Detecting and Measuring Transit and Planet-Star Radius Ratio of Exoplanet HD 189733 b

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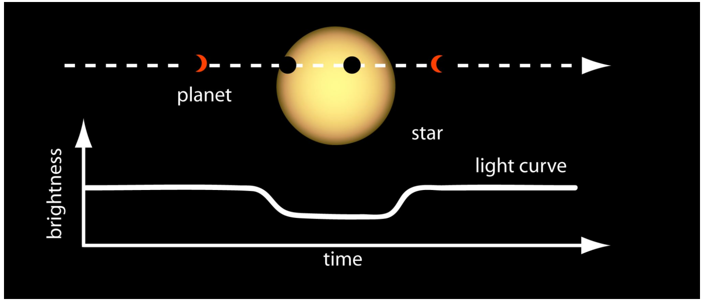
Background and Introduction

- Exoplanets: planets orbiting other stars
- Transit: detection of exoplanet when it passes in front of star and blocks light
- Observation date: 31 August – 01 September 2022
- Objectives
  - Detect transit of exoplanet HD 189733 b
  - Measure transit depth
  - Calculate planet-to-star radius ratio



Overview schematic of exoplanet transit [NASA Ames]

Target Selection

HD 189733

- RA = $20^h\ 00^m\ 43.713^s$, Dec = $+22^o\ 42'\ 39.073''$
- BY Draconis Variable
- Spectral type K2V
- Bright star: 7.648 (V) or 8.578 (B) app mag
- One of the largest exoplanet transit dips: 2.5% [1]
- Frequently referenced

HD 189733 properties obtained from SIMBAD

[1] Cauley, P. W., Redfield, S., & Jensen, A. G. 2017, The Astronomical Journal, 153, 217, doi: 10.3847/1538-3881/aa6a15

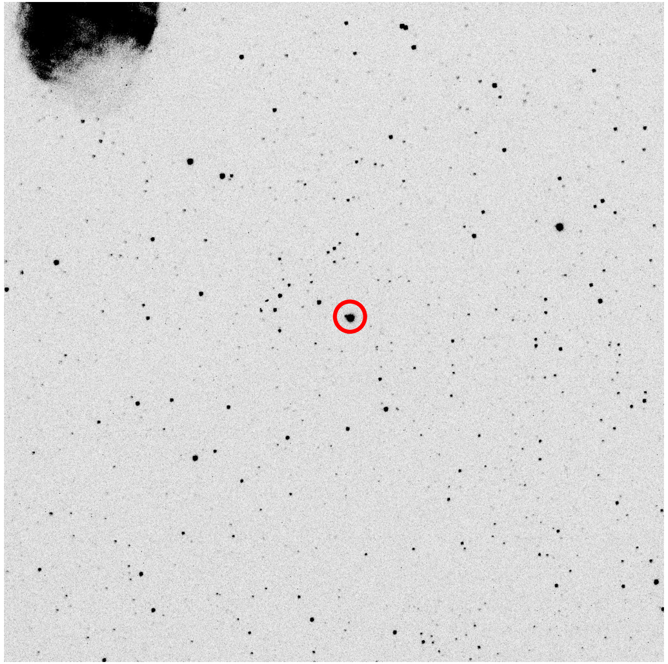
Data Acquisition

Equipment

- Mt. Stony Brook 14-inch telescope
- Hα filter + STL-1001E CCD camera

Procedure

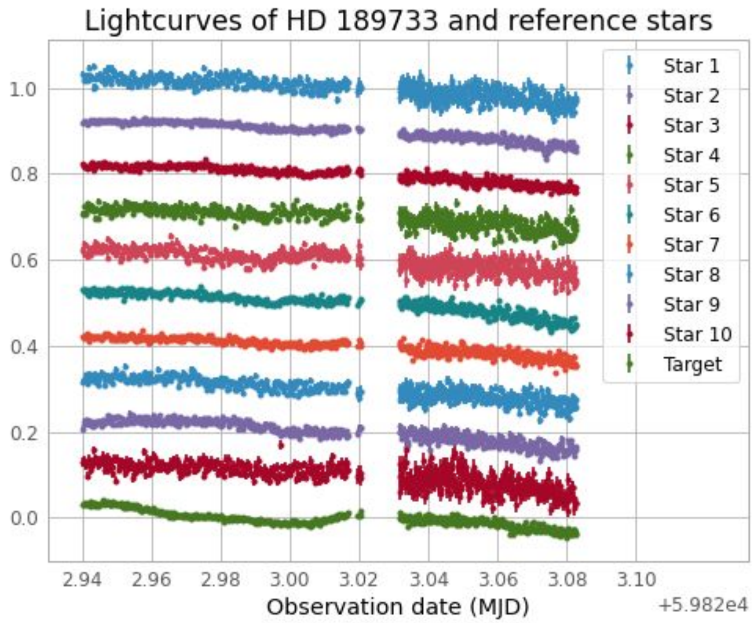
- 1 observing run on Aug 31 - Sep 01
- ~600 images of target star
- Exposure times
    - Early: 30s
    - Middle: 10s
    - Late: 12s
- Take dark and flat frames, apply corrections to science images



A representative calibrated science image after dark and flat corrections. HD 189733 is indicated in red.

Data Reduction

- Dark and flat corrections + astrometric coordinate solving
- Source extraction
  - Detect stars in each science image
- Aperture photometry
  - Extract counts of target + 10 reference stars, divide by exposure time to get flux
  - Normalize stars by their average flux
  - Plot normalized flux vs time
- We observe: atmospheric seeing causes reference star fluxes to decrease over time



Lightcurves of HD 189733 and reference stars.

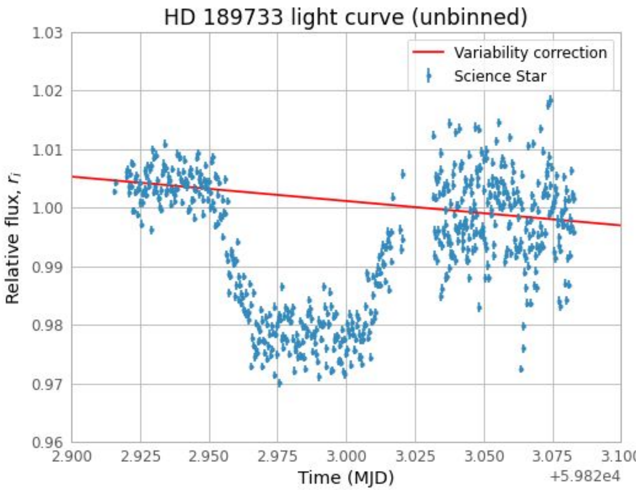
Data Reduction

Correcting target star for seeing

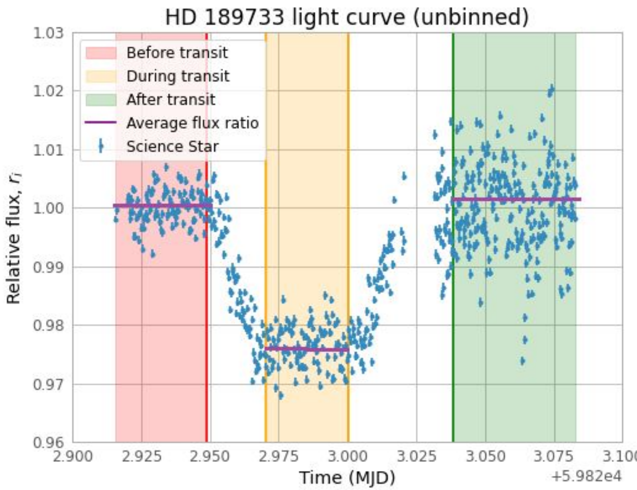
- Create a mean reference star lightcurve
- For each image: Calculate mean flux of all 10 reference stars + error on mean
  - Each star flux weighted on noise
  - Reduces statistical uncertainty of star fluxes and systematic uncertainty from star variabilities
- Divide target star lightcurve by mean reference star lightcurve
  - Accounts for atmospheric seeing changes

Results

- HD 189733 is a BY Draconis variable star
  - Correct with linear fit to data before and after transit



Lightcurve without variability correction. Luminosity of HD 189733 decreases through observing run.



Lightcurve with variability correction and fitted means before, during, and after transit

Results

Mean flux calculated with linear fit to binned data

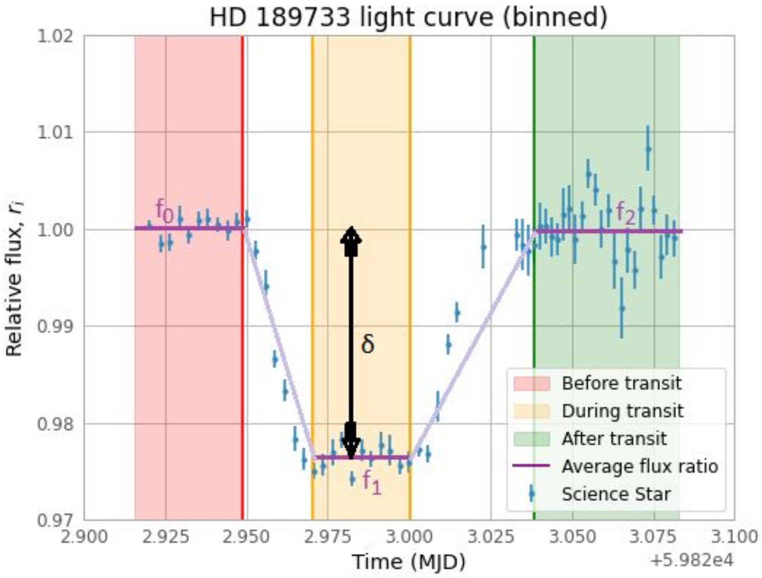
- Flux before transit: f_0 = 1.0001 ± 0.0009
- Flux during transit: f_1 = 0.9766 ± 0.0015
- Flux after transit: f_2 = 1.0001 ± 0.0012

Transit depth, δ

- Difference between mean in-transit flux f_1 and mean baseline flux ½(f_0+f_2) [1]

$$\delta = \frac{1}{2}(f_0 + f_2) - f_1$$

- δ = 2.3500 ± 0.0017%



Lightcurve binned in 10-point intervals.

[1] Winn, J. N. 2010, Transits and Occultations, arXiv, doi: 10.48550/ARXIV.1001.2010

Analysis and Discussion

Transit detection

$$\frac{|f_1 - \frac{1}{2}(f_0 + f_2)|}{\sqrt{\sigma_{f_1}^2 + \frac{1}{4}(\sigma_{f_0}^2 + \sigma_{f_2}^2)}} = \frac{|0.9766 - 1.0001|}{\sqrt{0.0015^2 + \frac{1}{4}(0.0009^2 + 0.0012^2)}} = 13.82\sigma$$

- Detection significant (13.82σ > 3σ)

Transit depth

- Experimental: δ = 2.3500 ± 0.0017%
- Literature: δ = 2.40% [2]
- Agrees with literature (0.29σ < 3σ)

[2] Cauley, P. W., Redfield, S., & Jensen, A. G. 2017, The Astronomical Journal, 153, 217, doi: 10.3847/1538-3881/aa6a15

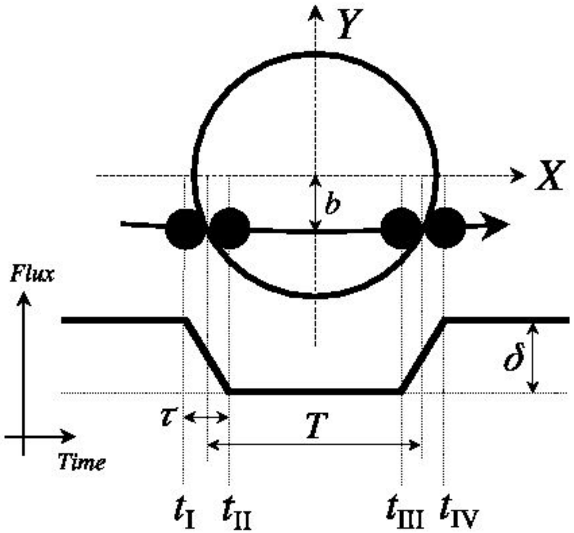
Analysis and Discussion

Planet-to-star radius ratio R_p/R_* [1]

- Planet disk crosses star disk during transit
- Transit depth: proportion of star flux covered by planet, or ratio of disk areas

$$\delta = \frac{R_p^2}{R_*^2}$$

- Result: $R_p/R_* = 0.153 \pm 0.006$



A diagram showing the calculation of transit depth δ from baseline and transit fluxes. The transit depth is equivalent to planet-to-star area ratio. [2]

[1] 2022, Caltech. https://exoplanetarchive.ipac.caltech.edu/docs/transit/transit algorithms.html
[2] Winn, J. N. 2010, Transits and Occultations, arXiv, doi: 10.48550/ARXIV.1001.2010

Analysis and Discussion

Planet-to-star radius ratio

- Experimental: $R_p/R_* = 0.153 \pm 0.006$
- Literature: $R_p/R_* = 0.155$ [1]
- Agrees with literature ($0.33\sigma < 3\sigma$)

[1] Sing, D. K., Désert, J.-M., Lecavelier des Etangs, A., et al. 2009, A&A, 505, 891, doi: 10.1051/0004-6361/200912776

Sources of error

Systematic error

- Telescope focus
  - Photometric aperture may contain too few or too many pixels of target star
  - Star became brighter later in night possibly due to focus improving
  - Compensate by reducing exposure time 30s to 12s, to keep pixel counts in linear regime
- Variability in star
  - Divide by linear fit to baseline flux

Statistical error

- CCD thermal noise
- Seeing
  - Decreases SNR
  - Reduces flux when star is lower
  - Correct for this by normalizing over mean reference star lightcurve
- Data is Poisson
  - Uncertainty in each data point

Conclusions

Results

- Successful detection of transit 13.82σ > 3σ
- Transit depth 2.3500 ± 0.0017% agrees with literature (0.29σ < 3σ)
- Planet-to-star radius ratio 0.153 ± 0.006 agrees with literature (0.33σ < 3σ)

Sources of Error: telescope focus, stellar variability, seeing, CCD noise

Future investigations

- Based on planet-to-star radius ratio and star radius, calculate HD 189733 b radius