Follow-up Methods and Elimination of False Positives

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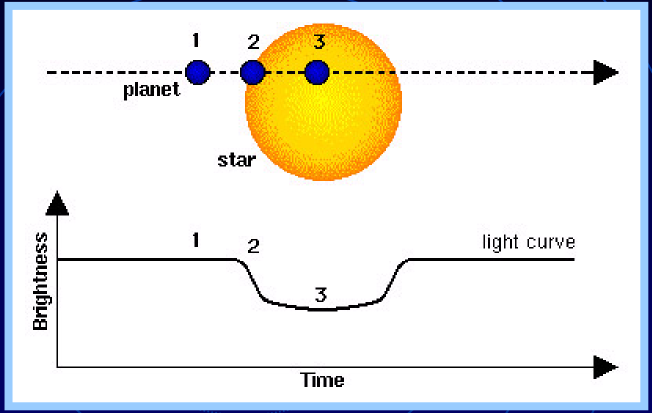
The Transit Technique

(Quick summary)



- Recent development (~7 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%
- 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

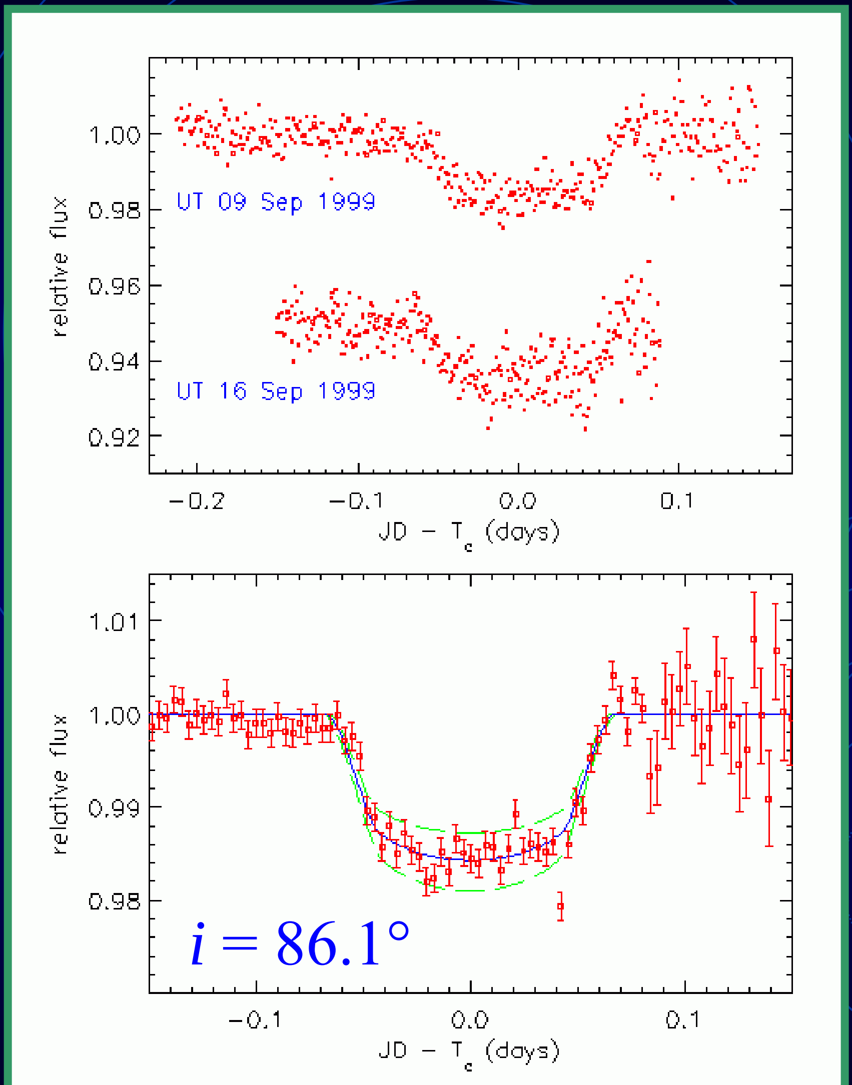
HD 209458b: First Transiting Planet Discovered

P = 3.52433 days

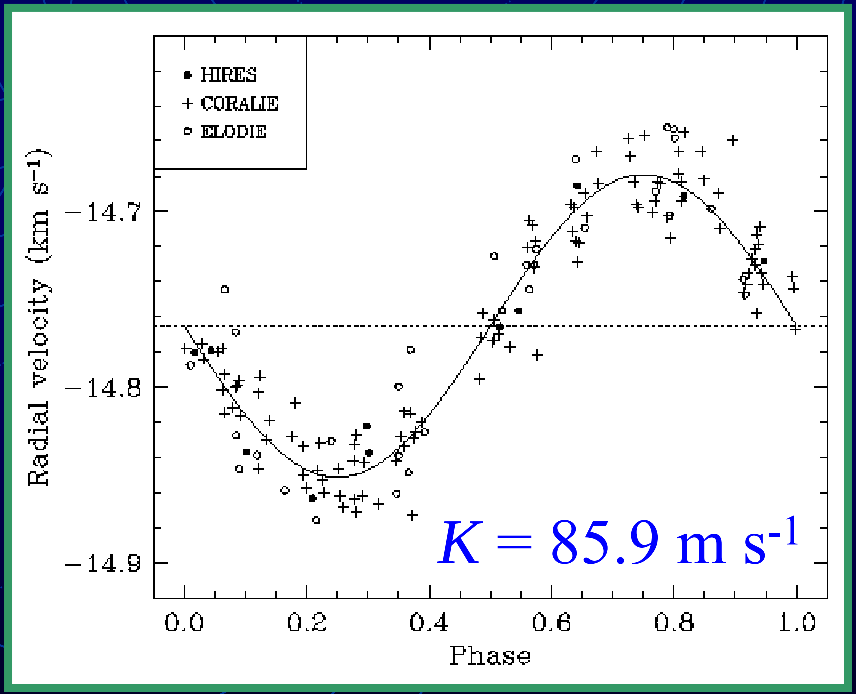
Planetary mass = 0.69 M_{Jup}

Planetary radius = 1.4 R_{Jup}

Density = 0.31 g cm^{-3}



Charbonneau et al. (2000)

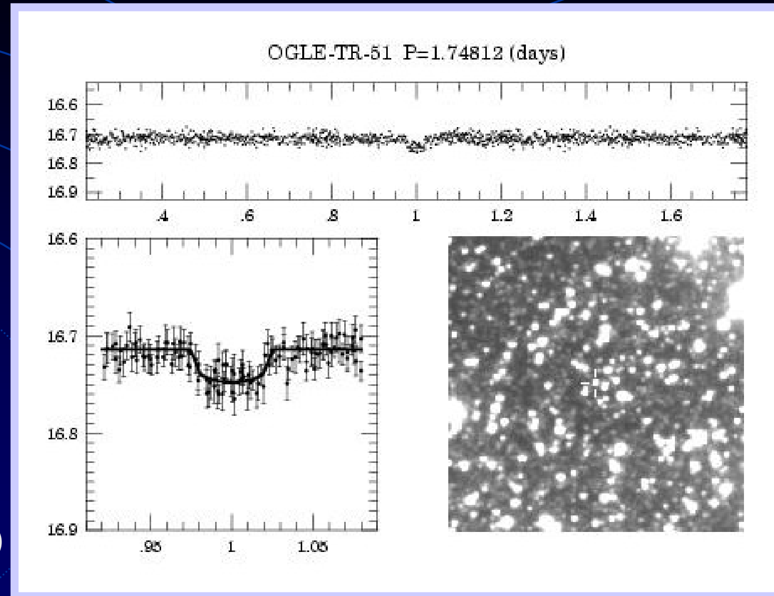


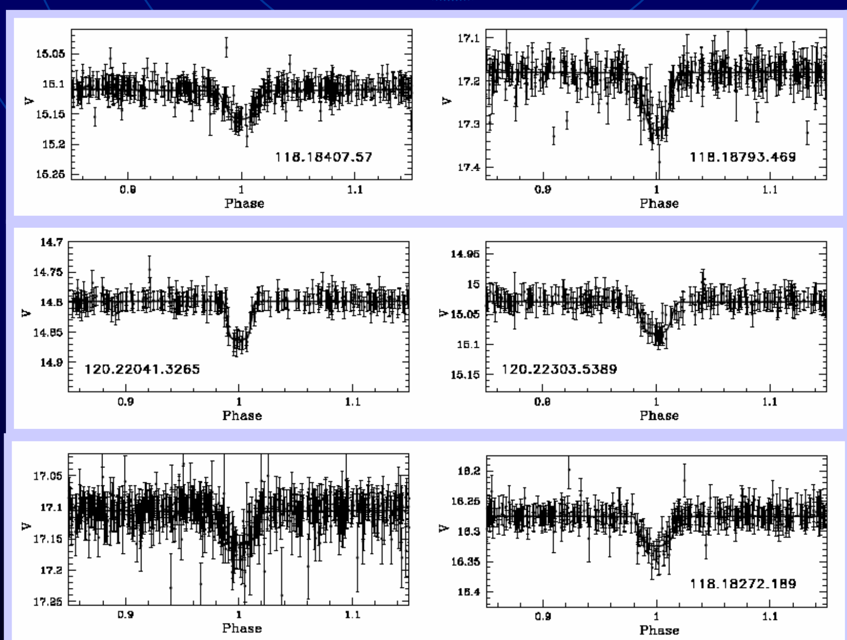
Mazeh et al. (2000)

Many candidates…

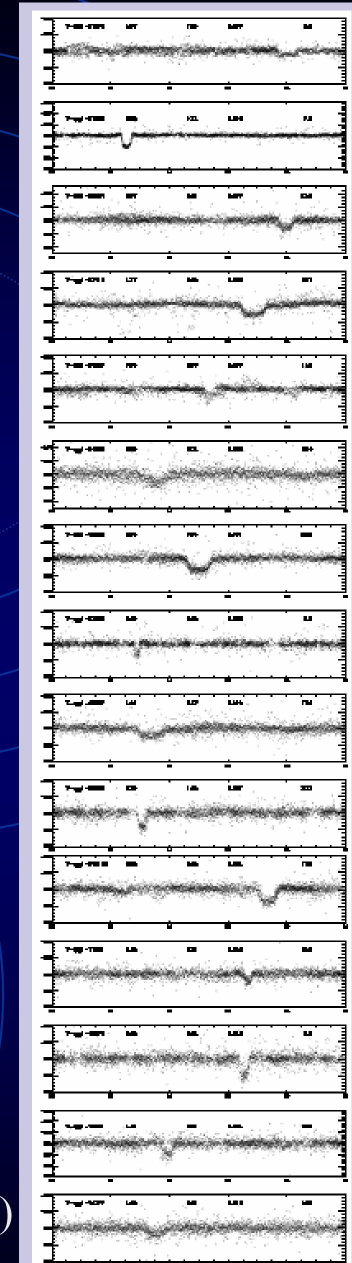
Why haven't more transiting planets been announced?

OGLE (Udalski et al. 2002)





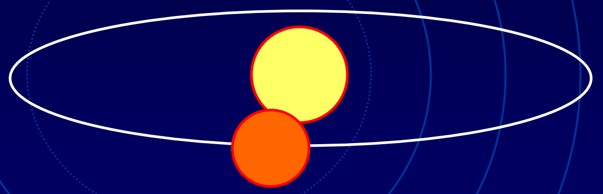
MACHO (Drake & Cook 2004)



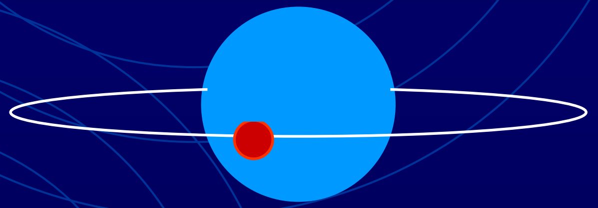
TrES (O'Donovan et al. 2005)

Astrophysical False Positives
(Other phenomena that mimic the transit signatures)

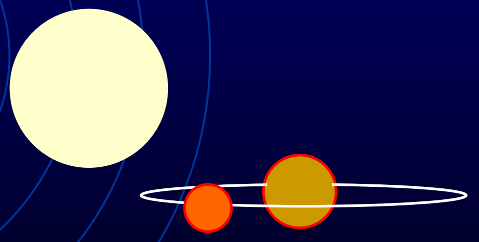
- Eclipsing binary with grazing orientation



- 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 With Photometry

- Light curve analysis
  - Curvature outside of eclipse (Drake 2003; Sirko & Paczyński 2003) indicating a stellar binary (proximity effects such as tidal and rotational distortion, reflection, gravity darkening)
  - Presence of shallow secondary eclipses
  - Test for equal eclipse depth when doubling the period
  - Shape and duration of the transits (Seager & Mallén-Ornelas 2003)
  - Wavelength dependence of transit depth (multi-color photometry)
- Changes in image position (motion of photocenter) or image shape in phase with the period

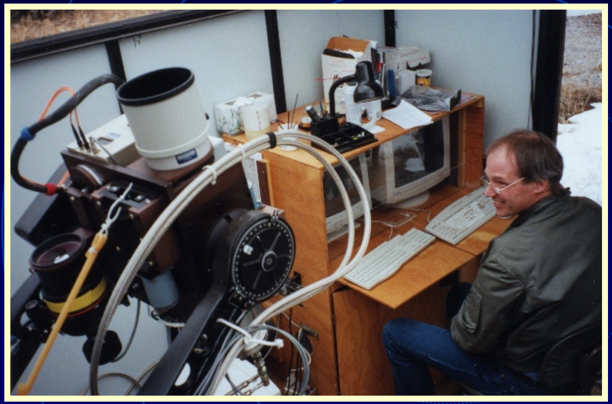
Ruling Out False Positives With Spectroscopy

- Spectral classification (spectral type and luminosity class)
  - Early type stars (too big for us to see the planet)
  - Giants (too big for us to see the planet)
- Radial velocity monitoring (high precision not needed)
  - Signs of other stars in the spectrum
  - Stellar binaries with grazing incidence
  - Low mass stellar companions
- Changes in the shape of the spectral line profiles
  - Bisector analysis

Other Useful Information For Ruling Out False Positives

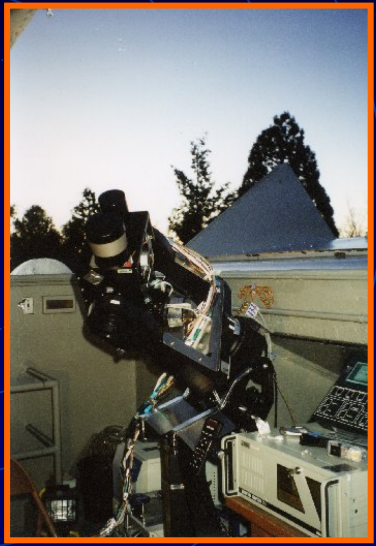
- Proper motions (USNO-B, etc.)
  - Candidates with large proper motions are most likely dwarfs
  - Small proper motions are inconclusive
- Color index (2MASS, etc.)
  - $J–K$ is often a good discriminator between dwarfs and giants: candidates with $J–K \geq 0.5$ are predominantly giants (Brown 2003)
- High-resolution imaging to check for possible contamination from nearby companions

Trans-Atlantic Exoplanet Survey (TrES)



PSST, Arizona

STARE, Canary Islands

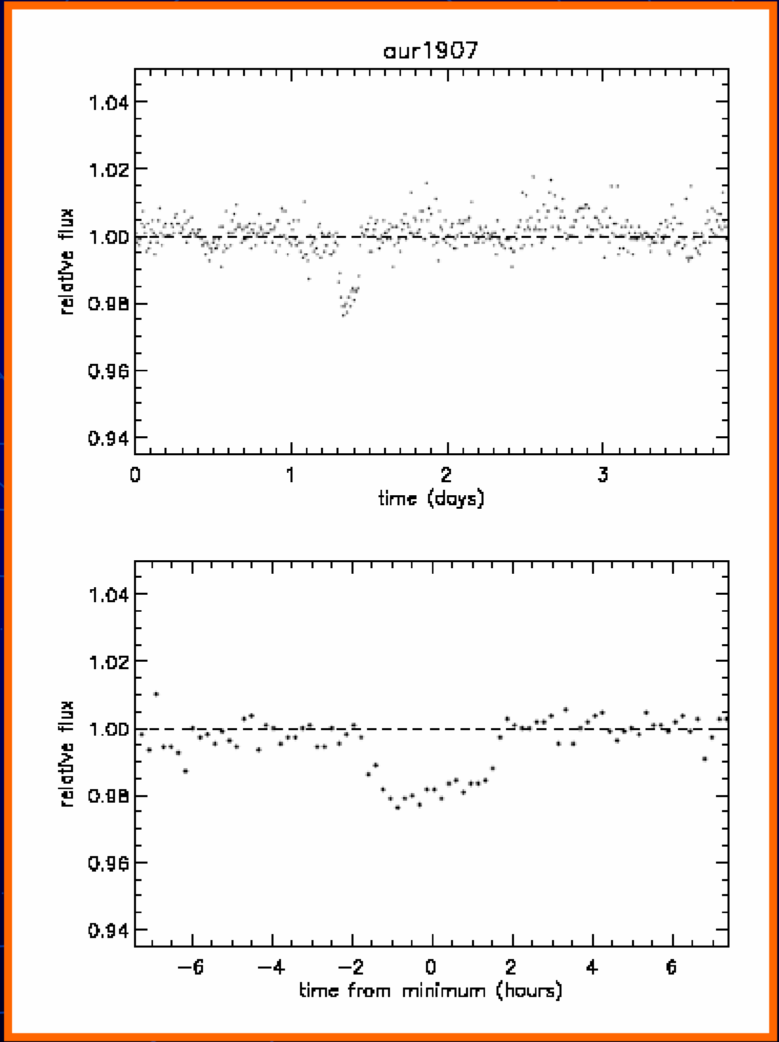


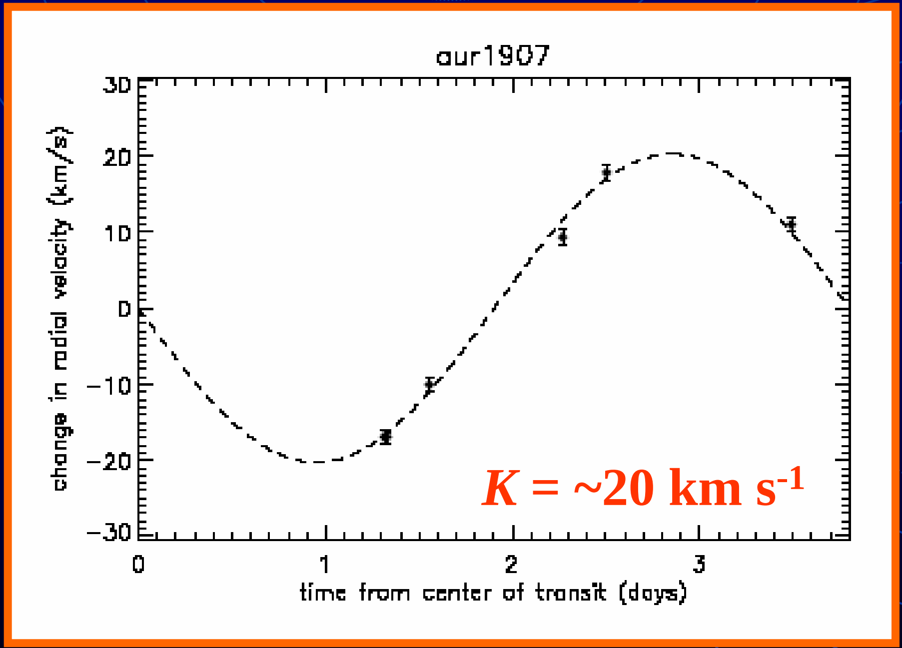
Sleuth, California

- Network of three 10-cm telescopes
- 6º × 6º field of view, ~20" PSF, *R* band
- ~10000 stars per field, with $V = 9–15$, observed for 2–3 months
- Typically 6–20 reasonably good looking candidates per field
- All candidates are carefully followed up

- Example of an M dwarf in eclipse (PSST, Lowell Obs.)
  - Period = 3.80 days
  - $V = 11.2$, $B–V = 0.2$
  - Transit depth = 1.9%
  - Flat-bottomed within the errors
  - Large RV variations

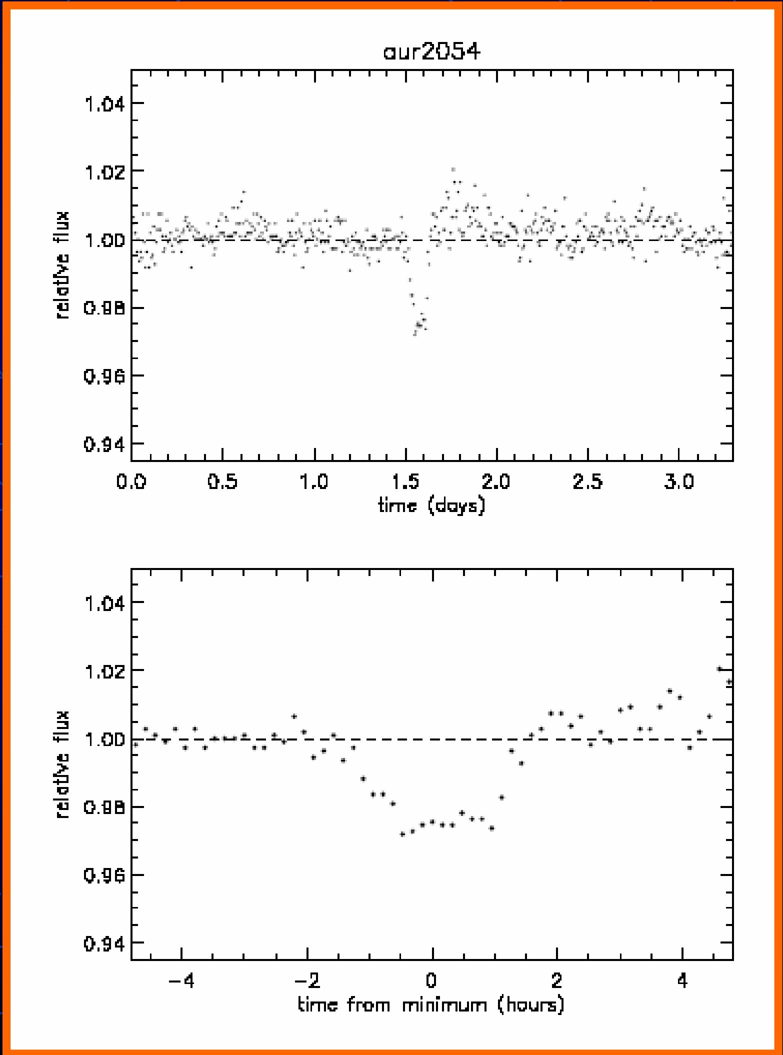
Charbonneau et al. (2004)

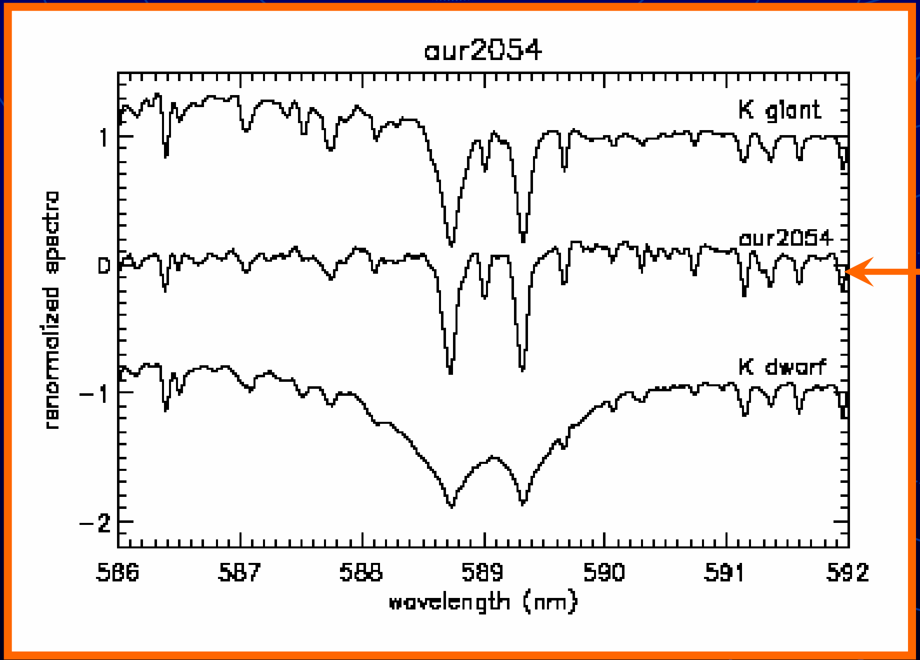




- Eclipsing binary blended with a giant star
  - Period = 3.29 days
  - $V = 11.3$, $B–V = 1.5$
  - Transit depth = 2.3%
  - Flat-bottomed within the errors
  - Sodium D lines indicate a giant

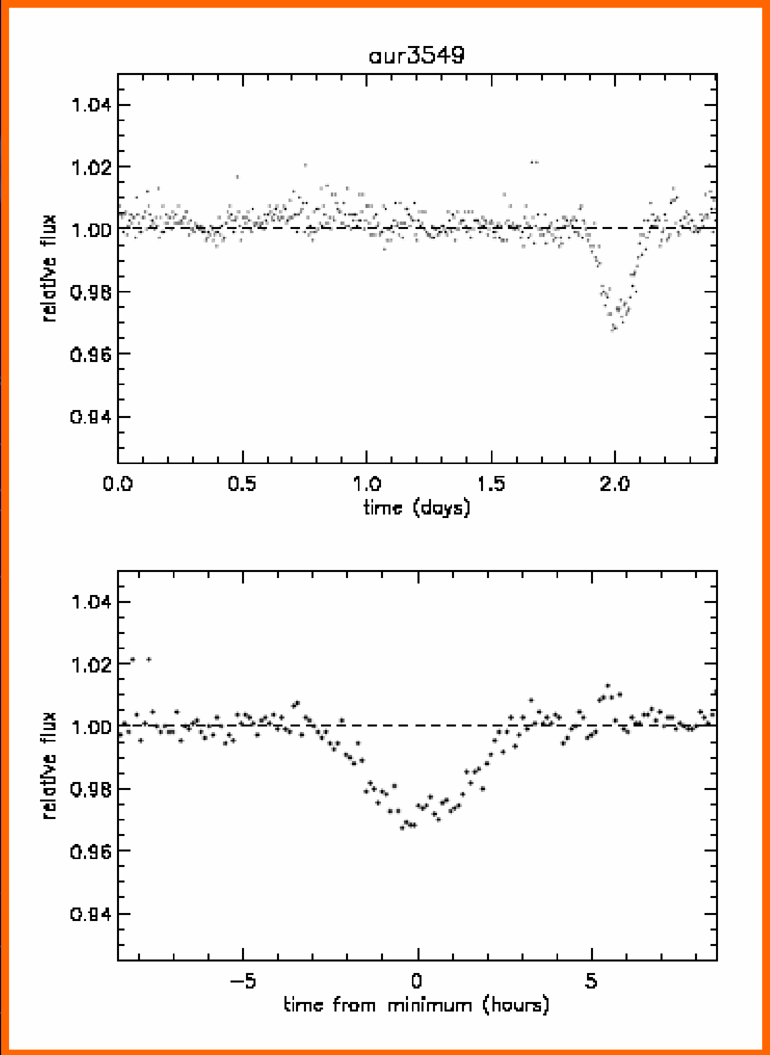
Charbonneau et al. (2004)

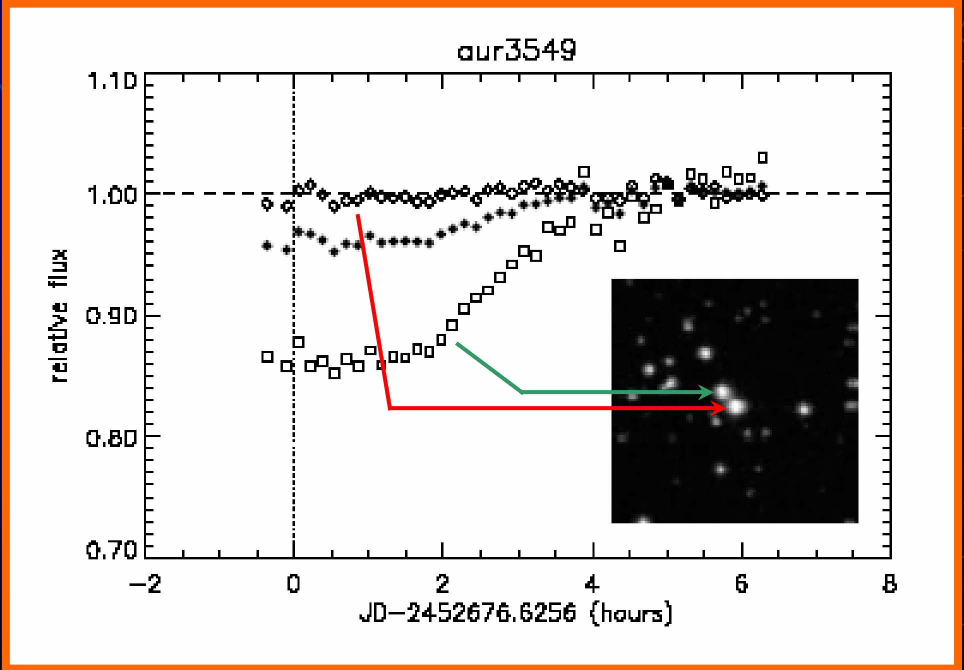




- Eclipsing binary blended with an unassociated star
  - Period = 2.41 days
  - $V = 11.6$, $B–V = 1.1$
  - Transit depth = 2.8% (deep)
  - V-shaped
  - DSS image shows companion

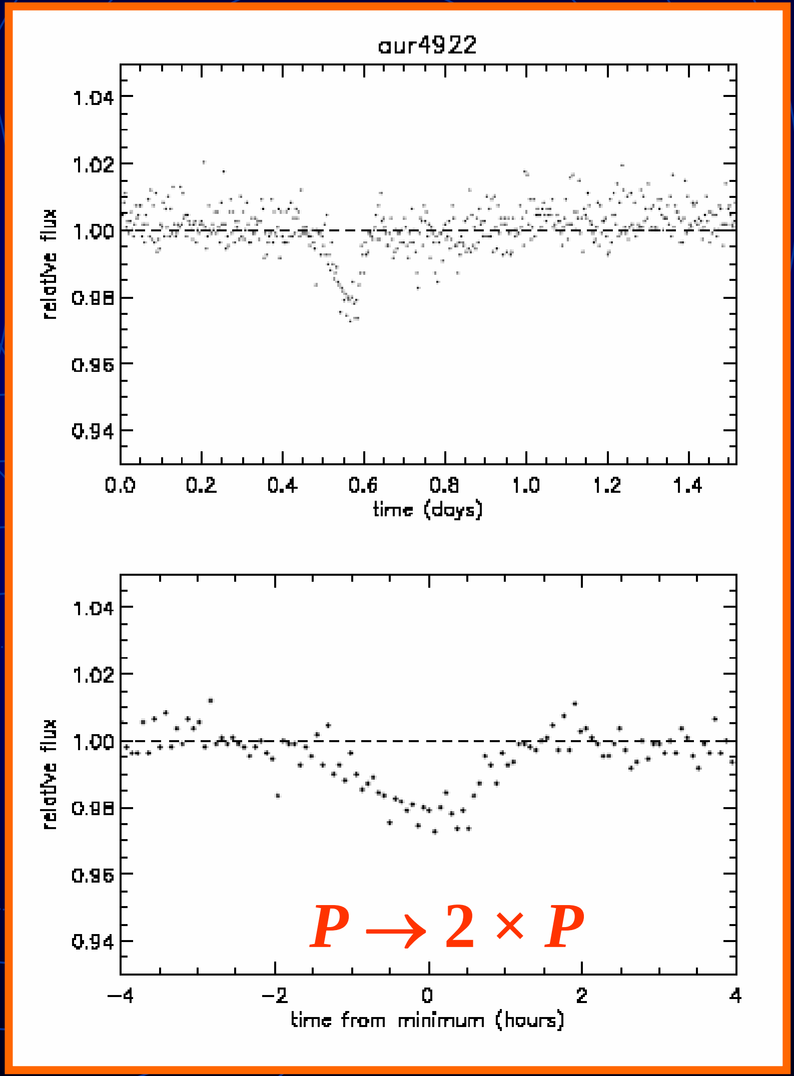
Charbonneau et al. (2004)

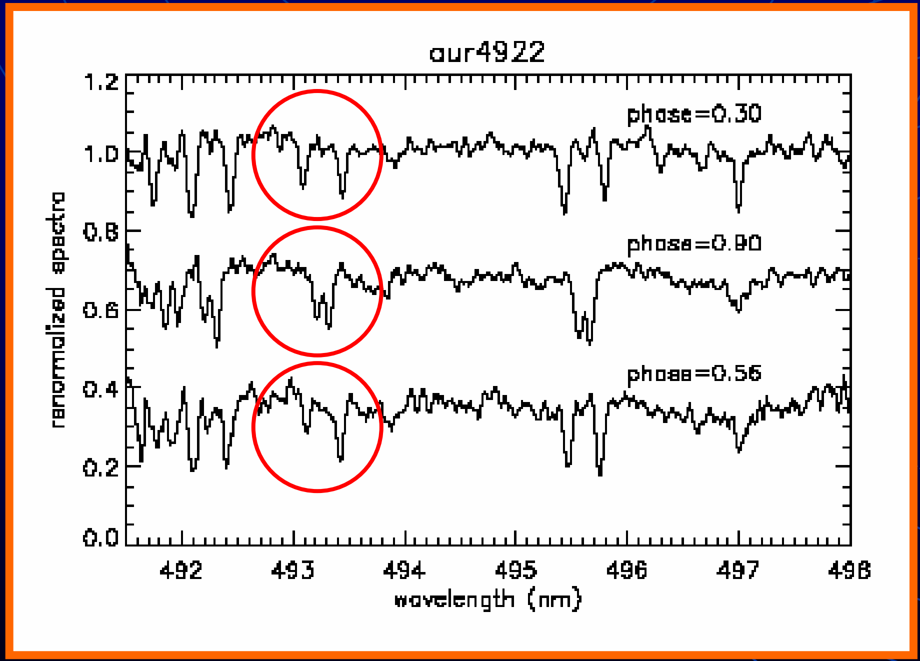




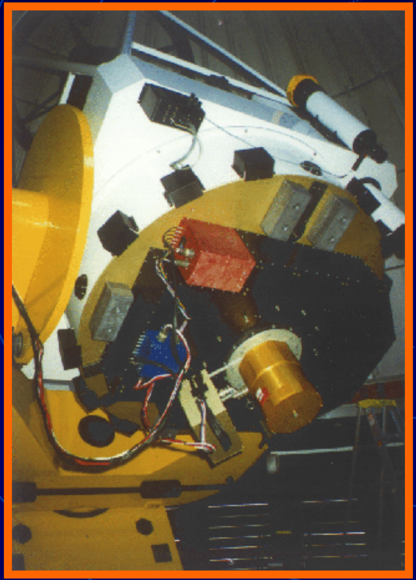
- Eclipsing binary with grazing orientation
  - Period = 1.52 days
  - $V = 12.0$, $B\text{–}V = 0.4$
  - Transit depth = 2.1%
  - V-shaped
  - Spectrum shows double lines

Charbonneau et al. (2004)





Optical Gravitational Lensing Experiment
(OGLE-III, Udalski et al. 1992)



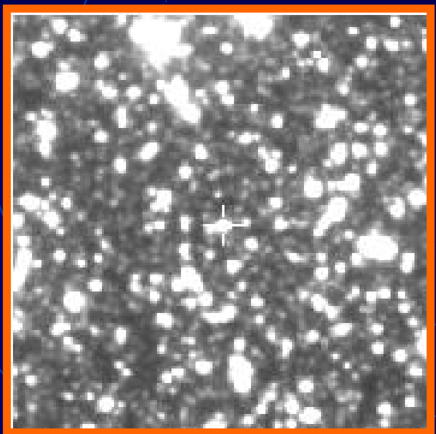
- 1.3-m Polish telescope located at Las Campanas Observatory (Chile)
- Fields near the Galactic center and Carina
- Millions of stars measured photometrically for about two months, with *V* = 15–19
- ~170 candidate transiting planets published

- 35'×35' field of view
- Mosaic of eight 2048×4096 CCDs, with 0.26" pixels
- Observations in the *I* band (8900 Å)

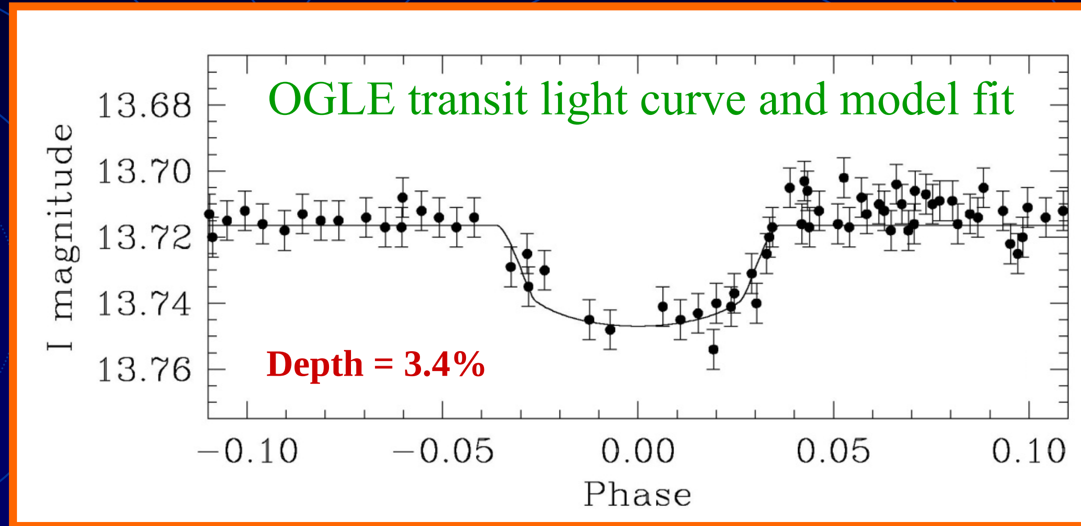
A Promising Candidate: OGLE-TR-33

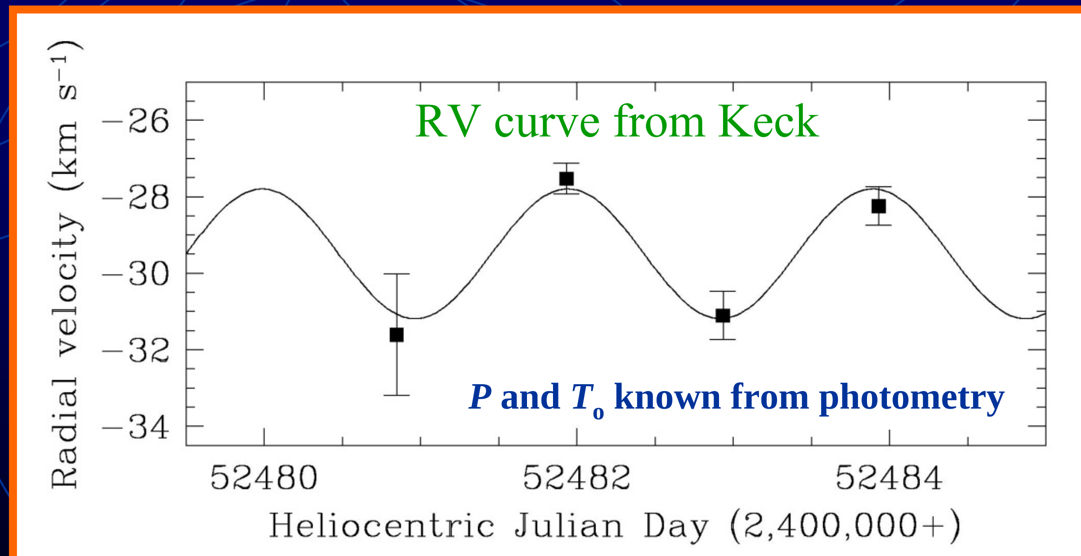
Transit candidate toward the Galactic center ($V = 14.7$)

60"



(Udalski et al. 2002)





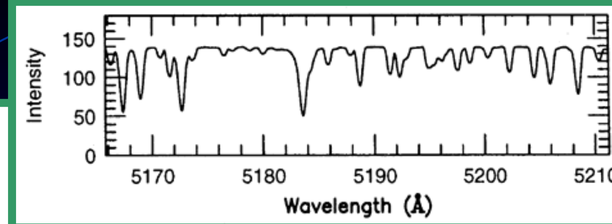
(Torres et al. 2004)

$P = 1.95$ days

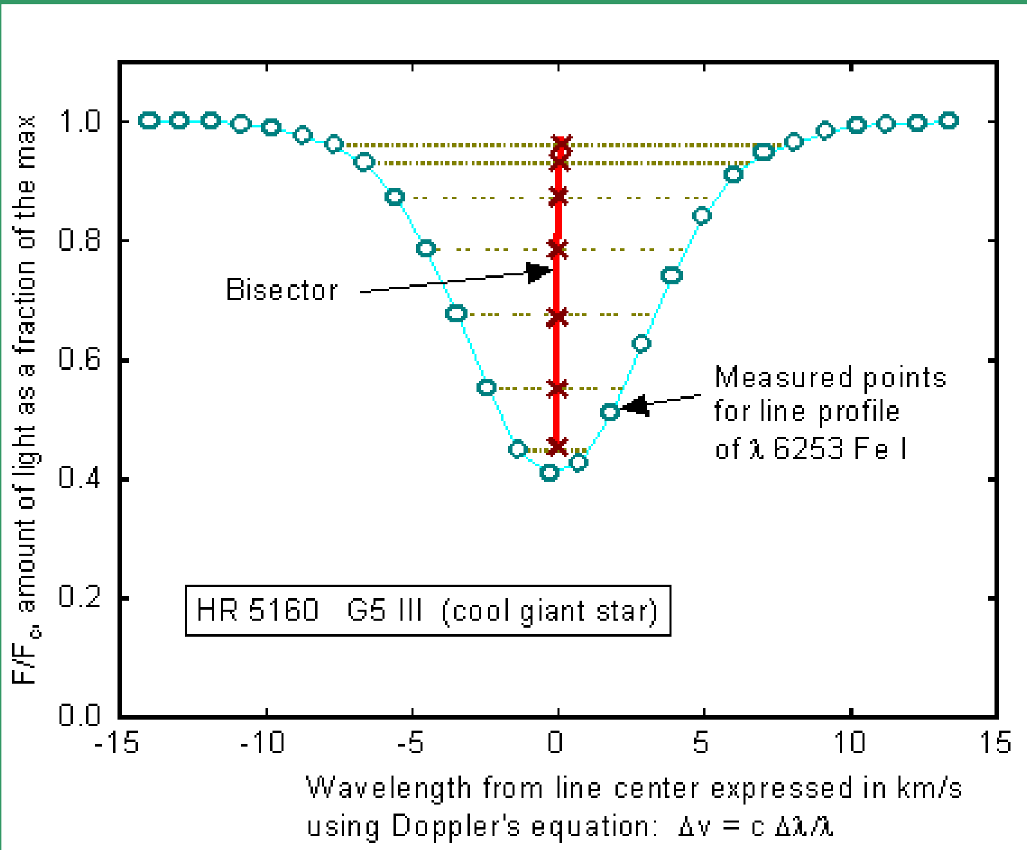
$K = 1.70 \pm 0.27$ km s^{-1}

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

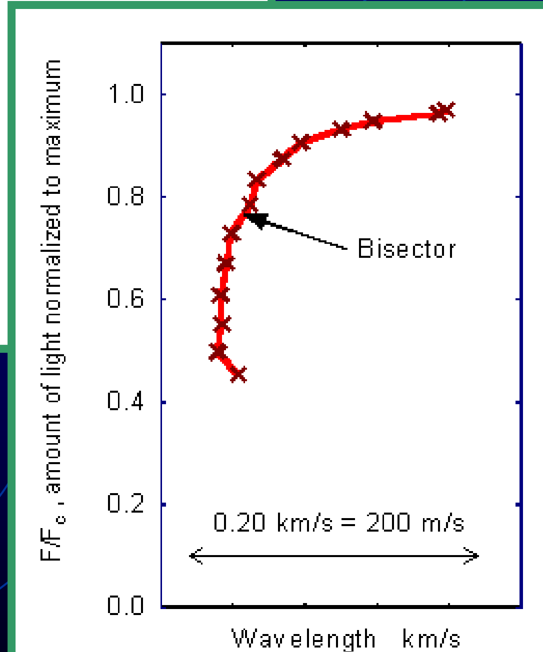
$R_p = 2.1 \pm 0.1\ R_{Jup}$



Stellar spectrum



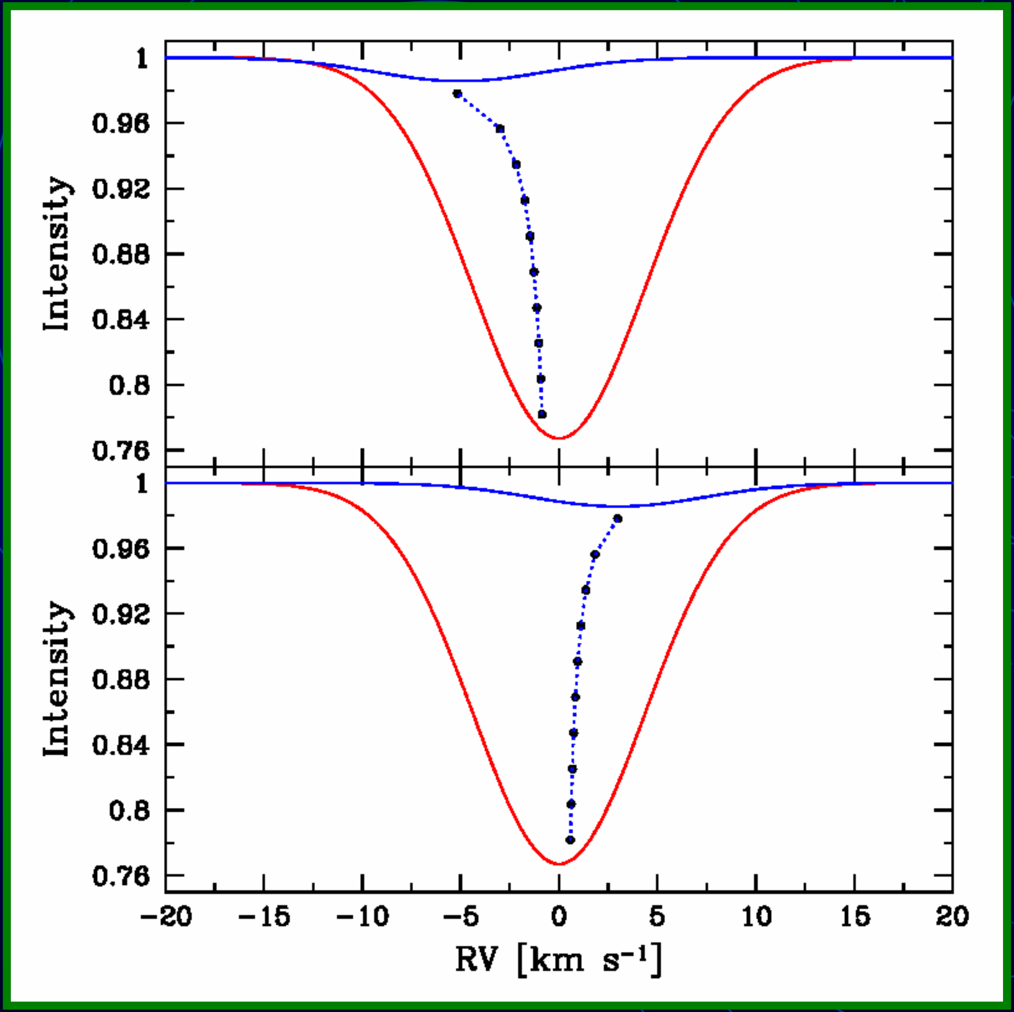
The line bisector is the locus of points made up of the midpoints of the the horizontal segments running from the left side of the profile to the right side (dashed lines).



Measuring spectral line asymmetries:

The line bisector

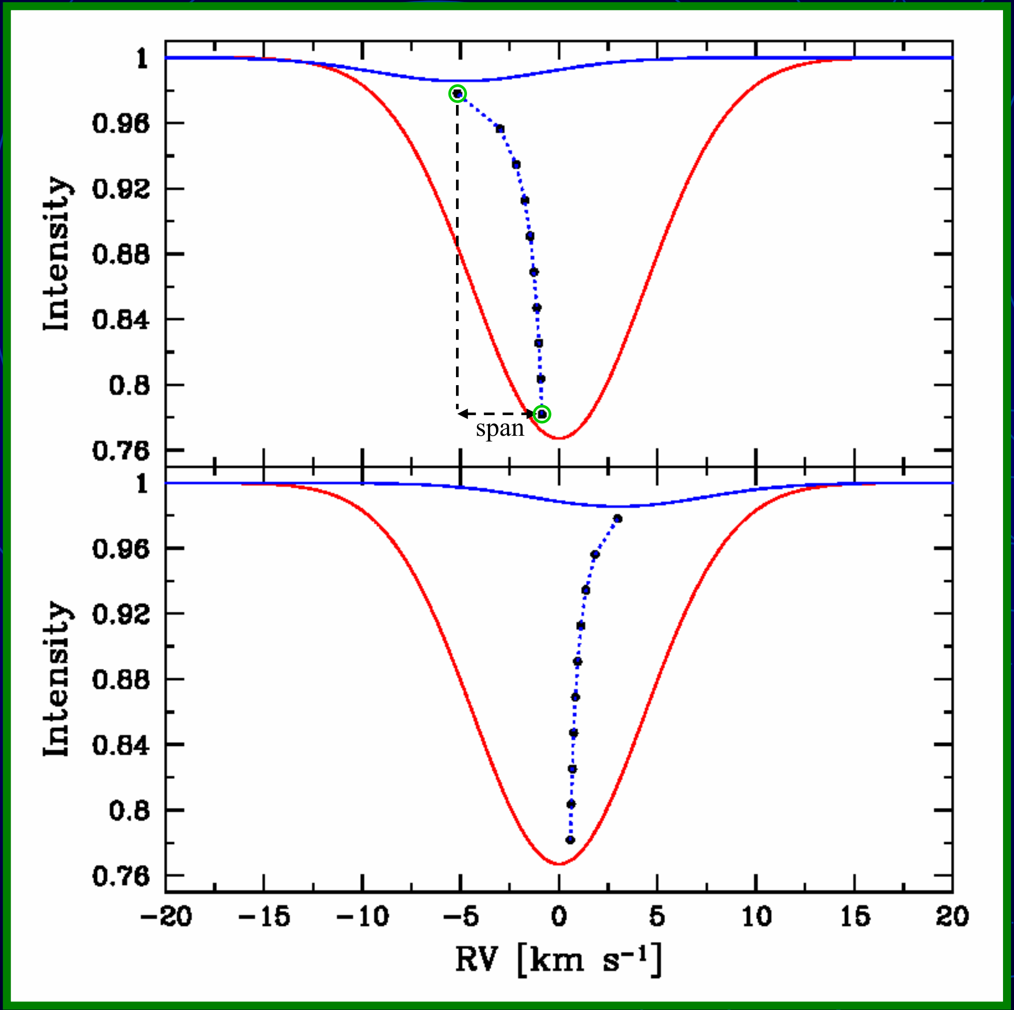
Spectral Line Asymmetries Caused by Blends



The presence of lines of another star in the spectrum (even if the contaminating star 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



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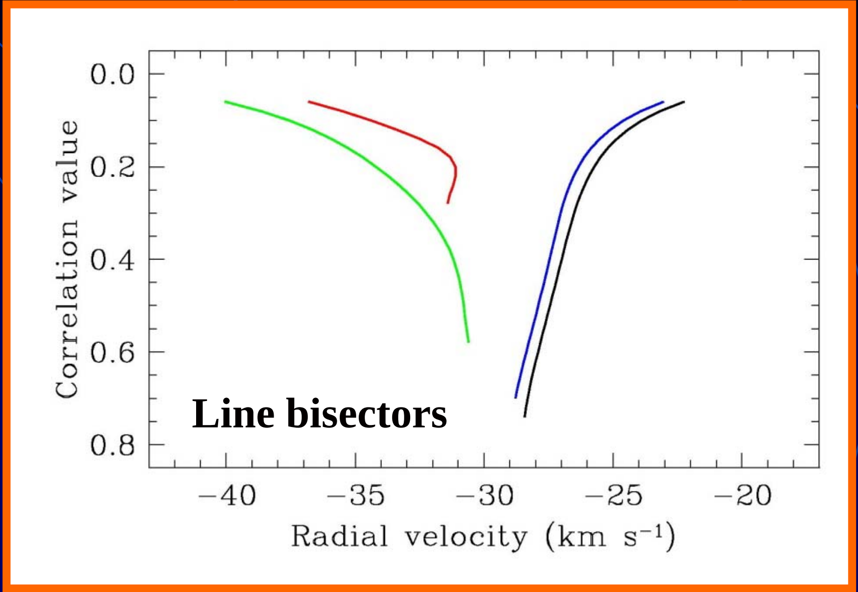
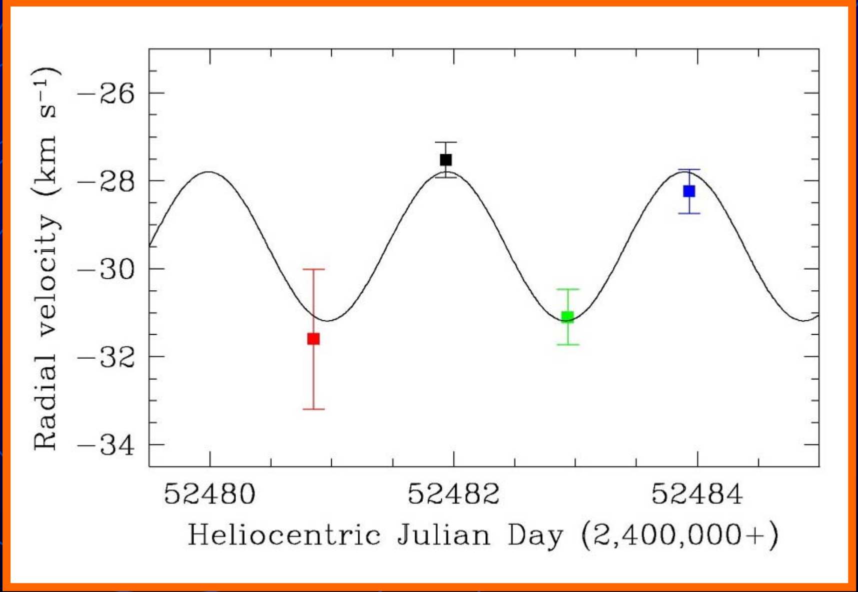
OGLE-TR-33

The spectral line asymmetries correlate with the photometric phase.

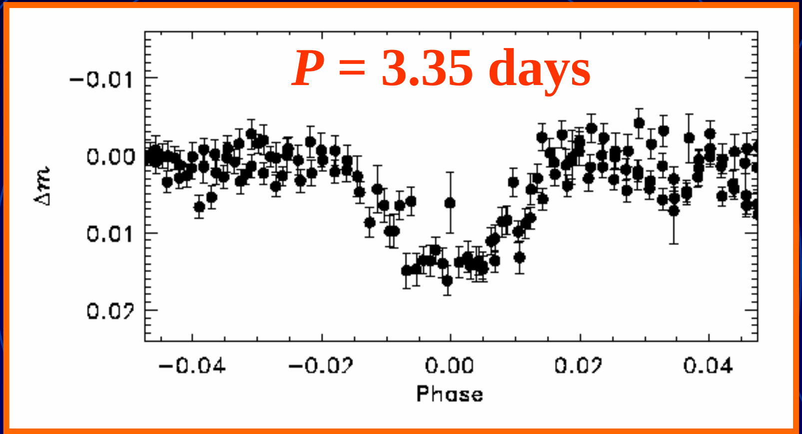
The radial velocities measured are spurious, and are caused only by the line asymmetries.

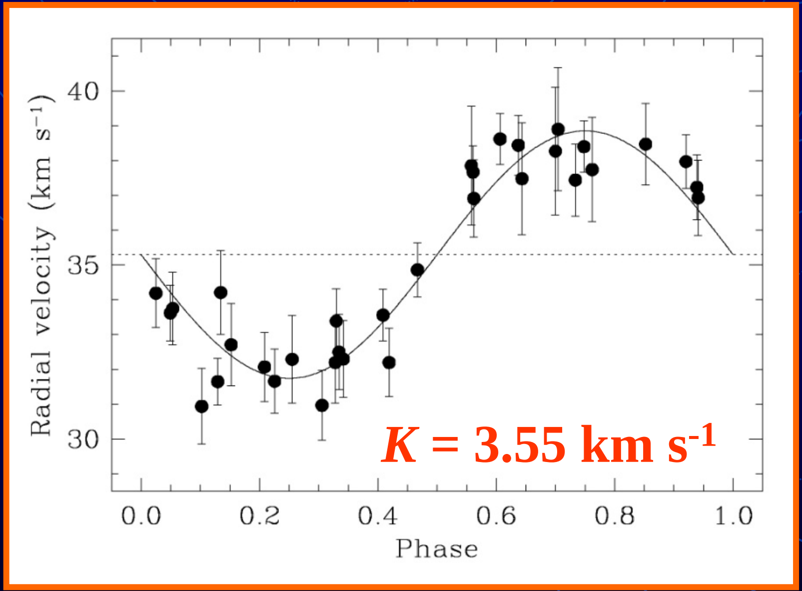
This is NOT a transiting planet





The TrES Candidate GSC 01944-02289





Mandushev et al. (2005)

R-band photometry (PSST)

$V = 10.4$, SpT = F5

Transit depth = 1.4%

Transit duration = 2.7 hours

Spectroscopic follow up (CfA)

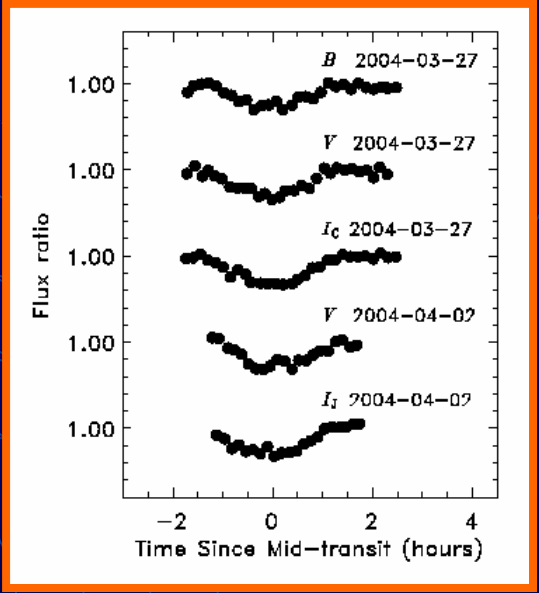
$K = 3.55 \pm 0.21$ km s $^{-1}$

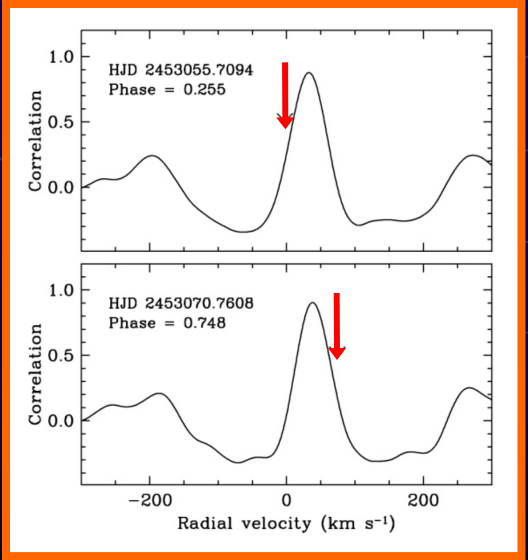
$M_p \cong 32\ M_{Jup}$ for $M_* \sim 1.3\ M_\odot$

The first transiting brown dwarf ?

Is This A Blend With An Eclipsing Binary?

- No bright companions within the 20" PSF
- No significant difference in the transit depths in *B*, *V*, and I_C





$v \sin i = 34$ km s^{-1}

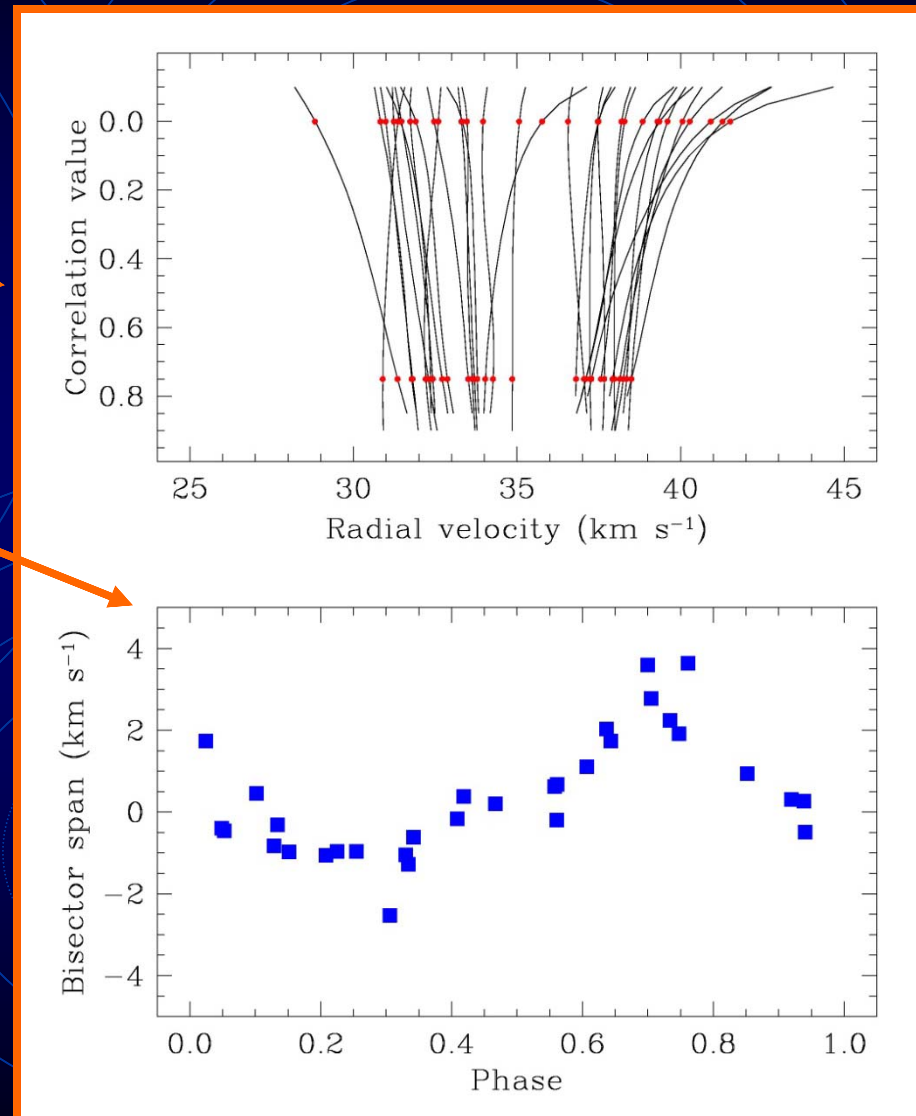
- No obvious spectroscopic evidence of another star

Line Profile Analysis For GSC 01944-02289

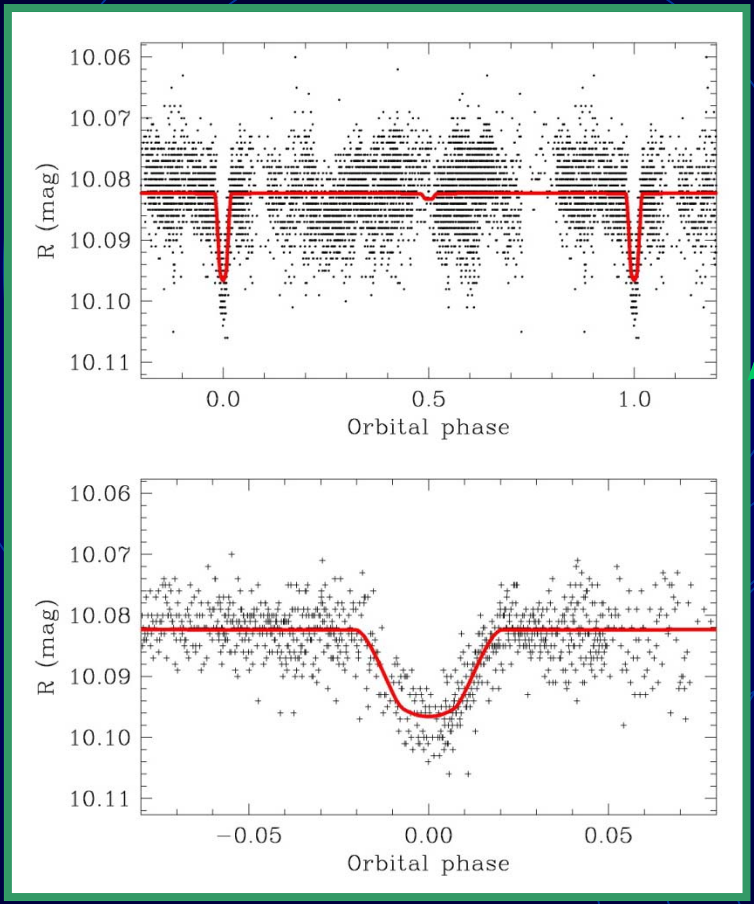
- Line bisectors show variable curvature
- Bisector spans vary with photometric phase, which is a clear indication of contaminating lines from another star

This is a blend

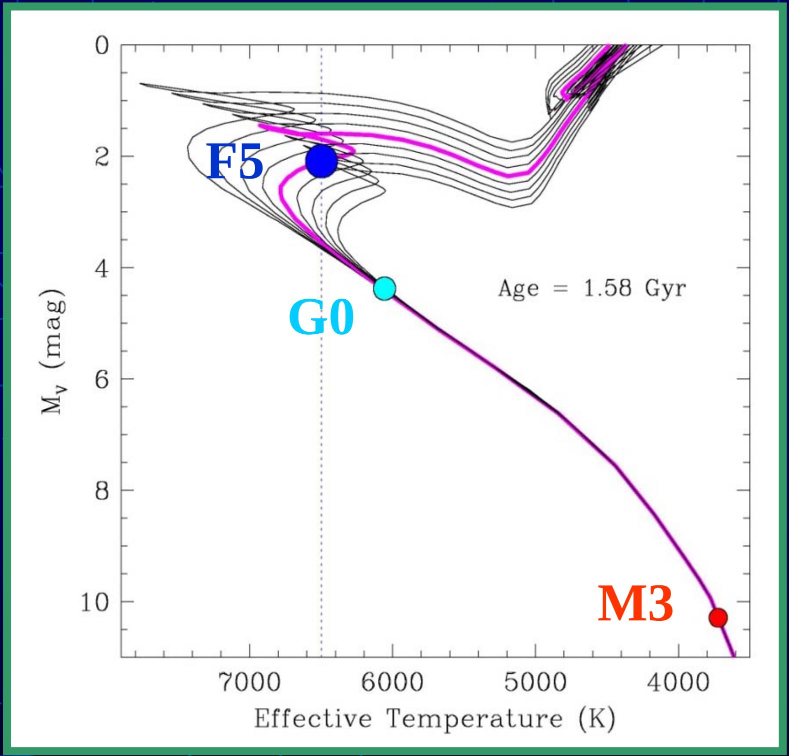
Hierarchical triple system, or chance alignment?



Detailed Light-Curve Modeling of a Blend



Eclipsing binary light curve diluted by the main star, fitted to the photometry



Stellar properties derived from model isochrones, with constraints from spectroscopy (T_{eff}, l_{EB}/l_{Star})

Inferred Properties of the Blend

Properties of the stars in GSC 01944-02289 conforming the blend.

Star	Mass ($M_\odot$)	$T_{\rm eff}$ (K)	Radius ($R_\odot$)	$\log g$ (cgs)	M_V (mag)	M_{R_C} (mag)	V (mag)	R_C (mag)
Main Star	1.68	6497	2.74	3.79	2.09	1.81	10.49	10.21
Primary of ecl. binary	1.12	6055	1.11	4.40	4.38	4.05	12.78	12.45
Secondary of ecl. binary ...	0.36	3721	0.36	4.89	10.29	9.36	18.69	17.76

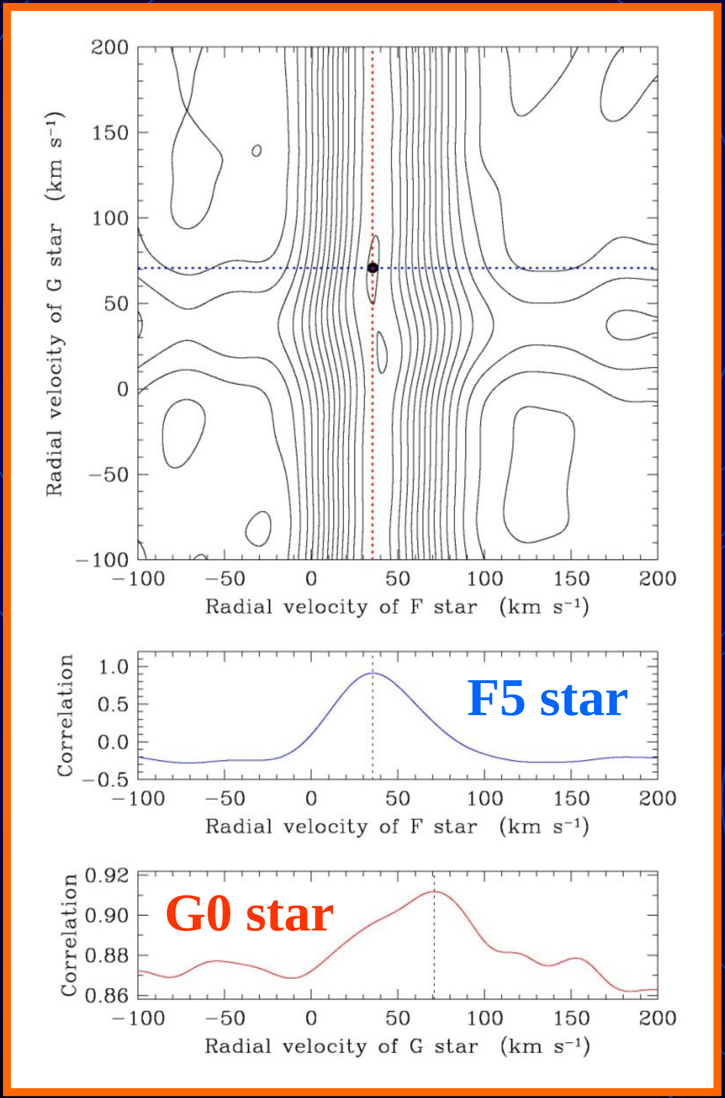
Mandushev et al. (2005)

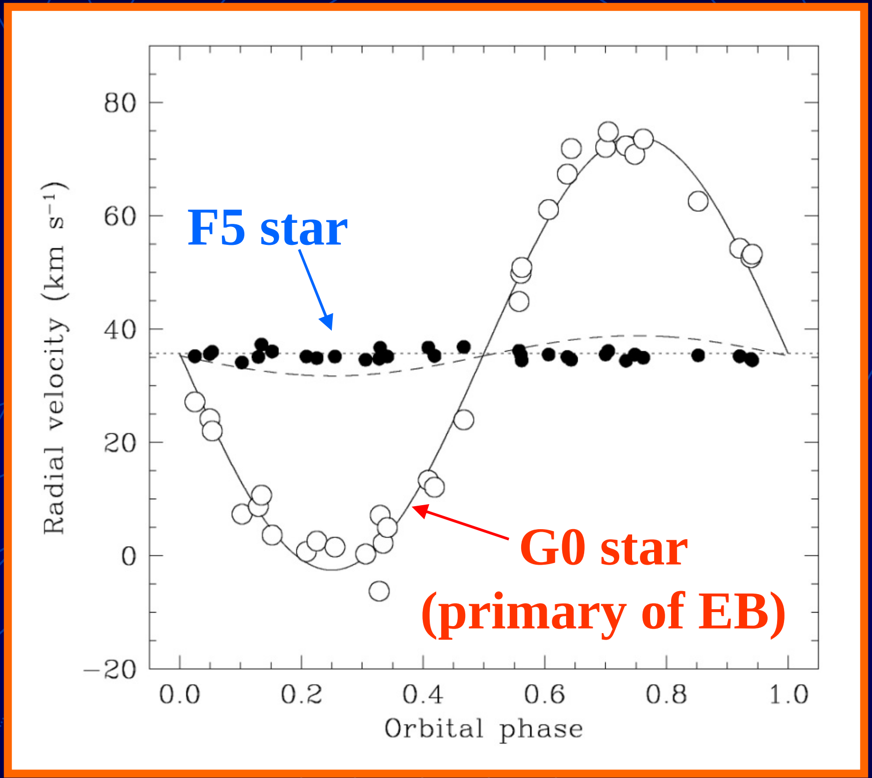
- K_{EB} = 39.4 km s^{-1}
- $v \sin i$ = 16.8 km s^{-1}
- l_{EB}/l_{Star} = 0.12

Can we detect the lines of the eclipsing binary in the spectra, and measure its velocity?

Direct detection of the eclipsing binary with TODCOR (Zucker & Mazeh 1994)

Mandushev et al. (2005)

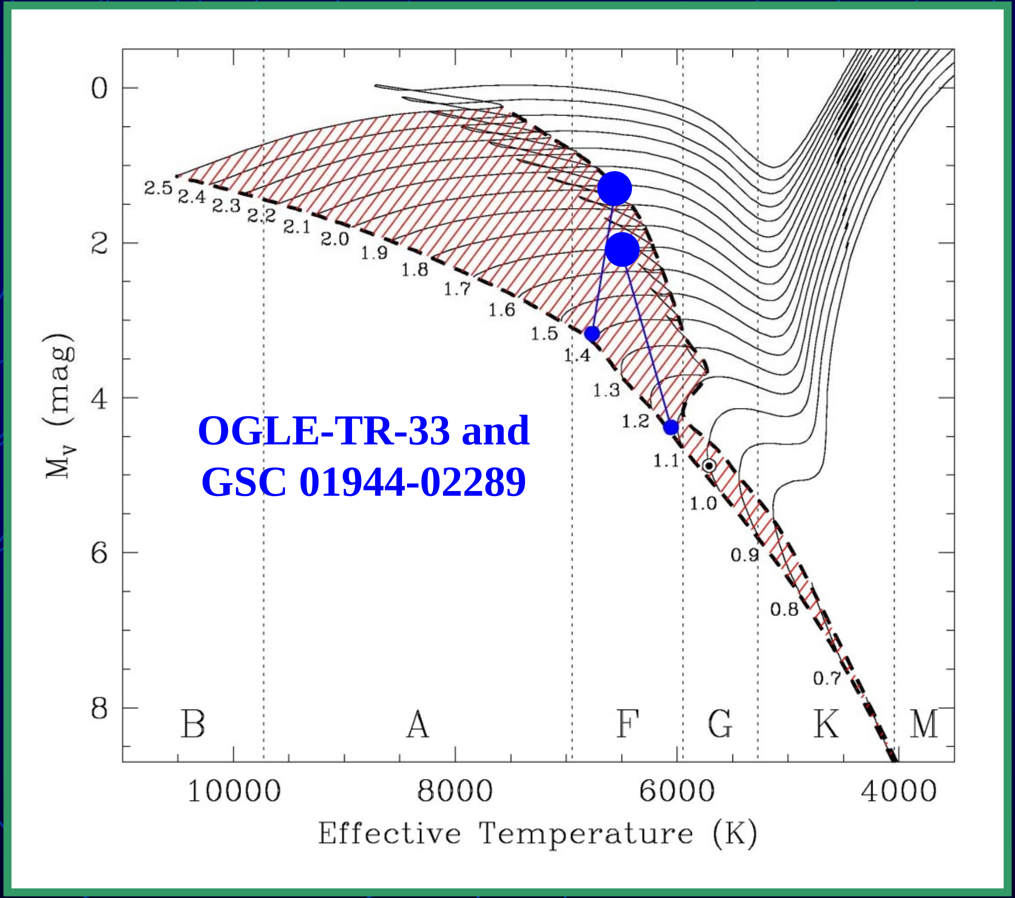




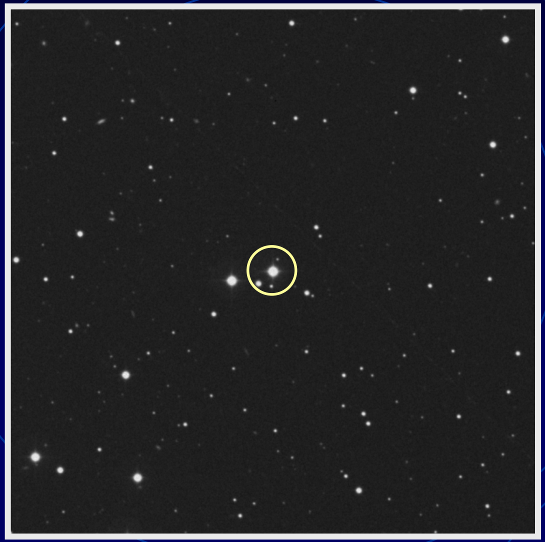
- $K = 38.24 \pm 0.80$ km s^{-1}
- $l_{EB}/l_{Star} = 0.12 \pm 0.02$

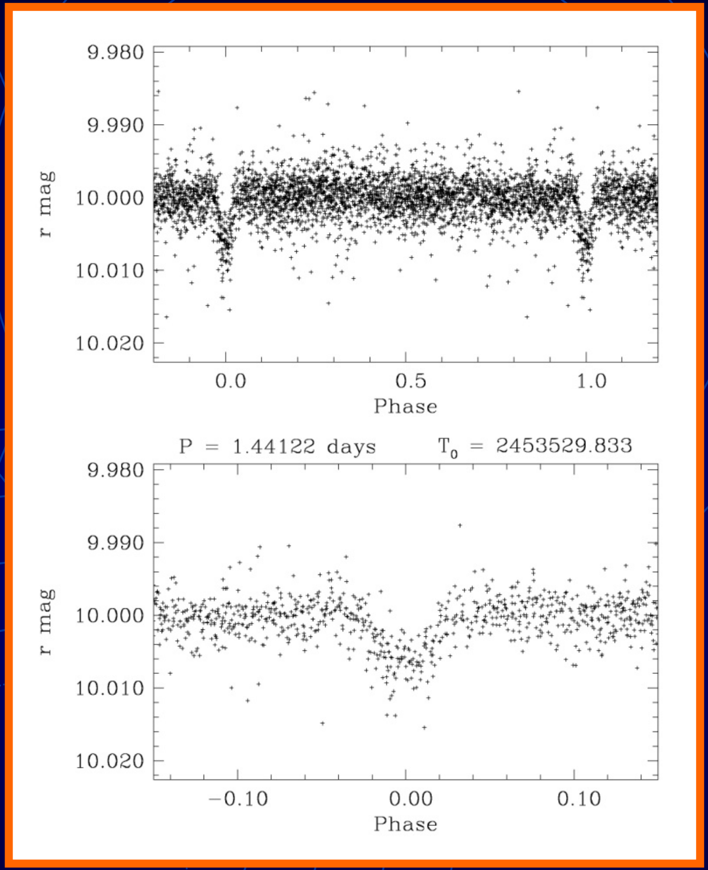
Conclusion: F Star Candidates Are Tricky

- F stars can be intrinsically brighter, making it easier to hide an eclipsing binary
- <u>They don't always show λ-dependent transit depth</u>, which would otherwise give away the blend
- Rotational broadening can mask signs of another star in the spectrum
- F stars are very common in magnitude-limited transit surveys



The Case of GSC 03885-00829





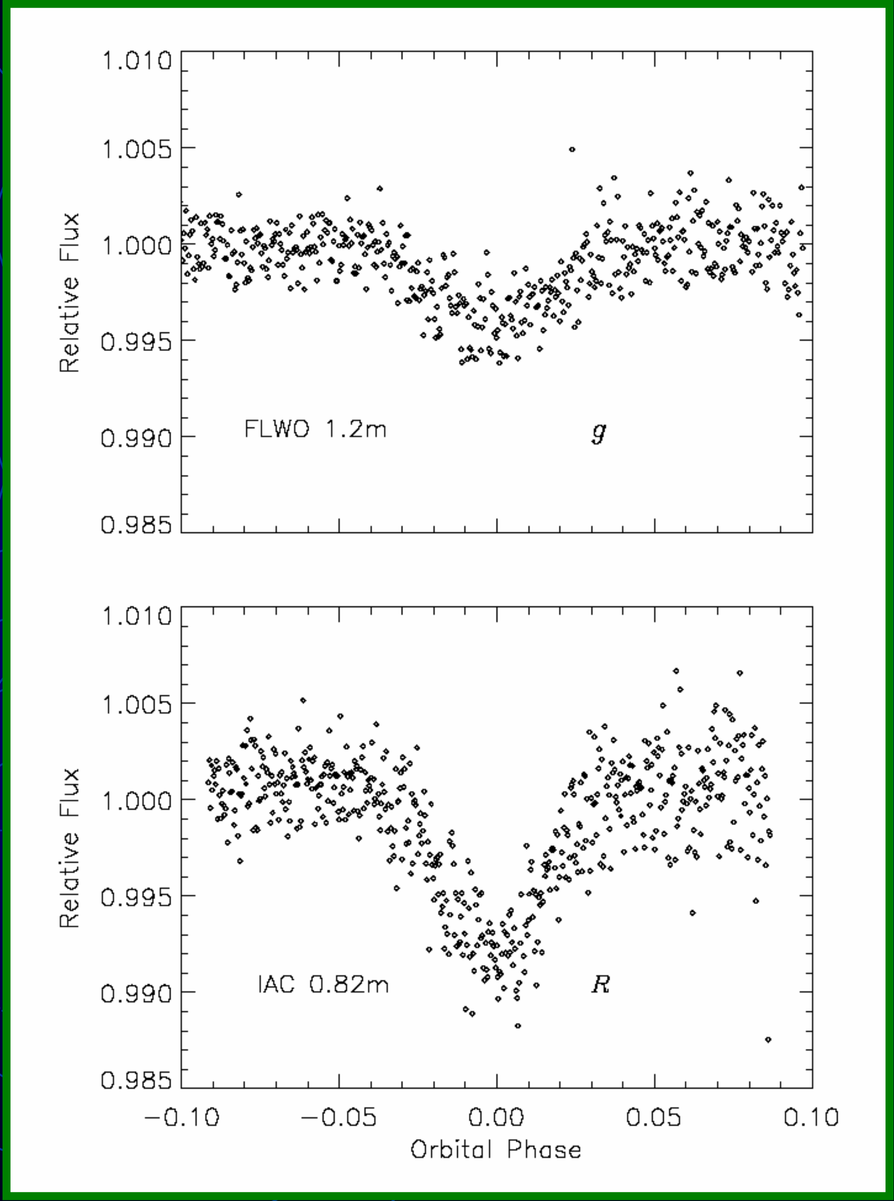
- V = 10.46 , spectral type late F
- Nearly 16,000 measurements
- P = 1.44122 days
- Transit depth = 0.006 mag in R , duration = 1.4 hours
- A Saturn-sized transiting planet?

Follow-up

- Large proper motion suggests a nearby dwarf
- Spectroscopic observations indicated no RV variation ($\sigma = 0.28$ km s^{-1})
- Photometric measurements in B, V, g, R_C, and I_C showed a wavelength dependence to the transit depth

A likely blend

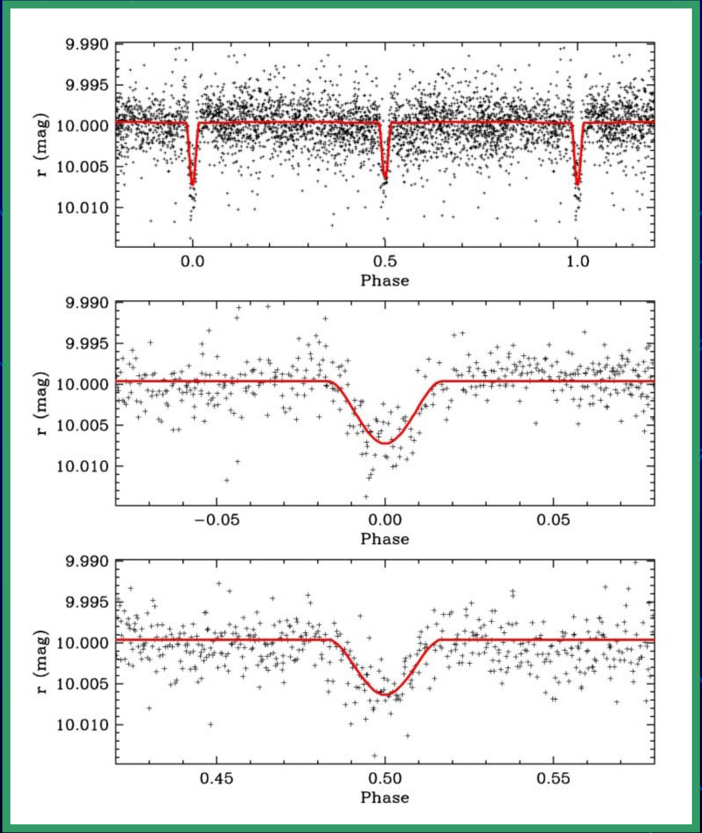
O'Donovan et al. (2005)

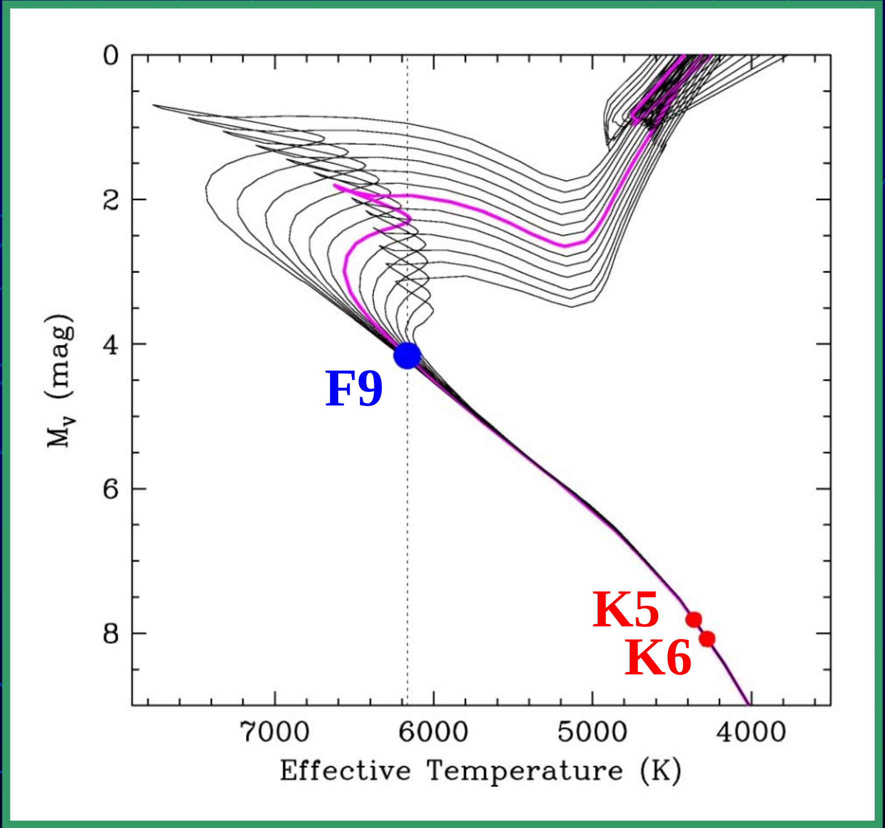


Modeling the Blend

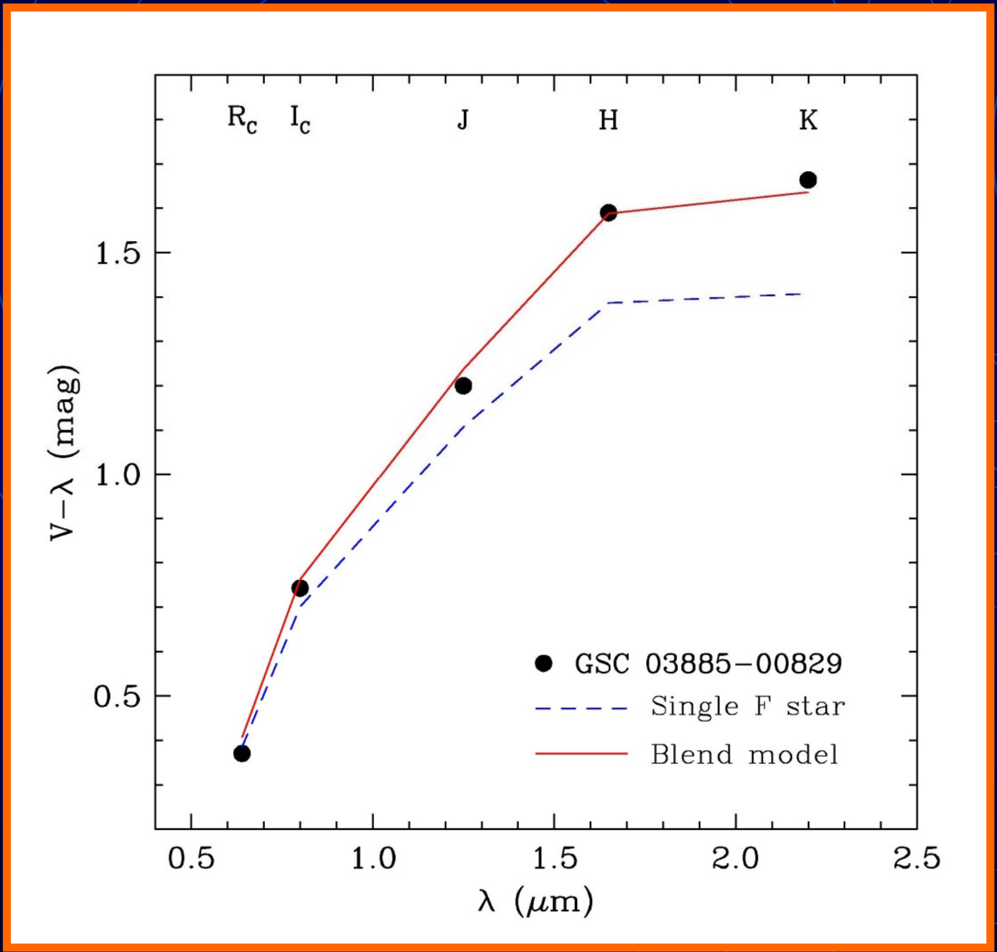
- Careful modeling of the light curve of the system as a blend (sum of 3 stars) gave a good fit to the transit depth, but a slightly shorter duration than observed
- Secondary eclipse negligible (and none observed)
- Fit predicted an eclipsing binary (early K + late M) bright enough to be detected in our spectra (15% of the light of the main F star)
- Inspection of the spectra revealed no sign of another set of lines
- Inconsistency: λ dependence of transit depth suggests a blend, but light curve modeling is unsatisfactory

- Modeling with twice the period works much better, and is consistent with all observations
- Model predicts eclipsing binary composed of two mid-K stars, producing nearly equal eclipses



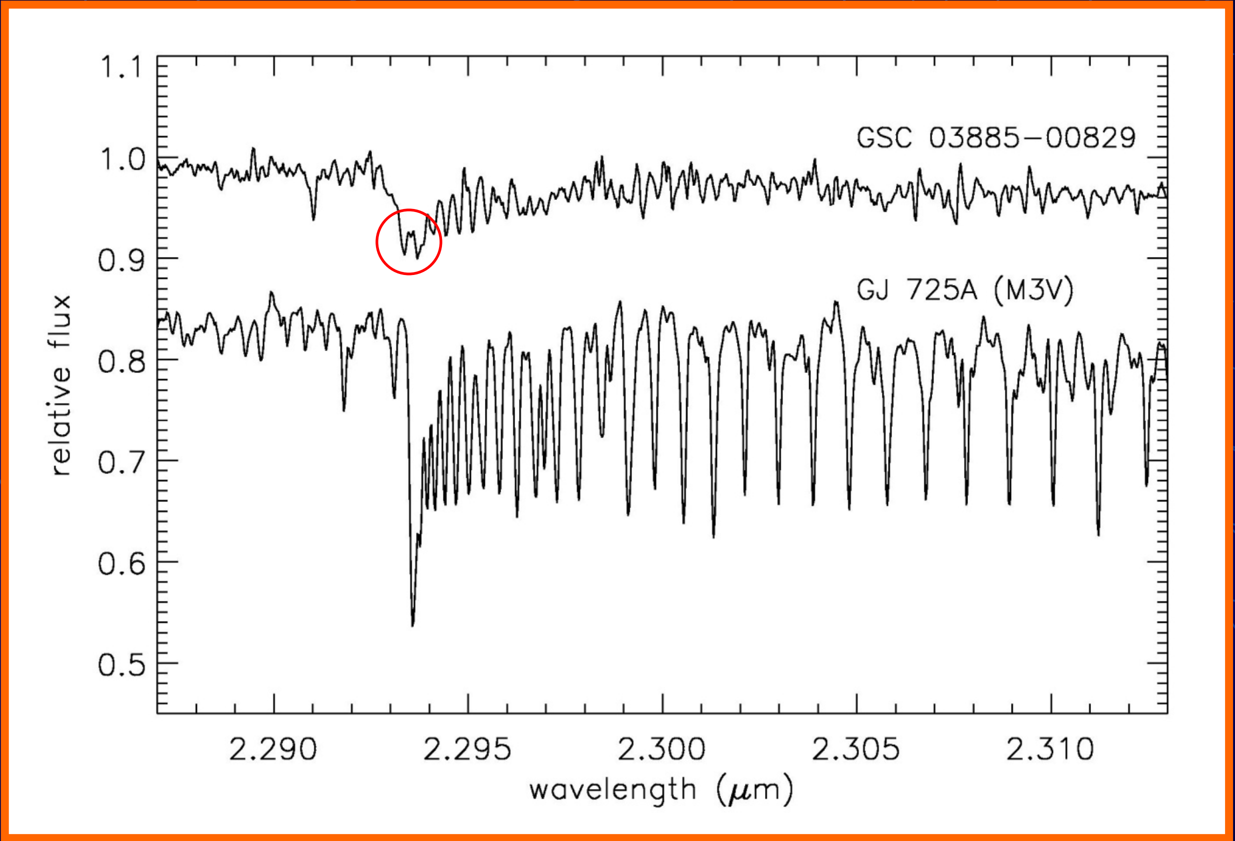


Checking the Blend Model: Infrared Excess



- Observed colors are redder than those of a single F star
- Blend model provides excellent agreement with the measured infrared excess, as a function of λ

Direct Evidence of the Eclipsing Binary



CO bandhead present
⇒ K stars are visible

Hint of double lines

High-resolution *K*-band spectrum with NIRSPEC on the Keck telescope

Summary

- Detection of extrasolar giant planets through transits is now a very successful technique
- Many surveys underway (from the ground and space), others completed, others to start soon
- Follow-up (both photometric and spectroscopic) is essential for confirmation of candidates
- False positives dominate in any sample of transit candidates
- These can usually be recognized with careful investigation. This will become important for space missions such as Kepler