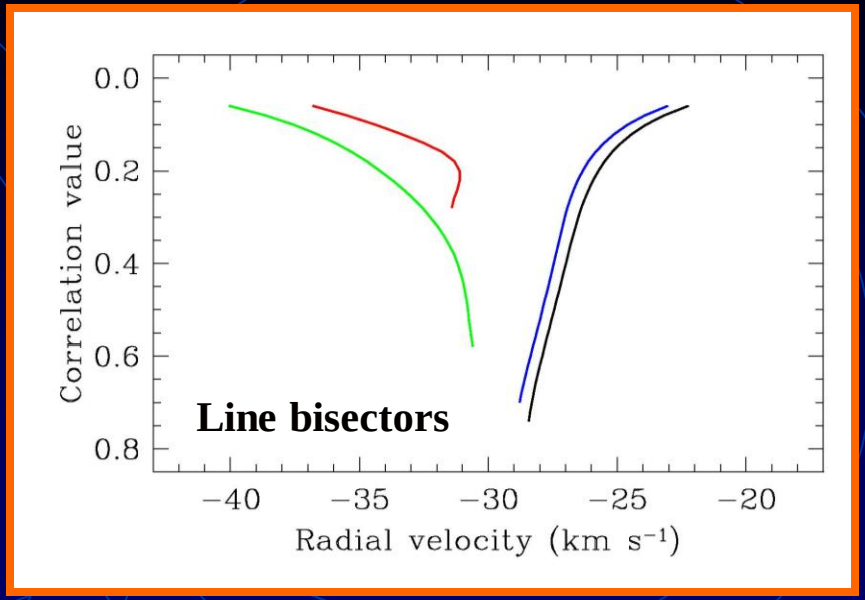
These asymmetries can be quantified by means of the “bisector spans” (e.g., Queloz et al. 2001; Torres et al. 2004)

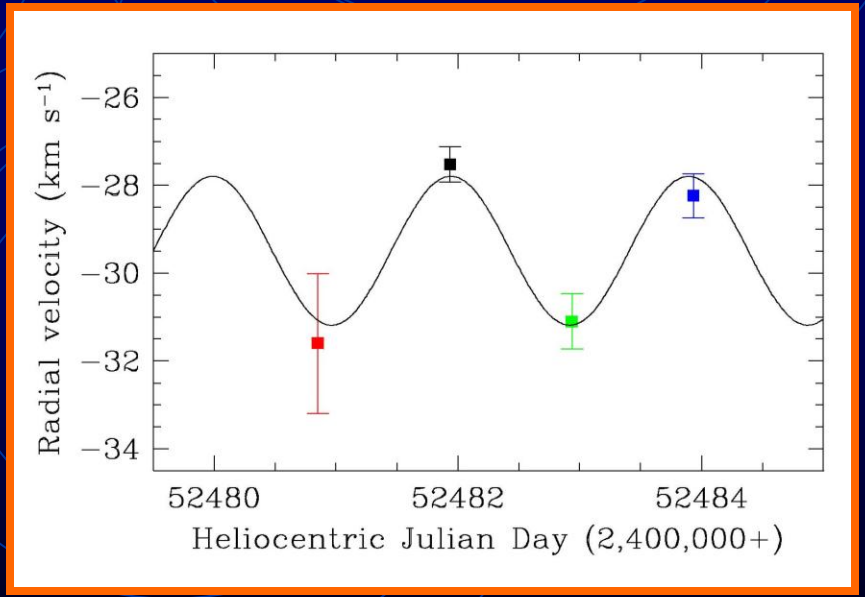
OGLE-TR-33

The spectral line asymmetries correlate with the photometric phase.

The radial velocities measured are spurious, and are caused only by the line asymmetries.

This is NOT a transiting planet





Summary

- Detection of extrasolar planets through transits is now a very successful technique; we have learned a tremendous amount about their formation, structure and composition
- Many surveys underway, both from the ground and from space, others completed
- False positives dominate in any sample of candidates, but can be recognized with careful investigation
- Several transiting Neptune-size planets have already been found from the ground (GJ 1214b has $R_p = 2.7\ R_\oplus$)
- Space searches have extended the field to the super-Earth-size or Earth-size regime; small habitable planets expected any day now!