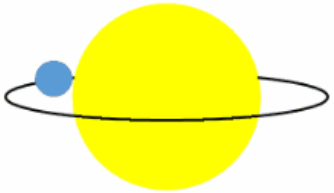
Exoplanet Observing Techniques



by
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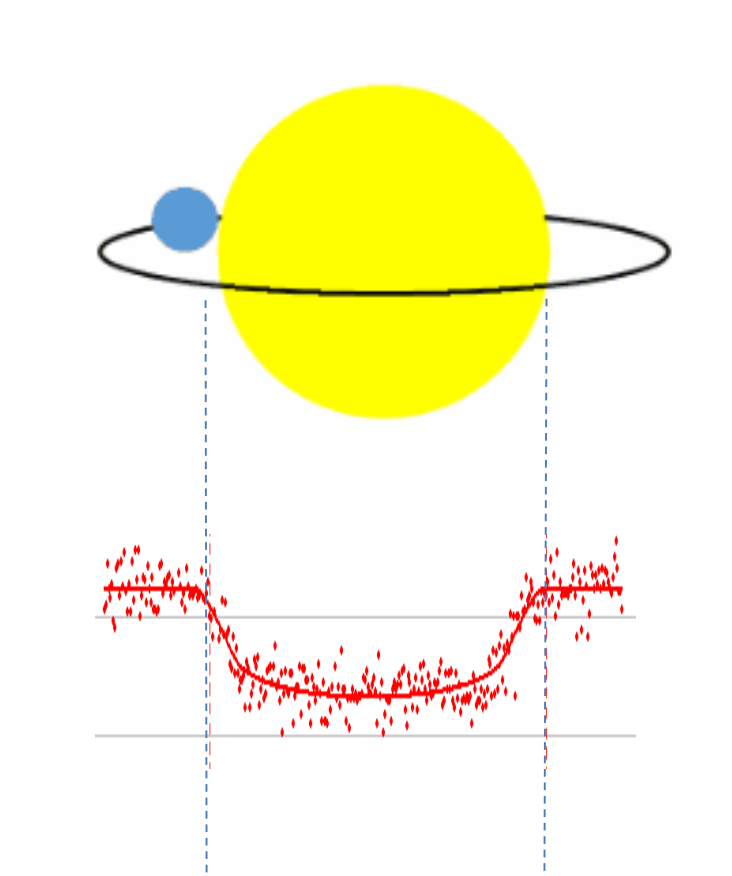
Overview

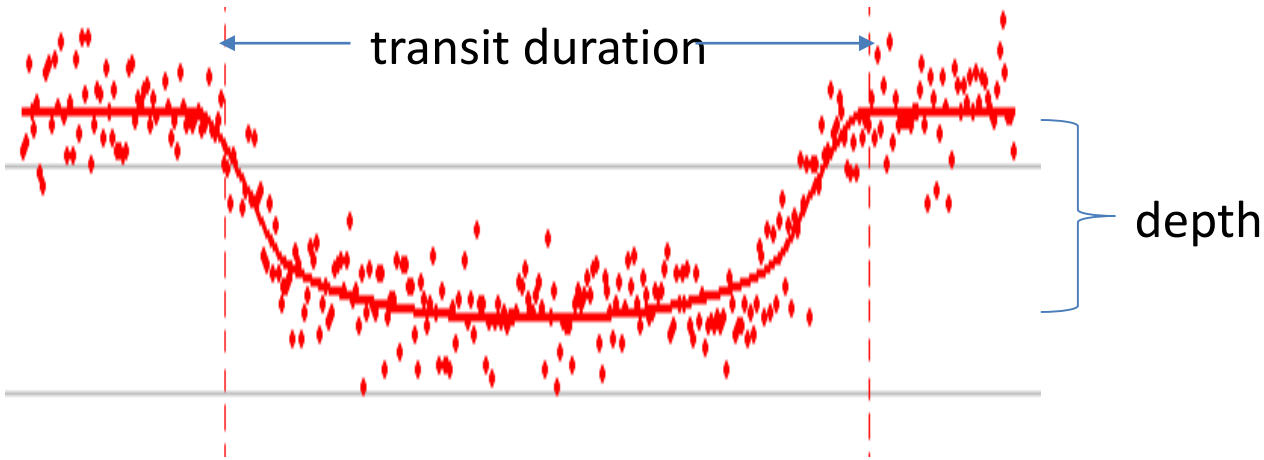
- The Transit Method and the Light Curve
- Time Standards
- Best Practices
- Online Resources
- Analysis and Modeling of WASP-12b Using AstroImageJ

The Transit Method

- Measures depth, length and shape of a light curve



What can we learn from the Light Curve?



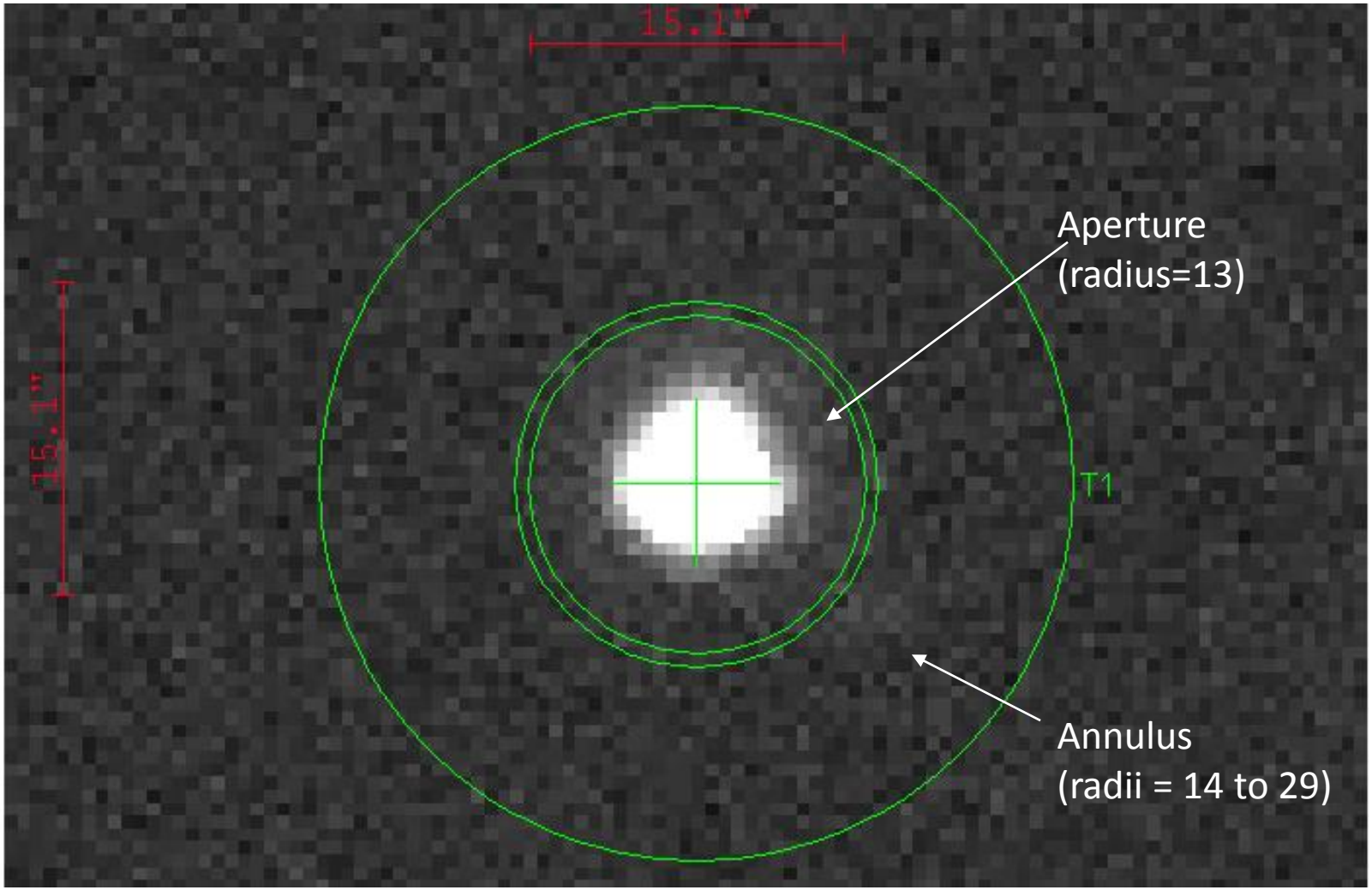
- Exoplanet radius
- Exoplanet orbital radius
- Exoplanet orbit inclination to our line-of-sight

Assumes knowledge of host star's radius and exoplanet's orbital period

How is the Light Curve Created?

- Differential Photometry is used to calculate the relative change in flux between the Host star and one or more comparison star
- The flux of the Host and comparison stars are first adjusted for background sky noise (due to light pollution, sky glow, moon light, etc.)
- A data point on the light curve = the relative change in flux of the Host star
- A best fit of the model of a transit is made based on these data points

The Key Tools of Differential Photometry: the Aperture and Annulus



What time did the transit begin?

Timestamp = reference location and time standard (clock)

- Local time at College Park, MD: 13:00 on June 30, 2016
- UTC time at Greenwich, England: 17:00 on June 30, 2016
- JD_{UTC} (above in Julian Date form): 2457570.208333
- HJD_{UTC} (Heliocentric Julian Date, UTC): 2457570.202599
- BJD_{TDB} (Barycentric Julian Date, Barycentric Dynamical Time): 2457570.203305

Best Practices

- Preparation Phase
- Image Capture Phase
- Calibration Phase
- Post-Processing and Modelling Phase

Preparation Phase

- Select an exoplanet target
- Collect preliminary information (use suggested Worksheet)
- Predict potential meridian flips for German Equatorial Mounts
- Choose appropriate exposure times: important that host and comparison stars do not reach saturation during the imaging session!
- Setup file directories: AIJ Analysis, Bias Files, Dark Files, Flat Files, Science Images
- Acclimate CCD camera to appropriate temperature
- Generate flat files (if twilight flats are used)
- Setup autoguiding system and make sure it is properly calibrated
- Synchronize image capture computer to USNO atomic clock (e.g., using Dimension 4 program)

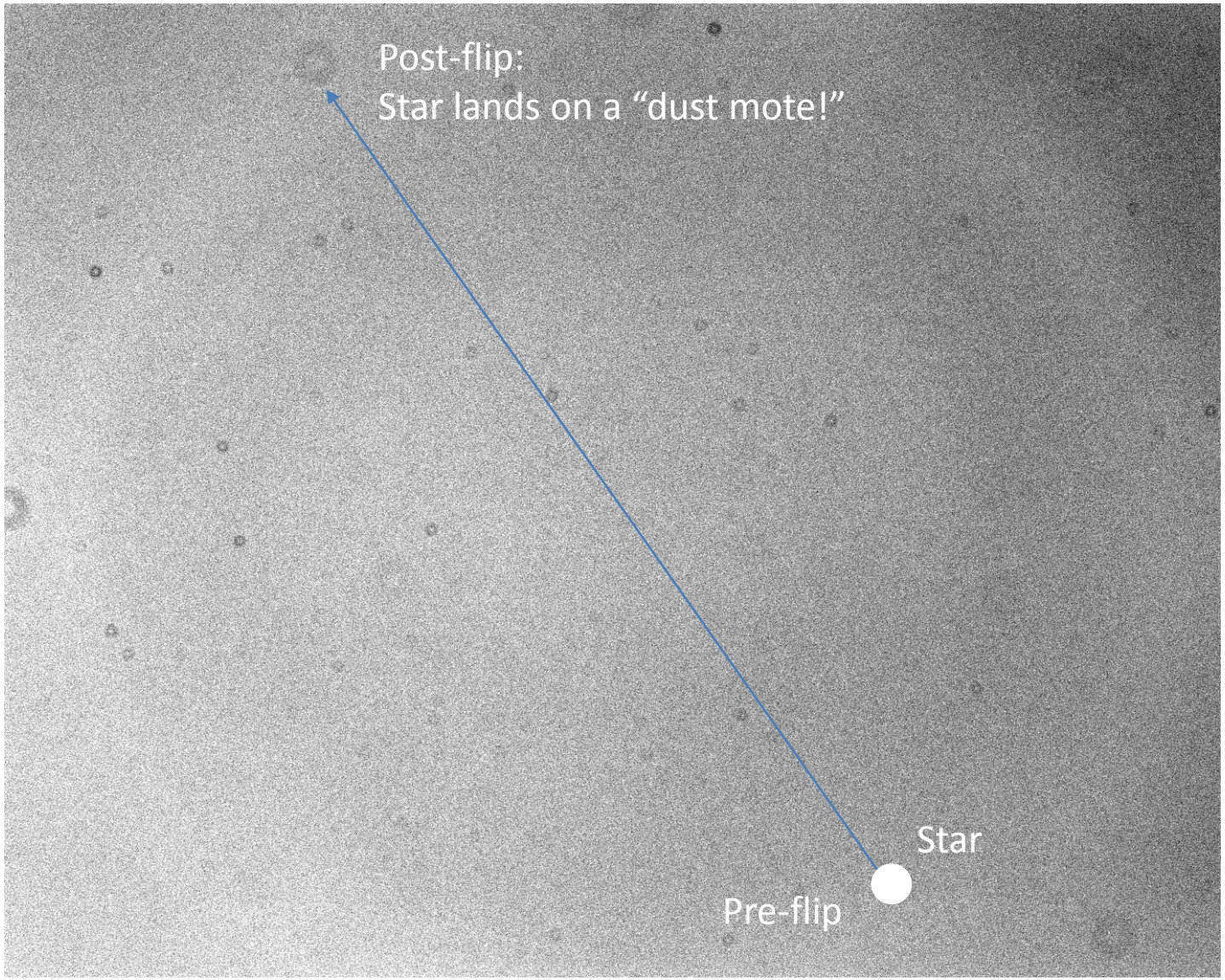
Image Capture Phase

- Begin imaging session 1 hour before predicted ingress time and end 1 hour after egress time
- Handle a meridian flip as expeditiously as possible
- After capturing Science Images, then conduct Calibration Phase

Calibration Phase

- Bias files – 0 second dark exposures
- Dark files – same exposure time as Science Images
- Flats:
  - Methods: twilight flats, dome flats, use of electroluminescence panels (preferred)
  - Exposure time set so that average ADU count = 50% of CCD linearity
- Flat darks – dark exposures at the same time as flats; however, not needed if scaling of above dark files is used
- Take an odd number so median combine can be used
- Take calibration files <u>for each observing session</u>!

The Importance of Uniform Flats



Post-Processing and Modelling

- Use AstroImageJ freeware to conduct this phase
- Calibrate raw images using bias, darks, flats
- Update FITS headers of calibrated files with AIRMASS and BJD_{TDB} times (Barycentric Julian Date/Barycentric Dynamical Time)
- Conduct differential photometry on calibrated files

Conduct Model Fit

- Enter into AstroImageJ:
  - Orbital period
  - Predicted ingress/egress times
  - Limb darkening coefficients
  - Optionally, mass of Host star
- Add appropriate detrend parameters
- Select and adjust placement of light curve plots
- Deselect any comparison stars whose flux is variable

Online Resources

- Exoplanet Transit Predictions:
  - NASA Exoplanet Archive: http://exoplanetarchive.ipac.caltech.edu/cgi-bin/TransitView/nph-visibletbls?dataset=transits
  - Exoplanet Transit Database (ETD) Website: http://var2.astro.cz/ETD/predictions.php
  - Extrasolar Planet Transit Finder: http://jefflcoughlin.com/transit.html
- Exoplanet and Host Star Parameters: http://exoplanets.org
- Time Conversion
  - Local time to JD_{UTC} : http://www.onlineconversion.com/julian_date.htm
  - JD_{UTC} to BJD_{TDB} : http://astroutils.astronomy.ohio-state.edu/time/utc2bjd.html
- Limb Darkening Coefficients: http://astroutils.astronomy.ohio-state.edu/exofast/limbdark.shtml

Analysis and Modeling of WASP-12b Using AstroImageJ

WASP-12b Observation

Observing Date/Time: January 5-6, 2016

Observing Site: Suburban Annapolis, MD

Image scale= 0.63 arc-sec/pixel

FOV=14x11 arc-min.

Filter: V

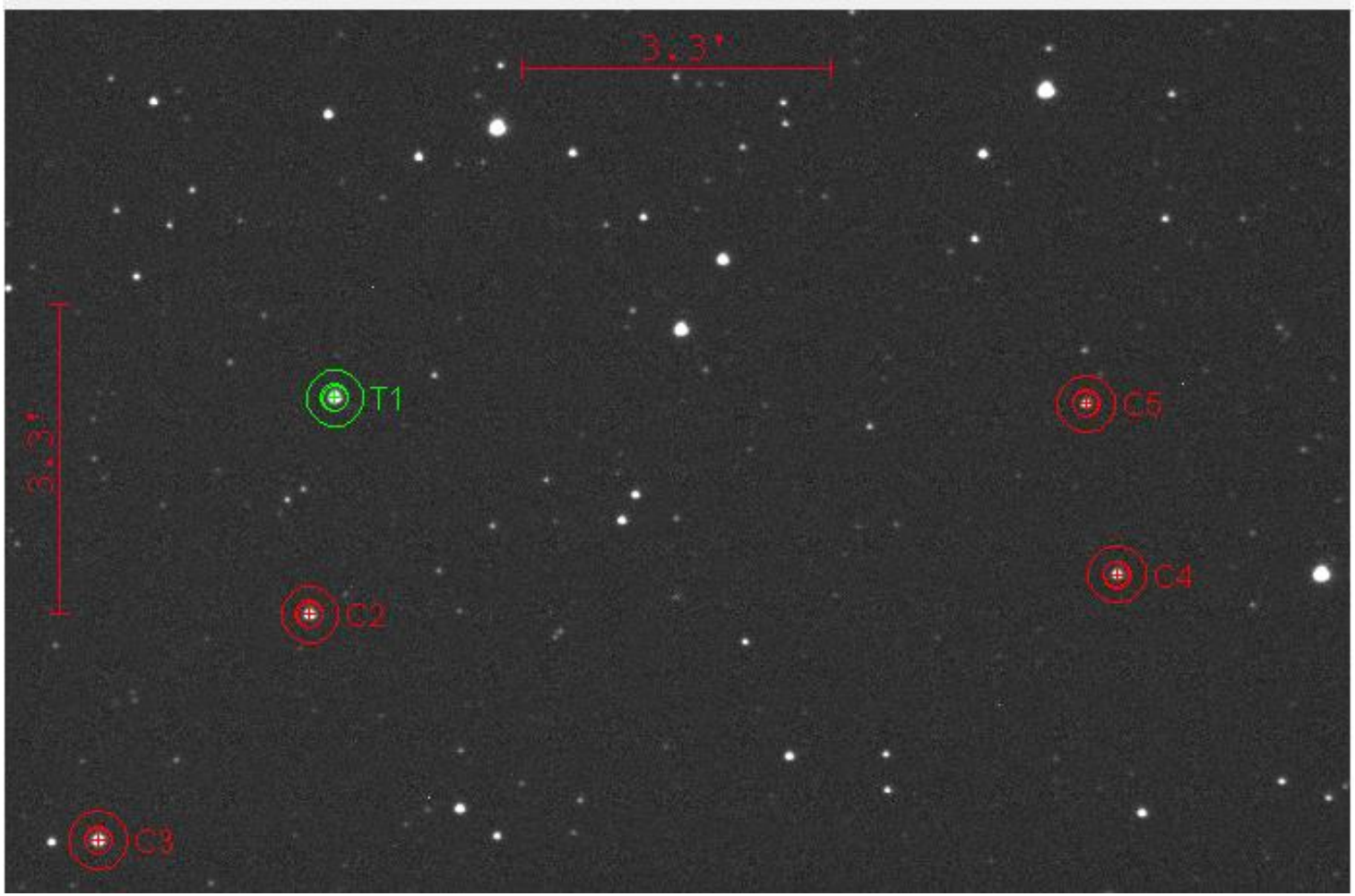
Exposures: 337@45 seconds each

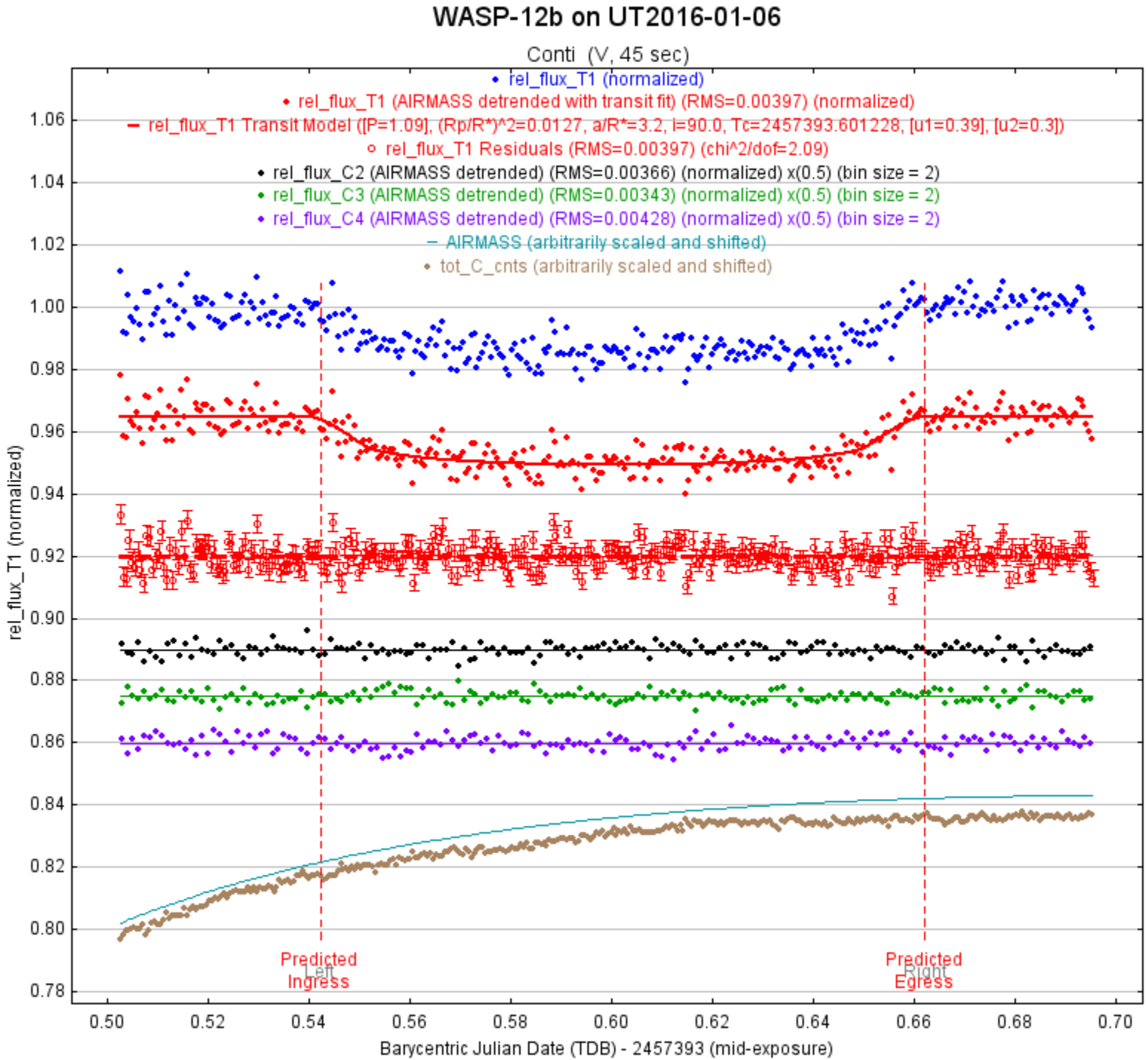
Observatory Setup
Location: Suburban Annapolis, MD

Worksheet

		Exoplanet:	**WASP-12b**		
		Observer:	**Dennis Conti**		
Item	Host Star/Exoplanet Information:	(click here)			
1	RA:	06:30:32.79			
2	Dec:	29:40:20.4			
3	Period (days):	1.0914			
4	R_*:	1.63			
5	T_{eff} :	6300			
6	V mag:	11.7			
	Suggested range of comp stars:	11.26 to 12.45 mag			
7	Link to Reference Paper (optional):				
8	Date of Observation (UT):	01/5-6/2016			
			BJD_TDB		
9	Ingress:		2457393.54874		
10	Egress:		2457393.67374		
	Predicted midpoint:		2457393.61124		
11	Model fit midpoint (T_c) in HJD_UTC (or BJD_TDB):				
	Approximate difference:			minutes	
	Observing Location:				
12	Latitude:		38:55:48.51 N		
13	Longitude:		76:29:17.78 W		
14	Altitude (m):		0		
15	Aperture (mm):		280		
16	Focal length (mm):		3010		
17	Make/model of CCD Camera:		SX694M		
18	Gain (e-/ADU):		0.3		
19	Readout noise (e-):		5.0		
20	Dark current (e-/pixel/sec):		0.003		
21	Point of where CCD goes non-linear (ADUs):		45,000		
		X	**Y**		
22	No. of pixels (unbinned):	2750	2200		
23	Pixel size (microns -unbinned):	4.54	4.54		
24	Binning used for this observation:	2	2		
25	Exposure time (secs):	45			
26	Filter used:	V			
	Limb darkening coefficients:	(click here)			
27	Quadratic LD u1:	0.39056081			
28	Quadratic LD u2:	0.3026992			
	Image scale (arcsec/pixel):	0.62	0.62		
	FOV (arcmin):	14.26	11.41		
29	FWHM (arcseconds):	2.68			
	FWHM (pixels):	4			
	Initial Settings:				
30	FWHM pixel multiplier:	3			
	Aperture radius:	13			
31	Inner annulus radius:	14			
	Outer annulus radius:	29			
	Final Settings:				
32	Aperture radius:	13			
33	Inner annulus radius:	14			
34	Outer annulus radius:	29			
		# of Science Images:			
35	Original #:	336	Final #:	336	
36	Images not used:				

Selection of Comparison Stars around WASP-12




WASP-12b on UT2016-01-06
Conti (V, 45 sec)
rel_flux_T1 (normalized)
rel_flux_T1 (AIRMASS detrended with transit fit) (RMS=0.00397) (normalized)
rel_flux_T1 Transit Model ([P=1.09], (Rp/R*)^2=0.0127, a/R*=3.2, i=90.0, Tc=2457393.601228, [u1=0.39], [u2=0.3])
rel_flux_T1 Residuals (RMS=0.00397) (chi^2/dof=2.09)
rel_flux_C2 (AIRMASS detrended) (RMS=0.00366) (normalized) x(0.5) (bin size = 2)
rel_flux_C3 (AIRMASS detrended) (RMS=0.00343) (normalized) x(0.5) (bin size = 2)
rel_flux_C4 (AIRMASS detrended) (RMS=0.00428) (normalized) x(0.5) (bin size = 2)
AIRMASS (arbitrarily scaled and shifted)
tot_C_cnts (arbitrarily scaled and shifted)
rel_flux_T1 (normalized)
1.06
1.04
1.02
1.00
0.98
0.96
0.94
0.92
0.90
0.88
0.86
0.84
0.82
0.80
0.78
Predicted
Left
Ingress
Predicted
Right
Egress
0.50
0.52
0.54
0.56
0.58
0.60
0.62
0.64
0.66
0.68
0.70
Barycentric Julian Date (TDB) - 2457393 (mid-exposure)

rel_flux_T1

User Specified Parameters (not fitted)

Orbital Parameters

Period (days)	Cir	Ecc	ω (deg)
1.09142245	☑	0.0	0.0

Host Star Parameters (enter one)

Sp.T.	Teff (K)	J-K	R* (Rsun)	M* (Msun)	ρ* (cgs)
A5V	7761	0.108	1.630	1.860	0.612

Transit Parameters

☑ Enable Transit Fit

☑ Auto Update Priors

Extract Prior Center Values From Light Curve, Orbit, and Fit Markers

Parameter	Best Fit	Lock	Prior Center	Use	Prior Width	Cust	StepSize
Baseline Flux (Raw)	0.559914002	☐	0.55974614	☐	0.111949228	☐	0.1
$(R_p / R_*)^2$	0.012724416	☐	0.014289873	☐	0.007144937	☐	0.014289873
a / R_*	3.216520358	☐	3.311238013	☐	1.9	☐	1.0
T_C	2457393.601228008	☐	2457393.602271072	☐	0.015	☐	0.01
Inclination (deg)	89.979982568	☐	82.5	☐	15.0	☐	1.0
Quad LD u1	0.390560810	☑	0.39056081	☐	1.0	☐	0.1
Quad LD u2	0.302699200	☑	0.3026992	☐	1.0	☐	0.1

Calculated from model	b	t14 (d)	t14 (hms)	t23 (d)	tau (d)	ρ* (cgs)	(e)SpT	Rp (Rjup)
	0.001	0.122729	02:56:44	0.097083	0.012823	0.5280	A5V	1.79

Detrend Parameters

Use	Parameter	Best Fit	Lock	Prior Center	Use	Prior Width	Cust	StepSize
☑	AIRMASS	-0.001602964152	☐	-0.008	☐	1.0	☐	0.1
☐	Meridian_Flip			0.0		1.0		0.1
☐	Width_T1			0.0		1.0		0.1
☐	Sky/Pixel_T1			0.0		1.0		0.1
☐	X(FITS)_T1			0.0		1.0		0.1
☐	Y(FITS)_T1			0.0		1.0		0.1
☐	tot_C_cnts			0.0		1.0		0.1
☐	BJD_TDB			0.0		1.0		0.1

Fit Statistics

Fit Statistics	RMS (norm)	chi²/dof	BIC	dof	chi²
	0.003969	2.089682	758.0445	330	689.5950

Plot Settings

		Line Color	Line Width	Symbol	Symbol Color	Shift
☑ Show Model	☑ Show in legend	red	2			
☑ Show Residuals	☑ Show in legend ☑ Show Error	red	2	circle	red	-0.045

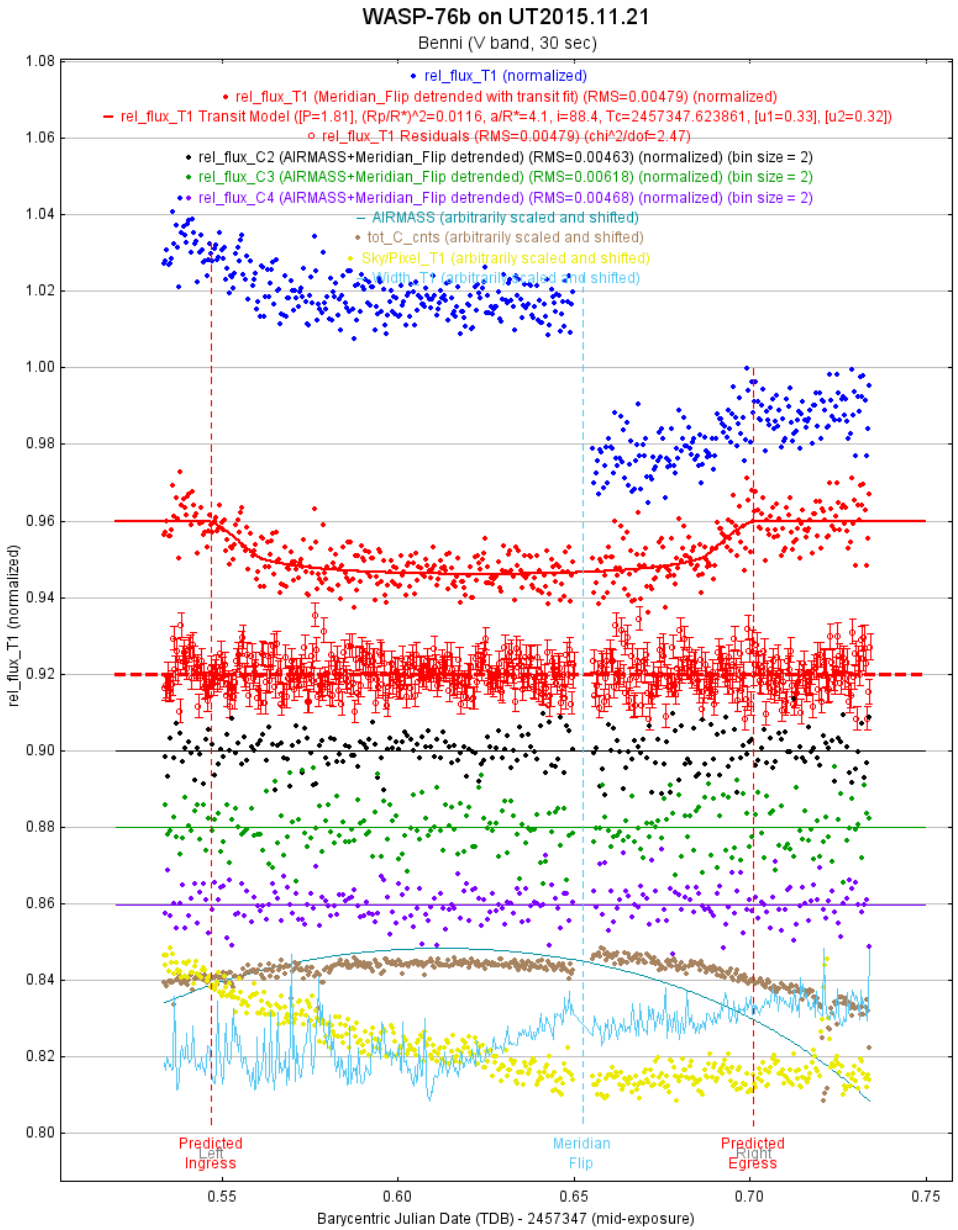
Fit Control

Fit Control	Fit Update Options		Fit Tolerance	Max Allowed Steps	Steps Taken
	☑ Auto Update Fit	Update Fit Now	1.0E-8	20,000	774

Accuracy of Model Fit Results for the Case Study

Parameter	Model Fit	Published	Accuracy
Transit depth	0.0127	0.0138	92.0%
Transit duration	176.7 min.	175.7 min	99.4%
Orbit radius	0.024 au	0.023 au	95.7%
Orbit inclination	90 °	82.5 °	90.9%
Planet radius	1.79_{Jup}	1.79_{Jup}	100%

Light Curve with Effects of Meridian Flip Detrended



Other Resources

1. A Practical Guide to Exoplanet Observing, Dennis M. Conti, http://astrodennis.com.

2. AstroImageJ, Karen Collins, http://www.astro.louisville.edu/software/astroimagej/.

3. Exoplanet Observing for Amateurs, Second Edition (Plus), Bruce L. Gary

4. The Exoplanet Handbook, Michael Perryman

5. The Handbook of Astronomical Image Processing, Richard Berry and James Burnell (comes with AIP4WIN photometry software)

6. The AAVSO Guide to CCD Photometry, Version 1.1, 2014

7. The AAVSO CCD Observing Manual, 2011