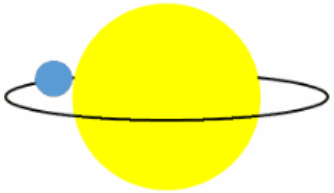
Exoplanet Analysis and Modeling Using AstroImageJ



by
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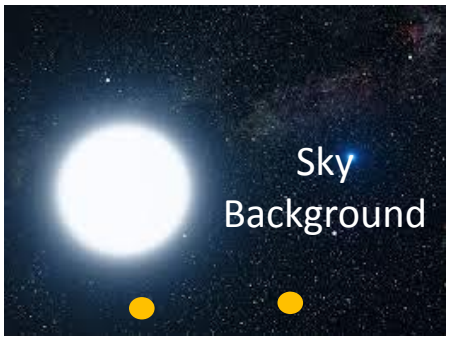
Overview

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

It’s all about counting photons!



Photons

Interstellar space

Earth’s atmosphere

QE of CCD detector

Electrons

Well

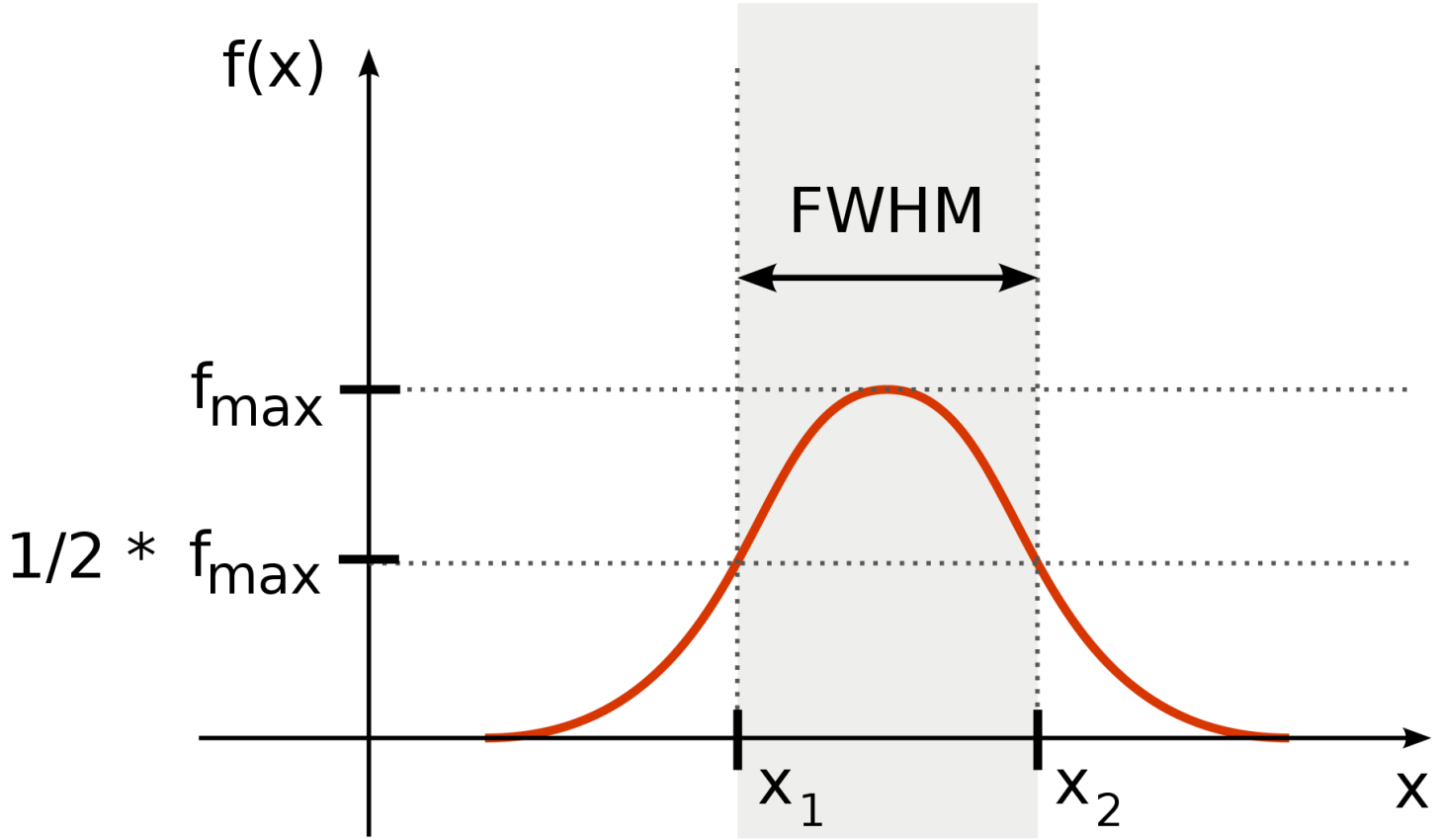
A/D Converter

CCD
Photosite

ADUs per Pixel

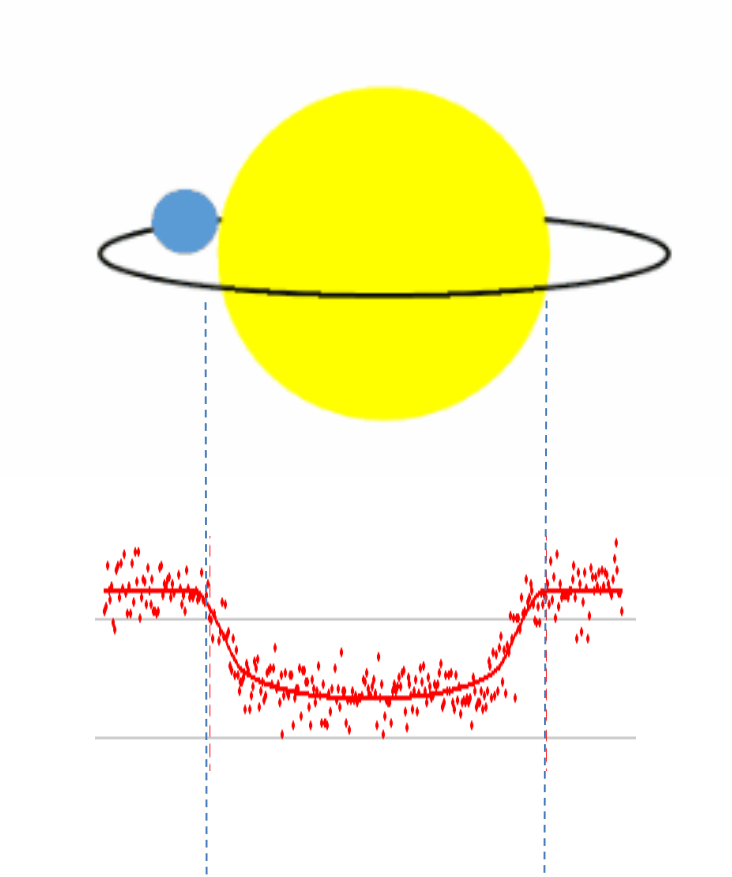
Pos	330	331	332	333	334	335	336	337	338	339	340	341	342
589	386	496	494	695	932	1170	1310	1198	1121	771	630	455	362
590	450	622	748	1052	1397	1916	1961	1815	1344	1069	883	590	466
591	494	687	936	1665	2356	3118	3425	2755	1967	1434	978	705	575
592	626	892	1461	2487	4470	5530	5689	4639	3051	2028	1251	672	610
593	768	1164	2195	4307	6910	9001	10074	7753	5251	2890	1713	1066	625
594	825	1538	3221	6535	10583	15120	15572	12125	7578	3886	2273	1346	748
595	930	1760	3530	7445	12876	18911	19476	15213	9978	5272	2919	1532	913
596	870	1521	3102	6141	11995	17968	18835	14734	9907	5523	2828	1696	958
597	664	1194	1898	4182	7531	10983	11624	10406	6526	3652	2275	1287	958
598	614	854	1179	1837	3298	4250	4765	4593	3258	1918	1346	881	589
599	409	452	732	1229	1471	1613	1678	1722	1385	1152	754	688	535
600	408	577	537	670	757	878	954	814	787	534	622	447	415
601	295	335	415	451	524	578	524	582	500	399	466	345	406

Full Width at Half Maximum (FWHM)

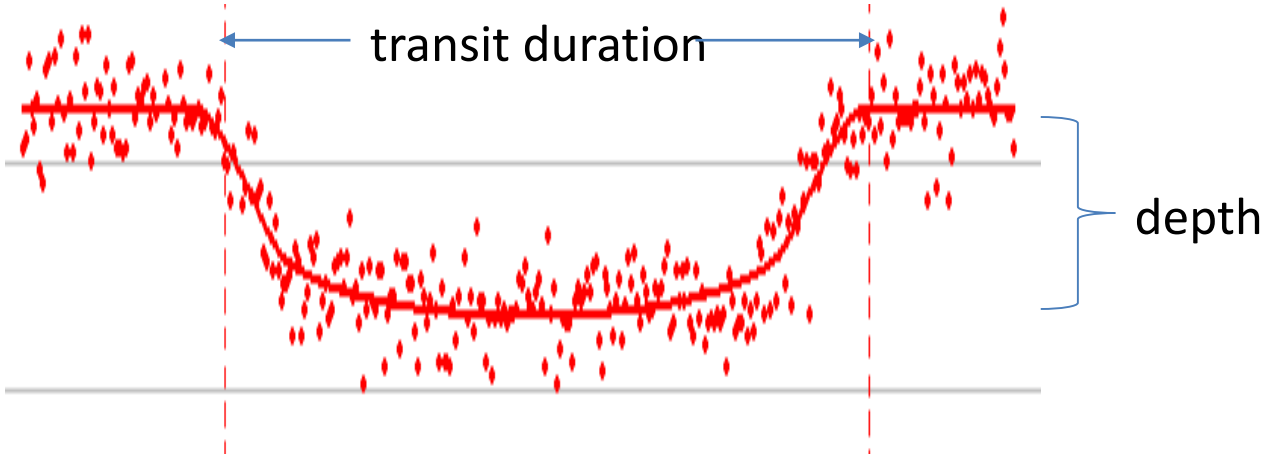


The Transit Method

- Measures depth, length and shape of a light curve



What can we learn from the Light Curve?



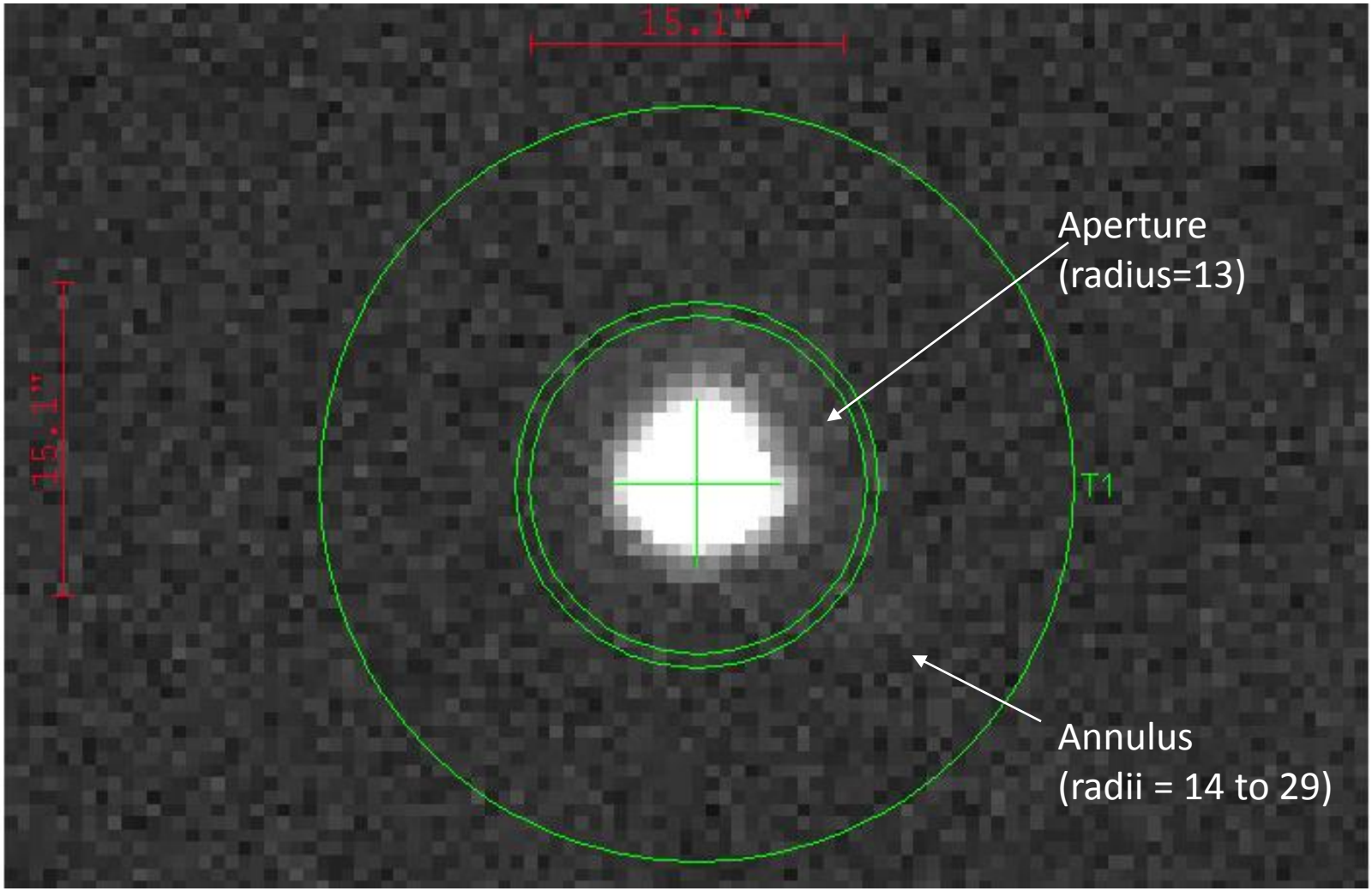
- Exoplanet radius
- Exoplanet orbital radius
- Exoplanet orbit inclination to our line-of-sight

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)

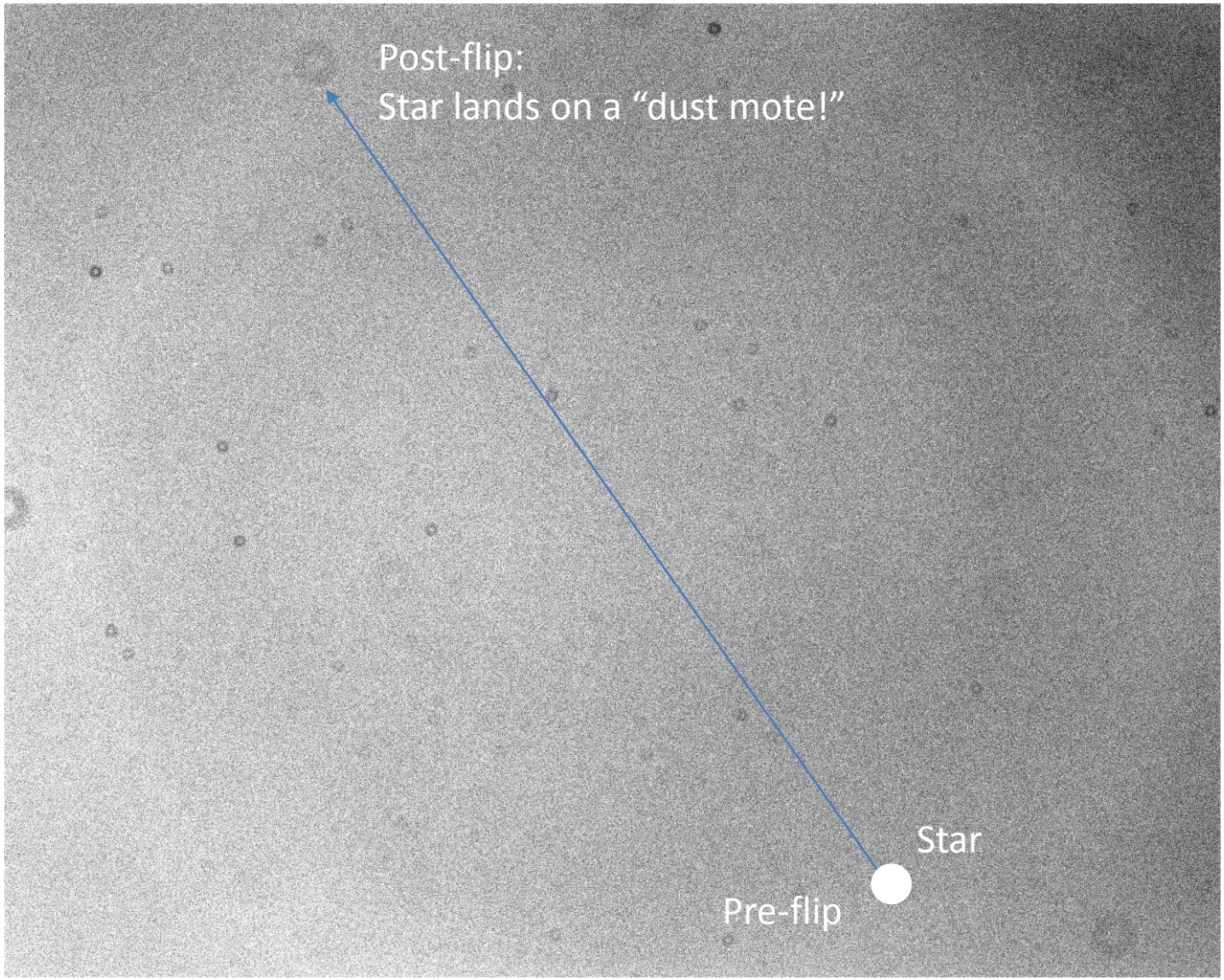
Image Capture Phase

- 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 for each observing session!

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

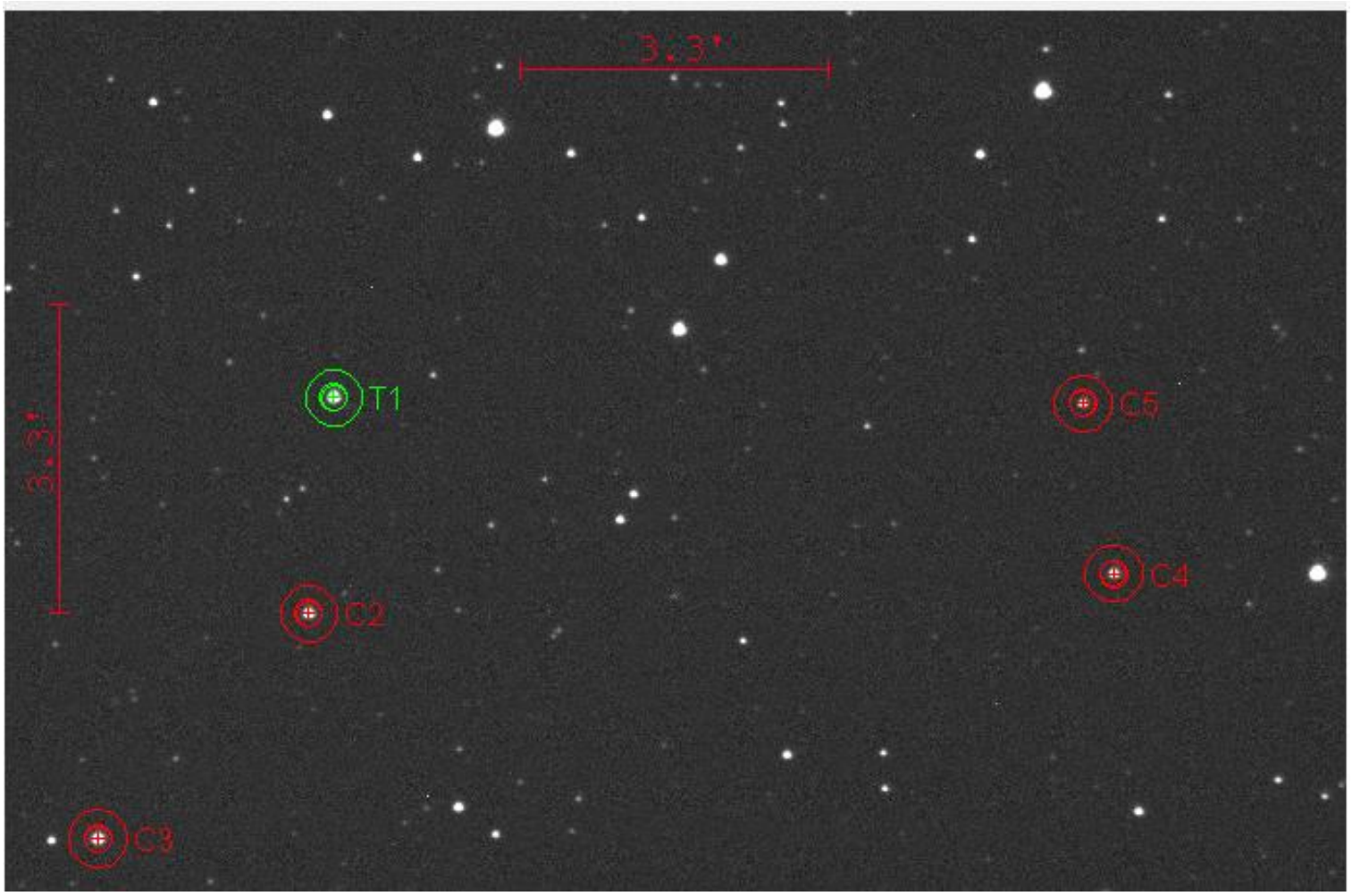
Exposures: 337@45 seconds each

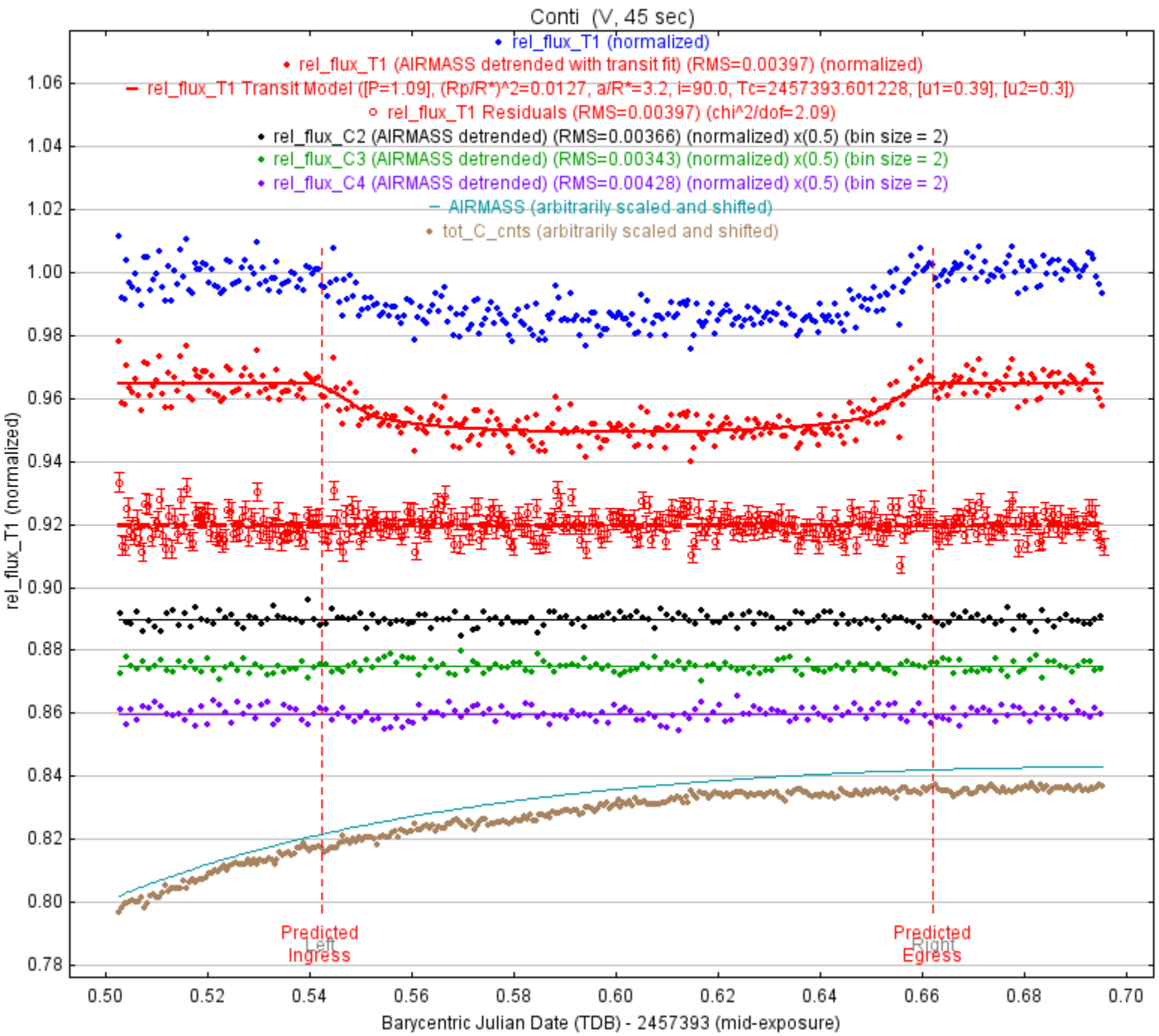
Observatory Setup
Location: Suburban Annapolis, MD

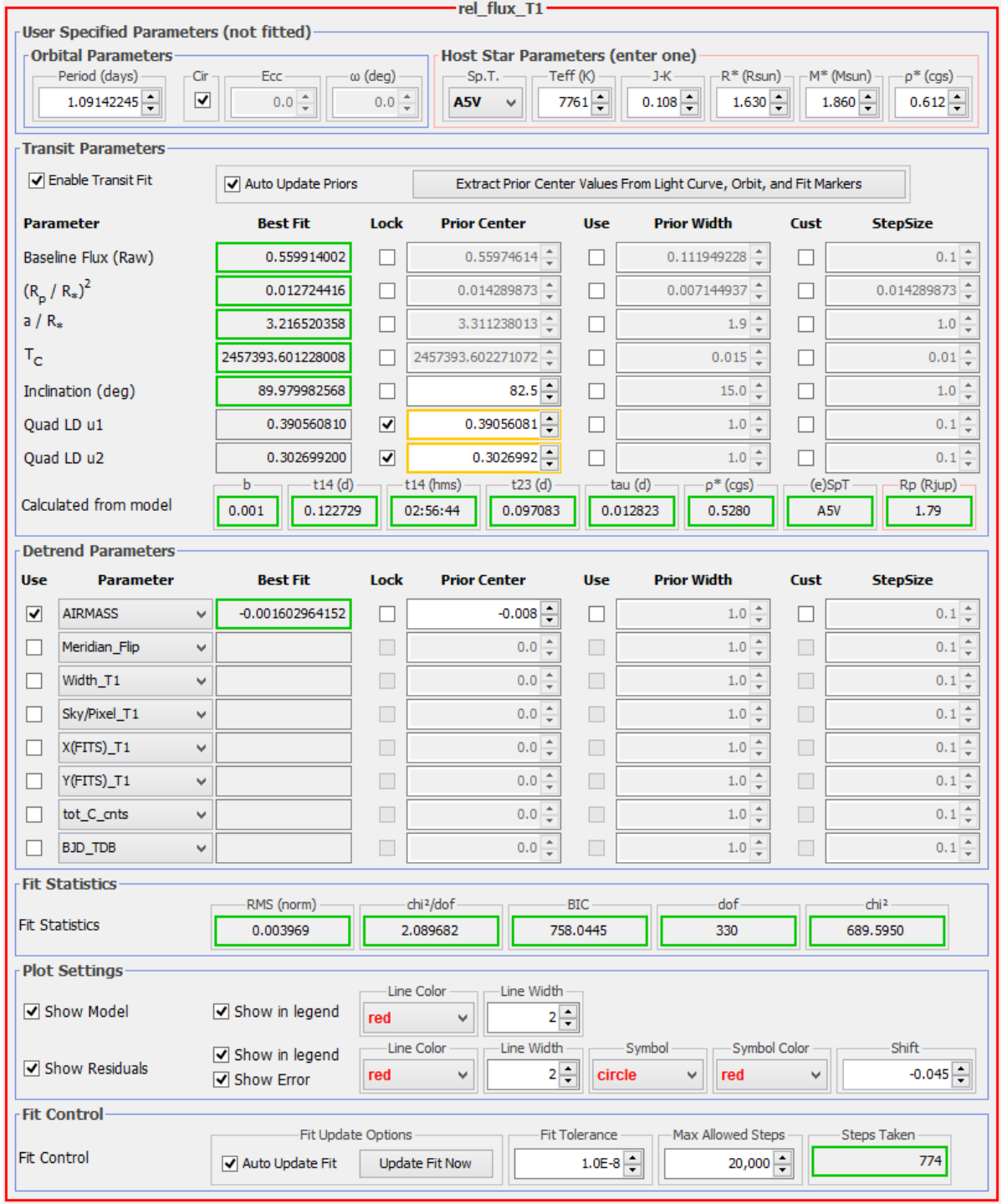
Worksheet

		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



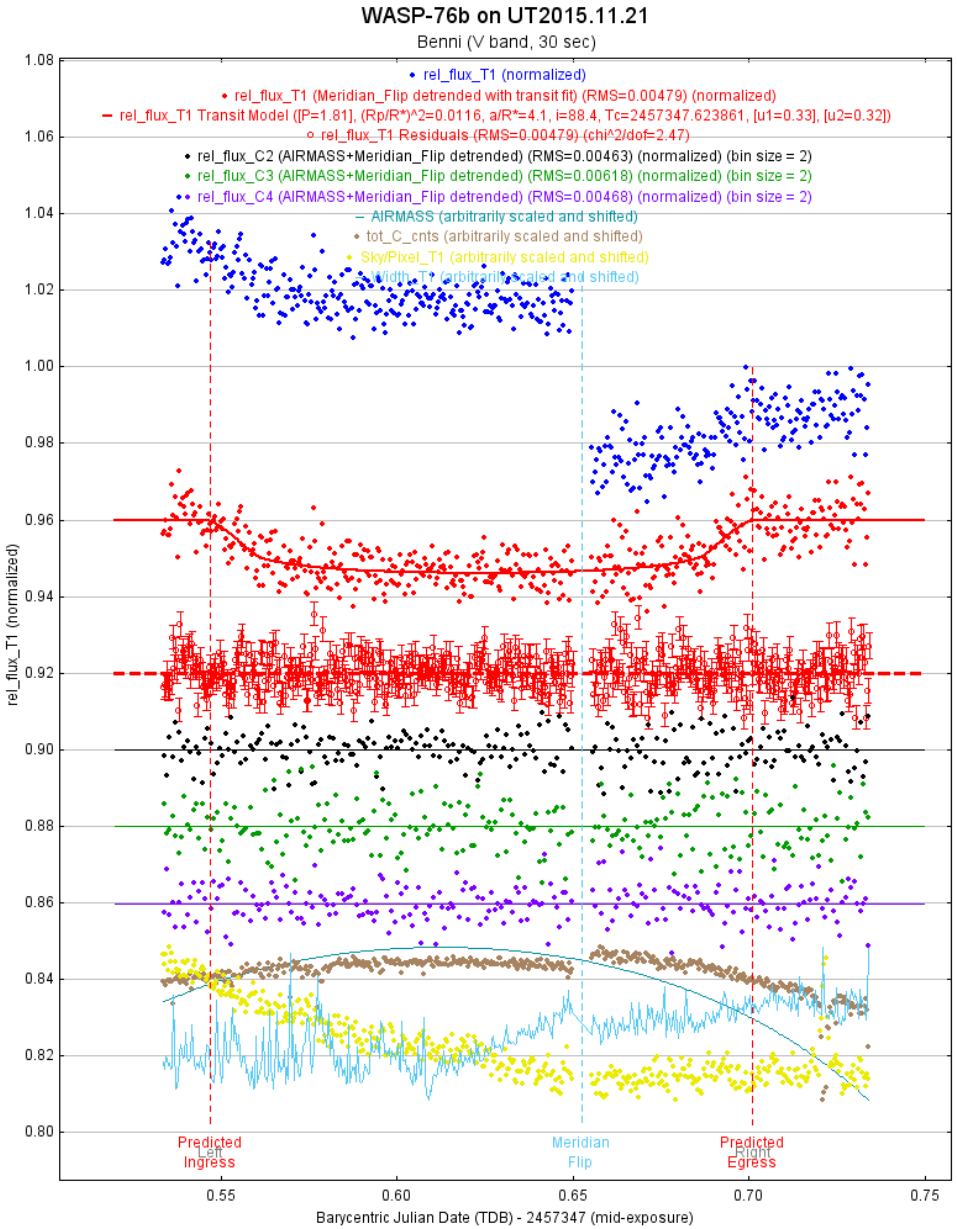

WASP-12b on UT2016-01-06
Conti (V, 45 sec)
rel_flux_T1 (normalized)
rel_flux_T1 (AIRMASS detrended with transit fit) (RMS=0.00397) (normalized)
rel_flux_T1 Transit Model ([P=1.09], (Rp/R*)^2=0.0127, a/R*=3.2, i=90.0, Tc=2457393.601228, [u1=0.39], [u2=0.3])
rel_flux_T1 Residuals (RMS=0.00397) (chi^2/dof=2.09)
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)
1.09142245
Cir
Ecc
0.0
ω (deg)
0.0
Host Star Parameters (enter one)
Sp.T.
A5V
Teff (K)
7761
J-K
0.108
R* (Rsun)
1.630
M* (Msun)
1.860
ρ* (cgs)
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
(Rp / R*)2
0.012724416
0.014289873
0.007144937
0.014289873
a / R*
3.216520358
3.311238013
1.9
1.0
TC
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
0.001
t14 (d)
0.122729
t14 (hms)
02:56:44
t23 (d)
0.097083
tau (d)
0.012823
ρ* (cgs)
0.5280
(e)SpT
A5V
Rp (Rjup)
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)
0.003969
chi²/dof
2.089682
BIC
758.0445
dof
330
chi²
689.5950
Plot Settings
Show Model
Show in legend
Line Color
red
Line Width
2
Show Residuals
Show in legend
Show Error
Line Color
red
Line Width
2
Symbol
circle
Symbol Color
red
Shift
-0.045
Fit Control
Fit Control
Fit Update Options
Auto Update Fit
Update Fit Now
Fit Tolerance
1.0E-8
Max Allowed Steps
20,000
Steps Taken
774

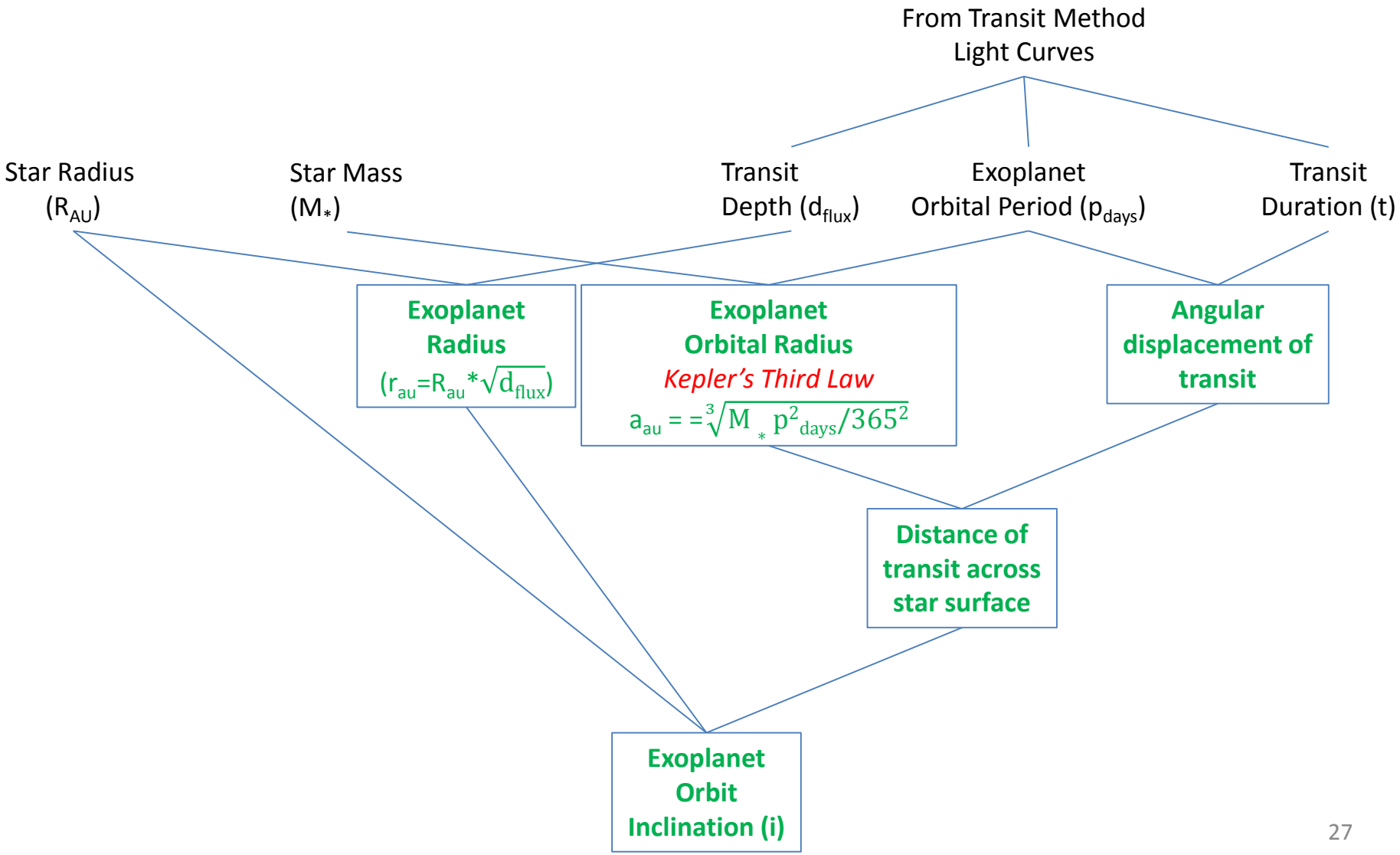
Accuracy of Model Fit Results for the Case Study

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



Derivation of Exoplanet Properties Using Transit Method



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